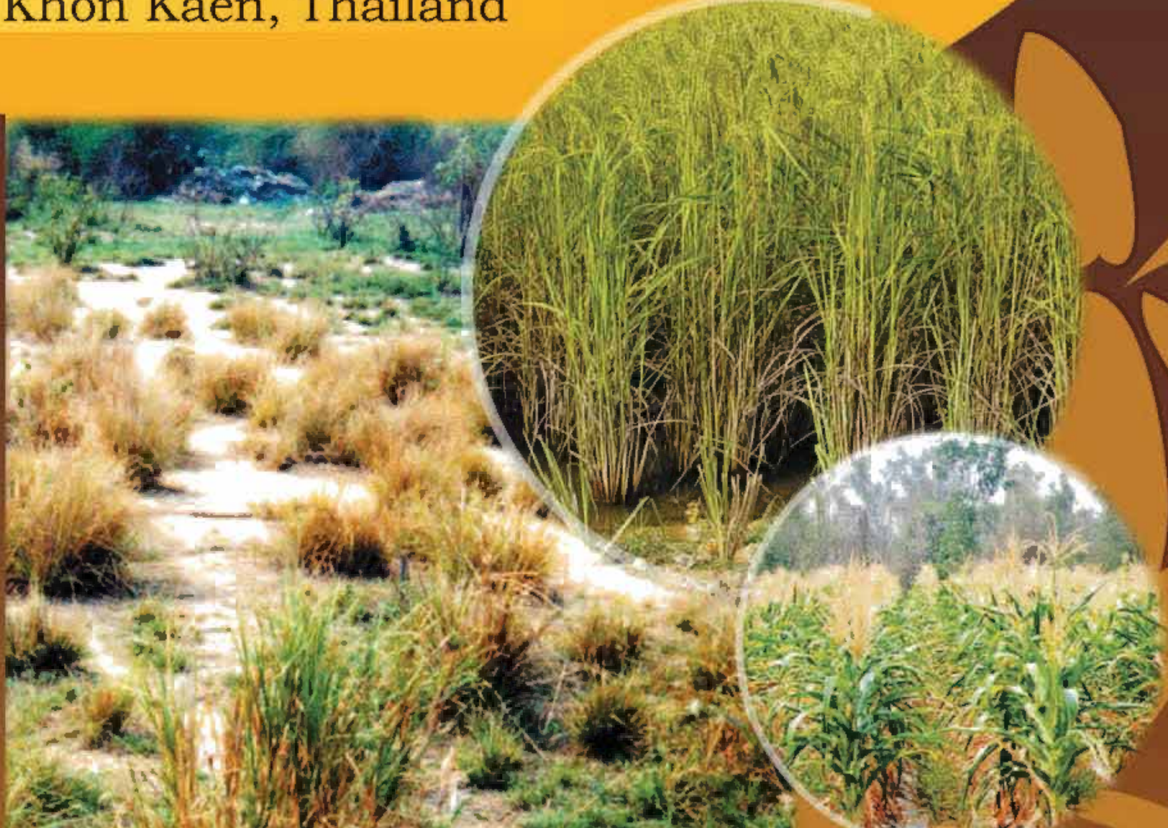
Management of Tropical Sandy Soils for Sustainable Agriculture

A holistic approach for sustainable development of problem soils in the tropics

27th November - 2nd December 2005
Khon Kaen, Thailand



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Preface

On behalf of the Organizing Committee of the first Symposium on the Management of Tropical Sandy Soils, we would like to extend our hearty welcome to all of you for making time available to attend the Symposium and more importantly, making your contributions in the form of papers and posters. This is the first of such a symposium and we hope that this will be the start of a regular series that will take place in different locations around the globe. The Symposium is jointly organized by the Land Development Department (LDD) of the Ministry of Agriculture and Cooperatives of the Royal Thai Government and the Institut de Recherche pour le Developpement (IRD) of the French Foreign Ministry. The International Water Management Institute (IWMI), Food and Agriculture Organization (FAO) of the United Nations, and Khon Kaen University (KKU) are co-organizers. We wish to acknowledge the financial support of the French Embassy in Thailand and for the scientific support of CSIRO Land and Water, and International Union of Soil Scientist (IUSS). In addition, thanks goes to all of the reviewers who had significant and valuable input in improving the quality of some of the contributions. Finally, I would like to extend a very special thanks to all the committees and individuals who gave up their time and devoted significant effort to making this event happen. Without their support and dedication this event would not have occurred.

The concept of such a symposium was conceived during a discussion between Drs Yuji Niino, Christian Hartmann and myself several years ago. We were discussing some the intrinsic properties of light textured soils from the tropics that included Thailand, Australia, South Africa, West Africa, the Congo and Brazil and their significance in the production of food, fibre and wood products for significant numbers of worlds population. In contrast to the unproductive sandy soils of arid and desert regions that most people associate with, these soils in the humid and semi-humid tropics are highly productive and of significant economic importance to several nations. Within the Mekong region alone more that 9 million hectares have soil textures that are characteristically light textured, with annual rainfall regimes of more than 1,200 mm that support large numbers of people. These soils were once covered by climax forests with highly efficient ecosystems that have to a large extent been cleared for alternative use. The question that arises is – are current changed land use practices sustainable and for how long? It was these questioned that were the drivers for the development of this symposium.

The response to the symposium exceeded all expectations of the Organizing Committee. There have been over 100 submissions as either oral or poster papers from participants from over 22 countries, of which the majority are from developing or emerging economies. These participants bring with them a wealth of knowledge and experiences to share and exchange. It is hoped that this symposium will be one that meets all of your expectations. Sawadee krup.

Andrew Noble
Secretary Organizing Committee
October 2005

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Executive Summary

Light textured sandy soils are ubiquitous throughout the tropics and constitute an important soil resource on which millions are dependent upon for their livelihoods. Spanning a range of rainfall regimes from the arid to the humid tropics, they present unique sustainability and environmental challenges to resource managers. Over the course of the symposium papers were presented on topics that focused on the physical, chemical and biological attributes of these soils as well as the important social and economic consequences of utilizing this resource.

Sandy soils are characterised by the predominance of rigid coarse particles that are inevitably associated with small amounts of clay minerals. These physical attributes contribute to the significant spatial and temporal variability that offers opportunities for greater use of spatial statistics in managing this variability. The inability of these soils to buffer changes in physical, chemical and biological predisposes them to accelerated rates of degradation.

A common thread in all of the presentations highlight large differences in soil behaviour associated with minor changes in intrinsic soil properties that cannot be entirely attributed to natural heterogeneity. This may in part be due to the precision and quality of analytical tools used to quantify clay and organic matter quantity and quality, bulk density, pore size distribution or continuity, and sand size distribution. Improved sandy soils characterization would lead to a better understanding of processes of soil change, a better classification of relevant factors into a hierarchical system and finally, to more precise management recommendation that would enhance the sustainable utilization of these soil.

Physical, chemical and biological characteristics of sandy soils often act as a severe limitation in crop production. Their sandy nature; low organic carbon content; high hydraulic conductivity rates; low nutrient and water supply capacity; limited buffering capacity; and inadequate biological diversity invariable necessitate high levels of external inputs. This has potential environmental implications under high rainfall or irrigated agriculture, elevated costs of production and very low levels of efficiency. By manipulating the constituent components of the soil through the addition and conservation of organic matter or through the physical application of organic waste and clay materials, the potential productivity of these soils can be realized. There are thus significant opportunities in developing innovative management strategies that enhance the productivity of these systems under the diverse range of climatic conditions in which these soils occur.

Any innovation must integrate not only the limited potential of the tropical sandy soils but also the socio-economic situation of the farmers. Within the tropics, these soils are predominantly occupied by resource poor and often marginalized communities that have limited capacity to address the aforementioned biophysical challenges. There is an urgent need for the disciplines of soil science, agronomy and the social sciences to come together to address these challenges in a holistic manner that effectively result in uplifting the livelihoods of the poorest. This is by no means a trivial task, but one that takes innovation and commitment by governments and leaders.

Welcome addresses

Deputy Minister of the Ministry of Agriculture and Cooperatives

Distinguished Participants, Guests, Ladies and Gentlemen,

It is with great pleasure that I join you today in officiating in the opening of this the First International Symposium on Tropical Sandy Soils. It is appropriate that this Symposium be held here in Khon Kaen, Northeast Thailand for several reasons as alluded to by the previous speakers.

The Government of Thailand recognizes that agricultural development is a key element in its goal to alleviate rural poverty and enhance the wellbeing of communities that are dependent on farming as their primary source of income. In the Ninth National Economic and Social Development Plan (2002-2006), the Government has set a target of less than 12 percent of the entire population will be afflicted by poverty. This is in line with targets set within the Millennium Development Goals. It is highly probably that this target will be reached under current favourable commodity prices.

There are several emerging issues that we are facing within the agricultural sector in Thailand itself and in the region as a whole. Significant demographic changes have occurred and will continue to occur in Thailand as people move from rural areas to the cities. Consequently there has been a significant decline in the numbers of young people adopting farming as a career. As a result labour-saving and productivity-enhancing technologies will need to be developed and adopted to support agricultural production in the years to come. We need to ensure that as we move to this new stage in agricultures evolution in Thailand that we have all the mechanisms and safe guards in place to ensure the adoption of sustainable and safe, environmentally friendly and economic enhancing agriculturally practices.

Added to this there will be significant increases in the global demands for grains. For example predictions have been made that if the pattern of Chinese food consumption in 2031 emulates current US consumption patterns, it would bring Chinese grain consumption to 1.3 billion tonnes from current levels of consumption of 382 million tonnes. The production of an additional 1 billion tonnes of grain with existing technologies would either require converting a large part of rainforests to agricultural land or the adoption of biotechnology and intensification of chemical agricultural, all with critical environmental implications. Consequently, there will be a requirement to significantly increase production of grain crops to levels never previously observed. These challenges will be even more significant when one considers that these improvements in production will have to occur within an environment with increases in demand for water from sectors other than agriculture, climatic change and declining land resources. These are challenges that you as scientist will need to overcome.

In conclusion I wish you all a fruitful and productive symposium and I do hope you will take the time to experience the hospitality and generosity of the Thai people.

Ladies and Gentlemen, I now declare the Symposium open. Thank you.

Director General of Land Development Department

Excellencies, Distinguished Participants, Ladies and Gentlemen,

I extend a warm welcome to you and hope your stay in Thailand will be memorable and fruitful.

I am particularly pleased that the of Land Development Department was invited to host this first meeting on light textured sandy soils and that Khon Kaen was chosen as the venue for this event.

The Northeast of Thailand has over 9.25 million hectares under agriculture and more than 2.2 million farms making it the foremost agricultural region of Thailand. However, farmers of the region have the lowest farm incomes in Thailand. In this respect the incidence of poverty in the region is approximately 37% of population. The poor physical attributes of the region are the primary cause for the low economic returns of farming enterprises and the high level of poverty in rural communities. The poor soil physical and chemical characteristics, erratic and uneven distribution of rainfall during the summer monsoon and limited irrigation development all contribute to low farm productivity. Unlike the highly productive Vertic soils of the Central Plain of Thailand, the northeast is dominated by deep light textured sandy soils of mixed origin with low nutrient holding capacity; low water holding capacity; and subject to physical degradation such as surface crusting and compaction. Added to this, over 3 million hectares are afflicted by some degree of secondary salinization derived from the mobilization of geological salt. The problem of salinization has been exacerbated by the extensive clearing of climax forests.

With all these soil and water related problems, the northeast is an ideal laboratory to evaluate and test new and innovative approaches in the management of these resources. In deed the Land Development Department has over the past 42 years undertaken significant research and development in addressing these problems. These have included the comprehensive surveying of the regions soils; routine mapping on a 10 year basis of the extent of saline soils; the introduction of innovative methods of addressing soil salinity and the reclamation of saline soils; the introduction of the highly successful ‘Soil Doctor’ test kit to villages to name a few. Some of our research and development will be presented here over the next few days in the form of papers, posters and the mid-symposium field tour.

As we move into the future, the role of the Land Development Department will become critical in addressing the soil and water related issues of the northeast in a development climate that can at best be described as dynamic. These challenges will include increasing the productivity of these marginal soils to ensure enhanced household incomes and more importantly, environmental sustainability and will only be achieved through a functional alliance between scientists, the community and policy makers. In addition, the skills and expertise that the Department has accumulated over the past four decades is and will be of significant benefit and assistance to our neighbours that may not be in the fortuitous position of Thailand.

I wish you all the very best in your deliberations over the next few days and I look forward to receiving the final report of the Symposium. To you all Thank you and Kop Khun krup.

Patrice Cayré, Director of the Department of Living Resources, l'Institut de Recherche pour le Développement (IRD)

Distinguished Participants, Guests, Ladies and Gentlemen,

It is a great pleasure for me, as co-organizer of this Symposium with the Land Development Department, to welcome all the delegates to Khon Kaen today.

IRD has the mandate to carry out strategic research with its partners in developing and emerging countries. It is therefore no surprise that we started to get interested in the properties and management of sandy soils as early as the late 40'. Indeed, sandy soils are widespread in the dry part of sub-Saharan Africa were IRD first developed its activities. There was an urgent need to characterize their characteristics and properties, and to find ways to overcome their limitations. Our researchers addressed this need and in most francophone countries of sub-Saharan Africa were surveyed and mapped in the 60' and the 70'. Then, in the 80', IRD started new collaborations in South America. The fate of the sandy soils was again an issue, in particular in Brazil and in French Guyana. As a logical consequence of this long past, our collaborations in the field of soil science, agriculture and environment started in Southeast Asia with projects associated with the sandy soils of Northeast Thailand.

We first started a project with the Land Development Department on the chemical and physical degradation and rehabilitation of the poor acid upland soils in an experimental station located in the Korat region. Further to these initial studies we jointly developed a project on soil salinity in the Khon Kaen region. Soil salinisation is an important issue in Northeast Thailand, as you will discover during this Symposium and the field trip, but also in many other areas around the world. We have lately been involved in a new project, with our two Thai partners (Land Development Department and Khon Kaen University) and in collaboration with the International Water Management Institute (IWMI). This project is focused on the effects of the rapid development of rubber cultivation on the soil and water resources of the region. When I say region, I mean Southeast Asia, which includes not only Thailand, but also Laos, Cambodia, Vietnam, and Southern China. Rubber tree is being extensively planted throughout Southeast Asia in marginal conditions, with drastic effects on the ecology and the livelihood of the farmers. We have decided to launch such a collaborative project because it provides an opportunity to both make good science and develop regional collaboration. Such collaboration would benefit all the countries involved and re-enforce the existing projects. Indeed, IRD has developed activities in Laos and in Vietnam in the last 5 years on the relationships between land use changes and soil properties in mountainous regions, and we hope to start new projects in Cambodia together with IWMI soon.

Thus IRD has given considerable attention to the sandy soils of Southeast Asian in the last ten years, and this was one of the reasons for co-organizing this Symposium. I must stress that all the projects have been based on strong collaboration with the governmental institutions of different countries with the strong support of the French Embassies, that we would like to thank here.

The Symposium will be a great opportunity to give a general overview of the present knowledge on the management of tropical sandy soils and to expose the latest results obtained throughout the world. We expect that it will help identify the research needs and suggest directions. IRD is committed to assist its partners in pursuing research projects on these promising tracks.

I wish you all a very interesting and fruitful Symposium. Thank you for your attention.

FAO Regional Office for Asia and the Pacific

The Vice Minister of Agriculture and Cooperatives
Governor of Khon Kaen Province
Distinguished delegates and participants
Representatives from partners, donors and NGOs
Ladies and gentlemen,

On behalf of Dr. He Changchui, Assistant Director-General and Regional Representative of FAO Regional Office for Asia and the Pacific, I would like to extend a warm welcome to this international symposium Management of Tropical Sandy Soils for Sustainable Agriculture.

Natural resources in the region are subjected to increasing degradation, pressure and competition, mainly due to population growth, urbanization and economic development. The transition from subsistence agriculture towards intensification, commercialization and industrialization in response to increased population and changing consumption patterns increases water pollution and consumption and degrades physical, chemical and biological properties of soil, resulting in lower productivity. Land becomes more vulnerable to natural disasters, in coastal areas, floodplains, rangelands, mountains and rural watersheds, and their impact becomes much more serious.

To address these issues, FAO focuses on activities aiming at improved management and sustainable use of land and water resources for food security and improved livelihoods. Priority areas of the current programme include sustainable land management, soil and water conservation, land resources evaluation and monitoring; integrated plant nutrient management; and soil biodiversity and fertility/productivity improvement.

The degradation and misuse of land and water resources affects the livelihood of rural people, the food security at the national level as well as the socio-economic development of the population in more than 110 countries. Particularly the poorer and marginal population groups and women, those who suffer from inequitable access to natural resources, are most affected while the income gap between rural and urban areas increases.

Land degradation reduces land quality and affects available water resources. An estimated $42 billion in income and 6 million hectares of productive land are lost every year due to land degradation and declining agricultural productivity. About 2000 million hectares of soil has been degraded through human activities. Land degradation is thus closely linked to poverty in developing countries and potential threat to poor people who live in areas with fragile soils and unreliable rainfall. Realizing traditional systems of land use are either breaking down or no longer appropriate due to population pressure, the alternative management and technology options to cope with the problems are needed.

Sandy soils cover some 900 million hectares, mainly in the dry zone. Several million hectares of highly leached sandy soils are found in the perhumid tropics, notably in South America and in parts of Southeast Asia. Small areas of sandy soils may occur in all parts of the world. Many sandy soils are non-used wastelands. Sandy soils in the tropics are chemically exhausted and highly sensitive to erosion and therefore demand cautious management if used for agriculture. Main production constraints are due to its course texture a low water holding capacity and high infiltration rate which represent the main production constraints.Nutrients contents and nutrient retention are normally low, thus causing a low inherent fertility status for agricultural production. However , sandy soils can be very productive when appropriate management is applied and water is available for crop cultivation by means of irrigation or because of a shallow water table.

FAO promotes and assists governments and the international community mitigating land degradation, desertification, deforestation and loss of biodiversity as crucial means for reducing hunger and alleviate poverty. Integrated planning and management of land resources to improve management of natural resources are addressed by developing and testing effective assessment methodology for land degradation. FAO will assist implementing national and regional projects to marshal the extensive knowledge and varied expertise already available worldwide by creating a new, more interactive and comprehensive framework of assessment methods, and by capacity building and testing this framework in real-world situations.

Ladies and gentlemen,

The overall goal of the symposium is to exchangeknowledge and experiences between scientists, extension practitioners and policy makers on land and water degradation and sustained management and remediation of degraded land and water resources.

It gives me much pleasure to see participants from all regions where large areas of sandy soils have been utilized for agriculture, and representatives from a large number of international and regional organizations at this symposium. The task ahead of us is challenging, and no single organization can deal with it effectively alone. FAO is ready and willing to work with partners to undertake the work that lies ahead for integrated approaches for sustainable management of tropical sandy soils.

I am confident that your collective wisdom and expertise provide a firm footing to build this strategy.

I wish you well in your endeavour and look forward to seeing the output of this symposium.

Thank you.

Conference key note addresses

Strategic management for poverty alleviation of people inhabiting problem soil areas

Rojanasoonthon, S.[1]

Abstract

The relationship between poverty and the inability of communities to acquire basic needs to improve their standards of living is quite distinct. In most cases, the lack of water and the incapability of individuals to deal with problem soils are the major factors leading to reduced well being of the people. His Majesty the King shows His utmost innovation in using the "natural way" to address this problem. The six development study centers located strategically throughout the country signify the problem soil areas and their rectified methods to be learnt by the farmers. A strategic approach is the key factor here and stems from first hand information of the area and the need of the local people. The so called "natural way" concentrates on retaining rain water longer in the soil or inducing more water in the area as well as in the soil. Building top soil, growing more crops and trees, bring back moisture or retaining water through vetiver grasses to the soil and in the area are necessary correction measures so that agriculture is possible. The approach is also multidisciplinary in nature with various participatory actors. The "New Theory" is another attempt by His Majesty to signify a sustainable unit that people can comfortably live with enough to eat. Full concepts of sufficiency economy are needed to apply in this context. The Royal Project in the north signifies good long activities that took 36 years to develop and has a truly sustainable approach. We are successfully running parallel value chain creation, having good management in teaching the hill tribes to grow valuable crops for the market as well as maintaining sustainable natural resources and a stable environment. Once these people have the sense of belonging to the highland area the parallel value chain as practices in the Royal Project Foundation is possible. Time is a necessary constraint in this type of endeavour. Intelligence, utmost thoroughness and carefulness are needed in bringing the various fields of knowledge to be used in every step of planning and executing the work to be done. Therefore, above all, good management is indispensable in this attempt. The final outcome is nevertheless, the ability to be self reliant by the hilltribes as well as maintaining the ecological sound principles of the natural resources and environment.

Introduction

Problem soils are substancial in occurrence in Thailand. Being sandy or infertile is only one of the very common conditions that influence peoples livelihood making it difficult to make a living. There are also many other soil related conditions such as saline soil, shallow soil, gravelly soil, hard pan soil, lateritic or plinthitic soil, acid sulphate soil, and many others. Many of these problem soils are the result of substantial use of the land without any rehabilitation processes being put in place. Soils become, depleted, degraded, eroded or washed away. This problem is spreading as time goes by, particularly with increasing population pressure or more mouths to feed. The situation is getting more serious, particularly when other conditions such as water crisis and related problems are escalating. Taking the problems of sandy and infertile land, production from such areas is limited, the people then, do not have enough to eat. They, finally, fall in the categories of poor or very poor. Mr. Anan Panyarachoon, a noble Thai statesman once, pointed out that there are 4 categories of conditions that relate to the poor. They are poor in money, opportunity, knowledge and life path. These are all related, being poor in one of the aforementioned condition will affect all the others. Likewise increasing one of these factors e.g. money, alone will not alleviate the poverty.

ADB reported that in the Asia and the Pacific region, there are at least 780 million people, consider poor, 57% earn less than $2 per day, and the "ultra" poor (Surarerk, 2005) with less than $1 per day amounts to 600 million people. Of all these, poor people, 300 million in India and 100 million in China. In Thailand the TDRI sets the number for the poor at 10 millions. Others think that the figure may be as high as 12 millions.

[1] Royal Project Foundation, Kasetsart University, Bangkhen, Bangkok 10900, Thailand

Alleviation of poverty is a very common strategy observed by most countries and international organization. How much, how far that they can achieve is one of the conditions that needs to the judged overtime using some specific indicators. In Thailand, every other government has tried their hand in poverty alleviation, usually with mixed success (Surarerk, 2005).

Thus, tropical sandy soil conditions are one of the very early causes of the problem which needs careful management. The inability to alleviate poverty in the past is due to the lack of a multidisciplinary approach, is needed for this kind of operation and management. The elaboration that follow covers the necessity of rehabilitation processes for strategic approaches.

His Majesty the King's initiative's has many cases studies that address soil problems and all these related activities are strongly delineated. They are all multidisciplinary in nature. The last coverage depicts the sustainable development approach as signified in the activities of the Royal Project Foundation following 36 years of experiences in development activities that have focused on the highlands, in Northern Thailand.

Rehabilitation Processes

Development for rehabilitation must take account of the local environment in terms of the physico-chemical environment, the socio-economical environment and the cultural environment. The first step in the process in to visit the location and find out what the people really want and then fully explain how they can best achieve their aims in practices. To be exact, it must answer the basic needs and improve the standard of living. The rehabilitation processes should cover the following main items.

Improvement of the soil and related factors

Constraints that affect the soil can be described are physically, chemically and biologically. If it is a sandy soil, fine material needs to be added directly or indirectly such as in case of His Majesty's deliberation. He suggests the slow method by trying to retain rain water longer in the soil so that plant could grow on them and improve further the moisture to the soil . If it is fruit tree, finer material can be placed in the planting hole at the establishment of the tree. A U shaped row of vetiver grasses could be planted immediately on the lower slope of each tree to retain moisture longer in the soil. If in the field crop area or vegetables, leguminous crops can be ploughed in several times to improve the texture and biological factors of the sandy soil. Chemical fertilizers could be added according to the results of analyses. This "natural" way of His Majesty usually takes time but it is reasonable and sustainable. If water can be obtained more readily through reservoirs or streams, the process may be faster. Rows of vetiver grasses are quite effective in helping water retention in the soil, and thus more available to plant growth. In the sloping area where vetiver grasses rows were most effectively produce the so called "living natural wall" to check erosion. Strategy has been used to describe this.

Another important factor that is often neglected, is the role of social factors in influencing development. In any rehabilitation procedure, among the villagers we should find their natural leaders or encourage the formation of groups to solve their own problems and lay the foundations for being self-sufficient. It closely follows the structure of traditional Asian society which usually follows a family – like pattern in its leadership. A "father figure" who will do what ever is necessary to keep them in good health and prosperity.

His Majesty's Approach on Multidisciplinary Improvement of Problem Soils

- ***Khao Hin Son, Chachoengsao Province***

This Royal Development study Center is located on sandy infertiled soils. Although the annual rainfall is as high as 1,200 mm/yr the soil can retain only half the amount of incoming precipitation. Severe erosions on open surfaces deplete all those would be nutrients of the soil. His Majesty the King pointed out that the aims should be to maintain the balance of nature and develop the soil to slowly sustain a variety of crops. Most of all to retain water longer in the soil so that the plant can grow. Vetiver grass was established, particularly along the contour lines of the hill slope. Top soil was missing due to erosion in the early stages of their development program. Leguminous green manures were ploughed in repeatedly to improve the top soil condition. His Majesty, after almost 15 years, indicated with pleasure that now the place is nice with trees, a lot of people helped to achieve this goal and now it can be a role model for the farmers. He also mentioned that earlier even cassava could not grow as these soils, now it was completely changed, and everybody was happy.

- ***Huai Sai, Phetchaburi Province***

The Huai Sai the site is an excellent rehabilitating example of truly bad land. The soil is sandy infertile with salt as well as a hard pan in the subsoil. Forests had been completely destroyed and erosion were very severe. When His Majesty saw the area he said if we did nothing to it, it will turn into a desert. With limited rainfall, there was a need to store water, consequently at least four reservoirs were constructed. According to His Majesty suggestion, there were many ingenious simple procedures that would assist in preserving the top soil during cultivation. He strongly suggested the use of vetiver grass as a natural dyke deep into the soil, since vetiver produces a thick deep root system. This natural dyke would help to retain the moisture longer in the soil, thus helping trees to grow as well as other crops including vegetables.

Two important phrases were said by His Majesty to signify the important role of people participation i.e. “Forester should plant trees into the people heart first, then those people will plant trees in the ground and look after them by themselves”. Also “If you leave the forest to regenerate by itself, given enough time it will turn to be full forest in due course.”

Two other types of land with problems associated with soil for comparison can be elaborated as well:

- ***At Khao Cha-Ngum, Ratchaburi Province***

This is an example of degraded soil in sloping areas together with sandy texture soil with gravelly laterite or phinthite pebbles. No top soil remain to begin with, His Majesty again, pointing out that the area needs moisture in order to facilitate plant growth. Manures and green manures through leguminous plants had been repeatedly ploughed in. In addition, vetiver grass was introduced and functions very well in retention of water when planted along the contour lines. Each fruit tree was reinforced with vetiver strip along diamond shaped polders to retain more water around the trees. It should be noted here that, this type of land, shallow soil with thick gravelly laterite pebbles in Thailand cover at least 68,765 km^2. Again, His Majesty and a group of soil experts finally, built up the area into a productive site once again it took more than 10 years.

- ***At Phikun Thong, Narathiwat Province***

Here the situation is quite different since this is the area in dominately by acid sulphate soil that a typical of low lying area in the south. The soil is very acid when dry and oxidized. His Majesty started off by visit the area and observed the yellow jarosite crytals that develop when these soil dry and oxidize, giving a very strong acid condition. He put up a very strong suggestion in tricking the soil or Klaeng Din that we should somehow, try to make an acid sulphate soil by ourselves (Vijarnsorn et.al. 2002). Nobody ever thought that this was possible. It took us almost 4 years with continuous wet and dry condition to inundate with acid water. His intention is very clear, if we can do that, then we should be able to make a reverse engineering and concurrently correct the situation of strong acid as found. The experiment was a success, it is the only one in the world. Among other things, it was from a non soil scientist, let alone being a King himself. The following recommendations were developed and offered to farmers to deal with the strongly acidic situations that common to the south. (Vijarnsorn, 2002)

1. It is imperative to control the water level above the pyrite mud layer.

2. Improve the soil conditions by flushing with rain water to regularly the acid from the profile. This can be significantly enhanced by the application of lime dust. It is always important to maintain the water level above the pyrite acid-prone mud layer as indicated earlier.

3. Modifying the topography of the area either by creating a slight slope that will allow surface drainage to occur. The building of raised bunds for cultivation will assist but core must be taken not to disturb the acid mud.

4. If possible, the whole area should be able to control water level at all time both at a desired depth and sloping surface for easier drain or wash out if desire.

The manual also give further detailed instruction for the specific cultivation of rice, vegetables, field crops and fruit trees, (Vijarnsorn, 1993)

■ ***At Phu Pan, Sakon Nakhon Province***

This area, in the northeast region covers at least 33% of the whole area of Thailand and is dominated by infertile soils. These soils are deprived of nutrients being sandy and have a low ability to retain water. In many places of the northeast there are numerous geological salt layers resulting in saline soils in many of the low land areas. To be exact the overall ecological system has been destroyed. His Majesty has stressed the rebuild "developing model" for the northeast, and the utmost need for water. The study at Phu Pan, was instrumental for His Majesty's creation of sustainable development in the form of the "New Theory".

■ ***At Huai Hong Khai, Chiang Mai Province***

The main theme is watershed management, creation of water reservoirs and conservation practices. Many suggestions were made such as check dams, wet forest and wet fire line and a suggestion by His Majesty for hill tribes to grow 3 types of wood for 4 benefits etc.

To round up the whole process, Khung Kraben Bay project represents a situation were saline soils are close to the sea in Chanthaburi Province. This project is representative of environment conservation and the coastal zone ecology management. Here, mangrove restoration is promoted since it is the breeding ground of all living animals of the sea.

Overall there projects summarizes the way His Majesty sees and suggests priorities of activities dealing with integrated approaches leading to the so called "natural way". We can summarized them as follows:

1. Conserve top soils by not ploughing and exposing the top soil since it's prone to erosion

2. Finding areas where rain water can be stored and use all possible ways to retain water. Small reservoirs, check dams, diversion dams can be built, with the help of vetiver roots, moisture can be retained in the soil longer.

3. Test plots for a bad soil situation (check plot) is needed to compare after the treatment.

4. Retain the "after plot" for comparison. It is advisable to plant trees and vetiver strips to retain moisture as well as other possible other crops.

5. If there is hardpan, it is advisable to use vetiver roots to open up the pan by punching holes in the pan and grow vetiver in the hole below the pan layer to assist in destroying the pan.

6. Retain all original trees as well as introduce varieties of fast growing species.

7. Determine the moisture holding capacity in the soil usually before planting appropriate type of trees. Control the overall level of water in canals and rivers (Bang Nara), His Majesty through their initiative has been able to contain the activity of the acid sulphate soil conditions in the south.

Strategic Approaches – Multidisciplinary in Action

Some of the very important principles that His Majesty seems to follow in his action are as follows:

> "In any venture, we are willing to put in money and effort which may seem useless, but in the end we may be able to reap the fruits directly or indirectly. The government, thus, will have to invest in many of this kind of development projects if we look closer, we will see that if the people enjoy a better standard of living, have a good income the government will be able to levy more taxes and gain more credit for the country as a whole."

His Majesty has also said "Our economy has traditionally been based upon agriculture. The national income which has contributed to creating prosperity to the country has been derived mainly from agricultural productivity. More importantly, he also stressed on the salient point that "To be successful in farming we must acquired knowledge of agriculture, marketing and elementary economics".

Four of the major concerns that His Majesty always keep in mind are:

1. His Majesty insists that instant prosperity can not be expected. The first step in any form of local development is for the community to be self supporting in food. Everything else is, naturally, of secondary importance.

2. The second most important point is that His Majesty clearly understands the need to integrate all the activities connected with production. One simply cannot say that an area needs to grow e.g. vegetable, without research into the type of soil needed at the site, the amount of water available, the amount of rainfall, the demand of the market, the distant to the market etc.
3. The third point concerns the transfer of technology. His Majesty creates the idea of setting up centres of development study so that the centres will function as living museums for the farmers. The centres integrate the results of the study into models of development which people can take as examples and apply it to their daily lives. All of the six development study sites situated mostly in area with their own typical problem soils. Thus, the farmers can learn directly on the problem solving criteria in any particular area.
4. Most of the problems stem from the inability to realize that you can not singly approach the problem. Only multidisciplinary or holistic approach is possible to remedy them in totally. In integrated, sustainable development, people participation is important. A good leader of a group of people in the lead with good followers should be identified. The ability to function properly in integration, take the precedent of activities and fitting jigsaw puzzle together at appropriate time is significant. It is a must and of course, it is part of the strategic management that should apply and operate in each situation accordingly.

One of the studies relating to economic self reliance of the rural people (TISTR, 1995) cover quite well the integration of major factors including social factors which make the integration more complete.

It is important to realize that impoverished people lack many things. A study on economic self-reliance of rural people (TISTR, 1995) came to the conclusion that there are 5 main factors that affect rural people. These conditions we call TERMS for short and it covers the following: Technology, Economics, Resources, Mind and Social condition. All these factors are commonly related and integrated therefore a lack one of these factors will normally lower the other four factors. The dominant condition of resources, in this case, sandy infertile soils, usually results in two important effects i.e. low water holding capacity for cropping and they are usually infertile due to a lack of nutrients. If you have your mind set on making thing better i.e. to improve the soil by enriching them with nutrients together with a process of adding organic matters and finer materials (clay). We should try to grow crops on them, particularly leguminous i.e. if we have enough water. It is thus, an indirect way to moisten up the soil but it is one of the necessities to building up soil quality for sustainable agriculture.

Sustainable Development-Definition

World commission on Environment and Development (1983) gives definition of sustainable development as follows:

> "Sustainable development is development that meets the needs of the present without compromising the ability of the future generation to meet their own needs"

In Thailand, the definition used by the committee attending international meeting on sustainable development at Johannesberg (2002) set the definition as follows:

> "Sustainable development in the Thai context is the development that relies on holistic nature with all aspects being equally. It is based on factors of natural resources, Thai local wisdom and culture together with participation from all sectors concerned and shows respect to each other. In particular, it should have the ability to become self-reliance and be just as good in quality of life as others.

One concise version of sustainable development is from our imminent monk Payutto (1998) "A development that has ability to maintain explicit balance between human activities and the law of nature". He gave also good explanation of 3 key words in sustainable development as follow. Sustainable development has a characteristic of **integration** i.e. make it **holistic** which mean all related components must integrate in total. Another characteristic is, it should have **balance** or make explicitly balance between human activities and the law of nature.

The National Economic and Social Development Board (NESDB) has spent considerable effort in promoting the concept of sustainable development (seminar in sustainable development in Thai context, 2002) that finally resulted in the definition as follow:

> "Development that creates balance in all measures of socio-economic, natural resources

and environment as well as enhancing long lasting good quality of life for all people."

Rojanasoonthon (2003) introduce a condition called "Dynamic Equilibrium" to signify the ability to change each time environment at factors change. This is paramount to sustainability. This aspect occurs continually with various lengths of time before it reaches a new equilibrium. Finally, Rojanasoonthon (2003) indicated that sustainable development is "Any strategy for development that contains ample ability to balance all change factors in natural resources, socio-economic and culture. That ability is called dynamic equilibrium. Any development that has there attributes is called sustainable development".

To sum up, sustainable development needs to cover 3 main factors i.e. environment, economics and social.

■ ***Sustainable development: philosophy***

Once the philosophy of thinking is basis on the culture of giving or teaching. The order of precedence is incorrect along such hierarchy. Since in real life however, the paradigm may be more correctly focused on the culture of seek or research before giving and teaching. His Majesty the King took such precedence seriously and was always prepared to find out or seek for himself by talking to local people and making first hand visits to the affected areas. His Majesty's decision therefore is based on sound factors affecting existing problems. Appropriate solutions are then applied, taking full account of all influencing factors. One of His Majesty approach towards sustainable development falls under the concept of the "New Theory", a philosophy that centres on. His Majesty tries to have sustainable agriculture for the farmers. The components should be simple and practical, with the connotation of the principle of a sufficiency economy. That is moderate and reasonable. The major issue is thus, the necessity of having an adequate internal immune system against any impacts caused by both external and internal changes.

The New Theory starts with the average holding of 15 rai (1 ha = 6.25 rai), the lowest possible area required to be sustainable (5 rai for rice field, 5 rai for horticultural crops, 3 rai for pond or reservoir and 2 rai for house) His Majesty said also that "the New Theory must be implemented in places where it is suitable for example Khao Wong District, Kalasin Province". Certain adaptations are possible for example in many places, water is not available or unreliable and the conditions, therefore are not sustainable for this design.

■ ***Time factor in sustainable development***

The importance of time is crucial for sustainability since adjustment as the result of various factors need different time intervals in adjusting to reach another equilibrium. For the new situation certain change may occur. For Khao Hin Son it took 15-20 years before the King was satisfied with what he saw. For another 3 places, Huai Sai, Khao Cha-Ngum and Phikun Thong, it took about similar time span. For Royal Project Foundation, of which we think it had all the conditions of true sustainable development, until now it is 36 years. Giuseppe di Gennaro, UNFDAC executive director in the early 1980, wrote himself (Renard, 2001), on a meeting he had with King Bhumibol Adulyadej on 30 June 1982. The King said that according to his point of view at least 30 years would be required to complete the task (work on the highland). Gennaro wrote that he argued with the King and stated that a long time frame such as that would not encourage financial support from external donors. The King listened in silence and Gennaro was so assured that he had change His Majesty's mind. He finally admitted that he was completely wrong. It was proven, by the fact that His Majesty knew even then that to make the hill tribes better off, grow no opium, cut no trees and even look after the forest. It took time as well to get all collective efforts for help from many people, many organizations in order to reach that goal. His estimation was 30 years at least.

■ ***Sustainable Development: case of: Royal Project Foundation***

Royal Project originated from His Majesty the King's private study in 1969 following his visits to the hill tribes in the North of Thailand. For almost four decades the Royal Project under the directorship of H.S.H. Prince Bhisatej Rajani has successfully fulfilled His Majesty's wish by placing emphasis mainly on R&D through marketing which lead to the proper cultivation of crops for opium substitution in the highland. Better standards of living of the tribes has been conceived which resulted in their willingness to look after the forest and watersheds. In 1992, the Royal Project Foundation was setup through a Royal Command purposely to render services effectively with permanent budget allocation. The project is now helping the hill tribes to help themselves in growing useful crops to sell in the market under "Doi Kham" brand and enable them to continue striving for better standards of living.

The Foundation has 3 major roles in doing research with 4 research stations, development and technology transfer through 37 development centres throughout the north covering 5 provinces (Chiang Mai, Lampoon, Mae Hong Son, Chiang Rai, Payao). In all we look after about 100,000 people in 306 villages covering about 2,000 km^2. In the market, our produce is marketed under the trade name of "Doi Kham" are safe with good quality. We have about 41 types of fruits (mostly temperate) about 67 kind of flowers and almost 137 varieties of vegetables and herbs. At present, our top vegetable products are sent to Thai International kitchen. We also airfreight vegetables and herbs to Singapore on a regular basis.

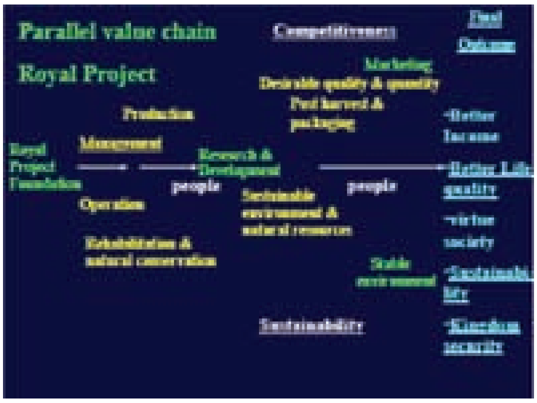
One of the attempts by the Royal Project Foundation is to deal with integrated factors in the highland is to use the computer based tool for modeling and simulation to process copious data in the highland. The project was setup in 1997 with the Australian National University which was sponsored by ACIAR (Australian Centre for International Agricultural Research). The Thai side by the Royal Project Foundation through Royal Thai government supports with full cooperation from various government agencies and universities i.e. Kasetsart, Chiang Mai and Mae Jo Universities and Forestry, Agriculture, National Park, Land Development Departments. The project is called IWRAM-DSS (Integrated Water Resources Assessment and Management Decision Support System). This flexible decision supports system software development methodology deal mainly with hydrology model, erosion model, crop model and socio-economic model. This IWRAM project can be applied to other river catchment, resource environment and promote its use by key stakeholder agencies (Jakeman, A. et al. 2005)

With 36 years of service up on the highland of the north, we now have enough time on our side for sustainable practice. The Royal Project has performed and continued to perform our original objectives in elevating the hill tribes standard of living as well as help them to help themselves. Most importantly, we are keeping a watchful eye on the natural resources and environment. Strict conservation practices on sloping land are observed. In fact, agriculture is preferred on the lower slope and flatland. Correct land use planning is applied. On sloping land, practices such as terracing, hill side ditch, orchard terrace, check dams, wet fire line, wet forest and many others conservation practices are commonly used. His Majesty has strongly recommended the use of vetiver grasses which have deep and profusely roots to reduce erosion and retain moisture longer in the soil. Roads or transporting routes were constructed and now connected to most of our development centres.

We are now, running parallel value chain creation. On one hand we are competing to produce best produce for the market and on the other hand we are looking after the sustainable environment and natural resources on the highland. Considering that we operate on the roof of Thailand, so our position there is significant and necessary. His Majesty even made a speech on such issue, by introducing a successful project dealing with opium replacement crops and stop the hill tribes from slash and burn practices. Then, we can retain them in one place, have a reasonable life also they help us to look after the forest and soil. The benefit occurring therefore will be significant and long lasting or in fact, sustainable.

Conclusion

Records show that whenever there is a case where people can not make a living out of the land are two main factors that we should take into account. i.e. soil and water. Water is normally quite apparent, but with soil the problem may not be so evidence. Attacking the soil problem solely, normally will not yield long lasting result. The approach has to be more of multidisciplinary in nature, problems are mostly related and integrated. This kind of dispute needs a somewhat "natural" approach such as outline by His Majesty's direct involvement in many of the examples delineated. One thing is certain, it normally will take time and we have to see into it that this factor has been taken as a necessity. Other factors that are always missing is the involvement of local people in the area together with the socio-economic factors which need to be taken into account from the start. A sense of belonging is quite important for the participation of the local stakeholders. Integration of various activities also involves many people and many authorities. Sustainability do need adjustment and dynamic equilibrium (ability to readjust as situation change).



His Majesty's concept on sufficiency economy specify moderation or reasonableness, including the necessity of having an adequate internal immune system against any impact caused by both external and internal changes is the main force behind sustainability.

Intelligence, utmost thoroughness and carefulness are needed in bringing the various fields of knowledge to be used in every step of planning and executing the work to be done. Therefore, above all good management is indispensable in this endeavor.

The very final question of all activities relating to people on development is: "Are they self reliant?" and may be we should add also "Are our natural resources still intact?" Again, it will be undoubtedly double our assurance if we have positive answers to both questions. Then, we can say that, we have real sustainable development.

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Poor soils make poor people and poor people make the soil worse

Alfred E. Hartemink[1]

Keywords: soil science, population growth, food production

Abstract

Throughout the world there is a strong evidence to support the link between poverty and soil conditions. In subsistence agriculture the wealth of people on low fertility sandy soils is much lower than those living on rich volcanic soils. But there are great differences between regions in the world and this talk focuses on historical developments in soil research in tropical and temperate regions. One-third of the soils of the world are situated in the tropics and as such support more than three-quarters of the world population, yet more is known about the soil resources of the temperate regions than these important soils of the topics. Since the Second World War, soil research has immensely contributed to crop production increases in the temperate regions and the discipline has greatly benefited from new instrumentation and developments in other sciences. Soil research in tropical regions started later and its scope has not changed much: the feeding of the growing population, land degradation and nutrient management remain important research themes. The amount of research in environmental protection, soil contamination and ecosystem health is relatively limited. Mineral surpluses are a major concern in many temperate soils under agriculture whereas the increase of soil fertility is an important research topic in many tropical regions. The impact of soil research on poverty alleviation, crop production or rural livelihoods will be discussed.

Introduction

Soil science is a relatively young science that emerged some 150 years ago. It developed in Europe, North America and the Russian Empire (Kellogg, 1974). Soil surveys started in sparsely populated areas where there was ample land for farm extension and thus a clear need for soil inventories (e.g. Russian Empire and the USA). In more densely populated Western Europe where land was relatively scarce research efforts were devoted to maintain and improve soil conditions, and in most European countries soil survey organizations were only established after the Second World War. Soil science has always had a strong focus on increasing agricultural production needed for an increasing human population (van Baren et al., 2000). One could argue that the focus of attention of soil research was related to the availability of land driven by human population pressures.

The increase in human population has been phenomenal with dramatic increases over the 100 years and has resulted in a continuous debate on man's role and impact on the earth. Much of the debate is related to food production, poverty and the environmental effects of increased land use pressure due to a growing population. Different views on the effects of a growing human population have been published and in this paper some of the arguments are discussed including an overview of facts and figures. The aim of this paper is to provide a brief historical overview of studies on the relation between soil science, population growth and food production. Much has been written about these subjects and this paper is not aiming to review all available literature, but to summarize some of the major outcomes from such studies in order to sketch the main trends and developments. It starts at the end of the 18th century – which is some decades before soil science emerged.

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Human population growth

Global population hardly changed up to 1000 BC and slightly decreased in medieval times (Figure 1). The real increase started from 1650 onwards when global population passed through the "J-bend" of the exponential growth curve. Population growth remained below 0.5% up to 1800 and was about 0.6% in the 19th century. In the first half of the 20th century growth was 1%, but the largest rate occurred in the second half of the 20th century when the world population grew over 2% in a few years.

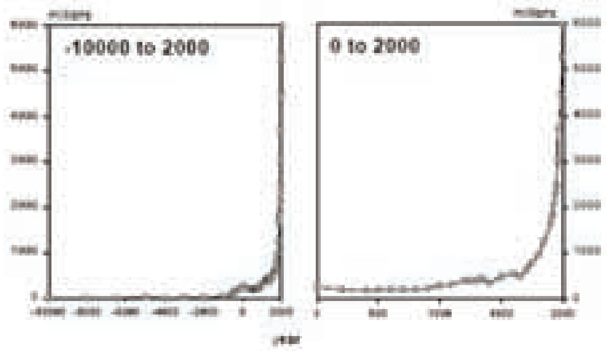

Figure 1. World population estimates for the years – 10,000 BC to 2000 and the years 0 to 2000. Based on reconciliation of published data

The main reason for the exponential increase in human population since the 1600s is science and technology – in particular medical, industrial and agricultural sciences. The conquest of infectious diseases in infancy and childhood and other medical inventions are the main contributors to the exponential growth of the human population. Another factor is the decline in traditional breastfeeding practices by urbanisation and by the premature introduction of animal milk or infant milk (Short, 1998). Also the increase in food production in Europe in the 17th and 18th century due to advanced cultural techniques (ploughing, liming) and more stable societies resulted in an increase in human population. Important inventions like the acidulation of bones by J.B. Lawes and technological marvels like the Haber-Bosch process that allowed the industrial production of urea indirectly caused a large increase in the European population.

Since 1950, the world population has grown almost linearly. Official statistics have shown that the annual increase in human population was 85 million in the late 1980s and had decreased to 80 million per year in 1995 (Smil, 1999). Currently the world population is growing by 1.3% per year, which is significantly less than the 2.0% growth rate of the late 1960s. Population growth has been different in different regions. More than 80% of the population lives in developing regions, and Asia accounts for 61% of the world total. Two out of five people in the world live either in China or India. According to the population division of the United Nations, Africa's population is now larger than that of Europe but in 1960 Africa had less than half Europe's population.

There are great differences in the age distribution of different countries. This is illustrated in Figure 2 where the age distribution of the population of New Zealand (top) and Uganda (bottom) is shown. Such uneven distributions may be further aggrevated by Aids and other infectious diseases that dramatically affect national population pyramids.

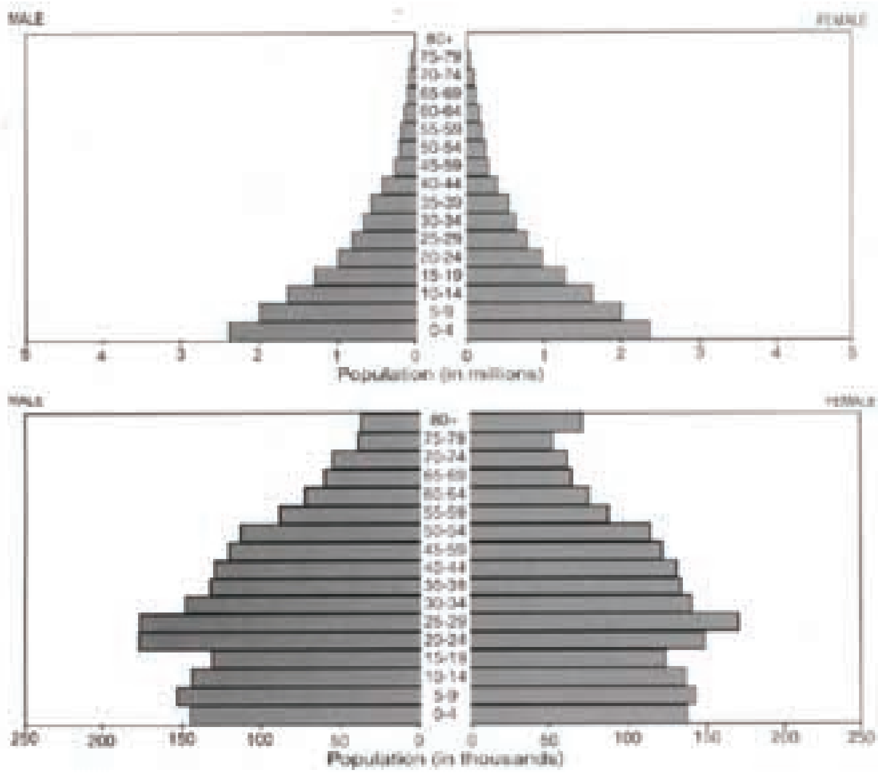

Figure 2. Population age distribution of Uganda (top) and New Zealand (bottom)

It has been estimated that the world population would be 9.4 billion by 2050. Fischer and Heilig (1997) estimated that the average population increase between now and 2015 is 80 million per year which will decrease to around 50 million per year in 2050. Doubling of the human population by 2050 is therefore unlikely and the UN Department of Social and Economic Affairs has also lowered its forecast to 8.9 billion in 2050 as global population growth is slowing down (Lutz et al., 1997; Smil, 1999). About one-third of this drop is due to the unexpectedly dire ravages of AIDS in sub-Saharan Africa and parts of the Indian subcontinent.

Population growth is also slowing down due to a change of attitude in the developing world, which accounts for over 95% of the population growth. In 1969, people in the developing world had an average of six children compared to three today. The population keeps on growing, however, because more babies survive and old people live longer and in Africa each women has on average five children. By 2050, there will be three times as many people in Africa than in Europe.

A new focus of attention is developing in demographic studies and in Western Europe and the USA the focus of the public, political and scientific debate has shifted from global population growth to population ageing (Lutz et al., 1997). Two hundred years after Malthus' essay that is quite a shift of focus – at least for those parts of the world where food is ample. The fear exists that the issue of ageing will detract the much-needed attention from those areas in the world where populations keep on increasing, hunger is widespread and a higher food production is needed to nourish current and future generations. That combination is mostly found in developing countries in tropical regions.

Food production and soil science

More food needs to be produced when the population grows if starvation is to be avoided. In the absence of massive food relocation, the extra food needs to come from either the available land through intensification, better crop husbandry practises and new high yielding varieties (yield increases) or through taking more land into production (area increases). Both production increase and area increase depend on a thorough knowledge of the soil and technological applications of this knowledge. Soil science, being essentially an interdisciplinary and applied science, has a long tradition of considering increased food production for the growth of the human population.

Soil erosion emerged in the first half of the 20th century as an obvious factor affecting food production in relation to the expanding human population. In the USA the question whether sufficient food could be produced for a growing population followed the "dustbowls" in the 1930s caused by severe erosion by wind. One of the first global overviews of soil erosion was prepared by Jacks and Whyte (1939) titled "The rape of the earth – A world survey of soil erosion". They concluded: the world food production was seriously affected if erosion would remain unchecked.

After the Second World War when international organisations such as the FAO were established and many countries were aiming at independence, the feeding of the growing population became an important area of research. Increasing food production was a concern in Western Europe because of the devastation after the war and the baby boom. Fortunately, science came out of the war with high status and was overall respected (Tinker, 1985). There was great optimism and positivism in the 1950s and agricultural research rapidly expanded. Most, if not all, agricultural research was directed towards agricultural production, which increased dramatically thanks to technological developments and major investments in agricultural infrastructure. Even though the term "green revolution" is mostly being reserved for agricultural production in developing countries, it could apply as well to post-war agriculture in Western Europe (Bouma and Hartemink, 2002). There is no doubt that soil science played an important role in the increase of agricultural productivity, and Malthus would have been correct predicting that population growth would outstrip food supplies but for the discoveries of soil scientists (Greenland, 1991).

Various books and journal articles have reviewed the history and developments in soil science (Greenwood, 1993; Hartemink, 2002; Russell and Williams, 1977; van Baren et al., 2000; Yaalon and Berkowicz, 1997). In addition, detailed reviews on developments in soil chemistry (Sparks, 2001), soil physics (Raats, 2001), soil microbiology (Insam, 2001), soil variation (Heuvelink and Webster, 2001) were recently published. These reviews all show the enormous progress that has been made in our understanding of the fundamentals of soil properties and processes. At the same time the reviews show in which areas (e.g. agriculture or the environment) soil science has made major contributions.

Lal (Lal, 2001) summarized the cause of increased food demand in the 19th and 20th century and a number of causes were related to the soil and its management: ploughing, terracing, soil erosion control, irrigation and soil fertility management through manure and inorganic fertilizers. Mermut and Eswaran, 2001 reviewed the developments in soil survey and mapping, soil technology, soil microscopy, pedology and classification of soils, and the mineral and organic components of soils. Several technologies have emerged from these developments including agroforestry, conservation tillage and precision agriculture. Major progress has been made in environmental soil science, and soil science has also been instrumental in studies on land degradation and sustainable use of natural resources and in studies on carbon cycling and sequestration (Mermut and Eswaran, 2001).

Future outlook for food production

The world produces more than enough food at present to feed everyone, but nevertheless many people still starve or are undernourished (Latham, 2000). In absolute terms the world already produces enough food to feed ten billion people but the problem is that most of it is fed to animals. It is poverty and not a physical shortage of food that is the primary cause of hunger in the world (Buringh, 1982; Latham, 2000; Pinstrup-Andersen, 1998). Additional problems are inequitable distribution of food supplies, spoilage and other losses between production and consumption, politics (Ross, 1999) and war and trading policies. Many international aid programmes aim to alleviate poverty for it is the main cause for hunger and environmental degradation (McCalla, 1999). So total global food production is not a good indicator, or as Dudal stated: It is not enough for the world as a whole to have the capability of feeding itself, it is necessary to produce more food where it is needed (Dudal, 1982).

Between 1960 and 2000 the world population doubled. But the green revolution during that period brought about substantial increase in food production and quality, these increases resulted from better varieties, improved irrigation and drainage, increased fertiliser use, improved pest and weed control, advances in food storage and transport, increased area under agriculture (Ross, 1999). The impact of land degradation on food productivity is largely unknown. In addition there is the loss of land to non-agricultural use which is high (Buringh, 1982). There is also limited extra land to bring into production (Eswaran et al., 1999; Young, 1999) which is contrary to predictions made in earlier studies (e.g. Buringh et al., 1975; Meadows et al., 1972).

Prospects for increasing food production depend on improved technologies, a biotechnological revolution, widening of food sources (e.g. sea weed), more land in production (Ross, 1999). Doubling yields in complex and intensive farming systems without damaging the environment is a significant challenge (McCalla, 1999). Progress towards a ‘greener agriculture’ will come from continued improvements in modern high-yield crop production methods combined with sophisticated use of both inorganic and organic nutrient sources, water, crop germplasm, pest management and beneficial organisms (Sinclair and Cassman, 1999).

An important consideration when discussing food production and population growth is under-nourishment, which is referred to by FAO as the status of persons whose food intake does not provide enough calories to meet their basic energy requirements (FAO, 2000). In 1999, FAO estimated the incidence of under-nourishment in the developing countries at some 800 million persons or 18% of the population. It was 960 million in the late 1960s, or 37% of the population (FAO, 2000). Projections indicate that it will decrease to 576 million by 2015, and to 401 million by 2030. So both absolutely and relatively the number of undernourished people is on the decline and projections for the future show improvement although hundreds of millions people remain undernourished in the future. Much depends on political resolutions and will-power but if all resources are harnessed, and adequate measures taken to minimise soil degradation, sufficient food to feed the population in 2020 can be produced, and probably sufficient for a few billion more (Greenland et al., 1997).

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Session 1

“Global extent of tropical sandy soils and their pedogenesis”

Sandy soils of Asia: a new frontier for agricultural development?

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Keywords: Sandy, skeletal soils, distribution, agricultural limitation.

Abstract

The three major groups of land that are generally considered fragile are the steep lands or hilly terrain, the swamps and the sandy and skeletal soils. The sandy and skeletal soils occupy about 86,000 km^2 in Asia (dunes and shifting sands in deserts are excluded in this discussion). Sandy or skeletal soils present problems beyond the capacity of poor resource farmers to address. Intensity of use of such systems was low to negligible in the past but this situation has rapidly changed. Exploitation of stressed ecosystems for arable cropping will increase with increasing population and the concomitant demand for food. From this perspective, it is important that sandy soils be viewed as the next frontier for agriculture and a comprehensive research agenda be developed to use the soils in a sustainable manner. If sandy and skeletal soils are presented as the next frontier for agricultural development, the time may be opportune to mount a concerted research and development effort. In practically all countries of Asia, there is constant pressure to expand the area of land under arable cropping. All countries also have fragile ecosystems and so the challenge is one of reducing ecological risk. Compared to other groups of soils, the sandy and skeletal soils pose minimum level of risk to the environment. Economically, they present immense problems for sustaining the livelihoods of resource poor farmers. Economic viability of agriculture on these soils is the challenge that research and development must address if these are to become the next frontier for agriculture development. With all the advances in technology, our ability to address this group of problem soils may be better today than ever before.

Introduction

The beginning of the new millennium saw tremendous advances particularly in information technology and with a general enhancement of the quality of life in most countries of the world there was optimism about the immediate future with respect to sustaining the anticipated population increases. Population growth, though viewed as a blessing at the family level, is a great concern at the national level, particularly in Asia. The current trends suggest that population growth rates have decreased slightly but even this is not adequate for many countries in Asia that would negate further significant increases in food production.

In practically every country in Asia, a large proportion of the energy and capital of a nation is used to address concerns of food security. In industrialized countries such as Japan, Singapore, and South Korea or countries that have adequate natural resources such as Malaysia, wealth is accumulated through non-agricultural means and food imports provide for national food needs. Other countries have to enhance the productivity of land and this implies sacrificing biodiversity and utilizing stressed lands. An earlier study of Eswaran et al. (1999) observed that, "Asia is losing its genetic resources at an alarming rate. Human incursions to natural systems are probably initiating an accelerated process of extinction of species greater than the disappearance of dinosaurs. The core problem is of course the addition of millions of humans at decreasing time spans. We must accept that in the threatened and critical zones, technological fixes may no longer be an option. We must not allow the pressures of poverty, greed, and development to destroy the very resources that can offer solutions to the problem. Soil and water protection, preservation, and conservation take on urgency never before felt in the history of Asian society."

In a recent study, Engelman et al., (2005) suggested that the limit of per capita arable land is about 0.07 hectares. This is the bare minimum land capable of supplying a vegetarian diet for one person under ideal conditions without the use of fertilizers or

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Table 1. Population and estimates of per capita arable land in selected Asian countries. Data Source: Engelman, R. et al. (2005)

Countries	POPULATION		ARABLE LAND		
	2000 (thousands)	2025 (thousands)	Arable land per capita. 1975 (hectares)	Arable land per capita. 2000 (hectares)	Arable land per capita. 2025 (hectares)
Singapore	4,018	4,998	0.00	0.00	0.00
Brunei Darussalam	328	473	0.07	0.02	0.01
Bangladesh	137,439	210,823	0.12	0.06	0.04
Bhutan	2,085	3,843	0.10	0.08	0.04
Japan	127,096	123,798	0.05	0.04	0.04
Republic of Korea	46,740	52,065	0.06	0.04	0.04
Viet Nam	78,137	105,488	0.13	0.09	0.07
Korea, Dem. People’s Rep.	22,268	25,872	0.12	0.09	0.08
Nepal	23,043	38,706	0.18	0.13	0.08
Papua New Guinea	4,809	8,023	0.19	0.14	0.08
Sri Lanka	18,924	22,529	0.14	0.10	0.08
China	1,282,437	1,479,994	0.11	0.11	0.09
Pakistan	141,256	250,981	0.28	0.15	0.09
Philippines	75,653	107,073	0.20	0.13	0.09
Indonesia	212,092	272,911	0.19	0.15	0.11
Lao People’s Democratic Republic	5,279	8,721	0.25	0.18	0.11
India	1,008,937	1,351,801	0.27	0.17	0.13
Cambodia	13,104	22,310	0.27	0.29	0.17
Myanmar	47,749	60,243	0.33	0.21	0.17
Afghanistan	21,765	45,193	0.56	0.37	0.18
Thailand	62,806	77,480	0.41	0.29	0.23
Malaysia	22,218	31,326	0.38	0.34	0.24
Mongolia	2,533	3,478	0.57	0.52	0.38

amendments. They estimate about 420 million people live in countries that have less than 0.07 hectares of cultivated land per person and about 75% of this is in Asia. When per capita arable land is projected to the year 2025 as undertaken by Engelman et al. (2005) the number of countries that reach this benchmark increases as shown in Table 1. Globally, the population belonging to this category is expected to increase to about a thousand million persons.

In practically every country of Asia, all suitable land is being used for agriculture and cultivation has also spilled over to marginal lands. With increasing rural populations, agriculture is moving upslope onto steep landscapes with all the negative consequences of erosion, or invading the wetlands with concomitant impacts on hydrology. Other negative effects on the ecosystem and biodiversity have been repeatedly emphasized. In many countries, there are sandy and skeletal soils, which are of inferior quality in comparison to lands that are currently cultivated but probably they are a much better alternative to steep lands or wetlands. These are two distinct groups with respect to management technology needs and land uses, however in this paper they are considered together as they also share similar constraints, particularly for resource-poor farmers.

The purpose of this paper is to report on previous assessments of the extent of sandy and skeletal soils in Asia, evaluate some general constraints for agriculture and then to justify their status as one of the new frontiers for agriculture. Research in the management of these soils has not received the attention they deserve. It is from this perspective of demanding special attention that such systems are considered as the next frontier for soil research.

Land Resource Stresses

The kinds of edaphic constraints to food production are summarized in Table 2. The study of Eswaran et al. (1999) showed that only about 21% of the land in Asia is stress-free land. There are about 58,000 km^2 of lands with long cold periods, which precludes use of the land for most agricultural

Table 2. Edaphic constraints to food production

Category	Examples of Stress Factors
INTRINSIC STRESSES	
Chemical conditions	Nutrient deficiencies; excess of soluble salts – salinity and alkalinity; low base saturation, low pH; aluminum and manganese toxicity; acid sulfate condition; high P and anion retention; calcareous or gypseous condition
Physical conditions	High susceptibility to erosion; steep slopes, shallow soils; surface crusting and sealing; low water-holding capacity; impeded drainage; low structural stability; root restricting layer; high swell/shrink potential
Climate-controlled	Soil moisture deficit; extreme temperature conditions regimes; insufficient length of growing season; flooding, water-logging; excessive nutrient leaching
Catastrophic events	Floods and droughts; landslides; seismic and volcanic activity
Biological conditions	Low or high organic matter content; high termite population
Holistic (Soil behavior) Conditions	Low soil resilience; natural soil degradation
INDUCED STRESSES	
Chemical conditions	Acidification, through use of acidifying fertilizers; contamination with toxicants
Physical conditions	Accelerated soil erosion; soil compaction; subsidence of drained organic soils
Biological conditions	High incidence of pests and diseases; allelopathy; loss of predators; colonization by exotic plant species (weeds)
Landscape conditions	Impaired ecosystems (Poor soil health); lack of aesthetic value of agricultural landscape

purposes. These are mainly in, Mongolia, Northern China and in the high mountains of Pakistan and India. The deserts of Asia are the Thar Desert of India and Pakistan, and the Taklamakan desert of China extending into Mongolia. Moisture availability is restricted unless irrigation is available. With good irrigation, as around Urumchi in China, the deserts are very productive. In the absence of appropriate drainage outlets, as in parts of Pakistan and India, there is a rapid build up of groundwater and salinity. Sustainable agricultural systems can be developed on the deserts if appropriate land management is practiced. Steep sloping land and soils with shallow depths, due mainly to underlying rock, cannot be used for most agriculture without capital-intensive inputs to prevent environmental degradation. Most countries of the region have such lands and if the climate is favourable, they are generally under forests. In the semi-arid and arid parts of the region, the steeper terrain and shallow soils are generally used for grazing of small ruminants. These four land resource constraints – continuous moisture stress, continuous low temperatures, steep slopes, and shallow soils – are land use constraints that cannot be corrected easily by technology. Such lands have great difficulties in supporting sustainable agriculture and are singled out here to compare with lands with sandy and skeletal soils. The latter also present constraints specifically for their function of crop production but in contrast to the other four mentioned earlier, many of the constraints can be overcome with appropriate technology.

Eswaran et al. (2003) developed a procedure to undertake a global assessment of land resources stresses using soil and climate information. They defined 24 broad stress classes for this global exercise. Other stresses may be important locally. These can be represented on national or regional maps. Each of the 24 stresses listed in Table 3 requires a different level of investment to correct for agriculture use. The ability to correct the stress with minimal cost is the overriding factor employed to prioritize the classes in the list. The cost of correcting the stress varies with the country and the kind of stress (Buol and Eswaran, 1994). For sustainable development, an understanding of the kinds of stresses and the costs involved in correction and maintenance is essential. This approach is used to make an assessment for Asian countries (Table 4). As a priority listing is followed and as multiple stresses are not considered, some of the classes in the beginning of the list may incorporate some stresses listed later. For example, areas designated as 'continuous moisture stress', which essentially are the deserts of the region, may have soils with salinity problems and if sandy or skeletal have low water holding capacity. As the assessment is made on a small-scale map, polygons on this map may have inclusions that may not have the depicted stress. This empirical assessment can be improved at national level by the use of detailed maps. However, the present assessment is made to provide regional information only and is reliable for this purpose.

Table 3. Description of major land resource stresses or conditions

STRESS CLASS	LAND QUALITY CLASS	MAJOR LAND STRESS FACTOR	CRITERIA FOR ASSIGNING STRESS
25	IX	Extended periods of moisture stress	Aridic SMR, rocky land, dunes
24	VIII	Extended periods of low temperatures	Gelisols
23	VIII	Steep lands	Slopes greater than 32%
22	VII	Shallow soils	Lithic subgroups, root restricting layers <25 cm
21	VII	Salinity/alkalinity	"Salic, halic, natric" categories;
20	VII	High organic matter	Histosols
19	***VI***	***Low water holding capacity***	***Sandy, gravelly, and skeletal families***
18	VI	Low moisture and nutrient status	Spodosols, ferritic, sesquic & oxidic families, aridic subgroups
17	VI	Acid sulfate conditions	"Sulf" great groups and subgroups
16	VI	High P, N, organic compounds retention	Anionic subgroups, acric great groups, oxidic, families
15	VI	Low nutrient holding capacity	Loamy families of Ultisols, Oxisols.
14	V	Excessive nutrient leaching	Soils with udic, perudic SMR, but lacking mollic, umbric, or argillic
13	V	Calcareous, gypseous conditions	With calcic, petrocalcic, gypsic, petrogypsic horizons; carbonatic and gypsic families; exclude Mollisols and Alfisols
12	V	High aluminum	pH <4.5 within 25 cm and Al saturation >60%
11	V	Seasonal moisture stress	Ustic or Xeric suborders but lacking mollic or umbric epipedon, argillic or kandic horizon; exclude Vertisols
10	IV	Impeded drainage	Aquic suborders, 'gloss' great groups
9	IV	High anion exchange capacity	Andisols
8	IV	Low structural stability and/or crusting	Loamy soils and Entisols except Fluvents
7	III	Short growing season due to low temperatures	Cryic or frigid STR
6	III	Minor root restricting layers	Soils with plinthite, fragipan, duripan, densipan, petroferric contact, placic, <100 cm
5	III	Seasonally excess water	Recent terraces, aquic subgroups
4	II	High temperatures	Isohyperthermic and isomegathermic STR excluding Mollisols and Alfisols
3	II	Low organic matter	With ochric epipedon
2	II	High shrink/swell potential	Vertisols, vertic subgroups
1	I	Few constraints	Other soils

From an analysis of the dominant stresses, Eswaran et al. (1999) estimated the land quality (Table 5). It is interesting to note that some countries do not have any Class I land. Afghanistan has also an insignificant amount of Class II land. Classes I to III lands are generally the most productive lands of a country though their ability to withstand mis-management varies. Of the three classes, Class II is least resilient which implies that they are most prone to degradation. It is probably correct to assume that, with the exception of a few countries such as Papua New Guinea, Class I to III lands are mostly under agriculture, unless they were set-aside a few decades ago as national parks or forest reserves. Classes IV to VI are generally more prone to degradation and are lands subjected to an onslaught by the land-less. These are the hilly lands and some of the swamps. Most governments are unable to prevent people from using these lands; the more astute governments try to assist the farmers to implement some kind of conservation technology. Land is a limiting resource in many of the countries. With time, the situation will worsen due to soil degradation which reduces the performance of the soil. Exponential growth of urban centres consumes large areas of prime land as the centres originally developed on land that had the potential to feed the

Table 4. Land quality classes in Asia. Data from Eswaran et al., 1999

COUNTRY	Land Area (Km²)		LAND QUALITY CLASSES								
	Total Land	Arable land	IX	VIII	VII	VI	V	IV	III	II	I
AFGHANISTAN	647,500	80,452	521,551	13,739	70,466	9,415	32,487		46		
BANGLADESH	133,910	96,486			3,692		33,893	88,156			
BHUTAN	47,000	1,340		651	11,378	1,286	33,676				
BRUNEI	6,627	337			1,786	41	4,800				
CHINA	9,326,410	972,981	2,001,504	1,942,030	2,145,410	426,145	1,144,529	832,285	426,324	370,226	37,491
INDIA	2,973,190	1,687,020	388,717	47,303	257,938	59,969	1,037,310	84,565	44,741	902,935	149,864
INDONESIA	1,826,440	317,294	1,493	20,178	259,885	401,403	691,849	194,988	26,586	217,715	13,143
JAPAN	374,744	45,391		166	161,491	547	64,375	107,722	2,677	37,647	
KAMPUCHEA	176,520	24,713				49,171	42,705	34,830	40,858	8,938	
LAOS	230,800	8,108			4,788	16,878	195,003		10,817	3,335	
MALAYSIA	328,550	48,387			27,023	39,248	244,747	10,817	101	7,233	
MONGOLIA	1,565,000	14,192	882,799	595,594	51,789				14,403		
MYANMAR	657,740	104,796	13,625		21,515	13,869	471,576	88,972	144	67,990	
NEPAL	136,800	23,804	228	15,442	29,663		79,544	11,785			
NORTH KOREA	120,410	20,128		381	88,917		2,992	1,640	1,239	23,729	1,516
PAKISTAN	778,720	212,674	650,528	9,674	67,001	44	39,282		83	10,477	1,623
P. N. G.	452,860	5,227		40,759	16,440	39,737	182,834	87,494	29,636	55,526	4,833
PHILIPPINES	298,170	93,230	94			155,272	48,844	22,057	32,676	36,189	2,977
SINGAPORE	638	10			327	56	76	136	25		
SOUTH KOREA	98,190	20,335			55,032		26,852	2,707		13,573	
SRI LANKA	64,740	18,898			1,748	2,706	10,018	2,411	421	35,789	2,954
TAIWAN	32,260	3,170				18,477	2,996	3,983	5,383		
THAILAND	511,770	209,130			15,362	97,140	226,722	23,939	121,642	26,959	
VIETNAM	325,360	65,610			13,592	76,168	169,816	39,265	7,700	17,067	1,607
TOTAL	21,115,069	5,242,475									

Table 5. Some of the land resource stresses in countries of Southern Asia (Area in km²). Land area of soils composed of sandy or skeletal materials (Class 19) is highlighted

COUNTRY	STRESS CLASS							
	18	19	20	21	22	23	24	25
AFGHANISTAN		**9,303**		23,653	45,977		13,576	515,367
BANGLADESH			3,595					
BHUTAN					9,088		520	
BRUNEI			1,786					
CHINA			23,831	305,401	1,751,670		1,883,637	1,941,323
INDIA		**6,206**		25,387	241,353		48,917	401,982
INDONESIA	37,774	**67,883**	175,463		53,108	17,747		1,313
JAPAN					135,139		139	
KAMPUCHEA								
LAOS					4,769			
MALAYSIA		**369**	21,497		4,264			
MONGOLIA				35,280	16,489		595,594	882,799
MYANMAR				4,403	16,878			13,477
NEPAL					29,607		15,413	228
NORTH KOREA			1,257		87,687		381	
PAKISTAN		**48**		9,761	62,979		10,503	706,251
P. N. GUINEA			3,480		11,161	36,138		
PHILIPPINES		**2,415**						68
SINGAPORE								
SOUTH KOREA					49,312			
SRI LANKA				581	1,167			
TAIWAN				277	18,200			
THAILAND			544		14,171			
VIETNAM			1,093		11,839			
Total	37,774	**86,224**	232,546	404,743	2,547,825	53,885	2,568,680	4,462,808

community and road or river links to other centres. Those countries which have opted for large scale irrigation programs to compliment their food producing capacity are generally at risk due to salinization and or alkalization which slowly but surely accompanies irrigation in arid and semi-arid envionments.

In the drier countries of the world the supply of water may become a limiting factor before the inability of the land to produce food is felt (Postel, 1989, 2000). Waterways traversing nations, or even states as in India, have become areas for conflict when limits of the resource base are reached. Further, the increasing requirements of non-agricultural water use will inflate prices resulting in stringent irrigation policies that will be reflected with gains in efficiencies of production. Inadequacies or inefficiencies of irrigation (Postel, 2000) continuously reduce the effective amount of land that can be used for food production.

A further factor that prevents efficient use of land in many developing countries is the purchasing power of the land users, which is the result of poverty (Swaminathan, 1986). Appropriate technological inputs in many of these countries can double production. However, farmers have no capital to invest in the land or there are no incentives, when they do not own the land. They have fewer facilities and an inadequate knowledge base to implement land management technologies and thus there can be few expectations of managing land degradation. Sustainability and the efficient use of the land can only occur through the appropriate application of modern knowledge. Reincarnating past technologies is not a solution to the challenges of today; it is an excuse for a lack of national will and ineptitude.

Incursions into Stressed Systems

A characteristic feature in most Asian countries is that the farm population is declining much faster than that observed in urban areas. Urban areas, in recent years, have seen dramatic increases in population but this is due to influx from rural areas where job opportunities are few. This is generally also an indication of the limits of land for farming. In practically all countries, land that is reasonably suitable for agriculture is already under agriculture. Protected lands are usually a small proportion of the nation’s land area but even these are prone to illegal land use. Table 5 lists a few constraints relevant to this paper (reader is referred to Eswaran et al., 2003, for the complete table). The three major groups of land, referred to previously, that are generally considered stressed are the steep lands or hilly terrain (classes 23 and 22), the swamps (class 20) and the sandy or skeletal soils (class 19). Unlike the steep lands and the swamps where the farmer can eke out a living by using these landscapes, sandy or skeletal soils present problems beyond the capacity of the resource-poor farmers. Thus intensity of use of sandy and skeletal soils or even incursions into such systems was low to negligible in the past but this situation is rapidly changing.

To a large extent, sandy deposits are characteristic of deserts and in the assessment these are considered as areas with continuous moisture stress (class 25) and keyed out earlier in Table 5. The sandy, gravelly and skeletal soils (class 19) are mainly in the areas of rain-fed agriculture. There is about 86,000 km^2 of such lands in Asia. The sandy soils are grouped with the skeletal soils (soils with high amounts of stones or lateritic gravel) because the land use problems are similar resulting in similar management constraints. The constraints are also a function of technology and this distinguishes this fragile ecosystem from the others.

Management Related Properties

As most of the papers in this Conference will deal with management of these soils, the purpose here is to highlight the major kinds of sandy or skeletal soils and important properties with respect to management. In Soil Taxonomy (Soil Survey Staff, 1999), dunes and shifting sands are considered as non-soils. The typical sandy soils are the Psamments, which are deep deposits of sand of alluvial or aeolian origin. Table 6 summarizes some selected properties of soils from Thailand having sandy textures. The Hua Hin Series represents the typical sandy soil, a deep sandy Entisol. The sand is composed of quartz, and there is less than 1% clay; organic matter is also extremely low. The code “WRD” on the second last column of Table 6 refers to Water Retention Difference. WRD is a measure of the water holding capacity and the very low values highlight the most constraining property of such soils. The low clay content points to the low nutrient holding capacity; any nutrients held are generally by the organic matter in such soils. When the soils have high amounts of gravel as in the Muak Lek Series, the effective volume of the active (clay) fraction is reduced. In skeletal soils, despite a relative high clay content, the soils behave like sands. The Ban Thon and Narathiwat Series show other kinds of soils on such deposits. Some of the pedological properties vary but the basic management related constraints are similar. This is also the case of Ultisols and Alfisols formed on sandy materials.

Table 6. Properties of some soils with sandy or sandy skeletal particle size classes

Depth (Cm)	Horizon	pH	% Clay	% Sand	% Gravel	Bulk Density	WRD (cm/cm)	O.C.%
Hua Hin; Quartzipsamment								
0 – 18	A_1	4.9	0.7	98.1		1.08	0.04	0.18
18 – 30	A_2	5.1	0.8	97.7		1.10	0.06	0.08
30 – 46	C_{11}	5.2	0.5	98.7		1.12	0.02	0.06
46 – 60	C_{12}	5.3	0.4	99.3		1.05	0.03	0.02
Muak Lek; Haplustalf								
Depth (Cm)	**Horizon**	**pH**	**% Clay**	**% Sand**	**% Gravel**	**Bulk Density**	**WRD (cm/cm)**	**O.C.%**
0 – 8	A	6.0	18.1	61.0	58	1.44	0.12	1.98
8 – 24	AB	5.5	20.4	59.1	46	1.36	0.10	1.19
24 – 41	Bt	5.8	24.4	54.5	42	1.24	0.16	1.13
41 – 86	C	6.4	21.4	54.0	52			
Ban Thon; Tropohumod								
Depth (Cm)	**Horizon**	**pH**	**% Clay**	**% Sand**	**% Gravel**	**Bulk Density**	**WRD (cm/cm)**	**O.C.%**
0 –17	Ap	4.2	1.6	96.4		1.63	0.05	1.08
17 – 37	E_1	4.7	2.2	97.1				0.20
37 – 80	E_2	5.0	0.8	98.3				0.12
80 – 90	Bh_1	4.4	6.2	88.5		1.37	0.11	4.32
Narathiwat; Sulfic Fluvaquent								
Depth (Cm)	**Horizon**	**pH**	**% Clay**	**% Sand**	**% Gravel**	**Bulk Density**	**WRD (cm/cm)**	**O.C.%**
0 – 8	A	5.6	3.9	92.0		1.13	0.25	2.55
8 – 18	A_2	5.5	0.4	93.0		0.98	0.23	2.92
18 – 53	C_1	3.4	2.2	92.1		0.5	0.41	8.15
53 – 110	C_2	4.0	8.8	74.2				10.91

Sandy or skeletal soils have a high proportion of drainage pores. Water and dissolved substances are rapidly lost to deeper layers in the soil or translocated to groundwater. These soils have been referred to as droughty soils and also nutrient deficient. From a productivity point of view, the soils are least attractive even to the ‘illiterate’ farmer. Other kinds of problems arise, when more intensive agriculture is initiated. Agricultural activities such as pesticide-mixing and tank rinsing, and storage of manure, fertilizer and fuels may pose many risks on sandy soils. Handling agrichemicals requires extra precautions on such soils due to their rapid contamination of groundwater and aquifers. Even wells on such soils must be a significant distance away from contaminant sources.

Higher doses of fertilizers are sometimes recommended to counteract the low fertility and the inability of the soils to retain nutrients. Over-fertilization with nitrogen frequently leads to contamination of the groundwater; high concentrations of nitrate in drinking water is a health hazard particularly to the very young and the very old. A nutrient-management plan, based on leaching losses and retention ability of the soil, should be adhered to. Sandy soils have poor structure and in semi-arid environments, it is extremely difficult to maintain a reasonable ground cover. Wind erosion will result and blown particles may carry applied fertilizers to water bodies. It is hence important to have residue enhancing crop rotations, cover cropping, reduced tillage, shelter belts, and even grassed waterways.

It is long been recognized that enhancing the organic matter content is key to alleviating the soil moisture and nutrient retention problems. Conventional agronomic practices have not been successful or the systems have not been sustainable and this presents one of the greatest and immediate research challenges for the use of these soils. One option is to test species of grasses that are drought prone and have the capacity to produce high amounts of above and below-ground biomass. *Miscanthus giganteus* is one such species and produces about 40-60 tonnes/ha of biomass. Its palatability to animals is not high but can be used as a component in other highly digestible fodders. A number of ornamental varieties of miscanthus are also known to exist under various common names. Miscanthus can be harvested every year with a sugar cane harvester and is normally grown in cool climates. However, it would be an interesting grass to be tested in the tropics. Like other bioenergy crops, the harvested stems of miscanthus may be used as fuel for the production of heat and electric power, or for conversion to other useful products such as ethanol. If miscanthus can be grown on sandy soils and the biomass is used for bioenergy, it would be one of the most efficient uses of such soils.

As suggested several times, water stress is the most important problem for crop production and the temptation of farmers is to apply as much water as possible. Irrigating sandy soils requires increases in fertilizer and pesticides for most crops to produce a maximum economic (profitable) yield. Nitrogen fertilizer and certain pesticides when applied to sandy soils have the potential to move downward (leach) in the soil profile, possibly into the groundwater. This is one of the reasons that the timing and amount of irrigation water applied are crucial decisions for each operator. Applying too much water means increased pumping costs, reduced water efficiency, and increased potential for nitrates’ and pesticides’ leaching below the rooting zone and into the groundwater. Delaying irrigation until plant stress is evident can result in economic yield loss and, consequently, poor use of some agrichemicals. Some under utilized chemicals are then subject to even greater leaching potential after the growing season when the greatest soil recharge events from rainfall usually occur.

Concluding Observations

Exploitation of stressed ecosystems for arable cropping will increase with increasing population and the concomitant demand for food. From this perspective, it is important that sandy soils be considered as the next frontier for agriculture and a research agenda developed to use the soils in a sustainable manner. The challenge, particularly on a global scale, can be viewed as being of sufficient importance in terms of land area involved globally and the proportion of people who will be impacted that it can be articulated as one of the main agriculture issues to be addressed in the Millennium Project of the United Nations. At the end of March 2005, the World Bank released on their website a preliminary report of the “Millennium Ecosystem Assessment Report” and reported that humans have changed ecosystems more rapidly and extensively in the last 50 years than in any other period. They do recognize that in some sectors there have been net gains in human well-being but in general economic development has been at the expense of degradation of other services. They stress that degradation of ecosystem services could grow significantly worse during this new Century.

Recommendation 5 of the 10 Key Recommendations in the Millennium Project reads, “*Developed and developing countries should jointly launch, in 2005, a group of Quick Win actions to save and improve millions of lives and to promote economic growth. They should also launch a massive effort to build expertise at the community level.*” Several Quick Win efforts have been identified and one is, “*A massive replenishment of soil nutrients for smallholder farmers on lands with nutrient-depleted soils, through free or subsidized distribution of chemical fertilizers and Agroforestry, by no later than the year 2006.*” Recommendation #9 is also relevant to this new frontier, “*International donors should mobilize support for global scientific research and development to address special needs of the poor in areas of health, agriculture, natural resource and environment management, energy, and climate.*”

The sustainable development of sandy and skeletal soils has never received any serious attention in the past for various reasons, including the fact that sustaining the productivity in other ecosystems also presented several challenges. If sandy and skeletal soils are presented as the next frontier for agricultural development, the time may be opportune to mount a concerted research and development effort. In practically all countries of Asia, there is a constant pressure to expand the area of land under arable cropping. All countries also have fragile ecosystems and so the challenge is one of reducing ecological risk. Compared to other groups of soils, the sandy and skeletal soils pose minimum level of risk to the environment. Economically, they present immense problems for sustaining the livelihood of the resource poor farmers. Economic viability of agriculture on these soils is the challenge that research and development must address if these are to become the next frontier for agriculture development. With all the advances in technology, our ability to address this group of problem soils may be better today than ever before.

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Analysis of spatial distribution patterns of soil properties and their determining factors on a sloped sandy cropland in Northeast Thailand

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Abstract

Sandy soils are widely distributed in Northeast Thailand. We analyzed spatial distribution patterns of soil properties and their possible determining factors on a sloped cropland near Khon Kaen City, Northeast Thailand. Our research site included a sugarcane field on a slope, a mango plantation in the lower slope, a wetland rice field in the lowland, and teak plantation on the opposite slope. In total 116 soil samples were collected from a 510 × 270 m field at a 30-m interval and the spatial distribution patterns of soil properties were evaluated using geostatistical analysis. As a result, a clear spatial variation was observed for soil organic C and N contents, particle size distribution, and their related properties. In the teak and/or mango plantations the soil texture was finer and the contents of C and N were higher than the sugarcane field. Soil organic matter (SOM) dynamics and soil erosion were postulated to be driving forces that could bring such heterogeneity of soil properties in the slope land. The SOM dynamics was analyzed at five representative plots on the slope in terms of topography and land use. Both the SOM stock in the upper 15 cm soil layers and annual soil respiration was higher under the tree vegetation than at the sugarcane plots. Annual soil respiration was high often exceeding 40% of the SOM stock. The SOM was considered to rapidly increase under tree vegetation through litter input. The condition of surface runoff generation, which was usually strongly related to the process of soil erosion, was analyzed on three slopes in Northern and Northeast Thailand using a runoff-gauge connected to a data-logger. The rainfall intensity of the Khon Kaen plot was higher than the other two plots in northern region and the surface runoff occasionally occurred throughout the rainy season with no clear seasonal trend, this not being observed on the other two plots, at which the surface runoff occurred more often during the latter half of the rainy season due to higher rainfall intensity and/or capillary saturation of surface soils. Thus redistribution of soil properties due to SOM dynamics and/or soil erosion was considered to proceed with ease on the sandy sloped land. It would be more reasonable to adapt agricultural systems to the unique conditions of these agro-ecozones through spatial or site-specific land management rather than to eliminate or decrease the risks of SOM decomposition or soil erosion.

Introduction

The agro-ecological conditions of Northeast Thailand are characterized by the wide distribution of sandy soils, irregular occurrence of rainfall events during the rainy season, and undulating topography with relatively gentle slopes. These conditions might traditionally have been disadvantageous for agricultural development in the area. Nowadays, after the development of transport infrastructure and domestic/international market economy, market-oriented agriculture is being widely adopted. Rainfed paddy rice in lower slope positions that is primarily for household consumption and sugarcane and/or cassava plantations as commercial crops in the middle to upper slopes are most widely observed especially in the northern half of Northeast Thailand. The humid climatic conditions of the region are conducive for the development of natural forests. It is said that a total of 490×10^6 ha of forest has been cleared for agricultural use during the period of 1961-1998 in the region (Royal Forest Department 1998). Because most of the changes have occurred over the past several decades, the sustainability of agricultural production in near future is not secure.

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When considering the sustainability of agricultural production on tropical sandy slopes, both spatial and temporal evaluation of the dynamics of soil resources are required as well as analyses of nutrient budgets and/or erosion risks at a representative plot scale. As a case study, we selected a cropped field extending several hundred-metres in extent on slopes, which included sugarcane fields, tree plantations and wetland rice cultivation. The following analyses were carried out in the present study: 1) analysis of the spatial distribution patterns of soil properties on slopes using a geostatistical technique, 2) evaluation of SOM dynamics under different land uses patterns on the slope and 3) analysis of the processes associated with surface runoff generation in comparison with that in other regions of Northern Thailand.

Geostatistical analysis of spatial variation of soil properties on a sloped sandy agricultural landscape in Khon Kaen Province

1. Materials and methods

Experimental field

The study was carried out on farmer's fields in Ban Sam Jan, Khon Kaen Province, which was located N 16°35-36′ and E 102°47-48′. The experimental field covered 270 m from southwest to northeast and 510 m from northwest to southeast with an average slope gradient of 5%, and included a sugarcane field on the slope, a mango plantation in the lower slope, wetland rice field at the bottom, and a teak plantation on the opposite slope (Figure 1). Soil was typically sandy (>90% sand fraction) and was classified as a Typic Ustipsamments according to Soil Taxonomy (Soil Survey Staff 2003). The mean annual temperature and precipitation are 27.4°C and 1,190 mm, respectively, at Khon Kaen City (1951-1975).

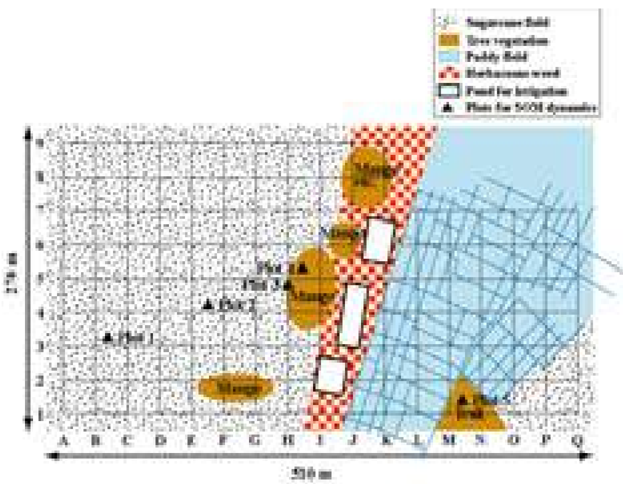


Figure 1. Land use and sampling plots in the SJ study site, Khon Kaen Province

Sampling method

A topographical map was developed by measuring relative elevation at 30 m intervals before the start of rainy season (March) in 2002. At the same time, soil samples were collected as a composite of 5 sub-samples from surface 0-10 cm layers of soil within a 50 cm circular area centred on each position. In total 116 samples were collected. After determination of moisture content of the fresh soils, they were air-dried and passed through a 2 mm mesh sieve prior to chemical analysis consisting of: pH (in water), total C and N (by dry combustion), available phosphate (Bray II method), exchangeable bases, and particle size distribution (by combination of sieving and pipette methods). Soil moisture content was again measured at the end of rainy season of the same year at the same plots.

Statistical analysis

Mean and coefficient of variation (CV) were determined for each soil property. A statistical software SYSTAT 8.0 was used in the analysis (SPSS Inc. 1998). In the geostatistical analysis, a semivariogram was used to evaluate the spatial variability of the properties, representing the relationship between the lag or any integral multiple of the sampling interval and the semivariance. In this study, two indices were used to evaluate the spatial dependence of the soil properties. One is the *Q* value, which indicates the spatial structure at the sampling scale (Goerres et al. 1997). This value is given by the following equation:

$$Q = (S - N) / S \qquad (1)$$

where S and N are the sill and the nugget variance, respectively. The value ranges between 0 and 1. If the value is 0, no spatial structure is detected on the sampling scale used, and as the *Q* value approaches 1, the spatial structure is more developed and more of the spatial variation can be explained by the semivariogram model on the analysis scale used. The other is the range, which indicates the limit of spatial dependence. In the analysis, the semivariogram model with the greatest r^2 value was used for the estimation of the semivariogram parameters. Maps of each property were computed subsequently using block kriging, by taking account of the data within the range distance. Block kriging was used instead of punctual kriging because it enables the evaluation of regional patterns of variation rather than local details, due to the construction of smoother maps with smaller estimation variances. A geostatistical software, GS+ Version 3.1 for Windows (Gamma Design Software), was used in the analysis (Robertson 1998).

2. Results and discussion

According to topographical map in Figure 2, the difference in the elevation was about 15 m along the longest side of the field. The northwestern part was the highest and the relative elevation decreased towards the southeast, reaching a low at the bottom of the slope in the paddy and then again increasing as one moved up the opposite slope. Table 1 summarizes the descriptive statistics, i.e. the mean, maximum, minimum values and CV of the 116 data for physico-chemical properties of the surface soils (0-10 cm) studied. The soils were generally sandy with an average sand content of 93.3%. The clay content varied

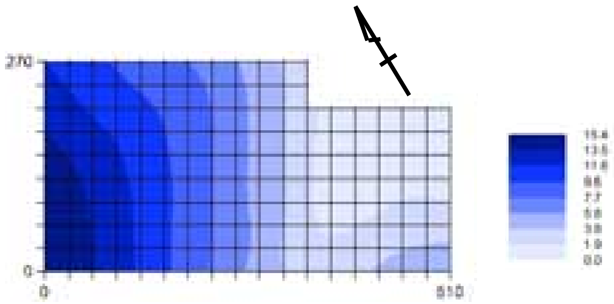


Figure 2. Relative elevation (m) of the SJ study site

Table 1. Descriptive statistics of physicochemical properties of the 0-10 cm depth on soils at the SJ site

	average	maximum	minimum	CV[a]
Sand (%)	93.3	98.3	81.6	3.2
Silt (%)	4.2	13.0	0.1	54
Clay (%)	2.5	6.1	0.2	48
Total carbon (g kg^{-1})	3.35	13.53	1.31	58
Total nitrogen (g kg^{-1})	0.29	0.87	0.05	49
Available phosphate (mg kg^{-1})	192	861	35.0	67
Exchangeable K (cmol$_c$ kg^{-1})	0.07	0.35	0.01	73
Exchangeable Mg (cmol$_c$ kg^{-1})	0.18	0.76	0.01	77
Exchangeable Ca (cmol$_c$ kg^{-1})	0.81	3.91	0.14	84
pH	5.46	7.42	4.16	11
Moisture content (Mar.) (%)	3.9	22.9	0.1	165
Moisture content (Nov.) (%)	13.1	49.9	0.7	77

[a] Coefficient of variation (%)

widely from 0.2 to 6.1% and as a result the contents of total C and N and exchangeable bases also varied with high CV values of greater than 50%, indicating a considerable within-field variability in the study field.

To investigate the spatial dependence of the soil properties, geostatistical analysis was applied. The range, nugget variance, sill and Q value for each property were estimated using the fitting model with the greatest r^2 value (Table 2). Maps of each property were computed subsequently using block kriging, by taking account of the data within the range distance (Figure 3). According to Figure 3a-c, the area around the mango plantation just above the lowest part of the main slope was covered by relatively fine soils, suggesting that the soil particles eroded from upslope were caught in this part of the slope. The soils in the middle part of the main slope exhibited predominantly a coarse texture. Table 2 shows that the values of the range were approximately 130 to 140 m for sand, silt and clay contents with Q values of around 0.5, indicating a moderate development of the spatial structure for these variables.

Table 2. Descriptive statistics of physicochemical properties of the 0-10 cm depth on soils at the site

	Nugget (N)	Sill (S)	Range (R)	Q value	Model	r^2
Sand (%)	4.98	9.97	140	0.50	Spher.[a]	0.91
Silt (%)	2.86	5.71	131	0.50	Spher.	0.82
Clay (%)	0.77	1.54	140	0.50	Spher.	0.56
Total carbon (g kg^{-1})	0.98	4.65	264	0.79	Expo.	0.97
Total nitrogen (g kg^{-1})	0.0065	0.0332	446	0.80	Spher.	0.99
Available phosphate (mg kg^{-1})	5660	17110	112	0.67	Spher.	0.64
Exchangeable K (cmol$_c$ kg^{-1})	0.001	0.028	218	0.50	Spher.	0.92
Exchangeable Mg (cmol$_c$ kg^{-1})	0.002	0.020	80.4	0.93	Spher.	0.86
Exchangeable Ca (cmol$_c$ kg^{-1})	0.305	0.923	811	0.67	Spher.	0.82
pH	0.180	0.381	266	0.53	Expo.	0.96
Moisture content (Mar) (%)	6.8	74.2	230	0.91	Expo.	0.97
Moisture content (Nov) (%)	0.1	311.1	762	1.00	Spher.	0.96

[a] Spher., spherical; Expo., exponential.

The soil properties relating to organic matter and nutritional elements (i.e. total C, total N, available P, exchangeable K, Mg and Ca) were also high in the area covered by the teak plantation on the opposite slope as well as in the lower part of the main slope covered by the mango plantation (Figure 3d-i). This might be due to the function of tree vegetation, at which some nutritional elements were obtained by tree roots from further down the soil profile and then returned to the surface soils together with litter fall. According to Table 2, the values of the range varied ranging from 80 to 800 m with Q values of 0.5 to 0.9. Thus the spatial distribution patterns of these properties were strongly developed by the presence of the tree vegetation.

The lowland soils are generally believed to be more fertile than the upland soils. The paddy field in the present study, however, exhibited a low fertility in terms of available P and exchangeable bases

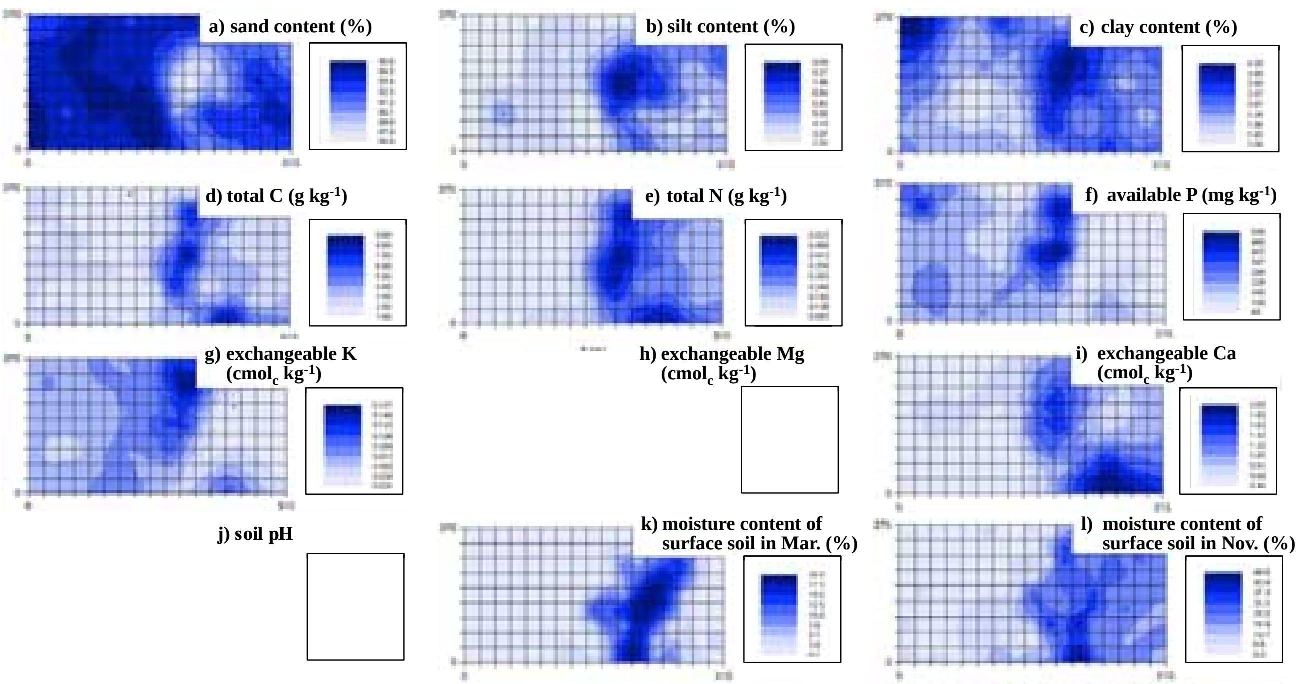


Figure 3. Spatial distribution of selected soil properties at the SJ site

(Figure 3f-i). Soil pH in the paddy field was also lower than in the lower part of the upland slopes (Figure 3j). Higher moisture contents both at the end of dry and rainy seasons suggested that in the lowland paddy the moisture regime was more percolative than the upland fields, resulting in nutrient losses in this location.

Thus accumulation of fine particles of soils, which were eroded from further up of the slopes by herbaceous weeds and/or tree vegetation and organic matter/nutrient turnover under different vegetations (i.e. sugarcane and tree vegetation) were postulated to be the driving forces that could bring spatial heterogeneity of soil properties in these undulating sandy cropland.

SOM dynamics under different vegetation on sandy slope land in Ban Sam Jan, Khon Kaen Province

1. Materials and methods

Based on the distribution patterns of soil resources (Figure 3), five plots were selected for field studies associated with determining SOM dynamics (Figure 1). Plots 1, 2 and 3 were located in the sugarcane field, whereas Plots 4 and 5 were situated under mango and teak plantation, respectively. To estimate the amount of C input into the soils under tree vegetation, we measured litter input at Plots 4 and 5 during the period of 22 April 2004 to 21 April 2005 using litter traps in five replications. The C output from the soils was estimated by measuring *in situ* field soil respiration rate using a closed chamber method. Soil respiration rate was measured 16 times during the period from May 2003 to April 2004. The procedure basically followed the guidelines of Andersen (1982). Two series of PVP cylinders were prepared in each of five replications on the five plots. One series (15 cm in height and 14.4 cm in diameter) were inserted into the soils to a depth of 5 cm, and the others (height 30 cm and diameter 14.4 cm) was inserted to a depth of 15 cm, the bottom of which was later covered with fine mesh to support inner soils. For each measurement, the bottom of the latter cylinders was covered by a plastic sheet to prevent carbon dioxide (CO_2) invasion from plant-root respiration. We assume that soil respiration in the former included both SOM decomposition and plant-root respiration, whereas that in the latter was assumed to practically exclude root respiration. The rate of soil respiration was calculated based on the increase of CO_2 concentration 30 min after covering the tops of the cylinders. Both the initial and final CO_2 concentration was measured using a portable infrared CO_2 analyser (Anagas CD98; Environmental Instruments, Leamington Spa, UK). At the same time, soil temperature and volumetric moisture content were measured at each plot. Soil temperature and moisture were also continuously monitored by data-logger (CR10X; Campbell Co. Ltd., Logan, USA) at Plot 2.

2. Results and discussion

According to the data-logger’s monitoring (data not presented here), the surface soils once being wet started to immediately dry down after each rainfall event even in the mid-rainy season on the sandy soils. In the year 2003, the rainy season commenced in late May and finished at the end of September, with a relatively long drought in July. Soil temperature was mostly above 25°C during the rainy season.

The seasonal fluctuation of litter fall in the forested plots (Plots 4 and 5) is given in Figure 4. At both plots, higher amounts of litter fall were evident in the latter half of the dry season presumably due to a higher water stress. On the other hand, as shown in Figure 5, soil respiration was higher during the rainy season. In order to estimate total soil respiration throughout the year, we first established an equation that represented the relationship of the *in situ* hourly soil respiration rate and environmental factors (such as soil temperature and moisture) by multiple regression analysis. We then calculated hourly soil respiration rate by substituting each parameter of the equation using monitored data, and summed up the hourly soil respiration rates for a given period. In the first step, we assume the Arrhenius-type relationship between soil temperature and respiration rate, as follows:

$$C_{em} = a\theta^{b}e^{-E/RT} \qquad (2)$$

where C_{em} is an hourly soil respiration rate with or without root respiration (mol C ha^{-1} h^{-1}), θ is a volumetric soil moisture content (L L^{-1}), E is the activation energy (J mol^{-1}), R is the gas constant (8.31 J mol^{-1} K^{-1}), T is an absolute soil temperature (K), and a and b are coefficients. The equation was then rewritten in the logarithm form:

$$\ln C_{em} = \ln a + b\ln\theta - E/RT \qquad (3)$$

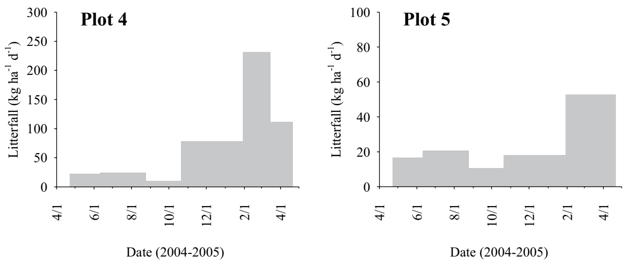


Figure 4. Seasonal fluctuation of litter fall in the mango plantation (Plot 4) and the teak stand (Plot 5) at the SJ from April 2004 to April 2005

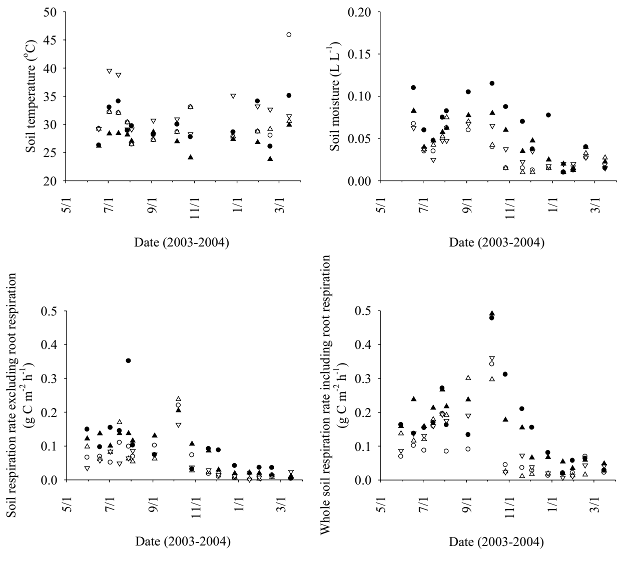


Figure 5. Soil temperature, moisture, and respiration rate measured at the experimental plots at the SJ ❍, Plot 1; Δ, Plot 2; ∇, Plot 3; ▲, Plot 4; ●, Plot 5

Following this, a series of coefficients (a, b and E) are calculated by stepwise multiple regression analysis (p = 0.15) using the measured data, C_{em}, θ and T (SPSS Inc. 1998).

The results of regression analysis are summarized in Table 3. The coefficients relating to soil temperature (E) was usually rejected (p = 0.15) except for the cases in whole soil respiration in Plots 3, 4 and 5, indicating that under the tropical climate in the present study the effects of seasonal fluctuation of temperature on soil respiration rate were rather limited. In contrast, coefficient b usually caused a fluctuation of the soil respiration rate due to the presence of a distinct dry season. In the trial, however, the value of r^2 was sometimes unexpectedly low. A possible short-term fluctuation of microbial biomass and/or its activity affected by temperature/moisture fluctuation in poorly covered surface soils may be one of the reasons for such low r^2.

Using these regression equations and soil temperature and moisture data monitored in Plot 2, cumulative soil respiration during the year was calculated. As the monitored data was available for only one of the five plots, fluctuations in soil temperature and moisture for the remaining four plots were assumed based on the relationship between the actual data and the monitored data of Plot 2. The results of these calculations are given in Table 4. Annual soil respiration without root respiration was the highest in Plot 5, followed by Plot 4, and then by sugarcane plots (Plots 1, 2 and 3), ranging from 4.01

Table 3. Parameters determined by stepwise analysis using the equation: $C_{em} = e^a\theta^b e^{-E/RT}$ and its logarithm form: $\ln C_{em} = a + b\ln\theta - E/RT$

	n	a	b	E (kJ mol^{-1})	r^2
Excluding plant roots					
Plot 1	16	5.90 ***	1.36 ***	----	0.43 ***
Plot 2	16	5.15 ***	1.19 ***	----	0.42 ***
Plot 3	16	7.05 ***	1.81 ***	----	0.45 ***
Plot 4	16	6.56 ***	1.57 ***	----	0.63 ***
Plot 5	15	5.02 ***	1.09 **	----	0.34 **
Including plant roots					
Plot 1	16	5.68 ***	1.14 ***	----	0.58 ***
Plot 2	16	6.59 ***	1.41 ***	----	0.74 ***
Plot 3	16	39.7 *	2.10 ***	78.4 *	0.55 ***
Plot 4	16	42.6 **	1.36 ***	89.6 *	0.79 ***
Plot 5	16	32.4 *	1.10 ***	67.6 *	0.71 ***

*, **, ***: Singnificant at 15%, 5%, and 1% levels, respectively.

to 8.57 Mg C ha^{-1} y^{-1}. The values from tree vegetation (Plots 4 and 5) were similar to those reported for tropical forests in Asia; for example, 8.5 Mg C ha^{-1} y^{-1} in peninsular Malaysia (Kira 1976) and 7.4 Mg ha^{-1} y^{-1} in Northeastern Thailand (Tulaphitak et al. 1985). Contrasting this, the annual soil respiration including plant root respiration ranged from 7.09 to 15.0 Mg C ha^{-1} y^{-1}. The contribution of root respiration on whole-soil respiration was calculated to be between 37-56%, which was similar to the estimation (50%) by Nakane (1980).

Table 4 also summarizes the amounts of SOM stock (up to 15 cm depth) in the soil profiles. Total SOM stock, including litter layer, in the soil profiles ranges from 4.5 to 18.6 Mg C ha^{-1} y^{-1}. Compared with the total stock, annual output of soil C via soil respiration is rather large (equivalent to 40-90% of SOM stock). This may be one of the unique features of sandy soils that would explain the lack of accumulation of high concentrations of SOM. Under field crops, the SOM stock would be exhausted within a few years after forest clearing. In contrast, as shown in Plot 4 (mango plantation), amount of litter fall was sometimes much higher than the annual soil respiration under tree vegetation, indicating that the SOM stocks were increasing quite rapidly. Even in the case of

Table 4. Fluxes and stocks of soil organic matter at each of the plot in SJ

	Soil respiration excluding root respiration[1] (Mg C ha^{-1} y^{-1})	Soil respiration including plant root respiration[1] (Mg C ha^{-1} y^{-1})	Amount of litter-fall[2] (Mg C ha^{-1} y^{-1})	Organic matter in litter layer (Mg C ha^{-1})	Soil organic matter in surface 15 cm layers (Mg C ha^{-1})
Plot 1	4.47	7.09	n.d.	0.16	5.63
Plot 2	4.08	9.18	n.d.	0.18	6.08
Plot 3	4.01	7.16	n.d.	0.17	4.28
Plot 4	7.66	14.8	13.7	2.89	13.5
Plot 5	8.57	15.0	4.55	1.01	17.6

[1] Determined for May 1, 2003 to Apr. 30, 2004.
[2] Determined for Apr. 22, 2004 to Apr. 21, 2005.

Plot 5 (teak plantation), litter input was expected to be higher than the measured value since dead root-litter could not be counted in this experiment. Thus SOM stocks can be easily increased under tree vegetation on the sandy soils studied. The overall positive correlation observed between SOM stock in the upper layer and annual soil respiration (r = 0.99, n = 5) indicates that we could calculate SOM decomposition rate based on the present stock. It is possible to simulate the future SOM status if we know the amount of litter input from tree and/or crop vegetation.

Comparative analysis on conditions for surface runoff generation in different regions of Northern and Northeast Thailand

1. Materials and methods

One of most serious problems after forest clearing for agricultural production is soil erosion, which removes fertile surface soils within a short period. In fact our experimental field in Ban Sam Jan has been affected by soil erosion and as a result noticeable spatial heterogeneity of soil resources was observed. Several factors can affect the intensity of soil erosion; i.e. rainfall intensity, length of slopes, slope gradient, and surface coverage (Wischemeier and Smith 1978; Sonneveld and Nearing 2003). In the present study, we investigated conditions for surface runoff generation, which can be closely related to soil erosion, in three different agricultural slopes in Northern and Northeast Thailand with special reference to weather factors such as rainfall intensity and/or soil conditions.

Three experimental plots were installed. One is the sugarcane field of Ban Sam Jan (SJ) in 2002, which was the same plot as Plot 2 in the previous discussed study. Detailed information on soils and landscape were presented previously. The slope gradient was about 5%. The second plot was installed in Ban Nam Rin (NR), upper north of Mae Hong Son Province, at which marketed vegetables were cultivated at a moderately high elevation (800 m). The soils in this area were derived from limestone and, hence, not strongly acidic and suitable for annual crops. They were classified into Udic Haplustalfs according to US Soil Taxonomy (Soil Survey Staff 2003). The slope gradient of the NR plot was approximately 35% (20º). The soil surface was kept bare during our experiment (2002). The last plot was installed in Ban Du La Poe (DP), Mae Hong Son Province, where traditional shifting farmers of Karen people inhabit this mountainous regions (1,200 m above sea level). The soils were derived from fine-textured sedimentary rocks and classified as Ustic Haplohumults. The slope gradient of the DP plot was about 60% (30º). Upland rice was planted after reclamation of fallow forest (7 years) in our study year (2001).

At these plots, one 2.5 m × 2.5 m plot at the SJ site and a duplicate 1 m × 1 m plots both in NR and DP were installed, which were surrounded by stainless steel plates in upper border and both sides; so that no runoff water entered the plots from outside. A water budget for the small plots was calculated at 10 min intervals based on the measured values of rainfall (by a rain gauge), volumetric soil moisture contents in 0-15 and 15-45 cm layers of soil (by TDR probes) and amount of surface runoff (using a hand-made runoff gauge) on a data-logger (CR-10X; Campbell Co. Ltd.).

Soil physical and physicochemical properties were determined using undisturbed core samples and air-dried soil samples (<2 mm), respectively. The eroded soils trapped in the bucket just below the runoff gauge were collected after termination of the experiment and total amount of soil erosion throughout the rainy season was determined at each plot.

2. *Results and discussion*

Table 5 presents selected physical and physicochemical properties of the soils studied. The soils of SJ were characterized by sandy texture, low SOM content, high bulk density and lower hydraulic conductivity with a low total porosity below 0.5 L L^{-1} compared to NR and DP. It should be noted that the moisture content at field capacity (-6 kPa or pF 1.8) was approximately 0.4 L L^{-1} in the clayey soils (NR and DP), whereas that was 0.25 L L^{-1} in the sandy soils in SJ.

Figure 6 shows daily rainfall and fluctuation of soil moisture contents in the study plots. It is of note that during a certain period data was not recorded due to a malfunction of the data-logger. Even in the rainy season, SJ experienced a clear drought from mid-June to July with little rainfall. Surface soil moisture fell to an equivalent level as observed in the dry season, i.e. around 0.05 L L^{-1}. After mid-August, as regular rainfall events occurred, the moisture content in the subsoils was continuously maintained at field capacity or capillary saturation (θ = 0.25). At the NR site, capillary saturation occurred earlier, that is, in mid-June the moisture condition of the subsoils reached the level of field capacity (θ = 0.4) and, though data were missing during a certain period, such a situation was considered to be maintained until the end of rainy season. After September, the moisture condition of surface soils also reached the level of the field capacity. Contrasting this, the moisture conditions of both the surface and subsoils at the DP site reached capillary saturation immediately after the start of rainy season (i.e. mid-May) and such a situation lasted to the end of the rainy season.

Figure 7 describes the proportion of rainfall distribution observed for rainfall events with different 10 min rainfall intensities, i.e. 0-1, 1-2, 2-5, 5-10, and >10 mm per 10 minutes, respectively, monitored at each experimental plot over two consecutive years. SJ was characterized by a higher occurrence of more intensive rainfall than the others, e.g. rainfall with intensity of >10 mm per 10 minutes occurred more than 10% of total rainfall. In contrast, at the DP site that is situated in the highlands, low intensity rainfall

Table 5. Physical and physicochemical properties of the soils for the runoff-experiments in three different regions in Northern and Northeast Thailand

Site	Depth (cm)	Bulk density (g cm^{-3})	Solid phase (L L^{-1})	Total porosity (L L^{-1})	Moisture content at field capacity (-6 k Pa or pF 1.8) (L L^{-1})	Saturated hydraulic conductivity (m s^{-1})	Particle size distribution sand (%)	silt (%)	clay (%)	Total C (g kg^{-1})
SJ	0-7	1.41	0.52	0.48	0.25	1.2×10^{-5}	88	5	3	2.71
	7-15	1.56	0.57	0.43	0.26	6.4×10^{-6}	89	6	5	1.22
	15-30	1.72	0.64	0.36	0.25	7.5×10^{-6}	86	6	7	0.24
	30-45	1.80	0.68	0.32	0.24	1.1×10^{-6}	80	5	12	0.53
NR	0-15	0.98	0.34	0.66	0.43	6.1×10^{-5}	23	20	57	33.4
	30-40	1.09	0.37	0.63	0.45	1.9×10^{-5}	23	11	66	14.1
DP	0-15	0.83	0.29	0.71	0.44	5.8×10^{-5}	40	13	47	43.5
	30-40	1.23	0.45	0.55	0.39	2.5×10^{-5}	36	13	51	19.7

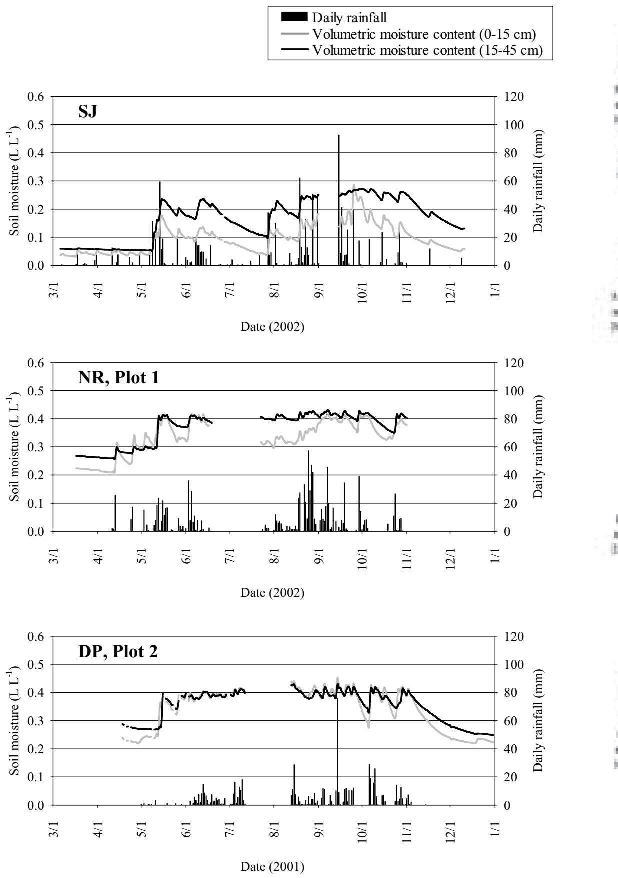


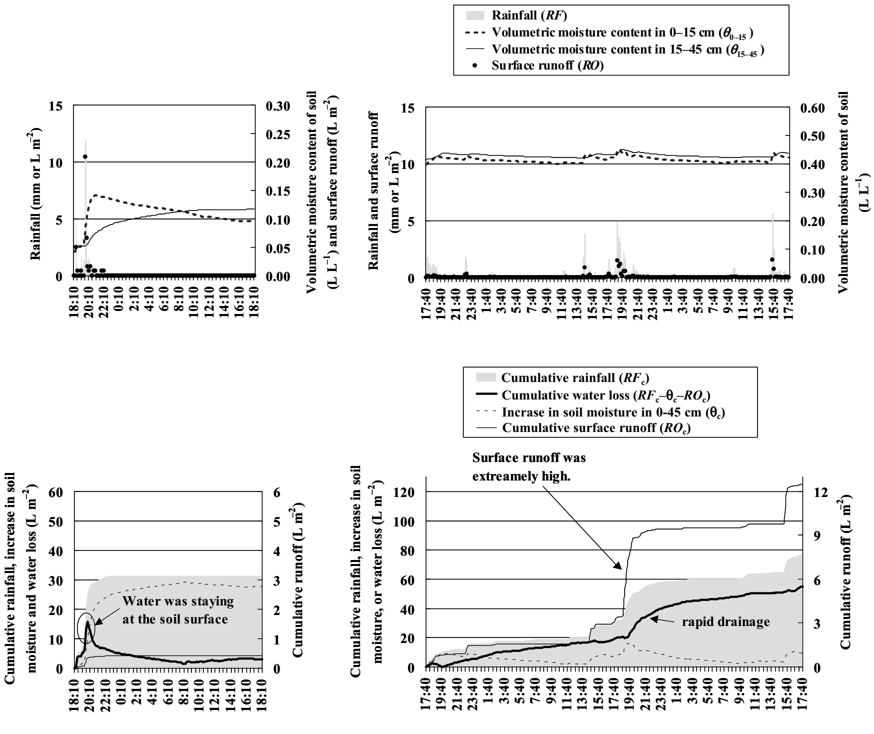
Figure 6. Fluctuation of soil moisture with daily precipitation at the SJ, NR and DP plots

Figure 7. Proportion of the amounts of rainfall having different 10-min rainfall intensities in different seasons at the SJ, NR, and DP plots

events of <1 mm per 10 minutes were dominant and almost no rainfall events of >10 mm were observed. A noticeable feature of the rainfall distribution in DP was that intensive rainfall events were distributed more often in the latter half of the rainy season (Aug.–Oct.). The situation of NR was intermediate between the SJ and DP sites.

In order to analyze water movement and runoff generation from each rainfall event under different soil conditions and/or rainfall intensity, soil moisture conditions and amounts of rainfall and surface runoff were monitored at 10 minutes interval. Figure 8 presents two representative cases of water movement at each rainfall event, i.e. the case of rainfall on a dry surface of sandy soil of SJ (a) and that on wet surface of a clayey soil at the NR site (b). In the upper figures, the amount of rainfall and fluctuation of soil moisture contents at 0-15 and 15-45 cm were shown together with surface runoff observed. The processed data are presented in the lower figures, that is, cumulative amounts of rainfall (RF_c) and surface runoff (RO_c) and total increase of soil moisture content in 0-45 cm depth (θ_c) since the start of the rainfall event. The cumulative water loss (WL_c) was calculated as: $WL_c = RF_c - \theta_c - RO_c$.

Using these data, we can trace the fate of water associated with a rainfall event. For example, the rainfall event (a) started at 18:10 on May 9. Both the surface and subsoils were dry as θ was 0.04 and 0.05 L L^{-1}, respectively. Even under such a condition, when an intensive rainfall (11.9 mm per 10 minutes) was observed at 19:40, water seemed to be stay on the soil surface judging from the fact that WL_c tentatively increased sharply (and subsequently decreased) as shown in the lower figure, and surface runoff occurred though the amount was rather small as 0.2 L m^{-2} (only 1.7% of the amount of rainfall water) (in the upper figure). At this stage water percolated into the soils rather easily, as shown in the upper figure, that is, the moisture content of the surface soil increased rapidly and then decreased slowly; on the other hand, the subsoil moisture content increased slowly as water percolated from the overlying layer. Since WL_c initially increased, it later declined to close to zero as puddle-



a) SJ; May 9-10, 2002

b) NR, Plot 1; Sept. 6-8, 2002

Figure 8. Examples of water dynamics on rainfall events under different conditions
a) Rainfall on dry surface of sandy soil of SJ
b) Rainfall on wet surface of clayey soil of NR

water on the surface percolated into the soils, downward movement of water further down to 45 cm depth of soils, or internal drainage, was limited.

In the case of rainfall event (b), both the surface and subsoils were already wet (θ = 0.40 and 0.42 L L^{-1}, respectively) at the start of rainfall at 17:40 on Sept. 6. During the following two days, total rainfall amounted to 77 mm with moderate intensities (5.6 mm per 10 minutes at the highest rate). Even so, very high surface runoff was observed when the rainfall intensity increased; e.g. 1.5 L m^{-2} with 4.9 mm of rainfall at 19:00, Sept. 7 and 1.6 L m^{-2} with 5.6 mm of rainfall at 15:30, Sept. 8, respectively. In these cases, water loss through surface runoff accounted for 31 and 29% of the total incoming rainfall, respectively. Rainfall water could not percolate immediately into the soil layers with high moisture content. But even after such a rainfall event accompanying the catastrophic surface runoff, moderately rapid increases in WL_c were observed (in lower figure), suggesting a rapid drainage from soil layers.

As analyzed for these rainfall events, both the rainfall intensity and soil moisture condition on each rainfall event seemed to affect the surface runoff generation. To analyze factors controlling runoff generation in each plot in more detail, stepwise multiple regression analysis was conducted using dataset of the amounts of rainfall (*RF*), surface runoff (*RO*), soil moisture contents in the 0-15 and 15-45 cm layers of soil (θ_{0-15} and θ_{15-45}, respectively) and water loss (*WL*). The dataset were composed of data collected from the start of the respective rainfall to 24-hours after the termination of the rainfall, and were sampled for rainfall events that had a cumulative rainfall of greater than 10 mm for each event. A total of 24, 20 and 19 rainfall events met these conditions in the SJ, NR and DP plots, respectively, during one rainy season. In NR and DP plots, data from the two plots were incorporated into a single analysis. The model functions in the stepwise multiple regression were as follows:

$$WL = aRF + b\theta_{0-15} + c\theta_{15-45} + d \qquad (4)$$

$$\log(RO) = aRF + b\theta_{0-15} + c\theta_{15-45} + d \qquad (5)$$

where $WL = RF - \Delta SM - RO$ and ΔSM is the increment in soil moisture content in the 0-45 cm layers for the time intervals. In the first equation above for determining *WL*, datasets with a 10-min interval were converted to a 4-hr interval to eliminate the influence of water puddles on the soil surface. WL was considered to be mainly composed of drainage and evapotranspiration and partially of direct evaporation from puddles on the soil and/or plant leaf surfaces after rainfall. On the other hand, in the second equation for *RO*, original dataset with a 10-min interval was used. A logarithm transformation of the *RO* data was undertaken with the value of zero omitted from the dataset.

The result of the regression analysis is given in Table 6. In all the cases both for the *WL* and *RO*, rainfall intensity was firstly selected as an independent (or explanatory) variable. An overall positive contribution of θ_{0-15} (SJ) or θ_{15-45} (NR and DP) to *WL* indicated generally well-drained characteristics of the soil studied (shown in upper column in Table 6); that is, moist condition did not interfere with the internal drainage, or when soil was dry rainfall water was firstly used to fill capillary porosity and did not drain directly through bypass flow. Although the soils were generally well-drained, the moisture content in the surface layer significantly affected the surface runoff generation (log(*RO*)), indicating that *RO* tended to increase when soil was wet due to interference of rapid percolation of rainfall water into soils. According to the equation obtained in Table 6 and the 10-minutes intervals' data monitored by the data-logger, the surface runoff generation was simulated and is presented in Figure 9. In general the equation obtained above simulated well the actual surface runoff measured. Based on the parameters of the regression equation and seasonal distribution pattern of surface runoff observed, we can assume the risk of surface runoff generation at each plot as well as its possible reasons as follows.

In SJ, in spite of its much lower slope gradient (i.e. 5%) compared to the other two (35% in NR and 60% in DP), noticeable and frequent surface runoff occurred with no clear seasonal trend, possibly with rainfall events with high intensities. It seems to be, therefore, difficult to decrease the high erosion risk using some time-course land management such as controlled seedling time of crops, etc. Spatial land management, i.e. incorporation of tree vegetation in some areas, would be a feasible option to decrease the overall risk of soil loss from agricultural land through erosion. On the other hand, it seemed that the surface runoff occurred more frequently in the later half of the rainy season on steeper slopes at the NR and DP sites due to more frequent capillary saturation at the NR or more distribution of heavier rainfall at the DP in that period. It would therefore be possible to decrease the probability of soil erosion through appropriate land management, e.g. selection of crops that do not result in the land being left bare during the later half of rainy season.

Table 7 summarizes total amounts of rainfall, surface runoff, and soil erosion in the same units (kg m^{-2}). The proportion of surface runoff generated against the unit amount of rainfall ($b/a \times 100$ (%) in the table) increased in the order of SJ < NR < DP. It was consistent with the order of slope gradient of the plots. The proportion of the amount of soil erosion on the unit surface runoff ($c/b \times 100$ (%) in the table), however, decreased in the same order, indicating that the sandy soils in SJ were more easily eroded than the

Table 6. Parameters for simulating water loss (*WL*) from the soil profiles and surface runoff (*LO*) using the rainfall intensity (*RF*) and initial soil moisture contents (θ_{0-15} and θ_{15-45}) determined by stepwise multiple regression analsis:

$$WL = aRF + b\theta_{0-15} + c\theta_{15-45} + d$$

$$\log(RO) = aRF + b\theta_{0-15} + c\theta_{15-45} + d$$

	a	*b*	*c*	*d*	r^2	*n*
Water loss (*WL*; 4-hr interval)						
SJ	0.374 ***	9.87 ***	-----	-0.409	0.70 ***	194
NR	0.389 ***	-----	16.1 ***	-5.27 ***	0.56 ***	639
DP	0.532 ***	-10.8 *	82.4 ***	-27.6 ***	0.57 ***	406
Surface runoff (log(*RO*); 10-min interval)						
SJ	0.145 ***	2.52 ***	-0.921 **	-1.95 ***	0.79 ***	182
NR	0.184 ***	3.14 ***	-----	-2.44 ***	0.59 ***	364
DP	0.194 ***	0.968 ***	-----	-1.64 ***	0.60 ***	453

*, **, ***: Singnificant at 15%, 5%, and 1% levels, respectively.

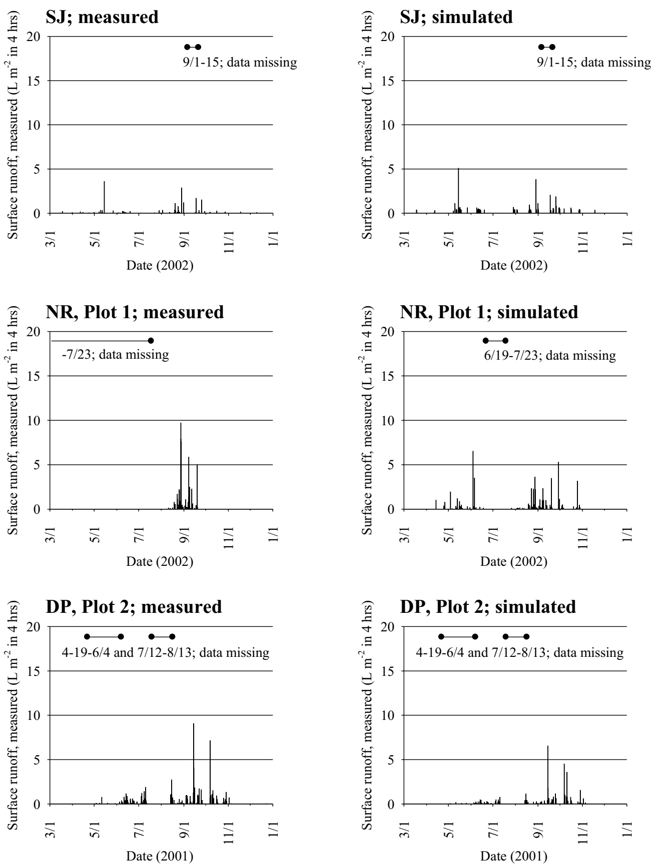


Figure 9. Measured and simulated values of surface runoff at selected plots of SJ, NR and DP

Table 7. Total amounts of rainfall, surface runoff, and soil erosion during the experiment

Site	Total amount of rainfall (*a*)* (kg m^{-2})	Amount of surface runoff generated (*b*) (kg m^{-2})	Amount of soil erosion (*c*) (kg m^{-2})	Proportion of surface runoff on total rainfall ($b/a \times 100$) (%)	Proportion of soil erosion on surface runoff ($c/b \times 100$) (%)	Term of the measurement
SJ	963	23.8	0.76	2.47	3.21	2002/3/6-12/31
NR	989	42.1	0.10	4.26	0.24	2002/3/17-11/1
DP	558	49.5	0.045	8.86	0.091	2001/4/18-12/31

* Amount of rainfall was converted to the area basis on slope.

clayey soils presumably due to weakly organized structure of soil aggregates. The sandy soils in SJ seemed to be quite susceptible to soil erosion.

Conclusion

Spatial heterogeneity of soil properties was clearly observed on the gentle slope of sandy soils in SJ, Northeast Thailand. SOM dynamics and surface erosion were postulated to be primary factors that resulted in the spatial distribution patterns of soil properties. Both processes were rather intensive on the tropical sandy soils and seemed to be difficult to be controlled. It is, therefore, suggested that adaptation of agricultural systems to the unique condition through spatial or site-specific land management may be an effective means of reducing negative impacts. This could include the incorporation of tree species in mosaic distribution, rather than to eliminate or decrease the risks of SOM decomposition or soil erosion.

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Sandy soils of Cambodia

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Keywords: **Cambodia, drought, erosion, farming systems, field crops, rainfed lowlands, rice, sandy soils, soil fertility, shallow groundwater, soil water**

Abstract

Siliceous sedimentary formations underlie much of Cambodia, consequently there is a propensity for sandy surface soils. Only the soils fringing the Tonle Sap lake, those of the alluvial plains along the major rivers (especially the Mekong), and soils developed on basalt deviate from the characteristic of sandy soils. Substantial areas of sandy, high permeability soils are used for lowland rainfed rice production. Due to their inherent high hydraulic conductivities, standing water in rice fields of the deep sandy soils drains rapidly after rainfall predisposing rice crops to drought and high rates of nutrient leaching. However, loss of soil water saturation may limit rice yield by inhibiting nutrient uptake more often than drought, per se. Prospects for growing field crops in sandy lowland soils are contingent on the amounts and reliability of early wet season rainfall or on amounts of stored water after harvesting rice. Apart from drought, waterlogging and inundation are significant water-related hazards that influence the growing of field crops in lowland soils. In addition, soil fertility constraints in the early wet season and dry season will likely differ from those encountered by rice due in part to the different soil water regime they encounter. In particular soil acidity, low nutrient status, hardsetting and shallow rooting depth have been identified as significant constraints for field crops. Vast areas of sandy upland soils occur in Cambodia but are only poorly described. Low soil fertility is likely to limit upland farming systems on the sandy uplands and erosion is a concern for their sustainable use. There is a need to hasten the pace of research and resource assessment of these uplands so that land suitability assessment and sustainable farming systems are available to guide the expansion of agriculture in these areas.

Introduction

Sandy materials cover a large proportion of the landscape of Cambodia, on account of the siliceous sedimentary formations that underlie much of the Kingdom (Workman 1972). Due to their prevalence in the lowlands of Cambodia, sandy, high permeability soils are commonly used for rainfed rice production (White et al. 1997). Increasingly in Cambodia, attention is being turned to the potential for crop diversification and the prospects for other land uses in sandy lowland soils (Bell et al. 2005). A key constraint for the use of sandy soils in Cambodia is the amount and reliability of rainfall during the early wet season (April to July) and main wet season (July to October) or the amounts of stored water after harvesting rice. Apart from drought, waterlogging and inundation are significant water-related hazards that influence the growing of field crops in lowland sandy soils (White et al. 1997; Bell and Seng 2004; Bell et al. 2005). In addition, soil acidity and low nutrient status have been identified as significant constraints for crops on sandy soils in Cambodia.

Vast areas of sandy upland soils occur in Cambodia but are only poorly described, and at present not extensively used for agriculture. Low soil water storage, and low soil fertility, including soil acidity, are likely to limit upland farming systems on the sandy uplands and erosion is a concern for their sustainable use. There is likely to be pressure to develop agriculture on these sandy uplands over the next 20 years. There is a need to hasten the pace of research and resource assessment of these sandy uplands so that land suitability assessment and sustainable farming systems are available to guide the expansion of agriculture in these areas.

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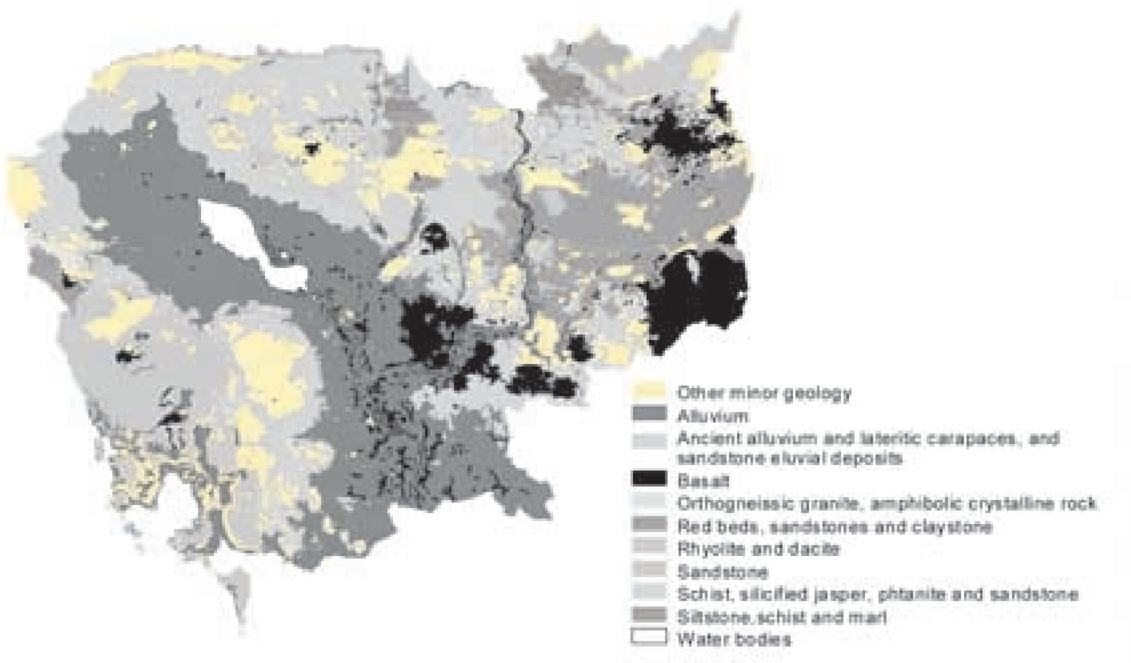

Figure 1. Generalised geology map of Cambodia. Source: Mekong River Commission

In this paper, we review the geological setting of Cambodia which helps to explain the prevalence and distribution of sandy soils. Since Cambodian agriculture is heavily dependent on lowland rainfed rice, we review the nature and properties of the sandy soils in the lowlands. Finally we review the limited knowledge-base of sandy soils in the upland areas that are likely to experience development pressure over the next two decades.

Surface geology and distribution of sandy soils

Mesozoic sandstone dominates most of the basement geology in Cambodia (Workman 1972: Figure 1) and hence will have a dominating influence on the properties of upland soils. Recent and Pleistocene alluvial/colluvial and lacustrine sediments that now form the parent material for most of the lowland agricultural soils of Cambodia are substantially derived from the weathering and erosional products of the Mesozoic sandstone (White et al. 1997). However, low hills from felsic igneous intrusions particularly in South and Southeast Cambodia have also supplied siliceous sediments for the recent and older alluvial/colluvial terraces. In the Northeast of Cambodia, basaltic lava flows from the Pleistocene covered significant areas of older alluvial terraces. The soils formed on weathered basalt and on the alluvial/colluvial sediments derived from basalt have very different properties to those of the siliceous parent materials that dominate most other soils (White et al. 1997). In the West of Cambodia, bordering Thailand substantial areas of siltstone limestone and marl occur (Figure 1), and this area is emerging as significant for upland crop production. Finally the sediments deposited by the Mekong River along its flood plain and in the basin of the Tonle Sap have resulted in a large part of Central Cambodia being dominated by recent alluvial/lacustrine sediments derived in part from the Mekong River basin and in part from the immediate basin of the Tonle Sap (Oberthur et al. 2000b).

No specific mapping of sandy soils has been undertaken in Cambodia. A soil map (1:250,000) of most of Cambodia was recently completed based on the FAO World Soils Map (1988) as part of a soil resources map for the lower Mekong Basin (MRC, 2002). Parts of Cambodia fall outside the lower Mekong Basin and hence were excluded from mapping, including the eastern provinces of Prey Veng and Svay Rieng, and parts of the southern provinces of Kampot, Kampong Som, Koh Kong, and Pursat. The rice growing soils have been mapped (Oberthur et al. 2000b) based in part on an old small scale map (1:900,000) of soils of the whole country. However, soil mapping coverage of the upland regions where soils are predominantly developed on sandstones and related siliceous formations are poorly described (Seng and White 2005).

In Cambodia, the Arenosols (sandy soils featuring very weak or no soil development) are mapped on only 1.6% of the land area (Table 1). Sandy surface textures are more prevalent than the deep sandy

Table 1. Chemical properties of surface layers of Prey Khmer (White et al. (1997) sandy rice soils in Cambodia and the percentage of the rice area they occupy (Data source: Oberthur et al. 2000a; White et al. 2000 and Seng et al. 2001b)

Property	Typical surface soil values
Sand	730 g kg^{-1}
Silt	220 g kg^{-1}
Clay	50 g kg^{-1}
pH (1:1 H_2O)	5.6
Organic C	4.7 g kg^{-1}
Total N	0.5 g kg^{-1}
Exch K	0.04 cmol kg^{-1}
Exch Na	0.05 cmol kg^{-1}
Exch Ca	0.61 cmol kg^{-1}
CEC	1.45 cmol kg^{-1}
Olsen P	1.3 mg kg^{-1}
Percentage of rice area	10-12%

soils that fit the definition for Arenosols. Sandy textured profiles are common amongst the most prevalent Soil Groups including Acrisols and Leptosols (MRC, 2002). The Acrisols are the most prevalent Soil Group occupying nearly half of the land area of Cambodia. The main subgroups are: Gleyic Acrisols (20.5%, Haplic Acrisols (13.3%), Plinthic Acrisol (8.7%) and Ferric Acrisol (6.3%).

Of the mapped rice soils (Oberthur et al. 2000b), Prey Khmer and Prateah Lang Soil Groups which comprise 39% of the rice-growing soils have very sandy surface horizons. Prey Khmer is sandy in both the surface and subsoil and will be the focus of the present paper (Table 2). However, the Prey Khmer soils even though having <18% clay and >65% sand in surface layers (Table 2) would not necessarily classify

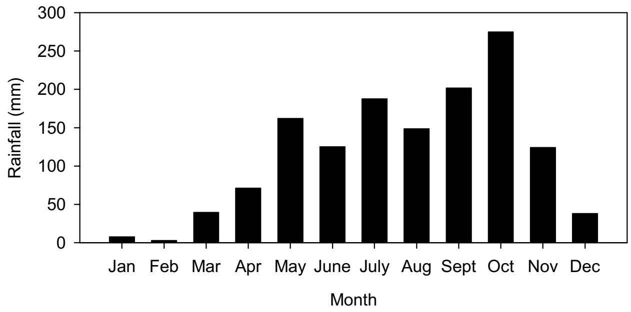

Figure 2. Average monthly rainfall for Takeo (40 years)

as Arenosols because the rice soil classification in Cambodia only considers properties to 50 cm, whereas Arenosols need to be sandy to 100 cm or more (Table 2).

Rainfall and cropping systems

In Cambodia, mean annual rainfall mostly falls in the range from 1,250-1,750 mm (e.g. see Figure 2) with increases up to 2,500 mm in the south, and east of the country (Nesbitt, 1997). The variations in average annual rainfall produce changes in cropping patterns, and options for pre-rice and post-rice cropping with field crops. The East and South of Cambodia has higher early wet season rainfall and may therefore be a more prospective area for expanding field crops on sandy soils (Figure 2).

Cropping in Cambodia revolves around three season: the early wet season (EWS) from April to July; main wet season from July to October; and dry season from November to March (Nesbitt, 1997). Rice is the dominant crop on lowlands in the main wet season with transplanting occurring as soon as sufficient rainfalls to allow cultivation of soils and the

Table 2. Soil profile description for a deep sandy soil from Tramkak District, Takeo Province, Cambodia. Classified as similar to Prey Khmer according to White et al. (1997) and Plinthic Alisol (World Reference Base 1998). Described by: N. Schoknecht, 6/6/03 Location: Datum: IND60 Zone: 48 448326 mE 1220774 mN

Horizon	Depth (cm)	Description
A	0-6	strong brown (7.5YR 5/6 moist), medium sand; very friable moist consistence; single grain structure; very fine, medium porosity, clear, smooth boundary.
A	6-20	brown (7.5YR 5/4 moist) medium sand; very friable moist consistence; single grain structure; very fine, medium porosity, gradual, wavy boundary.
A	20-60	light brown (7.5YR 6/4 moist) medium sand; medium faint reddish yellow (7.5YR 6/8 moist) mottles; very friable moist consistence; single grain structure; very fine, medium porosity, sharp, tongued boundary.
Ctv	60-85	grey (10YR 6/1 moist) sandy clay; medium prominent reddish yellow (5YR 6/6 moist) mottles; hard dry consistence; weak, medium, angular blocky structure; fine, low porosity, gradual, wavy boundary.
Ct	85-100+	yellowish brown (10YR 5/4 moist) clay; fine prominent reddish brown (2.5YR 4/4 moist) mottles and fine distinct grey (10YR 6/1 moist) mottles; firm moist consistence; few segregations, fine elongated black soft; fine, channels void.

accumulation of standing water in the fields. This may vary from June to later August depending on the season and landscape position of the field. Harvesting coincide with the early part of the dry season. Dry season crops can only be planted where there is sufficient stored soil water, as in some lowland rice fields, or where irrigation water is available. Throughout Cambodia substantial year-to-year variation in total rainfall is experienced as well as rainfall distribution pattern (Figure 3).

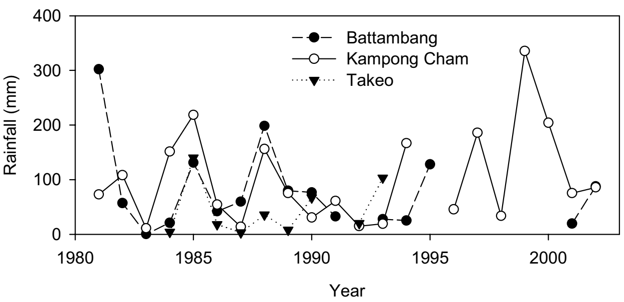

Figure 3. Rainfall (mm) in April at Battambang, Kampong Cham, and Takeo over the period 1980-2002. Source: Department of Meteorology, Cambodia. Note: rainfall records are incomplete for many stations in Cambodia over the last 35 years and this accounts for missing entries

Rice Soils

Rice is the dominant crop in Cambodia, with a production area equivalent to 90% of the agricultural land in Cambodia (Nesbitt 1997). The sandy Prey Khmer Soil Group comprises 11% of the rice-growing soils (White et al., 1997). The soil groups have been defined using the Cambodian Agronomic Soil Classification (CASC) which groups soils according to their effects on lowland rice production (White et al. 1997). It is adapted from the Fertility Capability Classification (Buol et al. 1973) rather than a soil classification based on concepts of soil genesis that emphasizes subsoil properties. The Cambodian Agronomic Soil Classification emphasizes surface soil properties since rice roots are relatively shallow. Even Prey Khmer Soil Group when used for lowland rice would generally not fall into Arenosols since only the 0-50 cm layers are considered in CASC (White et al. 1997).

The Prey Khmer soil has very low CEC, organic C, total N, exchangeable K and Olsen P (Table 1). In field trials in Cambodia, strong responses to N are generally reported in sandy rice soils (Seng et al. 2001b). However none of these soils respond to N alone. On the sandy Prey Khmer soils, N alone either has no effect on yield or decreases it (White et al. 1997, Seng et al. 2001b). On sandy soils, responses to P alone may be obtained although strongest responses generally require N and P, and on the lower fertility soils K and S fertilizers are also required for rice. Low levels of Mg and B have also been identified as potential production constraints for crops on the Prey Khmer soils, but have not been verified in rice in the field (Lor et al. 1996). Leaching of N and other nutrients may also limit productivity of these soils even when water is not limiting. The Prey Khmer soil in Cambodia has low potential productivity even with fertilizer application (White et al. 1997).

The dominant rice ecosystem in Cambodia is rainfed lowlands (Wade et al. 1999). The shallow, drought- and submergence-prone sub-ecosystem, is most widespread of the rice sub-ecosystems in Cambodia, in part due to the erratic rainfall, topography and the prevalence of sandy textures in the root zone of the rice crop. While the sub-ecosystem concept is useful in regional classifications of rice growing areas, in practice local surface hydrology can vary to such an extent as to overrides the influence of rainfall. Within a single farm or among adjacent fields, the upper terraces which are commonly sandy may be classified into the drought-prone sub-ecosystem and the lower terraces may belong to the submergence-prone or drought- and submergence-prone sub-ecosystem. Fields in the high or upper terraces of the lowlands lose large amounts of water, particularly after heavy rainfall, through surface runoff and subsurface lateral water movement, while those in the lower terraces may intercept the flows from the upper paddies (Fukai et al. 2000). Location of on-farm drains, road embankments and drains under roads can markedly affect where the runoff is directed. Water balance models are particularly useful for identifying key aspects of the surface hydrology experienced by rainfed rice. Fukai et al. (1995) have developed a water balance model for sandy soils in N.E. Thailand and this model may be useful for the sandy soils of Cambodia. Maintaining water in the root zone for rice is hindered on sandy soils by high percolation rates that are a common problem in the sandy lowland rice soils of Cambodia (White et al. 1997).

In the rainfed lowlands, significant periods of loss of soil-water saturation occur intermittently throughout the growing season (e.g. Seng et al. 1996; Fukai et al. 2000). Based on rainfall, its distribution and variability, it could be assumed that drought was the main soil water-related constraint for rice in the region. However, the more common effect of low soil water may be to limit nutrient availability and uptake rather than to cause drought per se. The implications of the temporary periods of loss of soil-water saturation for nutrient availability are not fully understood (Fukai et al. 1999), although variations in soil water saturation interact with nutrient availability (Bell et al. 2001). Fluctuating soil water regimes will have major effects on the forms and availability of N (Seng 2000), P (Seng et al. 1999) and on Fe and Al toxicities (Seng et al. 2004b).

Options for minimizing the impact of periods of loss of soil-water saturation are either to use cultivars that are efficient in P uptake and use, and presumably would be best able to cope with a temporary decline in P availability (Fukai et al. 1999); or to treat soil with straw (Seng et al. 1999). Straw keeps the redox potential lower during the period of soil-water saturation loss, thus decreasing the extent of Fe^{2+} oxidation and minimizing losses in P availability due to reaction with Fe oxides. Other forms of organic matter added to the soil at planting, including cow manure, or residues from pre-rice pulse crops or green manures like sesbania, can all help minimize losses of P during periods of soil-water saturation loss.

Iron toxicity has been reported for Prey Khmer soils in Cambodia. However, the impact on yield has not been quantified. Neither is there direct evidence of the consequences of intermittent loss of soil water saturation on the incidence and severity of Fe toxicity.

Application of clay to sandy soils has been suggested as a semi-permanent treatment to enhance water and nutrient retention (Noble et al. 2004). Initial research on the sandy soils of N.E. Thailand suggests very strong responses in growth can be achieved by clay amelioration. The use of claying presumes a ready local supply of clay. N.E. Thailand has numerous deposits of high activity clay in lacustrine sediments (S. Ruaysoongnern, personal communication). The relevance of this technology for the Prey Khmer (Arenosols) of Cambodia, warrants further research.

Upland sandy soils

Important upland crops in Cambodia are maize, rubber, soybean, mung bean, cassava, sesame, peanut and sugarcane (Bell et al. 2005). There is very limited information on the sandy upland soils of Cambodia. Only generalized comments can be made at this stage, based largely on understandings developed for rice soils with similar properties and on recent studies carried out in the west of Takeo Province (Bell et al. 2005) where sandy soils are prevalent.

The Prey Khmer soil is defined for rice production as having a sandy layer <50 cm deep, because deeper sand is unsuitable for rice. However, similar soils to the Prey Khmer are encountered in Tramkak with deeper sandy layers up to 80 cm. These soils are suitable for non-rice field crops and so the deep phases have been distinguished from the Prey Khmer as defined by White et al. (1997). A typical soil profile is shown in Table 3. The surface soil properties are similar to those reported above (Table 1). That is, low levels of organic C, N, Olsen P, exchangeable K are commonly found in surface layers. In addition, KCl_{40} extractable S levels, DTPA Cu, and Zn, and hot $CaCl_2$ extractable B levels were low.

From preliminary analysis of a range of upland soils from Takeo, soil acidity appears to be a significant limiting factor for a range of field crops (Table 4). In Prey Khmer soils in uplands of western Takeo Province, Al saturation values of 50-80% were found in the subsoil (Table 4). Aluminum saturation >20% is commonly regarded as a potential Al toxicity in sensitive crops, whereas in very tolerant crops >80% Al saturation is required to impair crop growth (Dierolf et al. 2001). Seng et al. (2004a) showed strong responses by upland rice to lime application on the acid Prateah Lang soils (pH $CaCl_2$ 4; Al saturation 80%) when maintained in an aerated state whereas no response was found when these soils were flooded.

Table 3. Soil chemical properties of two profiles from the District of Tramkak, Takeo Province classified as sandy soils. Profiles were classified as Prey Khmer (White et al. 1997). Site 5 has no phase specified; site 52 has a coarse sandy phase specified

Site	Depth (cm)	Total N g kg^{-1}	Olsen P mg kg^{-1}	KCl_{40} S mg kg^{-1}	DTPA Cu mg kg^{-1}	DTPA Zn mg kg^{-1}	DTPA Mn mg kg^{-1}	Hot $CaCl_2$ B mg kg^{-1}
5	0-6	<0.2	16.0	<1	0.14	0.19	3.46	0.2
	6-20	<0.2	26.0	<1	0.14	0.16	3.31	0.2
	20-60	<0.2	3.0	2.5	0.11	0.15	1.47	0.4
	60-85	<0.2	2.0	<1	0.29	0.18	5.29	0.3
	85-100	<0.2	3.0	<1	0.36	0.14	5.36	0.3
52	0-45	0.2	2.0	1.1	0.12	0.16	25.08	0.2
	45-95	0.1	2.0	1	0.18	0.12	11.6	0.2
	95-120	0.01	1.0	1	0.16	0.04	3.53	0.2

Table 4. Soil pH and exchangeable Al in soils of Tramkak District, Takeo

Soil Type	Depth (cm)	Phase	pH $CaCl_2$	Al ($cmol\ kg^{-1}$)	ECEC ($cmol\ kg^{-1}$)	Al saturation (%)
Prey Khmer (Site 5)	0-6		4.3	0.14	0.45	31
	6-20		4.3	0.29	0.56	52
	20-60		4.5	0.32	0.65	49
	60-85		4.1	3.24	5.6	58
	85-100		6.4	0	10.7	0
Prey Khmer	0-12	fine sandy phase	4.5	0.28	1.83	15
	12-60		4.2	1.57	1.81	87
	60-100		4.1	1.4	1.6	88
	100-120		4.2	1.32	1.48	89

Symptoms of Mn toxicity have also been observed on mung bean and peanut on acid Prey Khmer soils in Takeo Province. Hence even where Al toxicity is not a constraint, Mn toxicity may limit crop production on acid sandy soils.

Water supply is a key limiting factor for most areas of Cambodia because of the monsoonal rainfall pattern and the erratic rainfall distribution during the early wet (Figure 2) and main wet seasons. Most of the crops grown in the early and main wet season receive less than optimal rainfall in total (Bell et al. 2005). Hence the water storage capacity of the soil would have a large bearing on the regulation of water availability to crops especially on sandy soils. Deep sands are generally considered unsuitable or of low productivity for paddy rice because water is not retained in the shallow root zone of rice, and because a plough pan does not readily form to retain water (White et al. 1997). Deep sands (75-100 cm) will have a higher potential for production of deep rooted field crops than for rice. Subsoil Al may impede root growth and act as a limit on access to stored subsoil water (Table 4).

Discussion and further research needs

A major hindrance to the management of sandy soils in Cambodia is the dearth of knowledge about the distribution and properties of such soils in the uplands. There is a need for a land resource assessment of uplands of Cambodia. There will also need to be parallel development of sustainable farming systems for the sandy uplands.

The geographical proximity of Cambodia, Laos and Northeast Thailand, and the prevalence of rainfed lowland rice as the major crop in their agro-ecosystems suggest that the cross-flow of research information about sandy soils amongst these regions should be helpful. Coordination and collaboration amongst these countries could minimize duplication of research, and maximize synergies in their collective research. However, exchange needs to be based on a critical examination of the similarities and differences amongst them in agro-ecological classifications, in the prevalence of rainfed rice ecosystems, and in the soils used for rice and field crop production (Bell and Seng 2004).

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Soil characteristics and crop suitability of sandy soils in Hainan, China

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Keywords: HaiSOTER, sandy soil, crop suitability

Abstract

Sandy soils in Hainan Island are mainly distributed on marine sediments which cover nearly 10% of the island according to a recently established Hainan Soil and Terrain Digital Database (HaiSOTER). There is also a secondary, very small area of sandy soils associated with granitic parent material. Crop production in sandy soils is mainly limited by nutrient conditions. The main nutrient attributes, such as soil organic matter, cation exchange capacity (CEC), and N content, are significantly lower for sandy soils than for most other soils. Most sandy soils are covered by natural or crop plants, such as Casuarina equisetifolia, *coconut, eucalypt, peanut and cassava, in the meteorologically favourable parts of the island in the east and northeast, where rainfall is abundant. However, in the west and southwest part of the island, vegetation is sparse due to low rainfall and the very low water-holding capacity of these coarsely-textured soils. Crop suitability for particular regions of sandy soils is evaluated based on land quality classifications. For most sandy soils, nutrient availability is the most limiting factor. However, in the southwest part of this island, aridity becomes the most important limiting factor, and in the northeast, typhoon is another limiting factor. In such areas, wind-resistant trees and crops are suitable for planting. According to the Automated Land Evaluation System (ALES) land evaluation system, the sandy soils can play a more important role in tropical crop cultivation. It is concluded that when the technological and financial conditions are improved, the sandy soils in Hainan can be used for tropical crops more efficiently.*

Introduction

Hainan Island is located in the northern fringe of the tropics, and therefore enjoys advantageous hydrothermal conditions and rich plant resources. Agriculture is the dominant economic sector. Hainan Island is an important base for developing tropical crops in China, and therefore exports tropical fruits and winter vegetables throughout China. The sustainable and efficient use of land resources is an important issue for agricultural development of the island. Sandy soils cover a large area of the island. Much of these areas are cultivated, but often at a low production level. Using the HaiSOTER database, which was constructed from 1999 to 2003, soil quality and crop suitability were evaluated as a method of identifying limitations and potential uses of sandy soils on the island.

Climate

Mean annual temperature on Hainan Island ranges between 23ºC and 25ºC, and mean annual precipitation from 900 mm to 2,600 mm. Precipitation is unevenly distributed, with less received in winter and spring and more in summer and fall. During the summer and fall, typhoons are frequent, bringing about one-third of the year’s precipitation. As shown in Figure 1, there are regional differences in precipitation on the island. In the eastern parts, such as near Wanning and Qiongzhong, precipitation may reach 2,000 mm or more, while in the southwestern part, precipitation is less than 1,200 mm. Most soils of Hainan Island have a Hyperthermic soil temperature regime. With respect to soil moisture, soils in the broad central northern part have an aridity <1 and belong to

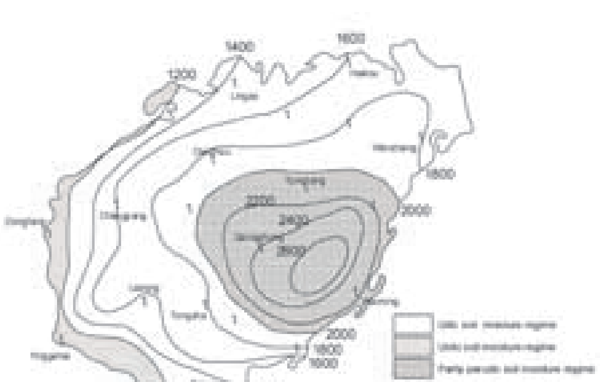

Figure 1. Soil moisture regimes of the Hainan Island

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the Udic moisture regime; those in the southwestern part have an aridity >1 and belong to the Ustic moisture regime; and those in the central mountainous region, where precipitation increases with elevation, belong to the Udic and Perudic moisture regimes (Gong et al., 2003).

Landform

The Hainan Island landform is characterized by high elevation in the centre surrounded by a low and flat circumference. With Wuzhishan (1,867 m) and Yinggeling (1,811 m) mountains at the centre, three concentric zones can be defined (Figure 2). The centre zone accounts for 25.5% of the island’s territory and consists of mountains and hills with elevations >400 m. It has steep slopes and mostly young soils seriously affected by erosion. The zone makes up 45.8% of the territory, and contains hills and plateaus with elevations ranging from 20 m to 400 m that are predominantly mature soils. The outer zone contains 28.7% of the island’s area, and has mostly flat coastal plains below 20 m in elevation. It is in this outer zone that human activities are the concentrated and is dominated by mostly anthropogenic soils.

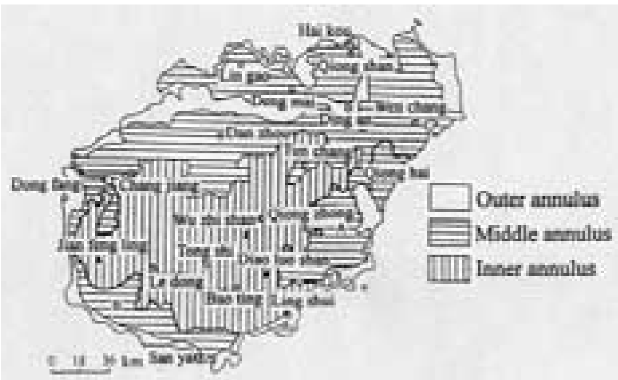


Figure 2. A schematic map of the general pattern of the annular distribution of the soils on Hainan Island

Materials and Methods

SOTER Methodology

SOTER (Soil and Terrain Digital Database) has been widely used as a world soil and terrain digital database (FAO, 1995). Underlying the SOTER methodology is the identification of areas of land with distinctive, often repetitive, patterns of landform, lithology, surface form, slope, parent material, and soils. Tracts of land distinguished in this manner are named SOTER units. Each SOTER unit represents one unique combination of terrain and soil characteristics.

There are two types of data in a SOTER database: geometric data and attribute data. The geometric component indicates the location and topology of SOTER units, while the attribute part describes the non-spatial characteristics. The geometric data is stored and handled by GIS software, while the attribute data is stored separately in a set of files, managed by a relational database system. A unique code is set up in both the geometric and attribute databases to link these two types of information for each SOTER unit.

A SOTER database at a scale of 1:200,000 was compiled for Hainan Island (HaiSOTER). Figure 3 shows the procedure of HaiSOTER (Zhao et al., 2005). The database consists of spatial and attribute data of the soil and terrain conditions, and associated data such as climate and land use. HaiSOTER database collected 153 soil profiles accoss the island. Each SOTER unit has its representative soil profiles.

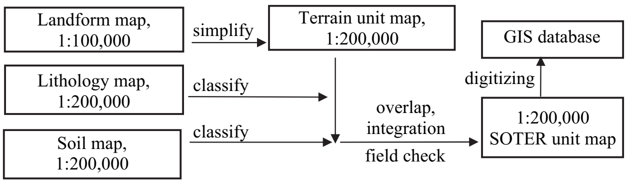


Figure 3. Flow chart of 1:200,000 HaiSOTER establishment

Crop Suitability Evaluation

An expert model for physical land evaluation developed in the Automated Land Evaluation System (ALES) was used to separate potentially suitable AEU (Agricultural Ecological Unit)’s from unsuitable ones. Soil depth, surface horizon depth, texture, structure, bulk density, cation exchange capacity (CEC), pH, total nitrogen (TN), total phosphorus (TP), exchangeable Ca, Mg, K, growing period, rainfall and typhoon occurrence were considered during the modeling processes.

The evaluation model for crops distinguishes between management types with different levels (low, medium and high) of input and degree of mechanization. Such specific types of land use are called ‘land utilization types’ (LUT). To illustrate how the evaluation model works, we take the case of banana, which is a common crop in Hainan with favourable marketing prospects. Four land utilization types of banana growing were defined for this study (Mantel et al., 2003):

Low input and low technology. This LUT includes a low application of organic fertilizer and simple implements for weeding and soil tillage. No terracing or artificial drainage is practiced.

Medium input and low technology. This LUT includes modest applications of inorganic or organic fertilizer and agrochemicals. It does not include use of mechanized tools for weeding and soil tillage. No terracing is practiced. Artificial drainage is not applied.

Medium input and medium technology. This LUT includes modest applications of inorganic or organic fertilizer and agrochemicals. Mechanized tools are used for weeding and soil tillage. No terracing is practiced. Artificial drainage is applied where required.

High input and medium technology. This LUT includes applications of inorganic or organic fertilizer and agrochemicals and mechanized tools for weeding and soil tillage. No terracing is practiced. Irrigation and artificial drainage is applied where required.

Other levels of input and degree of mechanization were not defined in the assessment model for banana in this study.

Results and Discussion

Soil Chemistry Attributes

There are four major parent materials in Hainan island (GPGSB, 1965): acid igneous rock, which forms Cambosols and Ferrosols; marine sediments, which form Primosols and Cambosols; inner land clastic sediments, which form Cambosols; and basic igneous rocks, which form Ferrolosols. Soils from these four parent materials cover 83.2% of the island. 138 of 153 soil profiles in HaiSOTER database were taken from these four types of parent materials, in which, 65 soil profiles on acid igneous rock, 35 sandy soil profiles on marine sediments, 23 on clastic sediment, 15 on basic igneous. Topsoil chemical attributes of sandy soils formed from marine sediments and soils from the other three parent materials are listed in Table 1, and illustrated in Figure 4 using standardized values to better compare and contrast the soils (Zhao et al., 2005).

Exchangeable bases: Because the silt and clay contents were very low for sandy soils, they contained less exchangeable bases. In terms of average values, exchangeable K, Ca, and Mg of sandy soils were lower than in soils developed from other parent materials. Exchangeable K content of sandy soils was lower than that of soils developed from acid igneous material and clastic sediments, and exchangeable Mg was lower than in soils formed from clastic sediments. There was no significant difference in exchangeable Na content among soils developed from four parent materials.

Sandy soils had the highest pH and lowest exchangeable acidity and Al. Normally in tropical climates with high precipitation such as those of Hainan, strong desilication and allitization are the main soil forming processes, and exchangeable Al dominates soil pH. However, sandy soils contain fewer weatherable minerals, making desilication and allitization weak. Also, there are shell and coral sediments in sandy soils with high Ca content that neutralize acid quickly.

Sandy soils in Hainan also had the lowest CEC, total carbon (TC), and TN values compared to the other soil types, which makes them unfavourable for growing most types of vegetation. Because of their coarse texture, many plant-essential nutrients elements can be easily leached. The TP content for soils developed from basic igneous material is lower than that of soils

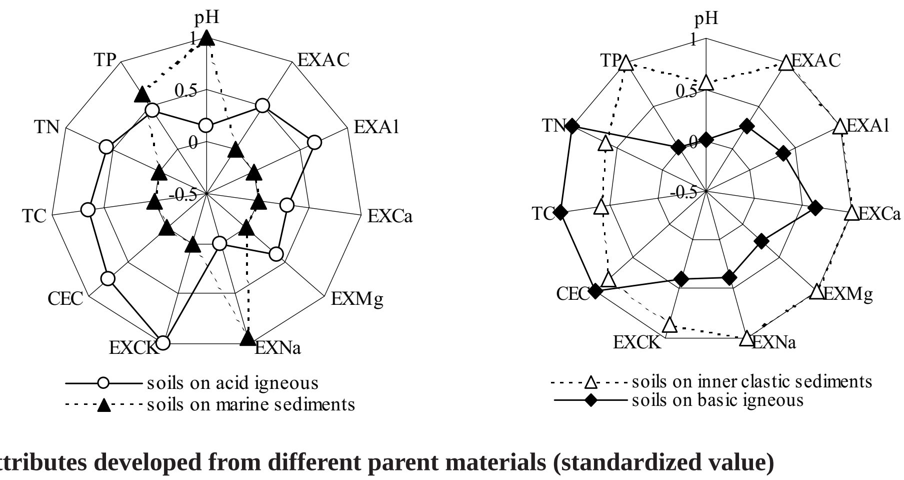


Figure 4. Topsoil attributes developed from different parent materials (standardized value)

Table 1. Differentiation of topsoil attributes developed from different parent materials (rocks)

ID	Parameter	Soils on Acid igneous n = 65	Sandy Soils on Marine sediment n = 35	Soils on Clastic sediment n = 23	Soils on Basic igneous n = 15
pH	pH (Water extractable)	5.0 bc	6.0 a	5.5 b	4.8 c
EXAC	Exc. acidity cmol kg^{-1}	1.5 ab	0.9 b	2.1 a	1.2 b
EXAl	Exc. Al cmol kg^{-1}	1.2 ab	0.7 b	1.6 a	1.0 ab
EXCa	Exc. Ca cmol kg^{-1}	1.4 a	1.2 a	1.9 a	1.7 a
EXMg	Exc. Mg cmol kg^{-1}	0.8 ab	0.6 b	1.2 a	0.7 ab
EXNa	Exc. Na cmol kg^{-1}	0.2 a	0.3 a	0.3 a	0.2 a
EXCK	Exc. K cmol kg^{-1}	0.5 a	0.2 b	0.4 a	0.3 ab
CEC	CEC cmol kg^{-1}	7.4 a	3.9 b	7.7 a	8.6 a
TC	Total C g kg^{-1}	15.2 a	7.3 b	14.6 a	19.6 a
TN	Total N g kg^{-1}	1.14 b	0.59 c	1.20 b	1.56 a
TP	Total P (P_2O_5) g kg^{-1}	1.36 ab	1.56 ab	1.97 a	0.86 b

Note: letters (i.e., a, b, ab) following table values is the results of multi comparison, different letters in one row mean significant difference existed for the soil attribute among 4 kinds of soils. SPSS10.0, Duncan

developed from clastic sediments. P content in clastic sediment maybe higher because of the erosion process brings P sediments from upper reaches.

Land use:

Figure 5 shows the land use distribution for sandy soils in Hainan, as interpreted from the TM satellite in the year 2000. As the data indicate, agriculture is the most important economic resource for Hainan. Nearly 70% of the area of sandy soils is under cultivation. The main crops include vegetables, cassava, coconut and peanut. In the eastern part of the Island, where water supply is abundant, rice is cultivated on sandy soils.

Agricultural exploitation on sandy soils mainly occurs in the middle circle (Figure 2) and not in the newly formed, unsuitable sand areas in the outer circle, where *Casuarina equisetifolia*, coconut and salt-tolerant grasses are the main vegetation types.

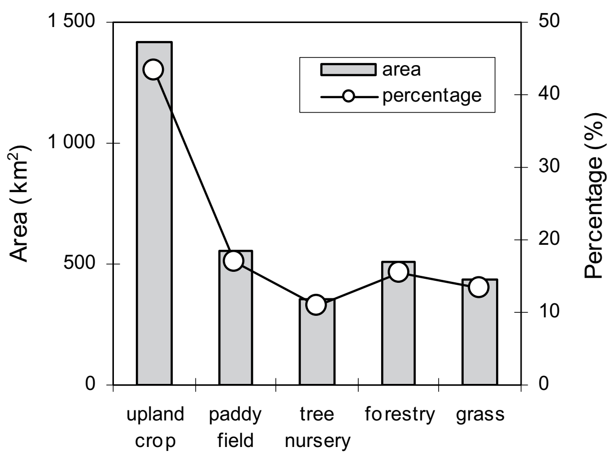
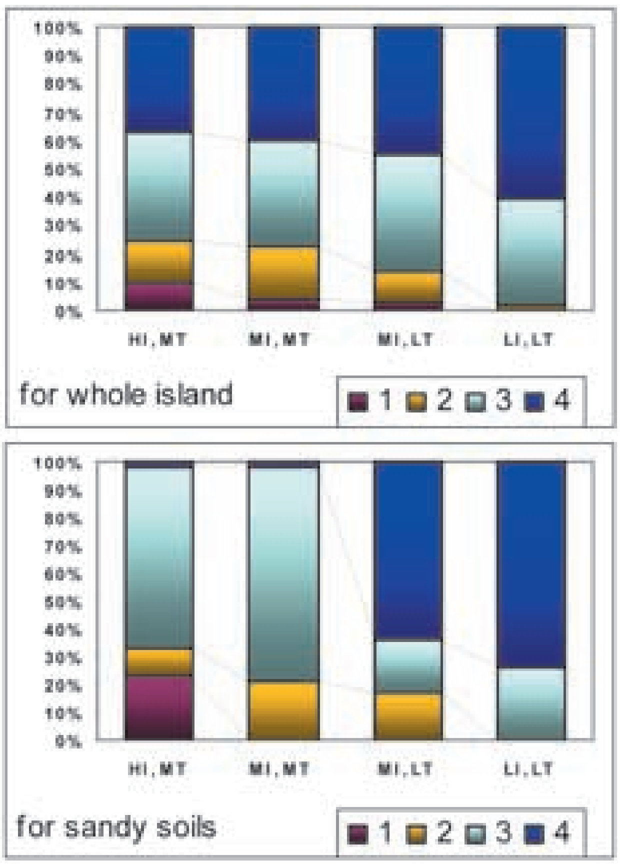


Figure 5. Land use for sandy soil in 2000 year

Crop suitability (Example of Banana)



Note: HI, MT: high input and moderate technology; MI, MT: moderate input and moderate technology; MI, LT: moderate input and low technology; LI, LT: low input and low technology;

1, highly suitable; 2, moderate suitable; 3, marginally suitable; 4, not suitable

Figure 6. Banana suitability under different input and technologic conditions

We use the example of banana in this paper to illustrate how crop suitability was evaluated for different soil and terrain types in Hainan. Banana suitability at four different input and technological conditions was demonstrated by Mantel et al. (2003). Poor native soil productivity is reflected by low suitability values under low input and low technological conditions. Because banana has high requirements for water and nutrients, and for low wind climates, almost none of the island’s land was found to be suitable for banana production under conditions of low input and technology (Figure 6). When the input and technological conditions were improved, the area suitable for production increased gradually for the whole island. For sandy soils, however, the increase is steeper (Figure 6). More than 30% of sandy soils can be used for banana planting at high input and moderate technological conditions. The sharper increase in suitability demonstrates that some sandy soils can be improved easily, because poor nutrient availability, their most limiting production factor, can be addressed by fertilizer input.

The sandy soils suitable for banana production are mainly distributed in the west and northern part of the island. Almost none of the sandy soils in the east part can be used for banana planting because of the typhoon risk. The prevailing direction of typhoon is from the south and southeast towards the north and northeast. Nutrient deficiencies are similar for sandy soils in both the western and eastern parts of the island. Water limitation is especially critical for sandy soils of the west part, because annual precipitation is less than 1,000 mm and evaporation is very high. However, with financial support to construct irrigation systems, this constraint can be removed in some areas.

Soils suitable for banana planting are mainly distributed on the old marine sediments towards the interior of the outer concentric zone shown in Figure 2, where soil texture and nutrient conditions of these soils have been improved by longer weathering and a longer history of cultivation.

Conclusions

Sandy soils play an important role for Hainan’s agriculture. Nearly 70% of the area of sandy soils is under cultivation. But sandy soils in Hainan are limited by poor nutrient conditions. The main nutrient attributes such as soil organic matter, CEC, and N content are significantly lower than those in other soils. However, they have the highest pH and lowest exchangeable acidity and Al.

Some sandy soils can be improved easily, because poor nutrient availability, their most limiting production factor, can easily be addressed by fertilizer input. More than 30% of sandy soils can be used for banana production at high input and moderate technological conditions.

Acknowledgement

The construction of HaiSOTER database was cooperatively done by Chinese Academy of Tropical Agricultural Sciences. Methodology was supported by the International Soil Reference Information Center. Mr. VWP. van Engelen, Mr. S. Mantel and Dr. X.L. Zhang completed the main work on assessment of crop suitability.

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Sandy soils in Southern and Eastern Africa: Extent, properties and management

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Keywords: SOTER, Arenosols, Africa, extent sandy soils, soil properties

Abstract

Sandy soils cover about 13% in sub-Saharan Africa and are widely spread in the Southern and Eastern parts of Africa. Although they occur in sparsely populated regions, many of these soils are under stress; they are brought into cultivation or are used for extensive grazing. This paper reviews the importance of sandy soils in 9 countries of Southern and Eastern Africa (Angola, Botswana, Kenya, Mozambique, Namibia, Tanzania, South Africa, Swaziland and Zimbabwe). Estimates of their extent are based on SOTER databases. The total extent of sandy soils in the 9 countries is about 176 million ha. Sandy soils occur extensively in Angola and Botswana (>50% of total land area) but also in Zimbabwe, South Africa and Mozambique (>15% of total land area). The SOTER Arenosol map was matched with the recent land-cover map of Africa to calculate the extent of Arenosols under agriculture. About 7 million ha of Arenosols are under cropland, most of which is located in Angola, Botswana and South Africa. From the SOTER databases, soil chemical properties were summarised. The average Arenosol topsoils in Namibia and South Africa are alkaline with a soil reaction over 7. In Angola, Zimbabwe and Tanzania the average topsoil pH of Arenosols is below 6. Organic carbon (C) is uniformly low in Arenosols of Southern and Eastern Africa and rarely exceeds 10 g kg^{-1}. Higher C contents are generally found in soils with higher clay content, whereas higher C contents are also associated with higher cation exchange capacities (CECs). Management of these soils is problematic, the low CEC and water holding capacity necessitates addition of organic manures, but quantities available are minimal and organic matter decomposes rapidly. Conservation practices result in major yield penalties even when large amounts of nutrients are added and the capacity of the soils to stabilize organic matter is limited by the very low clay and silt contents. Most appropriate management involves use of frequent but small doses of inorganic fertilizers.

Introduction

Sandy soils occur in all parts of the world. When these soils have greater than 70% sand and less than 15% clay, they are classified as Arenosols in the World Reference Base (FAO, 2001) and in Soil Taxonomy as sandy Entisols: Psamments when well-drained, or as Psammaquents when in tidal marshes, deltas and wetlands (Soil Survey Staff, 1999). In the World Reference Base, sandy soils may also occur in the reference groups Regosols, Leptosols and Fluvisols. Arenosols may have developed in residual sands, in the weathering products of quartz-rich rock or in recently deposited sands common to deserts and beaches (FAO, 2001).

Arenosols are particularly widespread in Africa where about 51% of the Arenosols of the world are found. About 21% of the Arenosols are found in Australasia whereas 10% of the Arenosols occur in South and Southeast Asia. Less than 14% of the global extent of Arenosols is found in South and Central America and only small patches are found in North America and Europe. Worldwide Arenosols cover approximately 9 million km^2 (900 million ha), compared to about 300 million ha of Vertisols and 700 million ha of Ferralsols. Yet, Arenosols have not received the same amount of research attention – possibly as many of the Arenosols are not used for agriculture or only in a very extensive way (i.e. for grazing or fuel wood collection).

Most Arenosols are or were located in arid or semiarid regions (van Wambeke, 1992). Arenosols are only weakly developed with little soil horizon formation. In general chemical weathering is often slow in these soils because of the prevalent hot and dry conditions under which they are formed in the arid and semi-arid tropics. Physical weathering is dominant

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resulting from extreme changes in diurnal temperatures and seasons. Wind erosion may be a problem in many areas dominated by Arenosols because of the lack of soil cover and weak soil structure (FAO, 2001). Characteristic properties of Arenosols are high water permeability, low water-holding capacity, low specific heat, and often minimal nutrient contents. In summary: Arenosols have a large number of unfavourable attributes for sustainable agriculture (van Wambeke, 1992). They are best kept covered by vegetation. Also under natural conditions it is difficult to establish dense plant communities on Arenosols due to the exploitation for firewood, grazing or the destructive effects on the tree layer by large vertebrates and periodic burning (Almendros et al., 2003). In many parts of Southern and Eastern Africa, Arenosols are increasingly used for arable farming because of pressure on the land forcing the cultivation of such unfavourable soils. Extensive rainfed production of annual crops is possible and groundnuts and cassava are often considered best adapted to Arenosols but also tobacco is grown on Arenosols. Perennial crops on Arenosols include cashew, coconuts, citrus, eucalyptus and pinus (van Wambeke, 1992).

In Africa, Arenosols cover about 273 million ha or almost 13% of the total land mass (Eswaran et al., 1997). They occur widely in the western part of the continent where much soil fertility research on sandy soils takes place (e.g. Mokwunye, 1991; Pieri, 1989; Sanginga et al., 1995; Vanlauwe et al., 2002). This work has greatly contributed to the sustainable management of Arenosols which – in essence – suffer from both poor soil chemical and physical properties. Relatively little work has been conducted on Arenosols in the southern and eastern part of the continent possibly as the extent of Arenosols is smaller, and their importance lower.

This paper focuses on Arenosols in Southern and Eastern Africa. The extent and properties are summarised. The objectives of this paper are to estimate the extent and properties of sandy soils in Southern and Eastern Africa based on SOTER databases, followed by a brief discussion on soil management strategies for sustainable crop production.

Databases and experimental data

Soil databases

Since the mid 1980s, a global soil and terrain database has been developed at a scale of 1:1 million. The scale independent database, named SOTER (Global SOils and TERrain Digital Database), holds information of a maximum of 118 soil and terrain attributes (Oldeman and van Engelen, 1993). SOTER is to replace the 1:5 million FAO-Unesco soil map of the world (van Engelen and Hartemink, 2000). Continental scale SOTER databases are available for Latin America and the Caribbean, Central and Eastern Europe and Southern Africa. The SOTER methodology has been applied at scales ranging from 1:250,000 to 1:5 M (Batjes, 2004) and a range of single value maps or data and interpretative products can be extracted. SOTER has been used in studies on vulnerability assessment to pollution mapping in Central and Eastern Europe, the impact of erosion on crop productivity in various tropical countries, global environmental change studies and agro-ecological zoning (Batjes, 2002; Batjes, 2004). SOTER databases can also be combined with remote sense imagery to investigate links between land use and soils.

SOTER consists of units that contain a distinctive, often repetitive, pattern of landform, lithology, surface form, slope, parent material and soil. SOTER puts emphasis on the relationships between landform, parent material and soils, integrating these into one unit: the SOTER unit. Each SOTER unit represents a unique combination of terrain and soil characteristics and a maximum of 118 attributes. As SOTER units consist of a combination of a terrain and soil component, they may contain several soil components. For example, a SOTER unit may consist of 60% Ferralsols, 20% Vertisols and 20% Acrisols, or a unit may have 80% Vertisols and 20% Fluvisols.

Southern Africa

The 1:5 M soil map of Africa was published in 1973. Early 2000, FAO and ISRIC – World Soil Information started to compile a SOTER database for Southern Africa. It included the compilation and harmonisation of a soil and terrain digital database for 8 countries in Southern Africa: Angola, Botswana, Mozambique, Namibia, South Africa, Swaziland, Tanzania and Zimbabwe (Dijkshoorn, 2003; FAO-ISRIC, 2003). The database was compiled from national SOTER databases combined with available soil maps and soil and terrain data including digital elevation models. The database has a generalised scale of 1:2 M but the detail and quality or information varies widely between and within countries (Dijkshoorn, 2003). For example, in South Africa SOTER units are based on a scale of 1:250,000 whereas in several other countries soils have been mapped at 1:1 M or smaller. SOTER units in Southern Africa are comprised of up to 7 soil components, with an average of 2. In total there are 941 soil profiles in the SOTER databases of Southern Africa, whereas the SOTER database for Kenya contains 366 soil profiles. Of these 1,307 soil profiles 165 are Arenosols (Table 1). From the databases, SOTER units were selected in which Arenosols were dominant and their extent exceeded 75%. These queries were made with ArcView 3.3. Successively, the total extent of Arenosols was calculated for each country and a map was produced showing the distribution of Arenosols in the 9 countries.

Table 1. SOTER units and soil profiles for the 9 countries in Southern Africa, based on the SOTER database for Southern Africa and Kenya

Country	SOTER units	Terrain com-ponents	Soil com-ponents	Number of soil Profiles	Number of Arenosols
Angola	238	322	887	150	60
Botswana	94	145	404	60	6
Kenya	39	?	?	366	11
Mozambique	225	325	641	127	30
Namibia	92	118	269	52	3
Tanzania	169	297	687	54	4
South Africa	3,039	7,006	11,822	328	39
Swaziland	19	32	72	14	?
Zimbabwe	143	200	294	156	12
Total	4,019	8,445	15,076	1,307	165

Land cover map

The land cover map of Africa has been used to identify land cover classes in Southern and Eastern Africa (Mayaux et al., 2003). The map (grid map, spatial resolution 1 km) shows the major vegetation formations of the continent with an improved thematic content over previous land cover maps. The majority of the data were acquired in 2000. The map identifies 24 land cover classes, but for this paper, we reduced the number of land cover classes to 5 (forest, grass and shrub land, crop land, stony desert, salt hard pans) by combining several individual classes. From this land cover map, the total area of cropland was calculated for each of the 9 countries. The SOTER Arenosol map was the matched with the land cover map (Mayaux et al., 2003). For each of the Arenosol polygons, zonal statistics of the grid were used to calculate the extent of Arenosols for the 5 land cover classes. These were summed up per country to arrive at the area under agriculture.

Extent and land-cover of sandy soils

Arenosols occupy large areas from Central and East Angola and Namibia to Zimbabwe and Botswana (Figure 1). The Arenosols in large areas of Botswana and in surrounding countries are derived from the Kalahari sands. In Zambia and the western part of Angola many soils are buried under the Kalahari sands (Eswaran et al., 1997). In Zimbabwe the Arenosols have been mostly derived from the weathering of the underlying granitic rocks that contain large amounts of quartz (Burt et al., 2001). In Eastern Africa, Arenosols are mainly found along the coast and although Arenosols occur in Tanzania they are not shown since they are not dominant (<75%) in the SOTER units.

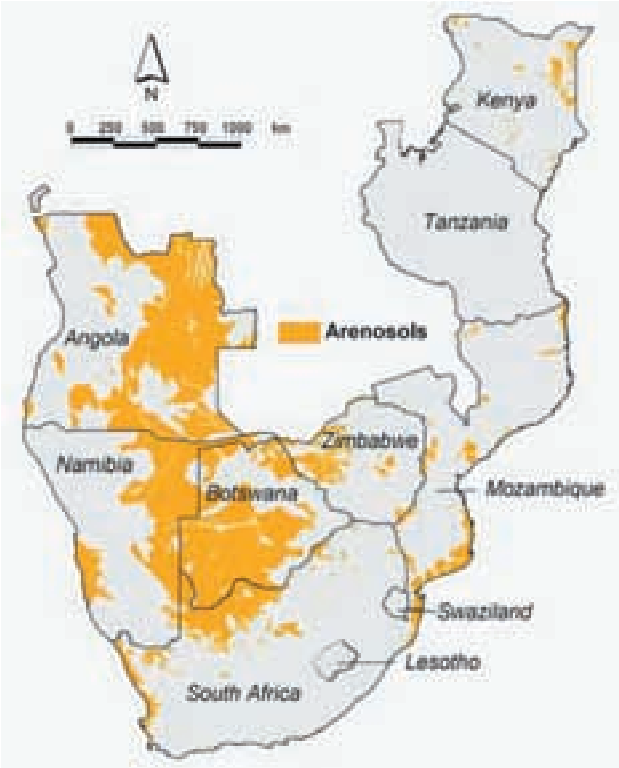

Figure 1. Distribution of Arenosols in Eastern and Southern Africa. Map shows the SOTER units in which Arenosols are dominant (>75% of the SOTER unit)

Total area of Arenosols in the 9 countries is estimated to be 176 million ha. The largest extent is found in Angola (63 million ha) where Arenosols cover about 51% of the total land area. In Botswana, Arenosols occupy 38 million ha or almost two-third of the whole country. Arenosols are also widespread in Namibia where they cover 26 million ha or 31% of the total land mass. Arenosols are also important in Mozambique, South Africa and Zimbabwe where they occupy million of hectares.

Of the total 176 million ha of Arenosols in Southern and Eastern Africa, about 7 million hectare are under cropland (Table 2). The largest extent is

Table 2. Extent of Arenosols, total area under cropland and total area Arenosols under cropland in 9 countries in Southern and Eastern Africa

Country	Land area million ha	Arenosols		Total area Arenosols under cropland		
		million ha	%	million ha	% of total extent Arenosols	% of total area under cropland
Angola	125	64	51	1.9	2	39
Botswana	58	38	66	1.1	2	23
Kenya	59	3	6	0.1	<0.5	3
Mozambique	79	17	21	0.4	<0.5	5
Namibia	83	26	31	0	<0.5	1
Tanzania	95	4	4	0	0	0
South Africa	125	18	15	2.6	2	10
Swaziland	2	0	0	0	<0.5	0
Zimbabwe	39	6	16	0.9	2	8
Total	665	176		7.0		

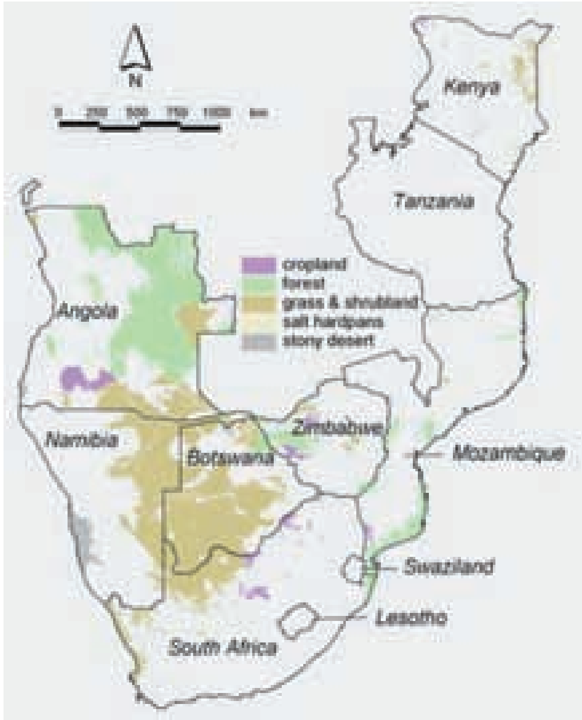

Figure 2. Simplified land-cover map of Arenosols in Eastern and Southern Africa, based on SOTER and land cover map of Mayaux et al. (2003)

found in the south central part of Angola where about 2 million ha of Arenosols are cultivated. Considerable areas of Arenosols in Zimbabwe and South Africa are also under cropland (Figure 2). From the land cover map it was calculated that most of the Arenosols in the Southern and Eastern of Africa are under grassland – with or without shrubs (85 million ha) and various types of forest and woody vegetation (49 million ha).

Properties of sandy soils

A summary of some key soil physical and chemical properties is given in Tables 3 and 4. The average sand content is highest in the topsoils of Arenosols in Angola, Zimbabwe, Namibia and Botswana (>92%) and lowest in the Arenosols of Kenya, Mozambique and Tanzania (<90%). Although this may appear an insignificant difference, the lower sand content (and thus higher silt and clay content) influences important characteristics such as water holding capacity and nutrient retention (Figure 3). Few bulk density data were available and most of the Arenosols have fairly high bulk densities, which is common for sandy soils.

The average Arenosol topsoils in Namibia and South Africa are alkaline with a soil reaction over 7. These soils have also base saturations of almost 100%.

Table 3. Summary of soil physical properties of Arenosols in Southern and Eastern Africa (mean ±1 SD). Number of profiles on which this summary is presented in parentheses

	m	Angola		Botswana		Kenya		Mozambique		Namibia		Tanzania		South Africa		Zimbabwe	
		(60)		(6)		(11)		(30)		(3)		(4)		(39)		(12)	
Sand	0-0.10	93	±3	94	±2	87	±7	89	±7	94	±2	88	±5	91	±8	93	±4
(%)	0.10-0.20	93	±3	94	±2	80	±27	89	±7	94	±2	88	±5	91	±8	92	±5
	0.20-0.30	93	±3	92	±2	86	±6	90	±5	93	±2	88	±4	90	±9	93	±4
Clay	0-0.10	5	±2	3	±2	6	±3	6	±3	3	±1	6	±2	5	±4	4	±2
(%)	0.10-0.20	5	±2	3	±2	6	±3	6	±3	3	±1	7	±2	5	±3	4	±2
	0.20-0.30	6	±3	4	±3	6	±4	6	±3	4	±1	6	±2	5	±4	5	±3
Bulk																	
Density	0-0.10	n.d.		1.65	±0.11	1.41	±0.30	1.47	±0.10	n.d.		n.d.		n.d.		n.d.	
(kg m^{-3})	0.10-0.20	n.d.		1.65	±0.11	1.41	±0.30	1.47	±0.10	n.d.		n.d.		n.d.		n.d.	
	0.20-0.30	n.d.		1.67	±0.09	1.42	±0.20	1.45	±0.07	n.d.		n.d.		n.d.		n.d.	

n.d. = no data

Table 4. Summary of soil physical properties of Arenosols in Southern and Eastern Africa (mean ±1 SD). Number of profiles on which this summary is based in parentheses

		Angola		Botswana		Kenya		Mozambique		Namibia		Tanzania		South Africa		Zimbabwe	
	m	(60)		(6)		(11)		(30)		(3)		(4)		(39)		(12)	
pH water	0-0.10	5.8	±0.7	6.6	±1.5	6.9	±1.3	6.0	±0.6	7.9	±0.4	5.4	±0.5	7.1	±1.1	5.2	
(1:2.5)	0.10-0.20	5.7	±0.8	6.6	±1.5	6.3	±2.5	5.9	±0.5	7.9	±0.3	5.4	±0.4	7.1	±1.2	5.2	
	0.20-0.30	5.7	±0.8	6.6	±1.6	6.8	±1.5	6.0	±0.5	7.5	±0.6	5.3	±0.3	6.8	±1.8	4.8	
Organic C	0-0.10	6.2	±4.2	2.9	±1.1	3.10	±2.29	7.0	±4.1	2.6	±0.7	9.23	±8.78	3.32	±4.60	3.58	±0.36
(g kg^{-1})	0.10-0.20	4.4	±4.0	2.8	±0.9	2.13	±2.37	5.9	±4.2	2.5	±0.7	8.88	±7.62	3.13	±4.72	2.21	±0.52
	0.20-0.30	3.1	±2.4	2.2	±1.0	1.17	±1.47	4.1	±3.2	1.7	±0.6	8.11	±7.97	2.87	±4.75	3.16	±0.77
Total N	0-0.10	0.44	±0.28	n.d.		0.21	±0.27	0.67	±0.48	0.25	±0.01	0.60	±0.28	n.d.		n.d.	
(g kg^{-1})	0.10-0.20	0.33	±0.26	n.d.		0.15	±0.23	0.51	±0.27	0.22	±0.04	0.60	±0.28	n.d.		n.d.	
	0.20-0.30	0.24	±0.18	n.d.		0.05	±0.11	0.36	±0.20	0.08	±0.11	0.50	±0.14	n.d.		n.d.	
CEC	0-0.10	3.4	±1.5	3.3	±2.0	3.8	±2.4	4.1	±2.9	1.5	±1.3	5.7	±6.2	3.0	±2.0	1.7	±0.8
(cmol kg^{-1})	0.10-0.20	2.9	±1.3	3.2	±2.0	3.6	±2.6	3.8	±3.1	1.5	±1.4	5.2	±6.6	3.0	±2.1	1.5	±0.7
	0.20-0.30	2.5	±1.2	3.1	±1.9	3.3	±2.7	3.8	±3.1	1.6	±1.9	5.0	±6.7	2.9	±2.0	1.4	±1.0
Base	0-0.10	40	±30	80	±19	91	±49	86	±71	100	0	25	±15	80	±27	80	±22
saturation	0.10-0.20	35	±31	79	±19	84	±45	77	±80	100	0	17	±16	80	±27	80	±24
(%)	0.20-0.30	32	±31	75	±25	92	±41	68	±81	100	0	14	±14	96	±48	100	±15
ESP	0-0.10	1	±1	1	±2	6	±9	2	±4	3	±1	2	±2	5	±7	5	±8
(%)	0.10-0.20	2	±1	2	±2	6	±9	2	±4	2	±1	3	±4	5	±6	5	±8
	0.20-0.30	2	±1	2	±3	10	±11	3	±3	2	±0.2	3	±4	5	±8	3	±4

n.d. = no data

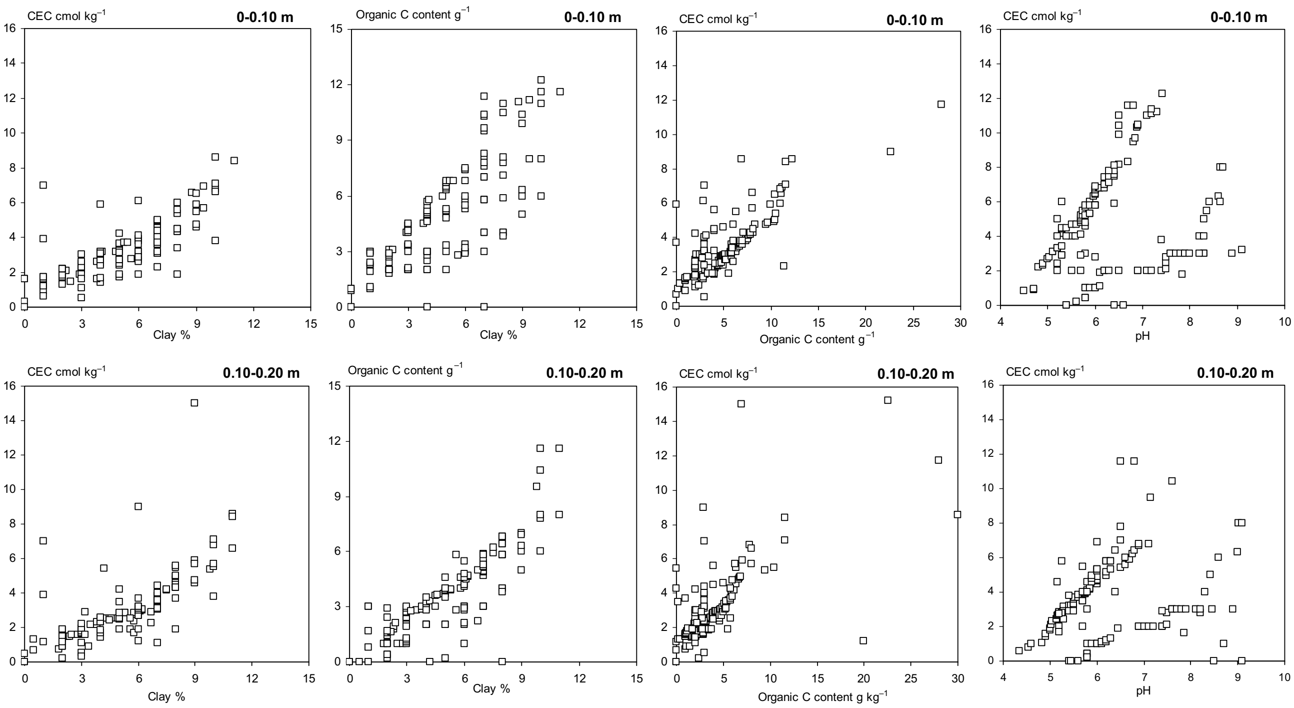

Figure 3. Relationships between clay content, CEC, organic C and pH in the topsoils (0-0.10 m and 0.10-0.20 m) of 166 Arenosols in Southern and Eastern Africa

In Angola, Zimbabwe and Tanzania the average topsoil pH of Arenosols is below 6 whereas in the other countries Arenosols have mostly a topsoil pH between 6 and 7. Organic C is uniformly low in Arenosols of Southern and Eastern Africa and rarely exceeds 10 g kg^{-1}. Higher C contents are generally found in the soils with higher clay content (Figure 3). Clay content in the 0-0.10 and 0.10-0.20 m soil horizons correlated well (r^2 >0.6) with both the CEC and the organic C contents. Higher organic C levels also increased the CEC whereas soil acidity seems to decrease the CEC in these Arenosols. The total N content of Arenosols in Southern and Eastern Africa is low and typically below 0.7 g kg^{-1}. The cation exchange capacity ranges from about 1.3 cmol kg^{-1} in the Arenosols of Namibia to on average over 5.7 cmol kg^{-1} in Tanzania.

Summary and conclusions

In this paper the spatial distribution of sandy soils in Southern and Eastern Africa were presented together with a summary of their main soil physical and chemical properties. Although the coverage of soil profiles is uneven across the 9 countries it was shown that the extent of Arenosols in Eastern and Southern Africa is considerable and higher than 170 million ha. The real extent is possibly larger as soils with high sandy content also occur in the reference groups Regols, Leptosols and Fluvisols. Also, we have selected only those SOTER units in which Arenosols were dominant and exceeded 75%. This implies that some units were ommitted that contained less than 75% Arenosols but also that in some SOTER units the extent of Arenosols was less than 100%.

More than 7 million ha are under cropland and obviously it requires careful management to maintain and increase crop production on such sandy soils. There has been considereable research efforts on the sustainable management of sandy soils in West Africa and in the introduction of the paper we have listed some key references. Research efforts in Southern and Eastern Africa have been less and exchange of experiences and research results may be beneficial for farmers in both regions.

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Coastal sandy soils and constraints for crops in Binh Thuan Province, Southern Central Vietnam

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Keywords: sandy soils, Central Vietnam, nutrient limitations

Abstract

Vietnam is a humid tropical country, covered by large areas of soils of light texture classified as Acrisols and Arenosols (marine sands). These soils are distributed in Thanh Hoa, Nghe An, Quang Binh, Thua Thien Hue, Ninh Thuan, Binh Thuan, Dong Nai, Vinh Phuc, and Phu Tho Provinces. The total area of light textured soils is estimated to be 20,504,076 ha, of which Arenosols comprise 533,434 ha and Acrisols, 19,970,642 ha. In Binh Thuan Province in the central coastal area of Vietnam there are 12,935 ha of Arenosols and 154,210 ha of Acrisols. This coastal region is characterized by very hot and dry weather, and low soil fertility, making agricultural production problematic.

With the aim of helping farmers to get more income and developing sustainable land use practices, a field study was carried out in Bac Binh District, Binh Thuan Province from 2001-2003. Two types of sandy soils representative of the cultivated lands in the district were described and tested to identify the nutrient limitations for crop production. Acidity, low organic matter, and multiple deficiencies of nutrient elements for crop growth are limiting factors for crops growing on these soils. Omission trials in the glasshouse identified that the limitations of nutrient elements for crop growth can be ranked as follows on these sandy soils: N > P > K and B > Mo > Zn; in the white sandy soil: P > N > K and B > Mo > Zn.

Field trials demonstrated that amendments with farmyard manure (FYM), lime and phosphate were remarkably effective in improving crop yields on these sandy coastal soils.

Introduction

Vietnam is a humid tropical country, covered by large areas of soils of light texture classified as Acrisols and Arenosols (marine sands). These soils are distributed in Thanh Hoa, Nghe An, Quang Binh, Thua Thien Hue, Ninh Thuan, Binh Thuan, Dong Nai, Vinh Phuc, and Phu Tho Provinces. The total area of light textured soils is estimated to be 20,504,076 ha, of which Arenosols comprise 533,434 ha and Acrisols, 19,970,642 ha. In Binh Thuan Province in the central coastal area of Vietnam there are 12,935 ha of Arenosols and 154,210 ha of Acrisols. This coastal region is characterized by very hot and dry weather, and low soil fertility, making agricultural production problematic.

Facilitating management practices that enable farmers to improve soil fertility is essential for economic development of the coastal zones. A participatory study with farmers was carried out in Bac Binh District, Binh Thuan Province to find out the limiting nutrient factors and to develop appropriate strategies for sustainable crop production. This study aims to: evaluate the soil fertility status of the dry coastal land and to identify the main limiting factors for crop growth; increase farmer understanding of soil characteristics and fertility of their fields for better crops; and facilitate farmer adoption of soil amelioration practices and soil environmental protection.

Materials and methods

Field survey

A field survey was carried out of the agricultural land of 4 communes (Luong Son, Song Luy, Song Binh and Binh Tan). Seventy six soil samples from 14 profiles were taken for analysis. The following analyses were undertaken: pH (1:2.5 water), Walkley Black organic C, Kjeldahl total N, total P_2O_5 and total K_2O using a concentrated H_2SO_4+ $HClO_3$ digest,

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available P_2O_5 using the Bray 2 extractant, and exchangeable Ca^{2+} , Mg^{2+} and CEC using NH4COOH, 1 M, pH 7.

Omission Trials

Glasshouse trials were undertaken following the guidelines for rate trails and omission trails recommended in “Diagnosis of nutritional limitation to plant growth by nutrient omission pot trials” (Asher and Grundon, 1998). The methodology comprises two main steps. The first defines suitable nutrient rates for the crop. This is done with rate trials of nutrients applied at rates ranging from 0 (control) to 4 times. Results indicate the most suitable rate of applied nutrients for crop growth in each soil. The second step in the methodology, based on the results of the first step, comprises an omission trail for 14 nutrient elements (Table 1). This step aims to find out the most limiting nutrients to the growth of the plant. If any element omitted, while other elements are applied at the most suitable rates, and plants grow weakly, then the tested element is a limiting factor for crop growth. Conversely, if any element is omitted, but plants are healthy, then that element is not a limiting factor for crop production. Pot trails were carried out in the greenhouse at the National Institute for Soils and Fertilizers. In this report, only the results of the omission trials are presented.

Table 1. Treatments applied in the omission trial in the glasshouse

1	All	6	All-Mg	11	All-Zn
2	All-N	7	All-S	12	All-Cu
3	All-P	8	All-Fe	13	All-Mo
4	All-K	9	All-B	14	All-Ni
5	All-Ca	10	All-Mn	15	All-Co

Nutrients were applied in solution form to the soil in pots. Soil moisture was maintained at field capacity with distilled water during 7 days after germination. Maize (Zea mays) seedlings were thinned to 3 plants/pot. Distilled water was added as often as necessary to keep the soil moisture around 80-85% of field capacity. This moisture content is considered to be the most effective for plant growth.

Field trials on fertilization for peanut

Field trials were laid out in a completely randomized block design with 4 replications. Treatments are indicated in Table 2.

Table 2. Treatments in field trial carried out for peanut on an Arenosol

Treatment	Input, kg/1,000 m^2	kg/ha (N, P, K)
1. Farmer’s practice	20 kg NPK, (20:20:15) + 5 kg Urea	63 N, 40 P_2O_5, 30 K_2O
2. Input 1	20 kg NPK + 5 kg Urea + 50 kg lime + 1,000 kg FYM	63 N, 40 P_2O_5, 30 K_2O
3. Input 2	10 kg Urea + 56 kg Super 15 kg KCl + 50 kg lime + 1,000 kg FYM	45 N, 90 P_2O_5, 90 K_2O
4. Input 3	13 kg Urea + 75 kg Super + 20 kg KCl + 50 kg lime + 1,000 kg FYM	60 N, 120 P_2O_5, 120 K_2O

Results and discussion

Site characterization

There are 4 soil types in Bac Binh District: Arenosols (sandy coastal soil) (53,670 ha = 29.1%), river alluvial soils (16,000 ha = 8.7%), Acrisols (21,900 ha = 11.9%) and Ferralsols (87,290 ha = 47.4%). Agricultural land comprises 38,000 ha. In general, soils in Bac Binh are light textured in the surface, have loose structure and non sticky plasticity. Soil is compact and has a low water holding capacity. Water and wind erosion occurs throughout the year. Climate data for the district are as follows: mean air temperature: 26-27ºC; difference between mean air temperatures day and night: 5-7ºC; mean relative humidity: 78.9%; rainy days in year: 50-60; annual precipitation: 750-1,200 mm; highest monthly rainfall (month): 157 mm (July); lowest monthly rainfall (month): 3.4 mm (March). The dry season lasts from October to next April with an average rainfall of 5 mm/month, although monthly rainfall can be less than 1 mm/month for 3 consecutive months. In addition, during the dry season there is very strong wind, causing sand movement.

Current farmer practice

Farmer awareness of environmental degradation and desertification is limited. Findings from a survey of the local indigenous knowledge in Binh Thuan found that farmers have a low understanding of soil fertility and fertilization, especially organic fertilizers. Farmyard manure (FYM) is not applied to the field but sent to others off-site. Moreover, farmers have no understanding of the role of phosphate fertilizer and lime, so neither of these is applied to the crop. As a consequence, cultivated soils are very poor in organic matter and phosphate, and are strongly acidic.

Table 3. Soil acidity and total nutrient contents of soils of four communes

Commune	Number samples	Range	pH_{KCl}	OC	N	P_2O_5	K_2O
				Total, %			
Luong Son	23	Min	4.07	0.177	0.025	0.005	0.012
		Max	5.84	1.228	0.134	0.069	0.676
		Average	4.91	0.51	0.06	0.02	0.21
		STDEV	0.50	0.30	0.03	0.02	0.21
		CV, %	10.22	59.26	49.57	81.03	97.36
Song Luy	15	Min	4.20	0.201	0.016	0.006	0.012
		Max	5.41	0.965	0.078	0.044	0.462
		Average	4.89	0.46	0.04	0.02	0.08
		STDEV	0.36	0.24	0.02	0.01	0.13
		CV, %	7.35	51.36	48.30	76.36	153.16
Song Binh	17	Min	3.60	0.145	0.021	0.006	0.0067
		Max	5.62	1.558	0.14	18.00	0.854
		Average	4.80	0.68	0.07	1.09	0.31
		STDEV	0.59	0.43	0.04	4.36	0.27
		CV, %	12.32	64.14	64.30	400.13	88.10
Binh Tan	16	Min	3.96	0.201	0.036	0.0074	0.03
		Max	5.71	1.211	0.154	0.112	0.723
		Average	4.90	0.71	0.08	0.04	0.31
		STDEV	0.49	0.26	0.04	0.03	0.24
		CV, %	10.04	37.09	44.31	86.16	77.60

Soil chemical characteristics

A soil survey was undertaken and 76 samples were collected for analysis. Data in Table 3 show that soil acidity ranges from moderately acid to strongly acid with pHKCl values of 3.6-5.8, average 4.79, with coefficients of variation (CV%) of 7.04-12.32%. Soil organic carbon (OC%) in the surface layer varied from 0.12-1.56%. Nitrogen varied from 0.016-0.078% N. Percentage of total P_2O_5 ranged from 0.006-0.112% while the percentage of total K_2O ranged from 0.012-0.85%. Values of total OC, N, P and K had high CV%.

Table 4 presents the extractable P, exchangeable cations and CEC of the soils. Both Bray II extractable P and exchangeable K have large ranges (0.21-18.65 mg P_2O_5/100 g soil and 1.2-26.13 mg K_2O/100 g soil). Data indicate that in general the soils are very poor in available P and K. Cation exchange capacity is generally low with an average of 7.35 meq/100 g soil. Exchangeable cations averaged 2.2 meq/100 g soil for Ca^{2+} and 1.43 meq/100 g soil for Mg^{2+}.

Distribution of nutrients in the soil profile

White dry sandy soil: This soil type is common in Bac Binh Distinct, being distributed on undulating hills and sandy dunes. Almost all of the district’s cashew is grown on this soil type. Cashew trees grow very well, but have very low yields, in some years producing no yield at all. This may be caused by nutrient imbalance or deficiency, or extremely low plant available water.

Profile LS1 is under cassava-cashew production (Table 5). Cashew is 10 years old with healthy trees. Cassava shows poor growth. Chemical properties are presented in Table 5. These data indicate that this type of soil is strongly acidic, and poor in organic matter and total N. Phosphorus and K are low in both total and available forms.

Red dry sandy soil: Red dry sandy soils are distributed in the Hoa Thang, Hong Phong, Binh Tan communes. These areas are being seriously degraded. Soils are very dry, and susceptible to wind and water erosion. Profile LS12 indicates that the soil is moderately acid and poor in plant nutrients, and has low cation exchange capacity throughout the profile.

Grey sandy soil derived from sandstone: This type of soil occurs in Song Binh and Binh Tan communes. Cropping systems are cassava, cashew, water melon, peanut and corn. Crops generally show very poor growth and yields. The soil is strongly acid, with low organic carbon and poor in plant nutrients (Table 7). Cation exchange capacity is very low.

Table 4. Available contents of P_2O_5 and K_2O and exchangeable cations in the soils of four communes

Commune	Number samples	Range	P_2O_5	K_2O	Ca^{2+}	Mg^{2+}	CEC
			mg/100 g soil		meq/100 g soil		
Luong Son	23	Min	0.25	1.12	0.23	0.23	3.40
		Max	13.13	30.01	7.44	5.21	9.60
		Average	2.57	6.97	3.02	2.39	5.33
		STDEV	3.84	8.46	2.00	1.46	2.32
		CV, %	149.47	121.27	66.23	61.10	43.58
Song Luy	15	Min	0.36	1.12	0.72	0.52	2.00
		Max	4.88	9.03	5.58	4.09	8.00
		Average	1.49	3.23	2.86	2.13	4.36
		STDEV	1.42	2.79	1.65	1.33	2.91
		CV, %	95.33	86.35	57.78	62.31	66.68
Song Binh	17	Min	0.22	1.51	1.35	0.67	9.20
		Max	31.89	51.92	10.79	7.80	14.20
		Average	4.67	7.73	4.13	3.38	11.70
		STDEV	8.26	11.58	2.48	2.37	3.54
		CV, %	177.06	149.85	59.98	70.00	30.22
Binh Tan	16	Min	0.133	1.51	0.23	0.23	3.00
		Max	27.90	16.56	7.44	6.32	12.00
		Average	7.01	5.42	3.42	2.36	8.53
		STDEV	7.83	4.66	2.28	1.70	4.84
		CV, %	111.76	86.02	66.79	72.29	56.75

Table 5. Soil chemical properties of a white dry sandy soil profile (Profile LS1)

Depth, cm	pH_{KCl}	C	N	P_2O_5	K_2O	P_2O_5	K_2O	Ca^{2+}	Mg^{2+}	CEC
		%				mg/100 g		meq/100 g		
0-18	4.67	0.398	0.020	0.007	0.018	0.47	1.51	0.103	1.80	2.00
18-30	4.60	0.402	0.020	0.017	0.018	0.52	1.12	0.74	0.58	2.03
30-50	4.60	0.387	0.016	0.011	0.019	0.46	1.21	1.04	0.83	
50-100	4.82	0.293	0.028	0.007	0.024	0.89	1.51	1.04	0.83	

Table 6. Soil chemical properties of a dry red sandy soil profile in Hong Phong (Profile LS12)

Depth, cm	pH_{KCl}	C	N	P_2O_5	K_2O	P_2O_5	K_2O	Ca^{2+}	Mg^{2+}
		%				mg/100 g		meq/100 g	
0-15	5.62	0.717	0.062	0.015	0.036	1.39	4.52	1.35	0.82
15-45	5.04	0.294	0.039	0.014	0.030	0.64	1.51	1.35	0.67
>45	4.98	0.220	0.032	0.011	0.031	0.53	1.23	0.82	0.52

Table 7. Soil chemical properties in the profile of a grey sandy soil in Binh Tan (Profile BT5)

Depth, cm	pH_{KCl}	C	N	P_2O_5	K_2O	P_2O_5	K_2O	Ca^{2+}	Mg^{2+}	CEC
		%				mg/100 g		meq/100 g		
0-15	4.95	0.468	0.054	0.012	0.012	0.53	1.51	0.92	0.61	4.00
15-30	4.52	0.389	0.036	0.007	0.012	0.32	1.51	1.25	0.93	–
30-55	4.25	0.300	0.027	0.006	0.012	0.27	1.35	0.81	0.56	–

Nutrients limiting growth in the soils in omission trials

Red dry sandy soils: Plant growth was markedly hindered by omission of macroelements. Compared to the control treatment, omission of P reduced plant height by 53%, omission of N caused a 45% reduction, and omission of K reduced height by 36%. Plant dry weight was reduced by 18-48% when macroelements were not added (Table 8). The lowest weight was recorded in Treatment 2, in which N was omitted. The second greatest macroelement deficiency factor was P, followed by K.

Table 8. Nutrient effects on corn growth on a red sandy soil, Hoa Thang

Treatment	Plant height		Plant fresh weight		Plant dry weight	
	cm	%	g/plant	%	g/plant	%
All	54.3	100.0	23.1	100.0	3.3	100.0
-N	30.0	55.2	10.1	43.7	1.7	51.5
-P	25.8	47.5	13.9	60.2	2.0	60.6
-K	34.8	64.1	18.1	78.4	2.7	81.8
-Ca	34.8	64.1	19.6	84.8	2.9	87.9
-Mg	31.5	58.0	23.9	103.5	3.1	93.9
-S	46.8	86.2	20.3	87.9	3.1	93.9
-Fe	49.5	91.2	18.8	81.4	2.5	75.8
-Cu	53.0	97.6	22.8	98.7	2.8	84.8
-Zn	41.5	76.4	16.5	71.4	2.1	63.6
-B	36.3	66.9	5.1	22.1	0.9	27.3
-Mo	38.8	71.5	7.3	31.6	1.0	30.3
-Mn	51.0	93.9	23.2	100.4	3.3	100.0
-Ni	50.5	93.0	20.8	90.0	2.9	87.9
-Co	53.3	98.2	21.9	94.8	3.1	93.9
LSD, 0.05	5.3		9.4		0.78	

Omission of Ca and Mg impaired corn growth more than the omission of S. Compared to the control treatment, omission of Ca reduced plant height by 36% and omission of Mg reduced height by 42%. Plant dry weight was reduced 6-12% when mesoelements were not added. The lowest weight was recorded in Treatment 7, in which Ca was omitted. The next most deficient element was Mg, then S. In the case of the micronutrients, plant height and dry weights were lowest when B and Mo were omitted, followed by Zn. However, when Mn was omitted, plant height and dry weight were similar to the control treatment. This indicates that Mn may be in surplus supply in the soil.

White dry sandy soils: The effects of nutrient omission on the white sandy soil are presented in Table 9. Plant heights were 42.5 cm (77%) when N was omitted, 44.3 cm (81%) without P, and 45.3 cm (82%) without K (Table 9). Plant weight was 50-55% less than the control treatment when N, P, and K were omitted (Table 9). These results show that N, P, and K are deficient in white sandy soil.

Table 9. Nutrient effects on corn growth on white sandy soil, Hoa Thang

Treatment	Plant height		Dry weight of plant	
	cm	%	g/plant	%
All	55.0	100.0	3.8	100.0
-N	42.5	77.3	1.9	50.0
-P	44.3	80.5	1.7	44.7
-K	45.3	82.4	1.8	47.4
-Ca	35.5	64.5	2.4	63.2
-Mg	32.5	59.1	1.6	42.1
-S	47.3	86.0	2.5	65.8
-Fe	48.3	87.8	3.2	84.2
-Cu	56.5	102.7	2.9	76.3
-Zn	39.8	72.4	1.6	42.1
-B	34.3	62.4	1.8	47.4
-Mo	49.0	89.1	2.3	60.5
-Mn	50.5	91.8	2.7	71.1
-Ni	48.5	88.2	2.0	52.6
-Co	39.8	72.4	1.9	50.0
LSD, 0.05	3.67		0.23	

Omission of S only reduced plant height by 14%, but omission of Ca reduced height by 36% and omission of Mg caused a 41% reduction (Table 9). Dry weight was reduced 34-58% when mesoelements were not added. The lowest weight was recorded when Mg was omitted, followed by Ca and S. For the micronutrients, plant height and weight were greatly reduced when Zn and B were omitted (Table 9). Plant dry weight was reduced by over 50% when either of these nutrients was omitted. Plant height was the same as the control treatment when Cu and Mn were omitted. The plant dry weights were reduced by 24% in the -Cu treatment and by 29% in the -Mn treatment compared to the control treatment.

Appropriate fertilization to improve soil fertility and crop yields

A field trial on fertilization for peanut was carried out on a white sandy soil inter-cropped under a cashew nut plantation more than 10 years old. This field experimentation aims to help the farmer get a better understanding of soil fertility/fertilization and economic returns from intercropped annual crop with perennial crops on white sandy soils.

Field trial results are presented in Table 10. Farmer practice applied 20 kg NPK (20:20:25) and 5 kg urea per sao (100 m^2). Lime and organic manure

Table 10. The effect of balanced fertilization on peanut yields (Mr. Hue’s field)

Treat-ment	Plant height		Dry pod yield		Dry stem yield		Harvest index
	cm	%	kg/ha	%	kg/ha	%	
T1	45.0	100.0	2,505.6	100.0	2,586.7	100.0	0.48
T2	45.3	100.7	2,791.0	111.4	2,700.9	104.4	0.52
T3	52.0	115.6	3,812.8	152.2	3,559.7	137.6	0.52
T4	47.0	104.4	2,753.5	109.9	3,077.3	119.0	0.47
LSD, 0.05	0.46		172.5		221.4		

were not applied. This type of soil is acid and low in organic matter. Peanut in farmer practice can give pod yields of 2,505.6 kg/ha. At the same rate of inorganic fertilizers as farmer practice, but with liming and application of organic fertilizer (T2) pod yield increased to 2,791 kg/ha, 11.4% higher than farmer practice.

With balanced NPK at the rates of 45 N, 90 P_2O_5, and 90 K_2O/ha, liming and FYM (T3), pod yield of peanut increased to 3,812.8 kg/ha, 52.2% higher than farmer practice. White dry sandy soil is very poor in organic manure, and NPK. It has low cation exchange capacity and consequently increasing high inorganic fertilizer may not increase pod yield because of the limited capacity of the soil to hold nutrient cations. In Treatment 4, increasing the rates of NPK up to 60 N, 120 P_2O_5, 120 K_2O/ha gave pod yield of 2,753 kg/ha, only 9.9% higher than farmer practice.

Economic effect of fertilizer for peanut

Investment in farmer fertilizer practice for peanut production is estimated to be 3,410 thousand VND/ha (Table 11). Improved treatments increased the outlays to 8,660-11,756 thousand VND/ha. Estimated economic returns were calculated as 15,033.6 thousand VND/ha for farmer practice. However at the higher fertilizer application rates, incomes can reach 16,746 thousand VND/ha in T2, 22,876 thousand VND/ha in T3 and 16,521 thousand VND/ha in T4. Improved fertilization increased returns from 1,712.4 to 7,843.2 thousand VND/ha/crop more than farmer practice (Table 11). This represents an increase in economic returns from 11.4-52.2%, compared to farmer practice.

White sandy soil is acid and poor in organic matter and available plant nutrients. Farmer practice is cultivation without organic manure, no liming and imbalanced low fertilization. In order to transfer the technologies on soil fertility and fertilization, field demonstrations were implemented with 4 treatments in 4 farmers fields (Table 12).

Table 11. Economic return (thousands of VND) in peanut experiment

Input	Items	T1	T2	T3	T4
		1,000 VND/ha			
	NPK	1,000	1,000	0	0
	Urea	210	210	420	546
	Super	0	0	2,240	3,000
	KCl	0	0	570	760
	FYM	0	5,000	5,000	5,000
	Lime	0	250	250	250
	Variety	2,200	2,200	2,200	2,200
	Total cost (C)	3,410	8,660	10,680	11,756
Benefit (B)		1,000 VND/ha			
	Income	15,033.6	16,746.0	22,876.8	16,521
	B/C ratio	4.41	1.93	2.14	1.41
	Compared to T1		1,712.4	7,843.2	1,487.4

Table 12. Treatments for field demonstrations of fertilization for peanut in Hoa Thang commune

Treatment	Fertilizer rate (kg/ha)				
	FYM	N	P_2O_5	K_2O	Lime
1. Farmer practice	0	18.4	12.8	0	0
2. NPK + lime	0	36.8	75.2	60	500
3. NPK + lime + FYM	5,000	36.8	75.2	60	500

Fertilizer and liming for autumn peanut on white sandy soils increased plant growth and yields remarkably (Table 13). Balanced application and liming for peanut increased branches by 16%, plant height by 29%, number of pod/plant by 67% and filled pods/plant by 111% compared to farmer practice. FYM addition in combination with fertilizer and liming, increased branches/plant, plant height, pods/plant and filled pods/plant over farmer practice by 32%, 49%, 147% and 228% respectively.

Table 13. Yield components and yields of peanut in field trails (mean of 4 field demonstration trials)

Treatment	Branches/ plant	Plant height, (cm)	Pods/ plant	Filled pods/ plant
1. Farmer practice	19	35	30	18
2. NPK + lime	22	45	50	38
3. NPK + lime + FYM	25	52	74	59
LSD, 0.05	1.76	8.94	12.90	12.71

Table 14. Peanut yields in participatory study in Hoa Thang. Values are means for 10 farms

Treatment	Dry weight (kg/m^2)		Dry yields			
	Stem & leaves	Pod	Tonne/ha	%	Tonne/ha	%
1. Farmer practice	247.5	82.5	2.48	100	0.83	100
2. NPK + lime	384.5	136.9	3.85	155	1.37	166
3. NPK + lime + FYM	549.5	207.2	5.49	222	2.07	249
LSD, 0.05	55.8	33.7	0.78		0.31	

In the second peanut crop (next spring), further demonstration trials were carried out on 10 farms. Results are shown in Table 14. Balanced fertilization (N, P, K, lime) treatments increased peanut yields by 55% for stover and 66% for pod, compared to farmer practice. Combination of NPK, lime and FYM increased stover yield by 122%, and pod yield by 149%, compared with farmer practice.

Conclusion

In general, coastal sandy soils in Bac Binh District, Binh Thuan Province are strongly acid, low in organic matter and poor in plant nutrients. Sandy land is suffering from serious wind and water soil erosion, and these are constraints for agricultural production. Pot trials indicated that the corn grown on two different soil types of Hoa Thang and Phan Hoa have different responses to the nutrient rates and elements. Omission trials indicated that deficiencies of nutrient elements for crop growth were arranged as follows:

- Red sandy soil: N > P > K and B > Mo >Zn.
- White sandy soil: P > N > K and B > Mo > Zn.

In both soils, omission of Mn increased yields. Balanced fertilizer, liming, and soil organic management could increase peanut yields by 66-149%, compared with farmer practice.

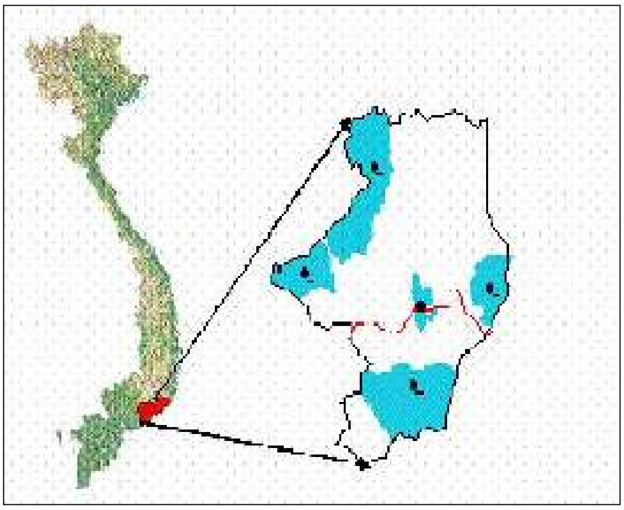

Figure 1. Bac Binh Province and project sites in the Bac Binh District

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Session 2

“Socio-economic imperatives”

Challenges for farmer-researcher partnerships for sandy soils in Northeast Thailand

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Keywords: Economic options, erosion, farm ponds, mini-watersheds, modeling

Abstract

Sandy soils cover 80% of Northeast Thailand. Three related challenges for farmer-researcher partnership in sandy soil mini-watersheds are presented. The first is how to reduce erosion in the uplands and its effects in paddies in mini-watersheds. Research with farmers is needed to develop practical solutions to retain more water in the uplands that are compatible with farmer crop and land use choices. The second challenge is how to model watersheds with multiple users for decision-making. Qualitative participatory modeling can lead to identification of needs that go beyond technical research. Institutional coordination and mechanisms are needed to support wider stakeholder involvement. Models combining hydrology, soil movement, pond water use, and crop outcomes, that farmers can use to explore aggregate effects of management options at the watershed scale are needed to complement qualitative participatory approaches. The third challenge is to give farmers more economic options in sandy soil mini-watersheds. Over 65,000 farm ponds have been built since the 1990s, but ponds are not being used intensively to generate income. One reason is inadequate pond water to support other needs, especially rice. Methods for channeling water from uplands into ponds need to be developed with farmers. Augmenting pond water with groundwater may be more compatible with current upland use. Techniques are needed to increase water use efficiency for fruits and vegetables and thereby increase the area that farm ponds can irrigate. Methods to enable farmers to see likely aggregate economic effects of individual decisions could help stimulate more coordination among farmers in marketing.

Introduction

Sandy soils are a key characteristic of Northeast Thailand, covering 80% of its area (Yuvaniyama, 2001). In contrast, sandy soils cover only 2%, 11%, and 9% of the North, Central/East, and Southern regions of Thailand (Office of Soil Survey & Land Use Planning, 2002). The alluvial plateau of the Korat basin makes up a large proportion of Northeast Thailand, with upland soils comprising 37% of the region’s area (Wongwiwatchai and Paisancharoen, 2002). The topography of the alluvial plateau is undulating, forming a series of mini-watersheds. Farmers in the northeast have converted the bottoms of mini-watersheds into paddies for rice, and plant sugarcane and cassava in the uplands. The climate of Northeast Thailand is characterized by distinct dry and wet seasons. From November to April, almost no rain falls in the region.

The above characteristics have created a complex of management problems for farmers. First, sandy soils have poor water-holding capacity. This means that in the rainy season, they reach saturation quickly. Excess water runs across the surface, and their loose texture makes them easily subjected to erosion. Water runs across fields of different owners in the mini-watershed. Much rainwater is lost to agriculture.

The low water-holding capacity of sandy soils, combined with their low fertility, in turn reduces the options that farmers can choose from for crop production. Sugarcane and cassava are able to produce well under these conditions of sandy soils and a long dry season. However, both require industrial processing for sale. This means that farmers have to sell to the processing plants in the area. In addition, sugarcane requires a large amount of labour and fertilization. These inputs are costly, and as a result, many farmers carry a high debt load. In one study in

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a village in Khon Kaen Province, 49% of farmers had debt greater than B50,000, or more than $1,250 (Ando, 2003).

How to address this complex of problems raises several challenges for research. In this paper, I will focus on three related challenges:

1. How to reduce erosion and its effects at the mini-watershed scale?
2. How to model watersheds with multiple users to support user decision-making?
3. How to give farmers more economic options in sandy soil mini-watersheds?

Each of these challenges cannot be addressed only through bio-physical improvements on a specific field, or even a specific farm. These problems result from interactions across farms mediated by water movement. They can only be solved through cooperation among watershed users. This in turn makes participation of watershed users essential for research and development aimed at improvement of sandy soil watersheds to result in change.

Reducing erosion and its effects at the mini-watershed scale

In the mini-watersheds of the Korat Plateau, erosion is more evident in fields planted in cassava and in fallow land, than in fields planted in sugarcane. However, over a large enough catchment area, water flowing through sugarcane fields can attain sufficient volume and carry enough sand to result in major problems in the paddy areas.

In the Rainfed Agriculture Project[1)], we have worked in one mini-watershed since 2001. In the first year, in a watershed users' meeting, farmers placed two transects in this watershed to orient researchers to their most important problems, and then we conducted a field survey with farmers having paddy and upland fields on each transect. Figure 1 shows this mini-watershed and the two transects. At the upstream end (to the right of Figure 1), farmers indicated that erosion in paddy fields was the greatest constraint. In the upstream paddy area marked in Figure 1, rice failed or was not planted in 18 of 20 plot-years. Only in one paddy plot, where soil erosion affected only 20% of the plot area, was any rice yield obtained, but even there,

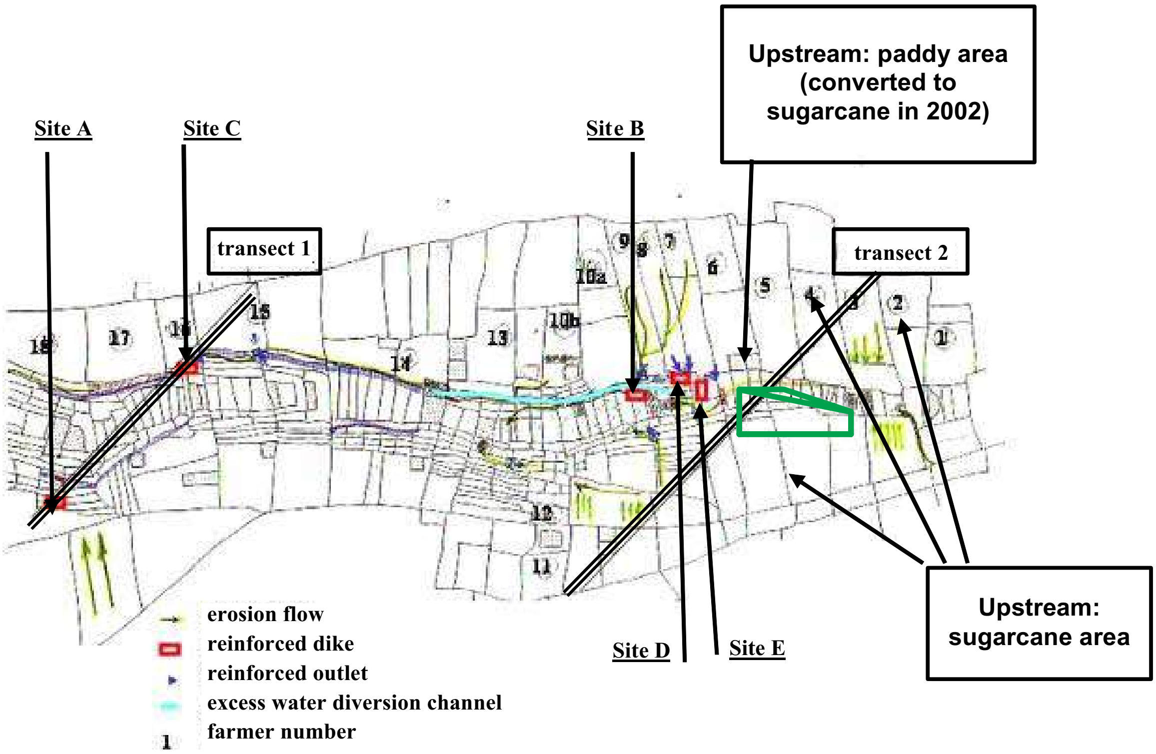

Figure 1. Soil erosion, effects, and management in a mini-watershed, Nong Saeng Village, Khon Kaen Province, 2001-2004 (erosion flow lines after T. Shiono, 2002, unpublished data)

2a **2b** **2c**

Figure 2a. Soil erosion in uplands leads to: Figure 2b. dike breakage, which results in: Figure 2c. sedimentation in central paddies and rice yield loss

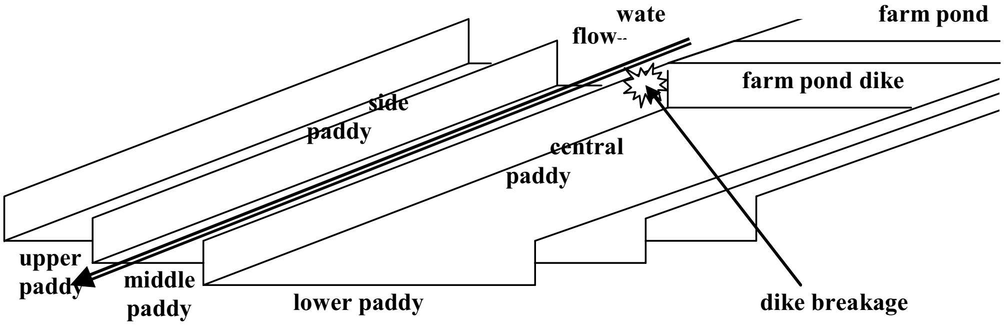

Figure 3. Flow of water downsteam through side paddies and dike breakage into central paddy area

normal yields were obtained in only one of five years. The principal reason for failure in these plots was sand deposition due to erosion from sugarcane fields surrounding the paddy plots, as shown in Figure 2a-c (Caldwell et al., 2002).

In 2002, farmers converted all of the upstream paddy area indicated in Figure 1 to sugarcane. However, this simply shifted the head of the paddy area downstream (to the area marked site E), and transferred the problem of erosion from the upland sugarcane fields and sand deposition into that paddy area.

In February 2002, we conducted another farmers' meeting to present the results of the transect survey together with five technologies from on-station research that had potential to address the two principal problems revealed by the transect survey: 1) erosion and consequent sand deposition in paddies; 2) inadequate water in farm ponds. Farmers choose a technology developed to reduce leakage from ponds and dikes, but proposed using this technology to reinforce dikes at strategic locations where breakages created an entry point for water into a large paddy area. Sites A and B were selected and reinforced in 2002, and sites C, D, and E reinforced in 2004 (Caldwell et al., 2004).

Plots in the paddy area can be classified in two ways. If paddies are viewed on a transect placed perpendicular (vertically in Figure 1) to the downstream flow of water through the watershed (to the left in Figure 1), we can classify paddies into upper, middle, and lower paddies (Ogura et al., 2005). This classification is especially useful for considering paddy water level for rice production, and farmer decision-making on paddy plot use between rice and rainy season fallow for livestock. However, if paddies are viewed in terms of water flow downstream through the watershed, it is useful to distinguish between central and side paddies (Figure 3). Central paddies are groups of lower paddies separated by farm ponds that stop the downstream flow of water. In contrast, side paddies are middle and lower paddies through which water can flow uninterrupted from upstream to downstream.

In Figure 3, a breakage in the dike between a side paddy and the central paddy area at the upstream end, near the farm pond, can provide the entry point for sand to come into the central paddy area and cause sedimentation. In Figure 1, reinforcement of dikes in side paddies at sites B and C protected central paddy areas successfully. The side paddies became water flow pathways for diversion of excess water, as shown in Figure 1. However, reinforcement at site E, at the head of the paddy area, could not handle the volume of water from the upstream sugarcane area. The problem of how to retain more water in the uplands remains. Agroforestry and grass strips are technically feasible, but may conflict with current farmer land use. Splitting upland fields into smaller segments divided by trees or grass strips conflicts with land preparation and other operations done by tractor. Work with farmers to develop practical solutions compatible with farmer crop and land use choices is one challenge for management of sandy soil mini-watersheds.

Modeling watersheds with multiple users for user decision-making

In the mini-watershed shown in Figure 1, most farmers have land in long rectangles perpendicular to the flow of water downstream. Each farmer thus has upland fields on either side of a narrow section of the paddy area. Each farmer's paddies are affected by water flow coming from both upstream (to the right in Figure 1) and from higher land on either side of the farmer's section of the paddy area. In two farmers' meetings (November 2002 and February 2003), we used 3-dimensional watershed models as aids for farmer discussion and decision-making (Figure 4a-b).

In another farmers' meeting (May 2004), farmers in this watershed indicated that through this approach, they had for the first time realized that they shared problems together. However, to move beyond identification of problems to development of group solutions requires involvement of other stakeholders. Farmers were interested in obtaining support to make a canal along one side of the central paddy area, to be able to safely divert excess water. One approach might have been to invite the local Tambon Administrative Organization (TAO, or "Ow-Baw-Taw" in Thai) to participate in a similar exercise. However, this would go beyond research, and require coordination among multiple institutions. Institutional coordination and mechanisms are needed to move beyond farmer participation in developing technical solutions to wider stakeholder involvement for watershed management.

The use of 3-dimensional models is a qualitative approach. Qualitative approaches are very powerful in accessing farmer knowledge acquired through experience. However, they cannot simulate likely scenarios in the future based on scientific measurements of variables such as rainfall variability, rates of erosion depending on slope, water flow across surfaces, or water arriving at a specific point in the topography of a mini-watershed, such as site E in Figure 1. To complement qualitative participatory approaches with quantitative modeling, several issues need to be addressed:

1. What are the key parameters for which data are necessary for construction of a quantitative simulation model?
2. Which parameters must be measured in real-world watersheds?
3. How can we measure those parameters in real-world watersheds?
4. For which parameters can we extrapolate or apply results obtained under controlled conditions to estimate their values under conditions in real-world watersheds?
5. How can we construct a quantitative simulation model using farmers' terms and concepts, and make it accessible to farmers?

Figure 4a. Farmers discussing water flow and sites for water management and dike reinforcement

Figure 4b. Sites considered by farmers

The first four issues involve the components of a quantitative model. These are technical questions for soil scientists, hydrologists, and crop scientists. In contrast, the last issue involves development and use of participatory quantitative modeling. In terms of Figure 3, we are asking, how we can represent, based on quantitative measurements, the likely outcomes of different possible farmer decisions, and let farmers see these outcomes as they consider choices in a participatory setting?

One possible approach involves combining multi-agent systems (MAS) modeling with hydrological and soil movement models. Lacombe (2003) has linked a hydrological model to farmer decisions on farm pond water use. Suzuki and colleagues (2003, 2005) have developed a model linking watershed hydrology and rice yield. But neither of these models includes a soil erosion sub-model linked to surface water movement. And neither of these models has yet been used with farmers in simulation of potential aggregate effects of decisions. Construction of a hydrology and soil movement model coupled with pond use and crop outcomes models, that farmers could use together with researchers and other stakeholders to explore management options at the watershed scale, is another challenge for management of sandy soil mini-watersheds.

Increasing economic options in sandy soil mini-watersheds

To give farmers new economic options in sandy soil mini-watersheds requires a combination of technical research, farmer organization, and marketing research. The construction of over 65,000 farm ponds in the 1990s (Ruaysoongnern and Suphanchaimat, 2002) has created the possibility of small-scale, on-farm irrigation in the dry season. However, Ando (2003) has shown that in one village where 72% of 207 farmers have farm ponds, only 4% of a sample of 55 farms with ponds obtained 5,000 bahts or more income from vegetable production, and only 13% from fruit production. Ponds are not being used intensively.

One reason for lack of intensive use of ponds is inadequate water to support different needs. The same study by Ando (2003) found that 98% of the farmers with ponds used the ponds for rice production. Interaction with farmers in integrated farming trials in 2004 (Sukchan et al., 2005) indicates that farmer concern that pond water will not be sufficient for rice seedbeds and transplanting is a major reason for reluctance to increase fruit and vegetable production using pond water. This concern is supported by the finding of Ando (2003) that 68% of the ponds had less than 1.5 m water depth in April, near the end of the dry season. If the rainy season is late, recharge may not come in time for rice seedling production and transplanting. Better methods for slowing uncontrolled surface water flow across surrounding sandy soil uplands and channeling it into ponds could be one technical solution. However, bands to slow down water movement and water channeling routes need to be designed to be compatible with sugarcane and cassava production. Techniques to reduce water seepage from ponds could also help insure adequate pond water, but economic analysis is needed.

Augmenting pond water from rainfall with groundwater may be more compatible with current upland use. Hamada et al. (2005) have found that groundwater moves from recharge areas above 207 m elevation to discharge areas below 170 m elevation in a typical watershed area in Khon Kaen Province. In effect, this is an underground water transfer route. In low elevation areas, 300-400 m^3 day^{-1} km^{-2} could be taken out without adversely affecting water level (decrease <10 m within 15 years) (Srisuk et al., 2005). This groundwater could be exploited to augment pond water.

When pond water is a fixed quantity, increasing water efficiency is a way to effectively increase the area that ponds can irrigate. Oda et al. (2005) have developed techniques with farmers that enabled 84% of 44 plots to grow tomato in the dry season with less than 30 mm of applied water and less than 10 water applications. Similar techniques need to be developed with farmers for other vegetable crops and for fruit crops.

What may be a rational decision from the standpoint of farm management for one farmer may not necessarily produce the same expected benefits if many farmers make the same decision at the same time. Lacombe (2003) found that farm ponds would be less effective for early rice seeding if many farmers simultaneously decided to use pond water to seed early. Similarly, if many farmers decide to produce vegetables and fruits, the result may be flooding of the market and less income for all farmers. Marketing research is needed to provide information for simulation of likely aggregate economic effects for farmers to use in making decisions. The market is the economic equivalent of common water resources, and market channels are the economic equivalent of water flow hydrology. In the study by Ando (2003), mango farmers organized into a cooperative were the most successful. Methods to enable farmers to see likely aggregate economic effects of individual decisions could help stimulate more coordination among farmers for marketing.

Conclusions and Future Directions

During this symposium, we will have the opportunity to learn about many research and development approaches that can address the above challenges. Some presentations may add additional challenges. In particular, one area that we have not addressed is fertility management of sandy soils in mini-watersheds. In all of these challenges, we anticipate that we will see that solutions will require a combination of better technical information at multiple scales, and greater farmer participation in the development of solutions using new information.

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Notes

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Farming systems in the sandy area of the Thua Thien Hue Province, central Vietnam. Survey of socio-economic situation and constraints identified by farmers

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Keywords: Sandy soils, smallholders, animal production, crop production, farming systems, Central Vietnam

Abstract

The Thua Thien Hue Province situated in Central Vietnam encompasses 5,054 km^2 with a population of about 1.1 million people. The total cultivated area is 84,000 ha of which approximately 66,000 ha are soils classified as having a sandy texture. This sandy area is located along the coast and is the most densely populated of the province. The research aims at evaluating various aspects of the present situation including socio-economic aspects and farming systems on these light textured soils of this province. Using an interview-based questionnaire, a survey was conducted in villages by staff members of the Hue University of Agriculture and Forestry. Data were collected among 145 households in four districts of the coastal area of the Thua Thien Hue Province. The results show that hostile climate, poor quality of soils, lack of technical knowledge and experience in agricultural production of smallholders on sandy soils are major constraints that limit crop yields and induce a deficit in nutritive value of animal feed. Low income of farmer's households is an obvious consequence of this unfavourable situation. Our results also indicate that the present animal and cropping systems on sandy soils of Thua Thien Hue include a high diversity of local varieties of plants and local breeds of animals. Options for possible improvement of techniques will be suggested. This research is being conducted in the framework of a Vietnam-Belgium joint project towards a sustainable agricultural development in this area, mainly through the better use of organic resources within farming systems, and by integrated pest and disease management.

Introduction

Sustainable agriculture is a subject of great interest and lively debate over years in many parts of the world. According to Honeyman (1991), sustainable production is a combination of production techniques that enhance profit and improve the area's environmental and socio-economic condition. Descriptive observation studies on smallholder farming systems have been conducted in Solomon Island (De Fredrick, 1977). Integrated or mixed farming systems, crop and livestock are interdependent elements (Amir and Knipscheer, 1989).

Vietnam is an agricultural country with over 80% population living in rural areas and their livelihoods are mainly based on agriculture. Similarly, in Thua Thien Hue Province, farmers rely chiefly on farm production for their livelihoods while off-farm activities are under developed. Their life is still difficult and not easily changed. The situation is worse in sandy areas, where soil conditions are clearly not suitable for an efficient agriculture. Fortunately, local people own diverse resources of plant varieties and animals breed, which can be more efficient (thanks to low inputs) and more sustainable (due to less chemical use) agriculture.

A detailed survey was conducted to identify potentials and constraints in farming systems of the

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coastal sandy area in Thua Thien Hue Province. This research should provide reliable information for identifying options for improving farming systems namely by optimizing organic matter recycling, which is a key problem in tropical light textured soils.

Methods

Interviewee's selection

Interviewees (145 families) were selected from seven villages of the four coastal districts of Thua Thien Hue Province (Phong Dien, Quang Dien, Phu Vang, and Phu Loc; see Figure 1), after allocating households into three income groups: rich, with income >200,000 Vietnamese dông (VND), i.e. some 10 euros or 13 US$, per person per month, average with income from 140,000 to 200,000 VND, and poor with income less than 140,000 VND. These groups of farmers were categorized by village or hamlet chairpersons, who could make the best income estimation of their villagers. To make sure that one interviewee correctly met the selection criterion, a double check for eligibility at start of an interview was done.

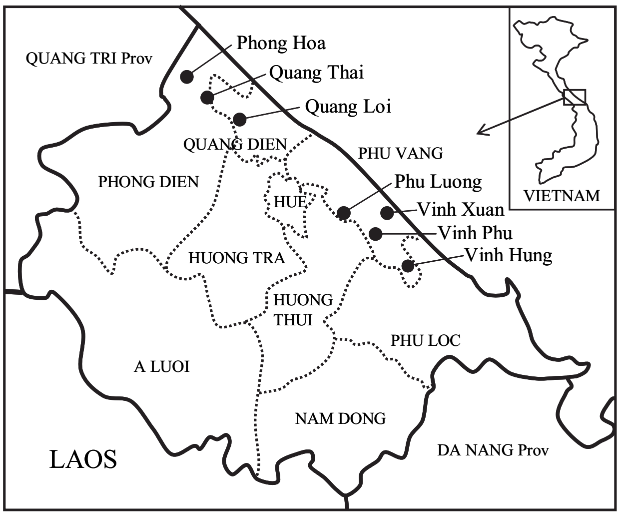

Figure 1. Map of Thua Thien Hue Province, with boundaries of districts (names in capital) and location of the targeted villages (names in lower-case)

Data collection and analysis

Information was collected using a questionnaire with oral interviews. This questionnaire covered various aspects of farming systems such as: family size, land and labor resources, crop and livestock production, organic matter utilization, etc. The education level of household heads was also surveyed as well as encountered pests and plant diseases. Income of households was estimated from animal and crop production, and from off-farm activities. Collected data were statistically analyzed using SPSS software (version 11.0).

Results and discussion

The main economic features of interviewed families are showed in Table 1. The family size averages 7.5 persons, often including 2 or 3, and sometimes 4, generations. On average, one family owns only 0.9 ha of farming land. But that area varies according to income level. The rich family has about 1.14 ha, while figures for average and poor families are 0.87 and 0.58 ha respectively. Large families and small farm sizes create increasing issues associated with population pressure at the family and community levels. In addition, soil type and quality (Table 2) do not adequately support farmers for sufficient crop production. Indeed, in the field plots cultivated by the 145 interviewed farmers, i.e. some 500 plots, sandy soils (white or yellow sand) represent 80% of the land and, according to farmers' opinion more than 40% are of bad or very bad quality. Farmers hardly expect high income from their crop and animal production. In the last decades, marginal arable land and high population pressure together resulted in splitting farmland from generation to generation, which caused many social problems and some farmers have become landless in the process.

The house is an important property of farmers in rural areas. Among the 145 visited households, we found that the type of houses show marked differences

Table 1. Mean values and coefficients of variation (CV) for different characteristics and income sources of the 145 surveyed farms in Thua Thien Hue Province

Characteristics	Mean values	CV%
N° of persons per family	7.46	20
Farmland size per family (m^2)	9,012	27
N° of ruminants per farm (heads)	2.7	47
N° of pigs per farm (heads)	4.7	23
N° of poultry per farm (birds)	26.6	41
Total income per farm (millions VND/year)	14.9	46
Crop income per farm (millions VND/year)	6.2	40
Animal income per farm (millions VND/year)	5.6	31
Other income per farm (millions VND/year)	3.1	35

Table 2. Texture and quality of soils (percentage of cultivated land) as evaluated by farmers in Thua Thien Hue Province

Soil texture			
White sand	**Yellow sand**	**Medium texture**	**Clay**
55.7%	26.5%	14.8%	3.0%
Soil quality			
Good	**Medium**	**Bad**	**Very bad**
4.4%	52.9%	32.3%	10.4%

between rich and poor farmers (Figure 2). There are about 5% poor households who have no house.

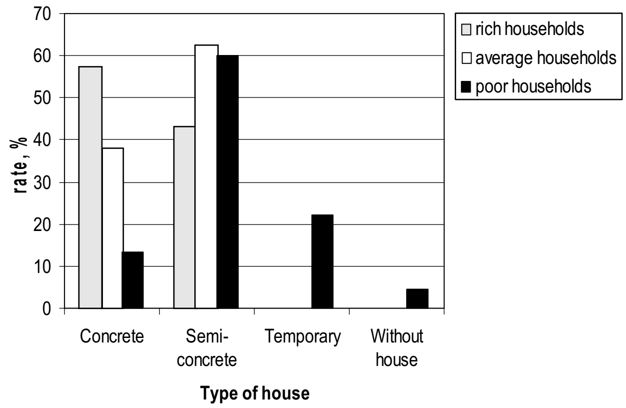

Figure 2. Characteristics of houses of 145 selected families in Thua Thien Hue Province as a fonction of estimated income classe

Pests and plant diseases reported in Table 3 reflect another constraint on agricultural production in the surveyed area. All four main crops (rice, cassava, sweet potato, and groundnut) are affected by many different types of insects and diseases, which, according to local people, are very important and, unfortunately, highly widespread. This situation is likely related to optimal climate conditions for pathogen development, and to fragility of crops grown on poor soils as well.

Table 3. Major pests and plant diseases observed by farmers of Thua Thien Hue Province and damages caused to main crops (+ + + : very widespread and very important; + + : widespread and important; + : locally important)

Scientific Name	English name	Local name	Distribution & damage level for plants			
			Rice	Cassava	Sweet potato	Groundnut
Major insects						
Cnaphalocrocis medinalis	Leaf folder	sau cuon la nho	+ + +	–	–	–
Scirpophaga incertulas W.	Yellow stem bore	Sau duc than 2 cham	+ +	–	–	–
Chilosupperessalis	–	5 vach dau nau	+	–	–	–
C. polychrysus	–	5 vach dau den	+	–	–	–
Spodoptera litura	–	sau keo	+	–	+ + +	–
Melanilis leda ismene	–	sau buom mat ran	+	–	–	–
Oxya sp.	–	chau chau lua	+	–	–	–
Nilaparvata lugens	–	ray nau	+ + +	–	–	+ + +
Nephotettix spp.	–	ray xan duoi den	++	–	–	–
Sogatella furcifera	–	ray lung trang	+	–	–	–
Leptocorisa oratorius	–	bo xit dai	++	–	–	–
Spodoptera litura	Taro caterpila	Sau khoang	–	+ + +	+ + +	+ + +
Agrotis ipsilon	Black cutworm	Sau xam	–	–	–	+ +
Helicoverga armigera	Cotton bollworm	Sau xanh	–	+ + +	+ + +	+ +
Lamprosema diemenalis	Soybean leaffolder	Sau cuon la	–	–	+ + +	+ + +
Heliothis spp.	Leaf-eating caterpillar	Sau rom	–	–	–	+ +
Aphis craccivora	Groundnut aphid	Rep muoi hai lac	–	–	–	+ + +
Epicauta gorhami M.	Blister beetle	Ban mieu	–	–	–	+ + +
Tetronichus bimacerlatus		Nhen do	–	+ + +	–	–
Cylas formicarius fabricius		Bo ha khoai lang			+++	
Omphisa anastomosalis		Duc la khoai lang			+++	
Major deseases						
Pyricularia oryzae	–	Dao on lua	+ +	–	–	–
Rhizoctonia solani K.	–	kho van	+ + +	–	–	–
Cercospora oryzae M.	–	Dom nau	+ + +	–	–	–
Grain discoloration	–		+ + +	–	–	–
Mycosphaerella arachidis	Early leaf spot	dom nau lac	–	–	–	+ + +
M. berkelevii	Later leaf spot	dom den lac	–	–	–	–
Aspergillus niger	Collar rot, seed rot	heo ru goc, thoi hat	–	–	–	+ + +
Puccinia arachidis	Rust	gi sat	–	–	–	+ + +
Peanut stripe virus	Groundnut stripe	la kham vang	–	–	–	+ + +
Ralstonia solanacearum	Bacteria wilt of potato	heo ru tai xanh	–	–	–	+ + +

Table 4. Average yield, with standard deviation (SD), of main crops as reported by the 145 interviewed farmers in Thua Thien Hue Province

Crops	Average yield ± SD (ton/ha/year)
Rice	4.30 ± 0.12
Cassava	11.36 ± 0.23
Sweet potato	2.67 ± 0.46
Groundnut	1.38 ± 0.03

As a consequence of these natural constraints, crop yield is generally low as compared to other areas of Vietnam (Table 4). For instance, rice yield (one or two crops per year) is only 4.3 tonnes per hectare per year according to farmers’ information, compared to some 10 tonnes per hectare per year in the Red River and Mekong deltas. Consequently, household food sufficiency is not ensured in Thua Thien Hue Province.

In animal husbandry, it was found that the number of heads per ha of cultivated land is 4.1 pigs, 38.4 poultry and 4.4 ruminants. Breeds are mainly indigenous with high adaptability to local unfavourable climate and poor nutrition. They require less input compared to improved breeds so they are preferred by farmers. The survey revealed high diversity in livestock species: 15 indigenous mammals and avian breed are raised in the region. The same situation was found for farmed vegetation, which consists of more than 40 plant varieties. These diverse bio-resources offer a good foundation for future development of agriculture toward sustainable, profitable and ecological approach.

As in many traditional systems, farmers in this area try to exploit all organic products (Table 5). Beside conventional agricultural byproducts such as straw and leftovers after crop harvest, some local people use other organic sources such as lagoon/seaweeds and hyacinth to improve soil fertility and to feed animals. Figure 3 presents the rate of organic manure utilization on different crops. However, a great number of interviewed farmers expressed their preference for using chemical fertilizers (urea and NPK fertilizers) instead of organic manure because they can bring immediate profits with respect to crop yield.

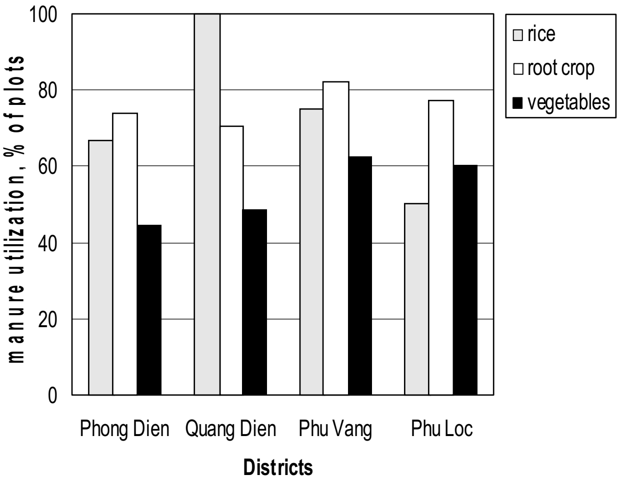

Figure 3. Rate of utilization of organic manure on different crops in the surveyed farms of the four coastal districts of Thua Thien Hue Province

Table 6 shows the average annual income from crop production and animal husbandry for the smallholders selected in the four districts. We calculated that the total output per hectare and per year ranges from 9.3 to 13.4 millions VND, which is very low compared to 40 to 50 millions VND per hectare per year in Habac, Hanoi or Thai Binh Provinces. According to the data presented in Table 1, plant production, animal husbandry, and off-farm activities account for 41.5%, 37.6%, and 20.9% of mean total income. The variation of those proportions with family classes (rich, average, poor) is shown in Figure 4.

Table 5. Utilization of organic resources in the 145 surveyed farms (+ + + : widespread use; ++ : medium use; + : local use only)

Utilization	Organic resources						
	Rice straw	Groundnut stem & leaves	Sweet potato stem & leaves	Cassava leaves	Hyacinth	Lagoon seaweed	Animal waste
Burned on the field	+	–	–	–	–	–	–
Returned to soil	+++	++	++	++	+	++	++
Animal feed	+++	++	+++	+	–	+	
Fish feed	–	–	–	+	–	+	+
Litter	+++	+	+	–	–	–	–
Mushroom substrate	+	–	–	–	–	–	–
Family fuel	+++	++	+	+	–	–	–

Table 6. Estimated annual revenue per hectare and per year from crop and animal productions in the selected farms of the 4 coastal districts of Thua Thien Hue Province

District	Mean estimated revenue ± SD millions VND/ha/year		
	Crop production	Animal production	Total
Phong Dien	6.33 ± 0.29	7.06 ± 1.15	13.39 ± 0.72
Quang Dien	7.02 ± 0.61	5.88 ± 0.52	12.90 ± 0.56
Phu Vang	5.94 ± 1.76	4.40 ± 0.49	10.34 ± 1.12
Phu Loc	3.19 ± 0.63	6.08 ± 0.92	9.27 ± 0.77

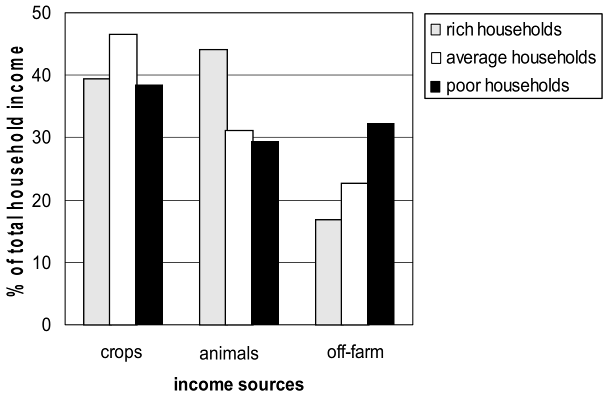

Figure 4. Relative income sources of the surveyed households in Thua Thien Hue Province as a function of their estimated living standards

Table 7. Problems and constraints perceived by farmers and possible tracks for solution in their opinion

Problems and constraints	Solutions suggested by local villagers
Soil	
Poor condition sandy soil Lack water in dried season and flood in rain season	They have no effective solution at moment Call for support to solve problem
Water	
Lack of water in dry season and floods in rainy season Irrigation not available, cropping mainly based on rainfall	Call to invest in irrigation system Improve service quality of existing irrigation
Technique	
Lack of technical knowledge and experience for agriculture Scientific research not yet applied in agriculture Not suitable use of chemicals	Want attending practical courses on crop and animal production
Plant production	
High diversity of plant varieties but low yield and economic income Plant varieties are not pure and yield is not stable Gardens with large area but low revenue	Want to have new plant varieties with high yield and better adaptation to sandy soil Supply fruit plant with high economic value Ask for assistance in using organic manure and chemicals effectively
Animal production	
Small scale and low benefit Lacking pure breed Low nutritive value of food Poor housing condition Lack experience of husbandry and management	Want for training in animal husbandry Supply pure breed with high performance
Pests and diseases of plants and animals	
Very frequent occurrence leading to decreasing yield and quality of product Too many kind of pesticides, difficulties to select and use them	They have no effective solution
Labour and capital resource	
Labour in excess, lacking jobs Lack of capital to invest for production and professional education Lack of experience for capital resource management and use	Call support of capital and education on management
Transportation	
Poor road system in rural area, not convenient for transporting materials from home to field, products from field to home and to market	Call to invest to improve local road and transportation system
Market	
Low farm gate price Lack of price stability	Ask for price control Farm gate price not forced by middle-men
Social	
Population pressure Farmers leave villages to find job in city Free immigration	Improve life quality Improve education condition and health care for women and children

Farmers were asked to identify the constraints responsible for their fragile economic situation and to suggest possible solutions to alleviate these constraints (Table 7). Obviously, many factors contribute to poverty of family farmers, including natural limitations due to soils and climate, farming characteristics and socio-economic organization.

Implementing

To improve soil fertility and food production, in sandy area, the locally available organic resource should be employed and appropriately used in system VAC (Garden, fish-pond and Animal husbandry). Some new varieties of cassava, groundnut can be introduced to increase yields of root plants.

Net garden system can be applied to reduce temperature and water evaporation as well as prevent the damage by pest and insect for vegetable production to improve income for farmers in this area.

Conclusion

As a conclusion, our survey stresses on the need of an integrated approach to improve living standards of rural smallholders in Thua Thien Hue Province and in Central Vietnam in general, as compared to other regions of Vietnam with more favourable natural and socio-economic conditions. Scientific, technical, social and economic research involving all aspects of farming systems (soil-plant-animal-human interactions) and wider environment is a great challenge for researchers and public authorities.

Ackowledgement

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Session 3

“Chemical properties and their effect on productivity”

Managing sandy soils in Northeast Thailand

Wada, H. [1]

Keywords: animal manure, ball fertilizer, core technique, green manure, salinization, reforestation

Abstract

Most of the arable soils in Northeast Thailand are typical tropical sandy soils. Their main primary and secondary minerals are quartz and kaolinite, respectively, because parent materials have been strongly weathered. As a result of the destruction of natural vegetation to make room for cultivation, the soil organic matter is low resulting in low cation exchange capacity (CEC) and low pH. Amelioration of these soils requires liming, fertilization and application of organic matter and 2:1 type clay minerals. Each of these ameliorating techniques encounters respective problems. Rather many farmers are using animal dung as an organic fertilizer for cash crops and/or rice seedlings. This practice has some limitations. Green manure has been considered to be useful, though its extension has not been successful due to lack of proper techniques of cultivation and utilization of suitable plants. A part of the arable soils in the region are salt-affected, salinization being intensified by deforestation. Reforestation is not always effective in desalinizing the salt-affected soils, because the degree of salinization varies markably according to the position in the relief and both short- and long-term strategies are needed. This paper discusses laboratory, greenhouse and field strategies for overcoming these problems in sandy soils of Thailand.

Introduction

Most of the arable soils in Northeast Thailand are sandy, acidic and infertile. Their primary and secondary minerals are mainly quartz and kaolinite, respectively. This is because their parent materials are highly weathered. These infertile soils are liable to be degraded by human activities. In this sense, these soils can be said to be typical tropical sandy soils. This paper discusses the characteristics and amelioration strategies of these soils mainly based on the research results of Agricultural Development Research Center in Northeast Thailand (ADRC), a project of Japan International Cooperation Agency (JICA).

Northeast Thailand is a square shaped plateau almost completely surrounded by mountain ranges and divided into two basins (Khorat Basin, Sakon Nakon Basin) by a relatively small mountain range (Phu Phang Range) (Figure 1). These basins are composed of hilly, undulating and flat low-lying regions. In the flat low lying region, large rivers (e.g. Mun River, Chi River) flow along these mountain ranges. According to Koppen's system, the climate belongs to tropical savanna with an alternation of rainy and dry seasons. In the rainy season, erratic and small rainfall shows

Figure 1. Landform

two peaks (Figure 2). In the past, a large part of Northeast Thailand was covered with the forests of Dypterocarpacae (Boulbet 1982, Ishizuka 1986). Deforestation has proceeded gradually in old times and rapidly in recent years in parallel with intensification of human activities (Tasaka 1991).

The main crops have been paddy rice and cassava, though other crops are replacing cassava. The

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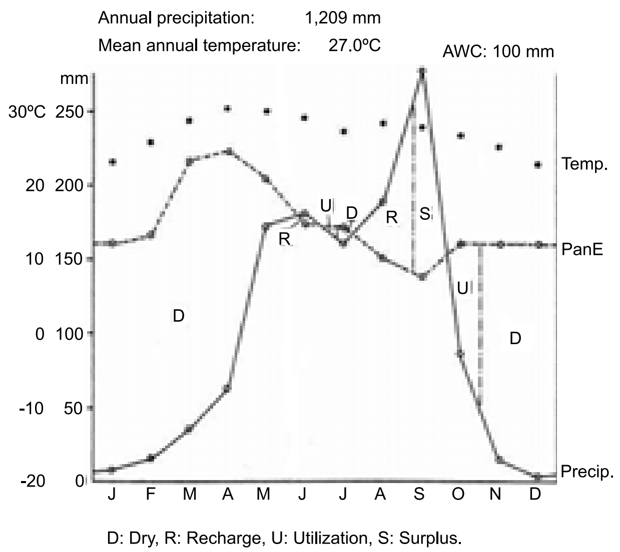

Figure 2. Moisture regime

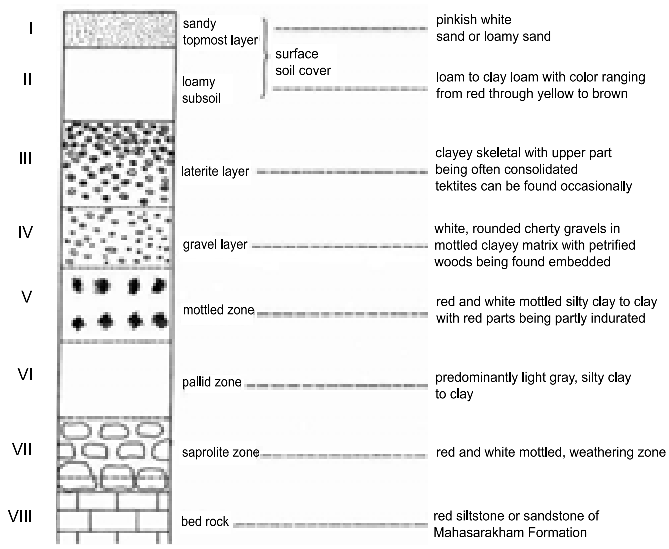

Figure 3. Vertical arrangement of horizons and layers

number of cattle is low due to a lack of pasture. Irrigation systems are not well established and a large part of the arable land, especially the paddy field, remains under rain-fed conditions. Traditionally, they transplant rice seedlings when the paddy field is sufficiently flooded without fear of drought. Under these circumstances, most of the farmers are very poor, eager to get cash income by working away from home and have not enough experience and knowledge to utilize high technologies. Accordingly, ameliorating technologies acceptable to the farmers must be cheap, simple and profitable. If technologies are really appealing to farmers they will adopt them without any effort of extension.

Nature and properties of the sandy soils Profile

Typical vertical arrangement of the soil horizons or layers is shown in Figure 3. The texture of the soil becomes finer with increasing depth. This may be mainly caused by selective erosion of fine fractions from the surface horizons (Mitsuchi et al. 1986). Two gravel layers are present between the soil and 4 substrata. Upper 3 substrata (mottled zone, pallid zone and saprolite zone) are actually weathered products of the 4th reddish stratum, which is the uppermost part of Mahasarakham formation of the Cretaceous to Tertiary period (Mitsuchi et al. 1986, Wada et al. 1994). The mottled zone and the pallid zone are enriched with 2:1 type clay minerals and $CaCO_3$. This profile suggests that the parent material of the sandy soil is transported by wind in the past when Northeast Thailand was significantly drier than the present. The gravel layers and the saprolite zone with cracks are an aquifer of shallow unconfined groundwater and an aquifer of deep semi-confined groundwater, respectively (Khoyama and Subhasaram 1993, Wada et al. 1994).

Other types of vertical profile are modifications of the above mentioned typical vertical profile. One type of the modified profiles is often found along the big rivers due to strong erosion and sedimentation for a long period.

Some chemical properties of the sandy soils

The arable sandy soils are acid, poor in organic matter and macro- and micro-nutrients and low in CEC (Motomura et al. 1979, Ogawa et al. 1980, Bell et al. 1990, Ishida et al. 1993). The low organic matter content may be caused by low ability of the soil to stabilize organic matter as well as by the rapid decomposition of organic matter under tropical conditions (Wada 1996). Arable soils are remarkably inferior to their corresponding native forest soils in terms of almost all the important properties relating to soil fertility (Ohta et al. 1992, 1996). In other words, deforestation lowers contents of organic matter and mineral nutrients, CEC and pH. The main reasons are: (1) Deforestation enhances loss of organic matter, because supply of organic matter in the form of litter is curtailed and decomposition of organic matter is accelerated, (2) CEC decreases in parallel with the decrease in organic matter content, because CEC is principally attributed to organic matter (Figure 5); (3) deforestation destroys the cycling of basic cations like Ca and K inside the forest by both runoff and leaching that carry away the basic cations which are supplied to the soil from the subsurface horizons through litter fall. (Figure 6). In addition, (1) main part of the soil organic matter takes the form of plant debris liable to be decomposed (Wada 1996), (2) the soil is rather easily acidified even to the subsoil by repeated application of chemical fertilizers, (3) the acid tropical soil contains Al^{3+} as well as H^{+}, probably due to low content of weatherable minerals (Yoshioka 1987, Patcharapreecha et al. 1990, 1992) and (4) the Al^{3+} is partially bound with organic matter (Patcharapreecha et al. 1990, 1992).

Accumulation of salt (salinization) in the sandy soils

A rather large part of the arable land is salt-affected to varying degrees (Figure 4). Generally, strongly salt-affected narrow areas are scattered at the western hilly to undulating regions and relatively weakly salt-affected wide areas are spread at the low-lying flat region, especially along the big rivers (Figure 4). This suggests in most cases (1) the salt comes up to the soil from a saline groundwater at localized places in the hilly to undulating regions and (2) the uplifted salt spreads along the big rivers through the groundwater. This suggestion is supported by the fact that the groundwater is usually saline at these salt-affected areas.

Figure 4. Soil salinity distribution (Arunin 1984)

Elevations inside the undulating region are conventionally classified into high, middle and low terraces according to their relative height (Moorman et al. 1964). Inside the salt-affected area, these terraces are differently affected with salt. Salt affects only the foot of high terrace, from the top to the foot of middle terrace and from the top till the foot of the low terrace.

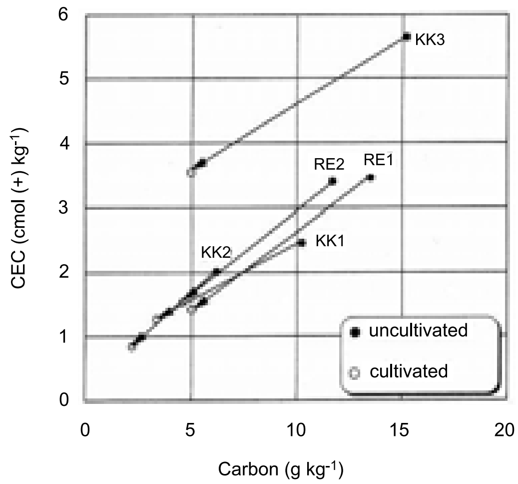

Figure 5. Decreases in organic C ad CEC by deforestation (Ota et al. 1996)

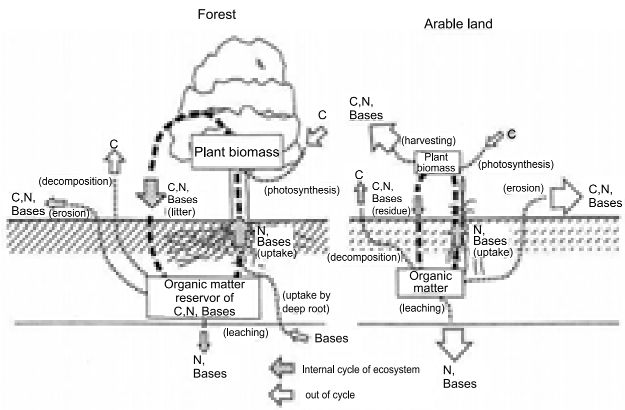

Figure 6. Change in cycling of bio-elements by deforestation (Ota et al. 1996)

In addition, narrow low ground amongst these terraces is often salt-affected. Small salty mounds called nam dun in Thai are distributed mainly at the top of the middle terrace. Salt of nam dun appears to move downward along the slope.

Based on these facts and other information, the following tentative theory was proposed for salinization in Northeast Thailand (Khoyama and Subhasaram 1993, Wada et al. 1994).

The salt is originated from a rock salt stratum in Mahasarakham formation and comes up to the confined deep groundwater through deep fractures formed at the boundary between the hilly and the undulating regions. The resulted saline confined deep groundwater rises and passes the overlying clayey strata (mottled zone and pallid zone) through their cracks developed mainly at the breast of middle terrace. The rising saline water (1) supplies salt to the unconfined shallow groundwater or (2) forms nam dun on the ground surface. Nam dun is enriched with not only salt but also clay and $CaCO_3$, because the rising saline water is supplied with these substances from the mottled zone and the pallid zone. Salt contained in nam dun moves downward along the slope by runoff, interflow and baseflow in the rainy season. On the contrary, salt in the shallow groundwater salinizes the overlying soils by capillary rise in the dry season.

Ameliorative technologies are somewhat different between the non-saline soils and the salt-affected soils, because the latter needs desalinization, an additional ameliorative technology. Accordingly, amelioration of the non-saline soil and the salt-affected soil will be separately discussed.

Amelioration of the non-saline soils

Conceivable technologies for ameliorating the above-mentioned infertile sandy acid soil are application of amendments such as liming material, chemical fertilizer, 2:1 type clay mineral, and organic fertilizer.

Liming material: Liming is surely effective for acid-susceptible crops. Liming the subsoil as well as to the surface soil is necessary if the subsoil is acidified by heavy application of chemical fertilizers (Ishida et al. 1993). However, the soil with low buffering capacity against pH-changes is liable to be over-limed and to induce deficiency of some micronutrients (e.g. Zn, B). To keep the neutralizing effect of liming for several years, coarse-grained $CaCO_3$ is recommendable, because liming materials are liable to be lost rather quickly from the sandy soil (Puengpan et al. 1992, Ishida et al. 1993). For growth of cotton in the acid soil, slaked lime + mixed chemical fertilizer was much inferior to a city compost alone or in combination with slaked lime and/or mixed chemical fertilizer (Chairoj et al. 1993). Five years of successive applications of chemical fertilizer resulted in poor growth of cotton due to rapid acidification of the soil. On the contrary, 5 years successive compost application resulted in healthy growth of cotton (Ishida et al. 1993). These results indicate the combination of coarse-grained $CaCO_3$ with compost is most effective to overcome acidity of the sandy soil.

Chemical fertilizers: Many farmers cannot apply sufficient amounts of chemical fertilizers to their crops, because yield of the crops is strongly controlled by erratic rainfall. This is especially so for paddy rice which is the main crop in Northeast Thailand. The problem of chemical fertilizers to acidify the soil is discussed above. Another problem of chemical N-fertilizer is its low efficiency mainly due to loss of NH_4^+ and/or NO_3^- by leaching in upland field (Yoshioka 1987) and by lateral flow of floodwater (Chanchareonsook 1983), denitrification and NH_3-volatilization in the paddy field. For finding methods to prevent such loss, both the combination of chemical fertilizers with organic matter (e.g. azolla) and the ball fertilizer were tested using a lysimeter (Ishida et al. 1994). Both methods, especially latter, were effective in suppressing leaching of NH_4^+ and NO_3^-. The ball fertilizer is a ball shaped solid fertilizer composed of chemical fertilizers and a matrix to make components of the chemical fertilizers release slowly to be efficiently taken up by the plant. In an experiment, a ball fertilizer of 4 mm in diameter was manually prepared by mixing chemical fertilizers with clayey material of the mottled or pallid zone rich in 2:1 type clay mineral. Accordingly, such manually prepared ball fertilizer may be recommendable for the poor farmers. In addition, ball fertilizer including commercial products may be recommended to the relatively rich farmers who are cultivating cash crops by applying large amounts of chemical fertilizers along the waterway in the suburbs of big cities like Khon Kaen, because excess amounts of chemical fertilizers are wasteful and potentially pollute water with NH_4^+, NO_3^- and phosphate.

Clay: A pot experiment confirmed addition of several kinds of clayey material to the sandy soil increased growth of sweet corn (Mitsuchi et al. 1986). One of the sources of the clayey material examined in this experiment was the pallid zone rich in 2:1 type of clay mineral. This material was obtained from the bank of a pond: the bank was constructed using mainly the material of the mottled zone and the pallid zone, which were dug out when the bottom of the pond reached the pallid zone. Farmers often cultivate cash crops on the banks of their ponds. Probably they recognize the soils of the banks are better than the sandy soils of their fields. However, they will not bring the clayey material from the pond to their remote fields for soil improvement, because it is too laborious. In this sense, the ball fertilizer containing the clayey material mentioned above may be regarded as a practical tool for applying the clayey material to the sandy soil.

Compost and animal dung: Effectiveness of compost-application in increasing rice yield and soil organic matter content, mainly in the form of plant debris, was confirmed by a long-term experiment in a paddy field at Surin (Takai 1983, Saenjan et al. 1992). However, compost-application is not traditional and the farmers have not accepted official recommendation to use compost. Probably, they dislike laborious work of preparation and application of compost. Actually, raw material of compost is not abundant and quality of common compost is not high. For instance, most of rice stubble left in the paddy field in large amounts is often burnt after being slightly grazed by cattle. Compost is usually prepared outdoors under exposure to the rain resulting in loss of water-soluble substances such as K. Traditionally, the farmers use animal dung for cultivating cash crops and rice seedlings in nursery beds. They may realize the effectiveness of animal dung in promoting growth of the crops and use the limited amount of animal dung as economically as possible. There are 2 reasons for the limited amount of animal dung. The first is small number of domestic animals. The second is that the farmers utilize only the dung excreted and stored under the floor of the farmers’ houses and will not gather up the dung scattered outdoors, probably they consider the weathered dung is ineffective.

Techniques to slow down the rate of microbial decomposition of the compost and the animal dung are necessary for enhancing their utility, because the mineral nutrients quickly released from them are liable to be lost in the same way as the chemical fertilizers before being taken up by the crops. In addition, the techniques to slow down microbial decomposition of organic matter in the soil should be necessary for increasing soil organic matter content and for suppressing the increase in atmospheric CO_2 content.

For this purpose, addition of Al or Fe salts to the compost and the animal dung was expected to be promising, because both metals have ability to strongly combine with organic matter and retard its microbial decomposition. A laboratory experiment confirmed these additives somewhat suppressed microbial decomposition of a buffalo dung, a city compost and a rice straw compost and a field experiment showed that the compost added with these additives was better than the compost alone in enhancing growth of baby corn in spite of that these additives themselves were harmful to the crop (Saenjan et al. 1991, 1993). Furthermore, addition of polyvinyl alcohol to the cow dung appears effective also in suppressing microbial decomposition of the cow dung (Dejbhimon 2004).

Green manure: Utilization of green manure has been considered to be useful for increasing yield of crops and several plants have been recommended for green manure. For example, aquatic legumes have been regarded to be suitable for the rice cultivating in the rain-fed paddy fields, because these plants can grow under both drained and flooded conditions. However, farmers have not accepted the role of green manures in their production systems. The reasons are (1) the seeds of recommended plants are not readily available, (2) chemical fertilizers should be applied to the field to get sufficient amount of green manure, (3) many natural enemies attack the recommended plants and (4) organic acids toxic to rice seedlings are produced when green manure is plowed under in the flooded paddy field. In addition, we must be careful about the problem of methane emission from the flooded paddy field when green manures are applied. This additional problem is especially serious for the sandy soil poor in reactive iron oxide, because the amount of methane produced in the submerged soil becomes high when the soil is poor in reactive iron oxide (Takai, 1961) and the produced methane easily bubbles out from the soil without oxidation at the oxidized layer by methane oxidizing bacteria (Chanchareonsook et al., 1983; Taja, 1994).

Many experiments conducted in the laboratory and in the greenhouse (Patcharapreecha et al., 1993; Taja, 1994) revealed: (1) among aquatic legumes examined, *Sesbania rostrata* with stem-nodules as well as root-nodules was the most promising plant for paddy rice, because it can rapidly grow by actively fixing N_2, (2) P was only one nutrient necessary for healthy growth of the plant and phosphate rock could be used as a P-fertilizer, (3) the amount of organic acids (e.g. acetic acid, butyric acid) produced from green manure in the submerged soil increased, reached a maximum, decreased and became very small 1 week after incubation, (4) healthy growth of rice seedlings was secured when they were transplanted about 1 week after plowing under green manure in the submerged, (5) methane was actively produced within 2 weeks after plowing under green manure in the submerged soil and (6) the methane production was remarkably suppressed by placing green manure for about one week on the surface of the submerged soil before mixing with the submerged soil.

Furthermore, several field experiments (Patcharapreecha et al. 1993, Sukchan 1994, Taja 1994) have shown: (1) drought, injurious nematodes and weeds as well as P-deficiency were important factors limiting growth of *S. rostrata* in the field though the harm of drought and nematodes were negligible and the weed-problem was not serious in the paddy field, (2) *S. rostrata* could grow well in the moist upland field also and its growth was vigorous at the place temporarily flooded on occasion of heavy rain, (3) toxicity of the organic acids could be avoided by placing green manure on the ground surface of flooded paddy field for about 1 week before plowing under in the soil, when bad smell of butyric acid almost disappeared, (4) phosphate rock was better than triple superphophate, a common P-fertilizer in Thailand, in the moist upland field where the injurious nematode was active, (5) the recommended way of green manure-application helped a farmer to get rice yield (4.7 t ha^{-1}), which was much higher than average (Figure 7) and higher than the estimated yield (4.2 t ha^{-1}) of this cultivar, RD6; (6) soil fertility was improved, (7) the desirable effects of phosphate rock continued in the paddy field for at least 3 years and (8) cattle grazed the tops of *S. rostrata* growing in the drained paddy field resulting in shortening of plant length, which was helpful for harvesting and handling of the plant.

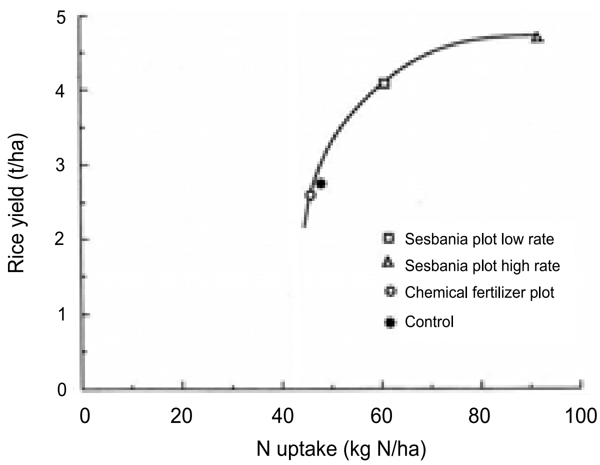

Figure 7. Effect of green manure on rice yield (Patcharapreecha et al. 1993)

The combination of *S. rostrata* and phosphate rock can be regarded as an *in situ* durable biological machine to produce P and N available for common crops from the phosphate rock and the atmospheric molecular N_2. However, several problems still remain to be solved for extending this combination to the farmers: For instance, it is necessary to establish seed systems of *S. rostrata* that ensure ease of accessibility to farmers, to supply phosphate rock of guaranteed quality to the farmers and to financially support the farmers, who will adopt the recommended techniques.

Management of the non-saline slope

In the undulating region, paddy fields are usually distributed on the gentle slope. In the rainy season, flooding gradually proceeds from the foot to the top of the slope. Accordingly, the paddy fields covered with poor weeds remain idle till flooding, even though absence of pasture limits the number of cattle

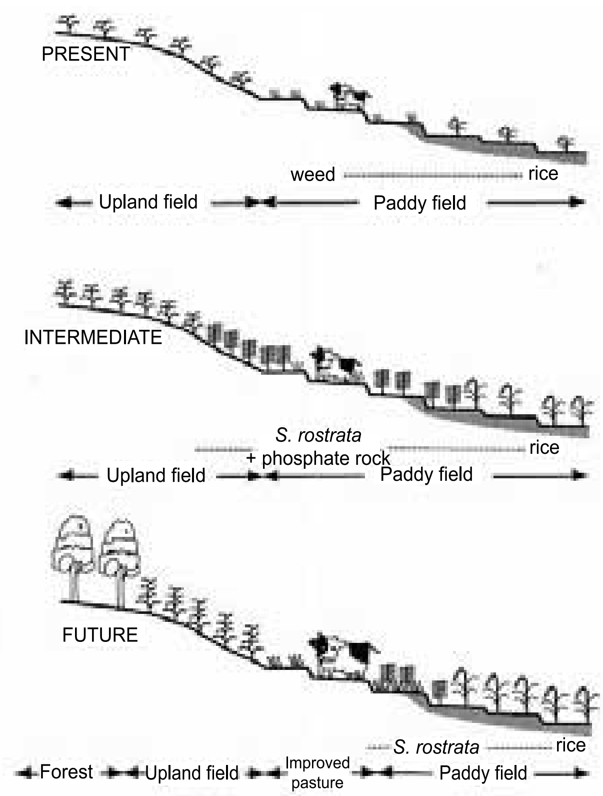

Figure 8. Efficient management of a slope by cultivating *Sesbania rostrata* (Patcharapreecha et al. 1993)

in Northeast Thailand. A tentative plan to efficiently utilize this kind of the slope was proposed as shown in Figure 8 (Patcharapreecha et al. 1993).

In the beginning of rainy season, all the paddy fields and the neighbouring moist upland fields on the slope are applied with phosphate rock and planted to *S. rostrata*. The plant growing in the paddy field is cultivated till the paddy field is sufficiently flooded and then used as green manure for paddy rice. The plant growing in the upland fields is also utilized as green manure for upland crops at appropriate time. During the period of cultivation of *S. rostrata,* the fields are used as pastures for fattening cattle. This is desirable for crops also, because soil fertility is increased with dropped dung and application of green manure becomes easy due to shortened plant length.

Amelioration of the salt-affected soil

As discussed above, degree and way of salinization widely vary according to the position in the macro- and micro-relief. This implies that desalinization technique should be different according to the position in the relief and that lowering the saline groundwater by reforestation, a widely accepted countermeasure of salinization, should be carefully implemented and/or supplemented by other countermeasures. At the same time, two aspects of desalinization strategy should be considered. One is a short-term strategy for farmers and aims at establishment of cheap, simple and profitable technologies suitable for increasing yield of crops through improving the soil of individual farmer's field. The other is a long-term strategy for the government and provides the government data and concepts for planning approaches to combat salinization at the watershed level. These 2 strategies should be well connected with each other so that the farmers and the government work together for reclaiming the salt-affected area.

Short-term strategy for the farmer

Salt-affected slope in the undulating region

Many experiments were conducted at a slope of a middle terrace in the salt-affected area (Puengpan et al. 1990, Puengpan et al. 1991, Wada et al. 1993, Subhasaram 1994,). This is because almost all types of the salt-affected soil exist side by side on the slope of the middle terrace. The slope was a mosaic of the salt and vegetated patches. The salt patch is bare and often covered with salt crust. Native weeds growing at the vegetated patch in the rainy season and those in the dry season are different. The former are annual and tolerant to wet injury while the latter are perennial and tolerant to desiccation and salinity (Puengpan et al. 1991). The salt patch is often related with a dark colored layer about 10 cm in thickness developed near the ground surface. Depth of the overlying sandy layer is thinner at the salt patch than at the vegetated patch. The dark colored layer was rich in both organic matter and clay and acted as an impermeable layer in the rainy and a hard pan in the dry season (Puengpan et al. 1990). In the rainy season, the dark colored layer inhibited desalinization by leaching and was strongly reduced. Thus, any native plants cannot grow at the places where the dark colored layer is present near the ground surface, resulting in the salt patch. Actually, destruction of the dark colored layer was useful for plant growth, especially at the weakly salt-affected places. The dark colored layer may be resulted from deforestation near the top of the slope: the surface layer rich in organic matter and clay of a former forest soil is selectively eroded and the material rich in organic matter and clay is sediments at surrounding lower places of the slope. At the foot of the slope, several paddy fields were abandoned due to salinization, which was mainly caused by intrusion of salty mud that came from the salinized slope by erosion and passed through broken dikes (Puengpan et al. 1991).

On the one hand, rather many kinds of plant were cultivated for more than 1 year with alternating dry and rainy seasons at a wide salt patch on the slope for selecting plants to be used for further experiments (Patcharapreecha et al. 1992, Puengpan et al. 1991). The selected plants were rhodes grass *(Chloris gayana), Panicum repens, S. rostrata, S. cannabina, Eucalyptus camaldulensis* and Casualina sp. Rhodes grass is a fodder plant and its seed is easily obtained from Live Stock Experimental Station. Seedlings of *Eucalyptus camaldulensis* are available in the market.

On the other hand, cores were vertically inserted into the ground surface for examining factors controlling desalinization and plant growth (Subhasaram et al. 1992, Subhasaram 1994). This experiment confirmed (1) the soil inside the core was much more quickly desalinzed than the soil outside the core, mainly due to enforced percolation of rainwater trapped inside the core, (2) the bottom of the core should reach the dark colored layer for avoiding lateral movement of water on this layer, (3) mulch was effective in suppressing accumulation of salt supplied by capillary rise of saline water on sunny days, (4) germination of seed and growth of a plant were possible inside the core even at the salt patch, (5) application of cow dung enhanced growth of the plant if the degree if salinization was not too high and (6) the inserted core was ineffective in both desalinization and germination at the place with high groundwater level, because the trapped rain water remained stagnant inside the core.

A large-scale experiment was conducted at another wide salt patch to verify effectiveness of 4 soil-treatments (destruction of the dark colored layer, mulch, core-insertion and application of cow dung or compost) on growth of 2 plants (rhodes grass and *Panicum repens*) in the beginning of rainy season (Subhasaram et al. 1992, Subhasaram 1994). It confirmed (1) each treatment was effective in promoting growth of both plants, (2) cow dung was more effective in promoting plant growth than compost, probably because compost contained only small amount of K, which was useful for plant growth in the salt-affected soil, (3) any combinations of these 4 treatments were more effective in plant growth than each component treatment, (4) combination of the 4 treatments could be selected according to characteristics of the site, (5) both plants can vigorously grew even at the place with salt crust if 4 treatments were combined together, (6) about 3 months after start of the experiment, the wide salt patch appeared fairly well covered with 2 plants and

(7) the vegetated patch, especially rodes grass patch, could be used as a pasture for cattle.

Four treatments and their combinations were collectively named "core technique".

The abandoned paddy field at the foot of the slope

The farmers will not repair the broken dike of the abandoned paddy field, though they recognize that runoff destroys the dike and that the paddy field is damaged with the salty mud intruding through the broken dike. This is because the repaired dike, which is made of the dispersible Na-saturated sandy soil, is easily broken by runoff. Accordingly, a dike was prepared by a new simple method: plates of cellocrete (synthetic concrete: Four Pattana Co., Thailand) were put vertically at the center of a prepared dike (Subhasaram 1994). This new dike prevented runoff of salty mud entering the field, resulting in growth and yield of rice inside the abandoned paddy field.

Paddy field in the low-lying flat region

The sandy paddy field in the low-lying flat region often consists of the salt and vegetated patches (Wada et al. 1994). Such paddy fields are usually underlain by thick clayey subsoil enriched with salt. Salt comes up from the subsoil to the sandy soil by capillary rise in the dry season, leading to the salt patch at the place where the sandy surface soil is thin. This implies the cause of the salt patch here is similar to that at the slope in the undulating region mentioned above. However, in the low-lying flat region with high groundwater level, the technologies of desalinization established in the undulating region should be modified in the following way: (Nagase 1992), mainly because destruction of the saline thick clayey layer is impossible.

The paddy field was mulched in the dry season and cultivated to *S. cannabina*, which was more tolerant to salinity than *S. rostrata* during initial period of the rainy season. When the paddy field was sufficiently flooded, *S. cannabina* was harvested and plowed under after surface placement for about 1 week. Then, rice seedlings were transplanted. This technique increased rice yield about 3 times higher than average. Isolation of the salt patch seemed effective in assisting the healthy growth of rice plant by inhibiting expansion of the salt accumulated at the salt patch to the whole paddy field through lateral flow of flood water.

Management of the salt-affected slope

Ameliorating technologies specific at each position of the slope should be consistent with each other. From this standpoint, the slope is divided into 4 sections: "upper section", "salt-supplying section", "erosion section" and "deposition section" (Figure 9) (Subhasaram 1994). At "salt-supplying section", salt is supplied from the confined deep groundwater. Salt moves upward from "salt-supplying section" to "upper section" mainly by diffusion. In the rainy season, the salt of "salt-supplying section" together with dispersed mineral particle flows down the slope through "erosion section" and deposits mainly at "deposition section". In the dry season, some amount of salt is supplied from the shallow groundwater by capillary rise to the soil on the slope. This is especially evident at "deposition section" with high level of the saline shallow groundwater. Thus, the whole slope is salinized, though process of salinization differs among 4 sections. The salinization is enhanced by deforestation, because without forest, not only level of the saline shallow groundwater rises, which favors the supply of salt from the shallow groundwater by capillary rise, but also erosion of the salty mud is accelerated by the strengthened runoff.

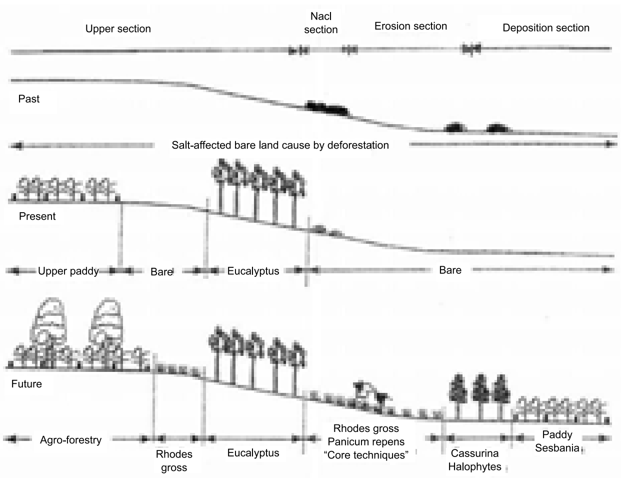

Figure 9. Management of a salt-affected slope (Subhasaram 1994, partially modified)

Reforestation has been widely accepted as a potent countermeasure to ameliorate the salt-affected soil through lowering of the level of saline groundwater by transpiration of the tree. Actually, in Northeast Thailand, several places have been forested with eucalyptus, which has high ability of transpiration, for amelioration of the salt-affected soils. However, these eucalyptus forests did not desalinize the soil within a few years and often dried up neighboring wells of villagers who are living principally at the non-saline area in the top of middle terrace. In this case, the forest may lower level the fresh shallow groundwater, which supplies water to the wells, probably because the forest is too wide in size and is too closely located to the wells.

Consequently, establishment of a “narrow forest” along the lower boundary of “upper section” is proposed. The “narrow forest” is expected to (1) inhibit migration of salt to “upper section” from “salt-supplying section”, (2) lower level of the saline shallow groundwater and suppress runoff at “erosion section” and (3) affect only slightly wells of the villagers. Actually, few farmers planted eucalyptus along the boundary between “upper section” and “salt-supplying section”. Probably, they have experienced such forest is effective to inhibit expansion of the salt patch to “upper section”. One caution in planting eucalyptus is that seedlings of the plant prefer the vegetated patch to the salt patch. In other words, the salt patch should be improved to be the vegetated patch before planting eucalyptus (Puengpan et al. 1991). At “erosion section”, “core technique” can be applied. At “deposition section”, dikes of the paddy fields should be reinforced using the new method (Subhasaram 1994), and should be managed according to the Nagase’s method mentioned above. The boundary between “erosion section” and “deposition section” is difficult to be managed, because groundwater level is too high for desalinization by “core technique” and too low for cultivating paddy rice. In Figure 9, planting of *Cassurina sp.* or halophytes is tentatively recommended in this area. Construction of beds with a thin coarse textured layer proposed by Sugi et al. was expected to be useful for this place, because surface of the bed is distant from the groundwater by the height of the bed and the coarse textured layer inhibits capillary rise of the saline groundwater (Takai et al. 1987). However, construction of the bed is laborious and dispersed fine soil particles quickly deteriorate the coarse textured layer by filling its non-capillary pores. The surface layer aggregated with polyvinyl alcohol is found to be better than the coarse textured layer for desalinization at this place (Dejbhimon 2004).

Long-term strategy for the government

Among various governmental tasks for ameliorating the salt-affected soil, only one task will be mentioned (Subhasaram 1994).

The farmer’s “narrow forest” is usually too narrow to play its all roles and is limited to the field of each farmer concerned. Government should make such incomplete “narrow forest” wide and dense enough for playing its all roles by paying due attention to the effect of completed “narrow forest” on the wells of villagers and should connect many fragmented farmer’s “narrow forests” to a continuous complete forest in the whole salt-affected catchment. The farmers may welcome this public work and agree to plant trees even in their arable fields if the government convinces the farmers of the intention and significance of this public work.

A rather wide and dense eucalyptus forest at the top of a middle terrace, which could be regarded as an example of the completed “narrow forest”, has been shown to lower the level of “shallow groundwater” year by year for a few years (Miura 1990). In spite of this, salinity of the soils on the deforested slope of the middle terrace was not much changed and growth of the plants was inhibited during this short period. However, 10 years later, salinity of almost all the soils on the slope was evidently decreased and plants including paddy rice succeeded to grow. This may be caused by slow leaching out of the salt accumulated in these soils due to lowered level of the shallow groundwater. This is one of the effects of the long-term strategies (Subhasaram and Wada 1999).

Concluding remarks

For achieving sustainable management of the tropical sandy soil in a region, it is imperative to understand the properties of the soil and also natural and social conditions of the region. This may help to understand the actual desires of the farmers and to conceive ameliorative techniques suitable for both the soil and the farmers in the region. It is important to carefully examine advantages and disadvantages of all the conceivable techniques in the laboratory, in the greenhouse and in the field. All results of the examinations should be accessible to every person concerned including the farmers and the governmental officers as well as the scientists. In this context, some experiments should be conducted at the farmers’ fields. Neighbouring farmers as well as owners of the fields will observe the field experiments with great interest and adopt some techniques demonstrated in the field experiments for managing their own fields. On the contrary, most of the farmers will not show any interest in the field experiments conducted in the Experimental Stations. In addition, we must be careful about the fact that the soils inside Experimental Stations are often different from those of the farmer’s fields in terms of fertility, though both of them are identified as the same series or same phase. The difference in the fertility is caused by difference in fertilization for many years. The scientists may improve the released technologies, which they are interested in. The government may decide policies based on the released technologies and concepts, which are desirable to both the farmers and the government.

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Changes in soil chemical properties under two contrasting plantation systems on the Zululand coastal plain, South Africa

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Keywords: Eucalyptus grandis, Pinus elliottii, pozolisation, charge characteristics

Abstract

Over the past 4 decades there has been considerable expansion in the plantation forestry along the eastern seaboard of South Africa. In particular there have been significant increases in eucalypt, and to a less extent, pine plantations on soils of a light sandy texture along the Zululand coastal plain. These soils are characteristically dominated by sands with low clay and organic matter contents, have low cation exchange capacity and water holding capacity. Pedogenesis and selected chemical attributes of a 49-year-old stand of ***Eucalyptus grandis*** *and* ***Pinus elliottii*** *established on these sands were compared. Changes in soil pH, exchangeable cations, organic carbon, extractable Fe and Al and the surface charge characteristics were investigated. Evidence of the development of bleached A2e horizon within the surface 0-5 cm depth interval under* ***E. grandis*** *was confirmed through the development of surface charge fingerprints, changes in organic carbon and Fe and Al mobilization for each of the pedogenetically distinct horizons. Such development was not observed under the* ***P. elliottii*** *stand, suggesting that this pine species has had less impact on the soil. It is argued that the rate of A2e horizon development is not dissimilar to that observed under native forest ecosystems in Australia, although considerably slower that those observed under reclaimed sand mining operations. Whilst these systems appear to be relatively stable due to no clear felling and timber product extraction, this could drastically change with the introduction of short-term rotations of fast growing clonal plantations, questioning the long-term sustainability of these production systems on these light textured sands.*

Introduction

The role of vegetation in processes associated with pedogenesis is well recognised. In this respect the effects of tree species and plantation forestry on soil properties have been the subject of numerous studies and it has been argued that specific plantation species reduce soil fertility, increase soil acidification and hence reduce productivity (Noble *et al.*, 1996; Routley and Routley 1975; Dasman 1972; Hamilton 1965; Khanna and Ulrich 1984). Many of these arguments were based on what was considered a parallel situation in Europe, where replacing broadleaved species with coniferous species (spruce) was the cause of podsolized and infertile soils (Turner and Kelly 1985). The establishment of eucalyptus plantations for the production of pulp and sawn timber has grown significantly over the past three decades in many countries other than Australia. This is in part due to the rapid growth rates of this species in environments that are devoid of natural predators, and more recently the development of clonal forestry with its associated high productivity and consistency of product. The impact of eucalyptus and other species on the rapid development of podzols on sands replaced after extensive mining of the coastal sand dunes of eastern Australia has been the subject of several studies (Paton *et al.,* 1976; Farmer *et al.,* 1983; Thompson, 1992; Prosser and Roseby, 1995). These studies have clearly indicated that the development of an A2 horizon is rapid (4.5-5 years) and is often associated with the period when the greatest degree of leaching occurs (Prosser and Roseby, 1995). In contrast, the establishment of *Eucalyptus camaldulensis* on mining spoils on the Jos Plateau of Nigeria had little effect on soil morphological attributes 15-20 years after establishment (Alexander, 1989). The species significantly increased the amount of organic carbon with an associated increase in cation exchange capacity (CEC). However, there was a significant decline in soil pH and base saturation and the author

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concludes that the long-term effect of eucalypts is one of progressive degradation of already poor soils (Alexander, 1989). Similarly, the leaching of soil columns using the water soluble component extracted from the litter of eucalypts has been shown to lower the pH of soils and mobilize both iron and aluminium (Bernhard-Reversat, 1999; Noble and Randall, 1999).

In the present study, we have analyzed soils for changes in soil chemical properties under *Eucalyptus grandis* and *Pinus elliottii* stands of similar age established on the same soil series on the Zululand coastal plain of South Africa. Of particular interest in this study was the quantification of changes in the surface charge characteristics of soils collected from under both species.

Materials and method

Study site

The Langepan Correlated Curve Trend (CCT) experiment with *Eucalyptus grandis* and *Pinus elliottii,* was established in 1952 on a site near KwaMbonambi (28º36′S; 32º13′E), KwaZulu Natal, South Africa. The experimental site is situated on the coastal plain that extends from Port Durnford in the south to the Mozambique border in the north and is at an altitude of 60 m a. s. l. The trial site is situated on the boundary of the humid and sub-humid zones of the summer rainfall region of South Africa (Bredenkamp, 1991). The mean annual rainfall is 1,400 mm, of which approximately 70% falls during the months of October to April. The range in temperature is relatively small due to the stabilizing influence of the warm Mozambique current flowing down the eastern coast of South Africa. Mean annual temperature, mean monthly maximum (January) and mean monthly minimum (June) are 21.8ºC, 30.9ºC and 11.9ºC respectively (Bredenkamp, 1991).

The coastal plain is an elevated marine platform that consists essentially of a thick deposit of aeolian sand underlain by almost horizontal Cretaceous to Recent beds, dipping slightly seaward (Bredenkamp, 1991). There are indications that the sands have been deposited at intervals. The sands are acidic, of low fertility and have poor horizon development. Due to wind transportation, the soils consist of medium sand (0.2-0.5 mm) grains with no coarse or fine sand and very little silt or clay (0-6%). These soils are generally poor in organic matter, due to rapid decomposition in the moist subtropical climate and the aerobic condition of the surface soils. The water storage capacity of these soils is very low, but this shortcoming is moderated by great depth. The soil was classified as belonging to the Fernwood series (ANON, 1991), a Dystric Regosol (FAO-UNESCO, 1990) or Quartzipsamment (Soil Survey Staff, 1990). Adjacent to this C.C.T. trial, is a stand of *Pinus elliottii* that was established at the same time as the CCT trial on the same soil type.

In order to assess the impact of the two species on soil chemical properties, two sites were selected in close proximity to the boundary between the plantation systems. Soil pits were dug to a depth of 1.2 m with an exposed face of 2.5 m in each of the plantation systems.

Soil analysis

Three soils samples were collected from the walls of the pits in 2001, 49 years after the establishment of the CCT trial, from each pedologically distinct horizon. The samples were air dried and sieved to pass a 2-mm mesh before pH was measured in water using a 1:5 soil:solution ratio. Basic exchangeable cations were determined by atomic absorption spectrometry after replacement with 0.1 M $BaCl_2/NH_4Cl$, as recommended by Gillman and Sumpter (1986). Acidic cations ($H^+ + Al^{3+}$) were extracted with 1 *M* KCl and the extractant titrated to pH 8.0 as described by Rayment and Higginson (1992). The effective cation exchange capacity (ECEC) was calculated as the sum of basic and acidic cations ($Ca^{2+} + Mg^{2+} + K^+ + Na^+ + Al^{3+} + H^+$). Soil organic carbon was determined by wet oxidation using the Walkley and Black method as modified by Rayment and Higginson (1992). In addition, soft concretionary material (segregates) was collected from depth intervals in which they occur, air dried in the same manner as the soil and ground to a fine powder for further analysis. Charge fingerprints are curves describing the total cation exchange capacity (CEC_T) and base cation exchange capacity (CEC_B) across a range of pH values. They were determined on composite samples from each of the depth intervals using the methodology described by Gillman and Sumpter (1986). In brief, soils were Ca^{2+} saturated and brought to equilibrium in a 0.002 *M* $CaCl_2$ matrix. Suspension pH was adjusted to six values ranging from approximately 4.5 to 6.5. Once the desired range of pH measurements had been achieved, exchangeable Ca^{2+} and Al^{3+} were displaced with NH_4NO_3. The Al^{3+} content in solution was determined using the pyrocatechol-violet method (Bartlett *et al.,* 1987). The amounts of Ca^{2+} and Al^{3+} adsorbed were calculated taking into account the amounts present in the entrained solutes.

The CEC_B is operationally defined as the Ca^{2+} adsorbed and CEC_T as the Ca^{2+} and Al^{3+} adsorbed. The pH buffer capacity of each layer collected was estimated from the amount of acid or base added during the development of the surface charge fingerprint. Linear regression plots were constructed of amounts of acid/base added ($mmol_c$ H^+/kg) versus pH. The inverse of the slope of the regression curve was taken to be indicative of the pH buffer capacity ($mmol_c$ H^+/kg.unit pH) of the soil.

Organic carbon (OC) was measured by dichromate oxidation and spectrophotometric estimation of residual dichromate on both the soil and soft segregate material (McLeod 1975). Organically complexed Fe and Al were extracted from 1 g of soil and soft segregate material with 100 mL of 0.1 *M* sodium pyrophosphate after overnight shaking (Bascomb, 1968). Amorphous inorganic Fe and Al were extracted from 1 g of soil and soft segregate material by 60 mL of 0.2 *M* ammonium oxalate adjusted to pH 3 and shaken in the dark for 4 hours (McKeague and Day 1966). Aluminium and Fe were determined by atomic absorption spectrometry on the oxalate (Al_{ox} and Fe_{ox}) and pyrophosphate (Al_{pp} and Fe_{pp}) extracts.

Results

Soil characteristics

The soil profile characteristics at each of the sampled depth intervals for the *E. grandis* and *P. elliottii* plantation systems are presented in Table 1. Using the classification system of Isbell (1996), the profile under the *E. grandis* stand was classified as an Acidic Regolithic Bleached-Leptic Tenosol whilst that under *P. elliottii* was classified as an Acidic Arenic Rudosol. Under the eucalyptus stand there was a distinct O1 horizon that was made up of organic materials at various stages of decomposition. The surface horizon (0-5 cm) was light brownish grey when moist (10YR 6/2), however upon drying it exhibited a bleached (10YR 7/2) nature indicative of the development of a spodic horizon. Within this layer a few (5%) soft organic segregations with a diameter of 2-6 mm were observed (Table 1). The horizon below (5-15 cm) became significantly darker and showed signs of the development of a Bhs horizon. The size and preponderance of soft organic segregations increased to occupy approximately 25% of the horizon. At depths below this horizon, the presence of these

Table 1. Soil profile descriptions from pits in an *E. grandis* and *P. elliottii* plantation

Depth (cm)	Horizon	Description
		E. grandis
0	O1	Organic materials in varying stages of decomposition; field pH 5.5.
0-5	A2e	Light brownish grey (10YR 6/2), bleached (10YR 7/2 dry), fine sand, apedal single grained; 2-10% (5%) medium sized (2-6 mm) organic (humified well decomposed organic matter) soft aggregations (10YR 3/1); field pH 6.0.
5-15	A11 Developing into a Bhs with strong mottles	Dark greyish brown (10YR 4/2), fine sand, apedal single grained; 20-50% (25%) organic soft segregations (10YR 3/1) [10% coarse (6-20 mm) + 10% medium (2-6 mm) + 5% (<2 mm)]; field pH 5.0.
15-45	A12	Greyish brown (10YR 5/2), fine sand, apedal single grained; 2-10% (10%) medium sized (2-6 mm) organic soft segregations (10YR 4/2); field pH 5.5.
45-55	A13	Dark greyish brown (10YR 4/2), fine sand, apedal single grained; very few (2%) medium sized (2-6 mm) organic soft segregations (10YR 3/2); field pH 5.5.
		P. elliottii
0-10	A11	Dark greyish brown (10YR 4/2) fine sand, apedal single grained; 2-10% (5%) medium sized (2-6 mm) organic (humified well decomposed organic matter) soft segregations (10YR 3/1), <2% fine (<2 mm) organic soft segregations; field pH 4.5.
10-22	A12	Dark grey (10YR 4/1) fine sand, apedal single grained; 10-20% (15%) medium sized (2-6 mm) organic soft aggregations (10YR 3/1), <2% fine sized (<2 mm) organic soft segregations; field pH 6.0.
22-42	A13	Dark greyish brown (10YR 4/2), fine sand, apedal single grained; very few (<2%) fine (<2 mm) organic soft segregations (10YR 3/1); field pH 6.5.
42-62	A14	Dark greyish brown (10YR 5/2), fine sand, apedal single grained; very few (<2%) medium (2-6 mm) and fine (<2 mm) sized organic soft segregations (10YR 3/2); field pH 5.5.

organic segregations dramatically declined so that at the 45-55 cm depth interval there was less that 2% of the horizon that was occupied by these materials. In contrast to the profile under the *E. grandis* stand, the *P. elliottii* profile was markedly different in that there was no evidence of the bleached spodic horizon development (Table 1). The presence of soft organic segregations was evident throughout the profile and occupied between <2% to 15% of any individual horizon (Table 1). These soft segregations left organic stains when crushed and wetted, with the internal fabric containing particle sizes comparable with surrounding material in the layer, suggesting that they were formed *in situ.*

pH, exchangeable cations, organic carbon and extractable Fe and Al

Selected soil chemical properties from each of the pits are presented in Table 2. Both profiles were acidic in reactivity with a mean profile $pH_{0.002}$ of 4.8 and 4.6 for *E. grandis* and *P. elliottii* respectively. The acidic nature of these profiles would account for the dominance of exchangeable acidity (Al^{3+} + H^+) on the exchange complex over most basic cations. Within the surface horizons (0-15 cm) of the eucalyptus profile the dominant cation on the exchange complex was Mg^{2+} with Ca^{2+} levels being significantly lower (Table 2). This trend was reversed under the pine stand with Ca^{2+} being the dominant cation in the 0-22 cm depth interval and Mg^{2+} being significantly lower. This may in part be due to Ca^{2+} lock up within the litter layer (O1 horizon) present under the eucalyptus stand. It is of note that the exchangeable K^+ levels in these soils were extremely low throughout the profiles of both species suggesting that this element may be limiting for optimal growth (Table 2). The effective cation exchange capacity (ECEC) of a soil is an indicative measure of the cation exchange capacity at field pH. In the *E. grandis* stand the ECEC ranged from 0.97 $cmol_c$ kg^{-1} in the 5-15 cm depth interval to a low of 0.50 $cmol_c$ kg^{-1} in the 45-55 cm depth interval. Contrasting this, under the *P. elliottii* stand the ECEC ranged from a high of 1.09 $cmol_c$ kg^{-1} in the 0-10 cm depth and declined gradually with depth to a low of 0.38 $cmol_c$ kg^{-1} in the 42-62 cm depth interval (Table 2).

The pH buffering capacity over all depth intervals was highest under the pine species and declined gradually with depth (Table 2). Contrasting this, the pH buffer capacity followed a similar trend as the ECEC under the *E. grandis* stand with the highest buffering occurring in the 5-15 cm depth interval (Table 2). In general, the buffering capacity as measured under both systems was low, suggesting limited internal resistance to changes in pH. Soil organic carbon contents for each depth interval and the segregations collected from the profiles are presented in Table 3. Distinct differences between the two plantation systems were clearly evident with the *E. grandis* profile exhibiting an almost doubling (0.55%) of carbon content in the 5-15 cm depth interval when compared to the horizons above and below, indicating an accumulation of organic carbon in this depth (Table 3). The OC content in the 0-5 and 45-55 cm remained constant at 0.27 and 0.26% OC respectively. Contrasting this, the OC content under the *P. elliottii* stand was highest (1.30%) in the 0-10 cm and declined sharply to 0.49% in the 10-22 cm depth to a low of 0.20% OC in the 42-62 cm depth interval (Table 3).

Table 2. Selected soil chemical properties collected from pits in a long-term *E. grandis* and *P. elliottii* stands. Values in parenthesis are the standard deviation from the mean

Depth (cm)	pH_w	[1]$pH_{0.002}$	EC	Na^+	K^+	Ca^{2+}	Mg^{2+}	Al^{2+} + H^+	ECEC	pH buffer capacity
E. grandis			(µS cm^{-1})			($cmol_c$ kg^{-1})				($mmol_c$ H^+ kg^{-1}. pH^{-1})
0-5	5.08	4.79	17.12 (0.35)	0.03 (0.00)	0.02 (0.00)	0.13 (0.01)	0.21 (0.02)	0.20 (0.01)	0.59 (0.04)	0.276
5-15	4.95	4.63	23.29 (0.38)	0.05 (0.00)	0.04 (0.00)	0.16 (0.01)	0.40 (0.03)	0.32 (0.01)	0.97 (0.03)	0.636
15-45	5.01	4.86	15.65 (0.39)	0.03 (0.00)	0.03 (0.00)	0.04 (0.00)	0.16 (0.01)	0.26 (0.00)	0.51 (0.01)	0.476
45-55	5.16	4.95	16.32 (1.89)	0.04 (0.00)	0.02 (0.00)	0.02 (0.00)	0.16 (0.01)	0.25 (0.01)	0.50 (0.01)	0.467
P. elliottii										
0-10	4.79	4.42	16.21 (0.48)	0.01 (0.00)	0.02 (0.00)	0.63 (0.04)	0.14 (0.00)	0.29 (0.02)	1.09 (0.06)	1.066
10-22	4.73	4.61	12.91 (0.30)	0.01 (0.00)	0.01 (0.00)	0.25 (0.00)	0.05 (0.01)	0.33 (0.00)	0.66 (0.00)	0.878
22-42	4.68	4.77	9.99 (0.32)	0.01 (0.00)	0.01 (0.00)	0.08 (0.00)	0.04 (0.01)	0.29 (0.01)	0.43 (0.00)	0.602
42-62	4.75	4.85	9.55 (0.51)	0.01 (0.00)	0.01 (0.00)	0.05 (0.00)	0.03 (0.00)	0.28 (0.01)	0.38 (0.01)	0.586

[1] $pH_{0.002}$ pH measured in 0.002 M $CaCl_2$ at the start of the equilibration process in the development of the surface charge fingerprints.
[2] $CEC_{6.0}$ the CEC as pH 6.0 that was determined from the surface charge fingerprint.

Table 3. Selected characteristics of two soil profiles under contrasting plantation species. OC: soil organic carbon; Fe_{ox}, Fe_{pp}, Al_{ox}, Al_{pp}: oxalate and pyrophosphate extracted Fe and Al

Sample description	OC	[1]?CEC_T	Fe_{ox}	Fe_{pp}	Al_{ox}	Al_{pp}
E. grandis	(%)	($cmol_c$ kg^{-1})		($g\ kg^{-1}$)		
0-5 cm	0.27 (0.01)	0.240	0.022	0.090	0.056	0.227
5-15 cm	0.55 (0.04)	0.846	0.120	0.372	0.181	1.180
15-45 cm	0.24 (0.01)	0.612	0.155	0.337	0.150	1.191
45-55 cm	0.26 (0.01)	0.722	0.196	0.477	0.238	1.606
Segregates	1.40 (0.00)	–	0.246	0.554	0.295	1.642
P. elliottii						
0-10 cm	1.30 (0.14)	1.644	0.126	0.195	0.206	0.582
10-22 cm	0.49 (0.01)	0.825	0.135	0.299	0.176	0.984
22-42 cm	0.24 (0.01)	0.602	0.189	0.356	0.187	1.181
42-62 cm	0.20 (0.01)	0.432	0.310	0.369	0.190	1.047
Segregates	0.89 (0.04)	–	0.216	0.398	0.231	1.081

[1]?CEC_T = difference in CEC_T between pH 4.5 and 6.5.

These results clearly demonstrate the greater amount of organic carbon accumulation under the pine plantation when compared to the eucalypt.

The downward movement in the soil profile of organic complexes of Fe and Al as determined by pyrophosphate extractions has been least under *P. elliottii* when compared to the *E. grandis* (Table 3). Oxalate should extract total translocated Fe and Al, including organic complexes extracted by pyrophosphate (Farmer *et al.*, 1983) although incomplete extraction of organic Al has been reported (Skjemstad *et al.*, 1992). Concentrations of Fe_{pp}, however are more than twice those of Fe_{ox} in the case of the *E. grandis* samples over all depth intervals (Table 3). In contrast, Fe_{pp} values were similar to Fe_{ox} in the 0-10 and 42-62 cm depth intervals under the *P. elliottii* stand suggesting that at these depths the Fe is predominantly found as an organic complex (Table 3). In all depth intervals regardless of species, Fe_{pp} values were considerably larger than Fe_{ox} indicating the predominance of organic complex Fe. The fact that the subsoil matrix under each of the plantation systems was little different in composition from the segregations suggests that these have formed *in situ*, leaving small islands of clayey material that have become hardened somewhat by Fe and Al oxides. However, it is of note that in the cases of the *E. grandis* plantation the segregates showed much greater Fe, Al and C accumulation suggesting that the effect of leaching solutions from the *E. grandis* litter have been more drastic resulting in the move towards the development of a spodic horizon. Indirect evidence for potential accelerated podzolisation under *E. grandis* stand can be implied from the greater propensity for the presence of segregation material as outlined in Table 1. Clearly the degree of mobilization of both Fe and Al has been more intense under the *E. grandis* than under the *P. elliottii* stands respectively.

Surface charge fingerprints

By evaluating the charge characteristics of these soils, a clear understanding of the impact of these two plantation systems on intrinsic soil chemical properties can be assessed. The concept of charge fingerprinting as described by Gillman and Sumpter (1986) provides an assessment of both the positive and negative charge characteristics of a soil over a pH range that has significance when assessing the impact of plantation systems on the soils resource. When used in conjunction with exchangeable cations extracted from the exchange complex, an assessment of current and potential nutrient-holding capacity and the impact of management can be assessed.

The methodology used to develop the charge fingerprint estimates the CEC_B and CEC_T at each pH point. The CEC_B is the total amount of basic cations that can be retained in an exchangeable form at any particular solution pH and ionic strength. The total cation exchange capacity (CEC_T) is the total amount of basic and acidic cations that can be retained in an exchangeable form at any particular solution pH and ionic strength. The approach distinguishes that portion of the cation exchange capacity (CEC) that retains basic cations, and predicts changes in CEC as soil solution pH and ionic strength are varied. For brevity only the CEC_T is discussed.

These soils are dominated by sand with very little clay. Consequently, the surface charge generation potential associated with changes in pH is limited. Figure 1 shows charge fingerprints for composite samples collected from the 0-5, 5-15, 15-45 and 45-55 cm depth intervals for the *E. grandis* soil. A distinct characteristics of the curve derived for the 0-5 cm depth interval is the quantity of negative charges generated, namely 0.24 $cmol_c\ kg^{-1}$, over the pH range 4.5 to 6.5 (Figure 1 and Table 3). Contrasting this, in the 5-15 cm depth interval the amount of charge generated over the same pH range trebled to 0.846 $cmol_c\ kg^{-1}$, clearly indicating the influence of accumulated organic carbon or remaining carbon in this depth interval (Figure 1 and Table 3). Over the remaining depth intervals, the amount of charge generated over the pH range 4.5 to 6.5 remained relatively constant with values of 0.612 and 0.722 $cmol_c\ kg^{-1}$ respectively (Figure 1 and Table 3). In contrast, under the *P. elliottii* plantation the greatest amount of charge generated over the pH range 4.5 to 6.5 was 1.644 $cmol_c\ kg^{-1}$ in the surface 0-10 cm depth interval and declined progressively down the profile to a value of 0.420 $cmol_c\ kg^{-1}$ in the 42-62 cm depth interval corresponding to changes in soil organic carbon (Figure 1 and Table 3). The greatest difference in the shapes of the charge curves was in the surface horizons of the two plantation systems. This can be ascribed to the larger organic carbon content under the *P. elliottii* plantation when compared to the *E. grandis* and clearly quantifies the potentially deleterious impact of this species on exchange properties on soils with a small permanent charge. In short, the role of organic C in maintaining negative charge on these soils is critical for the retention of cations. In addition, an evaluation of the surface charge characteristics of these samples clearly indicates the position in the profile where the development of a spodic horizon (5-15 cm) has occurred under the *E. grandis* and quantifies the influence of these processes on the surface charge characteristics of these soils.

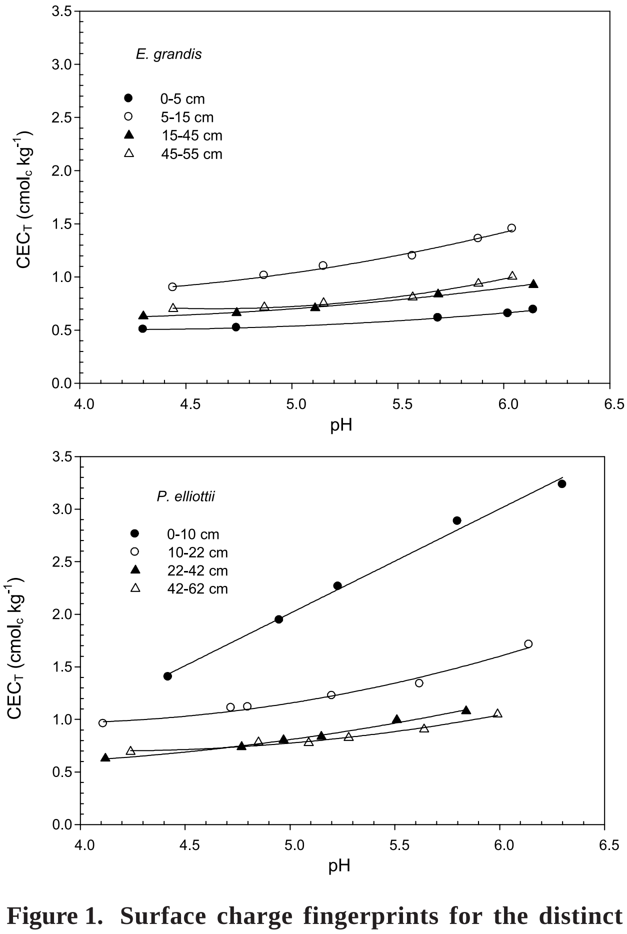

Figure 1. Surface charge fingerprints for the distinct horizons under *E. grandis* and *P. elliottii* respectively

If the basic and acidic cations removed by the $BaCl_2$-NH_4Cl and KCl extractants, respectively, are all exchangeable cations, then their sum (the ECEC) should be equal to CEC_T at soil pH, within the limits of the experimental error. A graph of ECEC against CEC_T at the soil’s pH (Figure 2) for the two plantation species shows good agreement between these independently determined properties for the surface samples. However, with depth there was less cations extracted than could be accounted for by CEC_T. This would suggest that cations that are present on the exchange complex are not accounted for in the $BaCl_2$-NH_4Cl and KCl extractants. A possible cation that may have contributed to an underestimation of the ECEC could be Fe. Indeed, as a significant amount of oxalate and pyrophosphate Fe was extracted from the soils, some may have been associated with the exchange complex (Table 3).

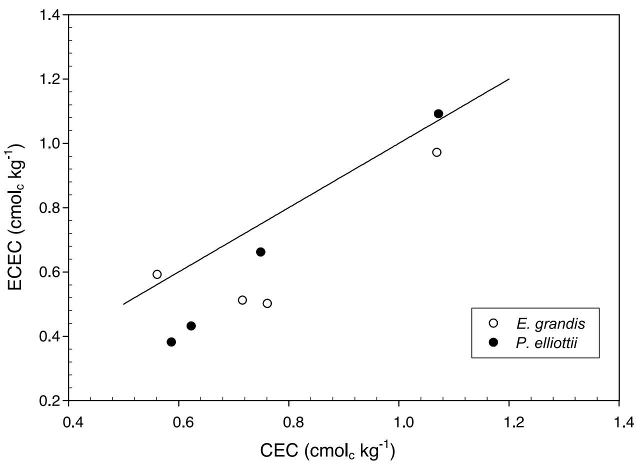

Figure 2. Relationship between total cation exchange capacity at soil pH and the effective cation exchange capacity (ECEC) for each of the depth intervals sampled. The line represents the 1:1 relationship between CEC and ECEC. The values falling close to the line are for the surface samples, *E. grandis* (0-5 cm) and *P. elliottii* (0-10 cm)

Discussion and Conclusions

Analysis of the soil pits assumes that differences between sites are due to the direct influence of the plantation species and that variations in parent material, topography and other factors are relatively unimportant. As the area has been extensively planted to eucalyptus and pines species, undisturbed or pristine sites containing native vegetation components could not be sampled as a control. Consequently it is assumed that at the time of establishment of these two production systems soil attributes were similar. Assuming that this was the case, an assessment of the chemical and morphological properties of soil profiles under each of the production systems clearly indicates that there have been considerable changes associated with the tree species. There is clear evidence that under *E. grandis* the early stages of a bleached spodic (A2e) horizon development is clearly evident in the 0-5 cm depth interval. In addition, constructing surface charge fingerprints confirms the presence of the spodic horizon and the development of a rudimentary Bhs horizon associated with the accumulation of organic complexes in the 5-15 cm depth. Such morphological and chemical changes in soil properties were not evident under the *P. elliottii* stand.

It is important to note that these two systems have had very little disturbance associated with traffic movement within the plantation. This has undoubted allowed the effective observation of horizon development from the surface to depth. This would not be the case in plantations that have had mechanical traffic through the plantation that would disturb surface soil horizons thereby homogenizing the soil making the delineation of a rudimentary A2e horizon difficult.

Studies into the development of podzols on the east coast of Australia have shown that thousands of years are required to develop mature profiles. For example, giant podzols with A2 horizons 12 to 22 m thick have formed over periods of up to 700,000 years (Tejan-Kella et al., 1990). At the younger end of the scale, the depth to the B horizon can be 1.6 m or less on Holocene dunes and less than 50 cm on dunes deposited over the last 3,000 years (Pye, 1981; Thom *et al.*, 1981; Thompson, 1983; Bowman, 1989). Contrasting this, Prosser *et al.*, (1995) reported the development of an A2 horizon to a depth of at least 3.7 m to have formed within 17 years on post mined sand dunes. In the present study the depth of the rudimentary A2 horizon was a mere 5 cm after 49 years. This rate of development is approximately 10 times faster than those reported above for Holocene dunes in Australia but considerable slower than that by Prosser *et al.* (1995). Prosser *et al.* (1995) attributed this unprecedented rate of pedogenesis to the high permeability of the sands, the low silt and clay content, the previous advanced stage of weathering and pedogenesis, and the homogenization of the soil during mining operations. Whilst the current study would suggest that the rate of development of an A2 horizon is not drastically dissimilar to natural systems, it is prudent to note that the stand had never been felled and hence would represent effectively a 'climax' stand; the leaching component under this system would be very small, thereby reducing the rate of A2 development; and most importantly, as these systems had not undergone any form of surface disturbance it allowed us to identify the presence of an A2 horizon. In the current climate of moving to short rotations (4-8 years) using clonal material that place a significant demand on soil and water resources including whole tree harvesting and potential for greater leaching to occur due to the reduced rotation length, the potential negative impact of such forestry systems on soil resources that have limited intrinsic attributes is great. The impact of *P. elliottii* under the prevailing circumstances would appear to be minimal when compared to other species and would support previously reported studies (Noble *et al.*, 1999). Finally, the development of surface charge fingerprints has demonstrated the usefulness of this technique in quantifying the influence of pedogenesis on intrinsic soil properties and could be a potential tool in assessing horizon development at an early stage.

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Clay mineral dissolution following intensive cultivation in a tropical sandy soil

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Keyword: clay mineral, acidification, analytical transmission electron microscopy, neoformation smetites

Abstract

Sandy soils of Northeast Thailand are predisposed to high acidification rates due to leaching and the export of alkalinity is associated with crop removal in these intensive cropping systems. Despite significant acid release, soil pH generally remains stable at a threshold value of around 4.0. Low organic matter content and the absence of weatherable primary minerals would suggest that clay mineral dissolution is responsible for the high degree of buffering commonly observed in these soils. The objective of this study was to investigate changes in nature and organisation of clay minerals following intensive cultivation in a typical sandy soil from Northeast Thailand. Surface soils were sampled under a forest (FS) and an adjacent area cultivated for 50 years (CS); they were compared with parent material sampled at 3.5 meter depth (PM) with the aim of characterising the evolution of clay minerals through pedogenesis and cultivation. The proportion of small particles (mode 0.1 µm) decreased according to pedogenesis – from parent material to soil, and land use – from forest to crop. Under the cultivated and forest soils, particles of kaolinite appeared to be very small (0.02-0.10 µm), poorly crystallised and eroded, often organised as aggregates of 1-2 µm. Expandable 2:1 clay minerals were associated with kaolinite. Chemical data of individual particles revealed that kaolinite contained iron and that expandable 2:1 clay minerals were smectite, vermiculite and mixed-layer illite/smectite. X-ray diffraction patterns of <2 µm-fractions indicated that kaolinite was the main phase, 78%, 88% and 88% in CS, FS and PM respectively, smectite being a minor phase with 20%, 6% and 12% respectively. Our results suggest that the dissolution of kaolinite was accelerated in cultivated system (CS), with a correlative neoformation of smectite, which buffers potential declines in soil pH.

Introduction

Sandy soils are widespread in the tropics and constitute an important economic resource for agriculture despite their inherent low fertility (FAO, 1975). Such soils occupy a large area of the Northeast Thailand plateau (Ragland and Boonpuckdee, 1987). These soils are often characterised as being of a light sandy texture, acidic to depth (pH around 4.0 in $CaCl_2$) with very low exchange properties (CEC <2 $cmol_c$ kg^{-1}) and therefore a low nutrient supplying capacity (Imsamut and Boonsompoppan, 1999). Soil acidification is a major concern in tropical sandy soils since climate and high leaching rates are prevailing conditions for the development of this phenomenon. Intensive cultivation results often in accelerated acidification which has brought into question the long-term sustainability of agronomic production systems (Helyar, 1976).

In Northeast Thailand, degradation of acid sandy soils by further acidification under permanent agriculture has been clearly highlighted (Noble *et al.*, 2000). However accelerated acidification occurs sometime without pH drop in these acid sandy soils (Lesturgez *et al.*, 2005). Regarding the low organic matter content and the absence of other weatherable minerals, the authors suggested the role of clay minerals in buffering the soil pH.

In order to ascertain the role of clay minerals in buffering capacity, a mineralogical study has been conducted in Northeast Thailand with the objective to

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identifying changes in nature and properties of clay minerals possibly induced by 50 years of intensive cultivation. The study has been conducted on a forest soil, an adjacent cultivated area and the parental material of these soils in order to highlight (i) general clay properties of the soils, (ii) evolution following pedogenesis and (iii) changes induced by 50years of intensive cultivation.

Materials and methods

Site and sampling

The study was conducted on a representative upland sandy soil of Northeast Thailand. The site selection was based on previous studies (Lesturgez, 2005) and a paired site approach was conducted to quantify differences between Dipterocarp forest (undeveloped) and agricultural (developed) areas. The soil at the studied sites belongs to Warin soil series (N 16º16′; E 102º47′): Dipterocarp forest and adjacent cultivated land that was deforested 50years ago and used for cassava and sugarcane cultivation to date. The same soil type was observed in both areas with little topographical differences (i.e. slope) between these two areas. The undisturbed Dipterocarp forest, close to agricultural field, had a well-defined boundary to separate the two land use systems. Selected characteristics of the soil at the studied sites are presented in Table1. Samples were collected at 0-10cm depth both in the soil under forest (FS) and in adjacent cultivated area (CS) and at 3.5 m depth for parent material (PM). Samples were air-dried and passed through 2mm sieve.

X-ray diffraction (XRD)

40g sub-samples of air -dried material were dispersed in water overnight by shaking. Clay fractions (<2 μm) were obtained by sedimentation from the initial samples after organic matter oxidation (H_2O_2-treated clay). Mineralogical analysis was performed by X-ray diffraction on oriented samples obtained by sedimentation of the <2 μm fractions on glass slides and air-dried. Samples were run in a Siemens D5000 system with CoKα radiation. The diffraction patterns were decomposed into elementary curves using the program DECOMPXR (Lanson, 1997) in order to quantify the proportion of different clay minerals. The decomposition was done on the 1st order diffraction peaks for kaolinite, illite and smectite (or vermiculite).

Table 1. Selected properties of the studied soils

Horizon	Depth (cm)	Particle size distribution (%)			pH	Bulk density ($Mg.m^{-3}$)
		Sand	Silt	Clay		
Forest soil (FS)						
A	0-15	78.7	18.5	2.8	5.4	1.4
E	15-65	74.9	18.0	7.1	5.2	1.4
B1	65-120+	67.9	15.3	16.8	4.9	1.5
Cultivated soil (CS)						
Ap	0-15	80.5	16.8	2.7	4.6	1.6
E	15-65	71.2	16.9	11.9	4.8	1.6
B1	65-120+	64.0	15.2	20.8	4.6	1.5
Parent material (PM)						
PM	350	77.4	9.5	13.1	–	–

Laser granulometry (LG)

Particle size distributions (PSD) were measured on <2 μm fractions dispersed in distilled water (ultrasound ~15 min).The quantity of material was adjusted in order to obtain adequate particle concentration (obscuration = 45%). PSD was produced using a LS-230 Beckman-Coulter laser grain-size analyser, with a range of particle size from 0.04 to 2000 μm, divided into 116 fractions. PSD was performed under agitation of clay suspension in the measuring cell. Three repeated measurements were undertaken in each sample.

Analytical transmission electron microscopy (TEM-EDS)

Dispersed clay suspensions were deposited on collodion-coated Cu grids and air-dried. Images were produced in a Philips 420 STEM transmission electron microscope operated at 120kV and equipped with a Megaview II CDD camera. Magnification at 10500x covered the particle-size ranged from 0.5-2.0 μm and magnification at 31000x ranged from 0.05 μm-1.00 μm.

Microanalyses were performed using an Oxford INCA energy dispersive spectrometer (EDS) with an ultrathin windowed Si (Li) detector connected to the microscope. In order to limit irradiation damages, analyses were done using a probe spot 100nm in diameter (Romero *et al.*, 1992). The chemical compositions (Al, Si, K, Ca, Mg, Fe, Na and Ti) were determined on individual particles selected regarding dispersion. A minimum of 100 particles was analysed for each sample in order to get a representative set of data. Minerals were identified by their chemical compositions, on the basis of calculated structural formula expressed in number of constituting cations. Quantitative discriminations were used to sort particle analyses into mineralogical classes (Figure1).

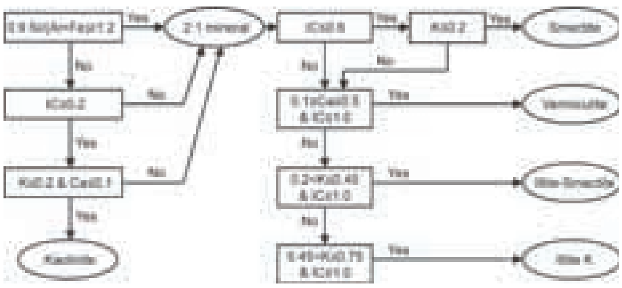

Figure 1. Procedure for identifying clay minerals using analytical data from TEM-EDS. Numbers of atoms in structural formulae are calculated on the basis of 11 and 7 oxygen atoms per half cell for 2:1 and 1:1 clay minerals, respectively. Si, Al, Fe, K, Ca: number of atoms in the calculated structural formula. IC: Interlayer Charge Value (Ca^{2+} + Na^{2++} K^{+}) of the particle

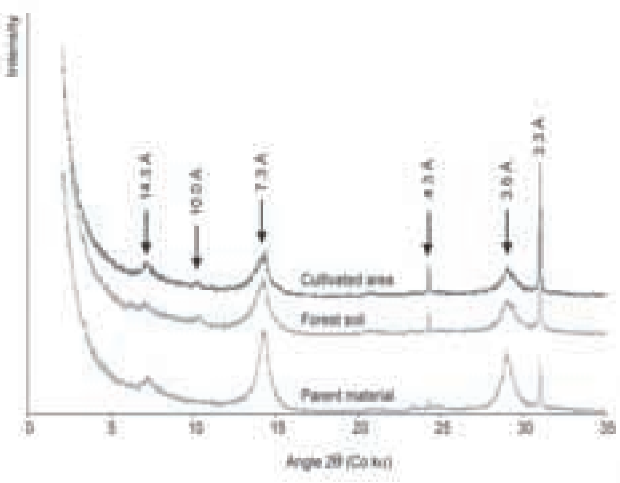

Figure 2. X-ray diffractograms (Co kα) of clay fractions (<2 μm) for cultivated soil, forest soil, and parent material

Results

Mineralogical determination of clay fraction by XRD

XRD patterns indicated the presence of quartz (4.3 and 3.3 Å), kaolinite (7.3 and 3.6 Å) and 2:1 clay minerals (illite at 10.0 Å and smectite at 14.3 Å) in all three samples (Figure 2).The intensity of quartz peaks (4.3 and 3.3Å) was higher in soils (CS and FS) than in parent material (PM). According to peak intensity, kaolinite was the main crystalline phase with 78%, 88% and 88% in CS, FS and PM, respectively (Table 2). On the other hand, the proportion of smectite was only of 20%, 6% and 12% in CS, FS and PM respectively. The diffraction intensity of illite was significant only in FS (6%). As the peaks of kaolinite were very large compared to a reference kaolinite (Brindley and Brown, 1980), they have been decomposed into three elementary peaks modelling crystallinity, each peak position corresponded to a structural order: highly disordered (7.37Å), slightly disordered (7.22Å) and well ordered (7.15 Å). The proportion of the three types of peaks within the kaolinite fraction has been recalculated and expressed in percentage of total peak surface (Table3). The proportion of highly disordered kaolinite was equivalent for CS and FS (40%) but lower in PM (34%). The slightly disordered kaolinite was correlatively more important in PM (66%) while the well ordered kaolinite was present only in CS (3%).

Table 2. Selected characteristics of the clay fractions (<2 μm) for parent material, forest and cultivated soil

	Parent material	Forest soil	Cultivated soil
Mineralogical determination by modelling the XRD diffractograms. Peak surface (%)			
Highly disordered kaolinite (7.37 Å)	30	35	31
Slightly disordered kaolinite (7.22 Å)	58	53	45
Well ordered kaolinite (7.15 Å)	0	0	2
Total kaolinite	88	88	78
Illite (10 Å)	0	6	2
Smectite (14.3 Å)	12	6	20
Particle size distribution by laser granulometry. Particle surface area vs. particle diameter (%)			
0.04-0.30 μm (%)	86	49	37
Mode value (μm)	0.088	0.117	0.106
0.30-10.00 μm (%)	14	51	63
Mode value (μm)	0.775	0.755	0.755
Quantitative mineralogy by analytical transmission electron microscopy (TEM-EDS). Particle number (%)			
Kaolinite	82	42	34
Smectite	10	29	54
Al-vermiculite	1	12	1
Mixed layer illite/smectite	5	14	3
Illite	2	2	8

Particle size distribution by laser granulometry (PSD)

Particle size distribution (PSD) was expressed in particle surface area (SA) as a function of the particle equivalent diameter. Average and standard deviation of the three replicates are presented in Figure3. Particle size distributions were bimodal shape in all samples. For PM, the main particle size mode was around 0.1 µm (0.04-0.30 µm) and covered 86% of total SA (Table2). PSD for CS and FS had two strong modes around 0.1 µm and 1.0 µm, thus appearing very different from PM. The SA of small particles (mode 0.1 µm) strongly decreased from PM to FS and CS. When comparing FS and CS, the SA of small particles decreased from FS to CS.

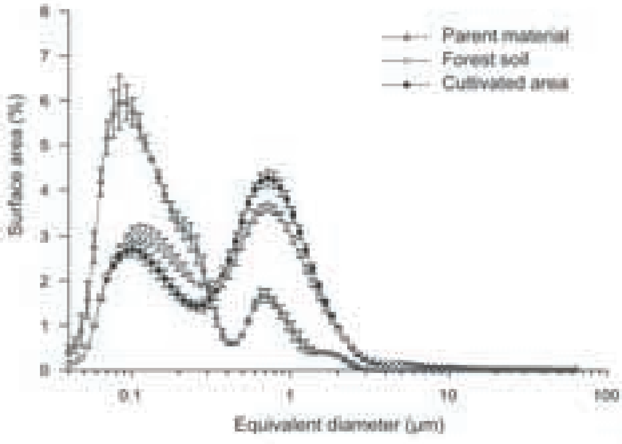

Figure 3. Particle size distributions of clay fractions (<2 µm) for cultivated soil, forest soil, and parent material by laser granulometry

Morphology and chemical composition of particles by TEM-EDS

Examples of TEM images are shown for FS (Figure4). The shape and size of particles were similar in CS and FS. The size of particles observed on TEM images allowed discrimination between quartz grains and clay minerals. Most of quartz grains were the large particles while clay minerals were much smaller (Figure4-A). A significant proportion of small particles was organised into aggregates of 0.5-2.0 µm (Figure4-B). Dispersed kaolinite particles appeared to be eroded both in CS and FS and constituted the majority of PM ranging between 40 and 120 nm. A great diversity of particle shapes was observed in Figure4-C.

Analytical transmission electron microscopy (TEM-EDS) revealed that kaolinite contained iron. The 2:1 clay minerals were smectite and mixed-layer illite/smectite in all samples, vermiculite was in FS and illite was only in CS. Smectite was associated with

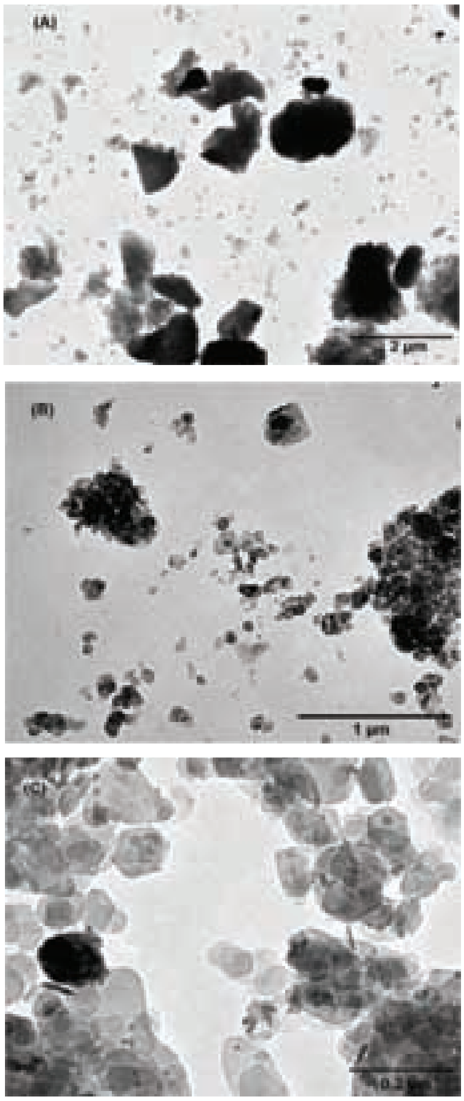

Figure 4. TEM images of clay fractions (<2 µm) for cultivated soil, forest soil, and parent material at magnification ×10500 (A), ×31000 (B) and ×105000 (C)

kaolinite in aggregates. Particles of titanium and iron were also detected. The main 2:1 clay mineral was smectite with 54, 29 and 10% in CS, FS and PM, respectively (Table2). Mixed-layer illite/smectite was low in proportion with 3, 14 and 5% in CS, FS and PM, respectively. Al-vermiculite developed mainly in FS (12%). The repartition of clay minerals was determined by EDS following the marked trends between samples, but their proportions were markedly different from XRD determinations.

Discussion

Methodological aspects

When comparing results obtained by XRD and EDS analyses, the discrepancy between quantitative data relates to two essential methodological aspects:

- XRD detected the diffraction ability of minerals, which depended on their crystallinity and chemical composition. It is worthy of note that kaolinite contains iron and the presence of this element strongly enhances the structure factor, i.e. the diffraction intensity. Furthermore, XRD technique is not suitable for poorly crystallised phases and not able to produce diffraction peaks for amorphous material or loose monolayers such as smectite, and even for loose bilayers (Dudek *et al.*, 2002).
- EDS analyses were sorted using strict rules applied to calculated structural formulae, discarding from the kaolinite group, all particles containing Mg and having a high interlayer-charge (K and Ca). Such particles are thus identified as 2:1 clay minerals.

XRD detected well crystallised phases of clay minerals in parent material but it was underestimated for the fine neoformed phases as well as dissolution products in soils. The discrepancy between XRD and EDS is not a trivial issue, but suggests a transition from 1:1 to 2:1 clay minerals in a significant part of the clay fraction.

Mineralogical properties of soils in Northeast Thailand

The studied soils contained a very small quantity of clay minerals. The clay fraction consisted of a mixture of 1:1 (kaolinite) and 2:1 clay minerals (illite and smectite), and contained a significant proportion of small quartz grains as noted in other soils of this region (Bruand et al., 2004). Kaolinite showed crystal disorder (XRD) and appeared to be dissolved (TEM) in soils as well as in parent material. Some iron was detected in kaolinite as a lattice substitution for Al. XRD patterns and EDS analysis confirmed the presence of expandable 2:1 clay minerals especially smectite, but EDS also identified mixed-layer illite-smectite and Al-vermiculite in small proportion. Kaolinite appeared to be disordered in these soils as well as in parent material since the XRD peak around 7Å was very lar ge.

Evolution through pedogenesis

To investigate in more detail changes in crystallinity between the different samples, the "kaolinite" XRD peaks have been decomposed. The proportion of highly disordered kaolinite is equivalent in CS and FS but more important in soils than in PM, and slightly disordered is correlatively more important in PM (Table3). Crystal disorder is probably related to kaolinite dissolution. This may be consistent with the hypothesis that kaolinite in parent material was poorly crystallised and this phenomenon has been accentuated by weathering through pedogenesis.

Table 3. Normalised proportions of disordered kaolinite species in kaolinite fraction

	Parent material	Forest soil	Cultivated soil
Highly disordered kaolinite/Total kaolinite	34	40	40
Slightly disordered kaolinite/Total kaolinite	66	60	58
Well ordered kaolinite/Total kaolinite	0	0	3

Particle size distributions of clay fractions showed the loss of finer particles (mode 0.1 µm) in soils when compared to those in PM. The value corresponding to the loss was 50% for CS and 37% for FS. On the other hand, EDS result indicated a higher proportion of kaolinite in PM (82%) than in the soils (34% in CS and 42% in FS). TEM images showed that the fine particles (mode 0.1 µm) corresponded to fine grained kaolinite. These results strongly suggested that a disappearance (completely dissolved) of the small particles of kaolinite may be due to their dissolution when buffering acid addition and/or their leaching to depth. On the other hand, EDS detected a much higher proportion of 2:1 clay minerals in soils than in parent material, suggesting that the clay neoformation may possibly occur on the basis of degraded kaolinite.

Evolution of mineralogy due to intensive cultivation

Particle size distributions of <2 µm fractions revealed a decrease of finer particles (mode 0.1 µm) in CS compared to FS. On the other hand, EDS analysis revealed a discrepancy in the content of mixed-layer illite/smectite and Al-vermiculite between CS (4%) and FS (26%) and a correlative discrepancy in the content of smectite between CS (54%) and FS (29%). These results pointed out the difference between these two soils: kaolinite dissolution was associated with a neoformation of smectite which appeared to be accentuated in CS.

Conclusion

The aim of this study was to evaluate the evolution of clay minerals, especially kaolinite and 2:1 clay minerals, in acid sandy soils of Northeast Thailand subjected to intensive cultivation. Our results have shown that the main clay mineral is kaolinite. Quartz is also present in all clay fractions but its grain size is coarser compared to clay minerals (TEM images). The presence of expandable 2:1 clay minerals has been highlighted, especially smectite as well as mixed-layer illite/smectite and vermiculite, though in smaller proportions. With respect to kaolinite, the great diversity of morphological shapes, very small particle size and the presence of iron in crystal structure were consistent with a dissolution process due to soil acidification. Kaolinite is thus characterised by fragility under acidic conditions.

Results also indicate, by using three different analytical methods (especially TEM-EDS analysis), that fine kaolinite particles become scarcer with increasing pedogenesis whereas 2:1 clay minerals tend to be neoformed. The first phenomenon may be related to dissolution of fine grained kaolinite particles and/or their leaching to depth. The second phenomenon can be linked to the properties of 2:1 clay minerals which are less readily eluviated.

The neoformation of smectite containing Ca as exchangeable cation appeared to dominate in cultivated soil, whereas in forest soil it appeared to be associated with neoformation of other 2:1 clay minerals such as Al-vermiculite and mixed-layer illite/smectite. Further studies, focusing on the clay evolution in soil profiles, are needed to validate these hypotheses and to investigate the role of smectite in soil pH buffering.

Acknowledgments

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Hydrotalcite: leaching-retarded fertilizers for sandy soils

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Keywords: exchangeable fertilizers, nitrate, anionic calys

Abstract

Despite the obvious benefits that the use of soluble fertilizers have afforded in raising world food production, there is rising concern about the detrimental effects in terms of economic inefficiency and environmental damage that may ensue if soluble fertilizers are applied inappropriately. This is particularly important in the management of light-textured soils, where leaching losses are common. This paper canvasses the use of a synthetic clay material, Hydrotalcite, for the delivery of anionic nutrients (nitrate, phosphate, sulfate etc.) in an exchangeable and therefore leaching-retarded form. This is analogous to the way nature provides mechanisms for retaining cationic nutrients (calcium, magnesium, potassium etc.) in many soils by the presence of phyllosilicate clays (smectite, kaolinite) as soil components. Anion-loaded hydrotalcite can be applied separately, can be added to conventional (particularly phosphatic) fertilizers, or can be used to stabilize phosphate in feedlot wastes that can then be used as soil amendments.

Introduction

To meet ever increasing worldwide demand for food and fibre on decreasing areas of land on which to produce them, farmers have turned to high-yielding crop varieties that generally require large amounts of soil nutrients for maximum production. This has led to a dramatic rise in the use of synthetic high-analysis fertilizers, whereby nutrients can be applied in a soluble and therefore plant-available form in a highly efficient manner. An unfortunate down-side of applying soluble fertilizer is the ease with which the chemical species can escape the producers' fields and pollute off-site environments.

The electrostatic retention of positively charged cationic species on negatively charged particle surfaces in soil is the basis of a well recognized phenomenon, referred to as soil Cation Exchange Capacity (CEC). The subject is exhaustively dealt with in the literature but is perhaps best summarized in a succinct entry in the Encyclopaedia of Soil Science by Bache (2002). In short, the negative charge on the surfaces of soil organic matter and soil clay particles is balanced by accumulation of cations such as Ca^{2+} and K^+ close to these surfaces, affording the cations some protection from leaching, while still being available for uptake by plant roots.

Nature does not provide a similar mechanism for the retention of negatively charged anions in soil, except in the relatively rare occurrence of a small amount of pH dependent positive surface charge in the deeper layers of oxidic soils (Schofield, 1949; Gillman, 1974). Instead, plant nutrients such as N, P, and S are normally retained in the compounds of soil organic matter, and are only released as anions (NO_3^-, $H_2PO_4^-$, and $SO4^=$) following organic matter mineralization. Limited amounts of P and S can enter soil solution by desorption from clay surfaces or from dissolution of primary minerals such as apatite and gypsum. The rate of release of N, P, and S from these sources is usually insufficient to satisfy plant demand in intensive agriculture, and synthetic fertilizers containing these anions are therefore applied. Being relatively or highly soluble, they are prone to leaching loss especially in light-textured soils (Brady and Weil, 1999).

A class of clay minerals known as layered double hydroxides (LDH) has in recent years been receiving a good deal of attention because of the wide range of uses to which they can be applied. Uses include catalysts for organic molecule conversion, fire retardants, anion scavenging, and medical and pharmaceutical preparations (Carlino, 1997). A distinguishing feature of LDH clays is their high structural positive charge density brought about by co-precipitation of di- and tri-valent cation hydroxides in proportions that allow the tri-valent cation to occupy some di-valent cation sites. Hydrotalcite (HT) the best known example, forms when 25-30% of the cation

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sites in the brucite ($Mg(OH)_2$) structure are occupied by Al, leading to a net positive charge that can theoretically reach about 400 $cmol_c$/kg. The similarity between bentonite and HT in the way structural charge arises, leading to intercalation of ionic species with opposite charge, is depicted in Figure 1.

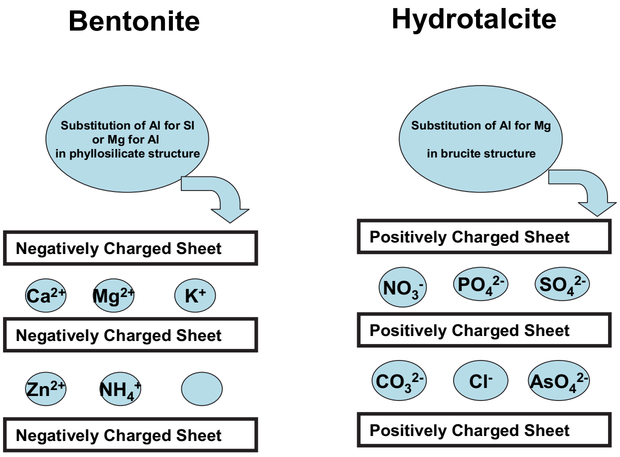

Figure 1. Illustrating the similarities between bentonite and hydrotalcite in the mechanism of retention of cations and anions on their surfaces

The HT used in the above-mentioned applications is usually in carbonated saturated form (CO_3-HT) and being of high purity, is expensive. However, technical grade HT, such as Cl-HT or NO_3-HT, useful for environmental applications discussed in this paper can be produced less expensively from magnesium sources such as magnesite ($MgCO_3$) or concentrated seawater, and aluminium sources such as bauxite ($Al(OH)_3$) or scrap aluminium (Gillman and Noble, 2005).

This paper discusses the use of HT as a platform for nutrient delivery to soils, more particularly to soils prone to nutrient leaching owing to their light texture. The results of laboratory experiments assessing the resistance of nitrate-saturated HT (NO_3-HT) to leaching and to denitrification are presented, along with comparison in greenhouse trials of NO_3-HT and urea as a nitrogen fertilizer in sandy soils. Finally, the concept of using NO_3-HT to stabilize soluble phosphate in feedlot wastes is canvassed as a means of closing the nutrient cycle in the animal-waste-fertilizer-soil-plant-animal cycle.

Designer Fertilizers Using Hydrotalcite

Three of the macronutrients required by plants viz. N, P, and S can be incorporated into the HT structure as nitrate, phosphate, and sulfate respectively, thereby allowing their addition to soil in exchangeable and therefore slow-release form. Micronutrients that can exist in anionic form (borate, silicate, molybdate etc.) could also be introduced in this manner. Furthermore, by manufacturing a range of HT products, with total saturation of each with only one anion type, complete flexibility is allowed for the design of fertilizer blends that match the requirements of soils and the crops to be grown on them. In fact, by combining this principle with another involving negatively charged substrates (e.g. bentonite) loaded with individual cationic nutrients, a totally flexible Designer Fertilizer concept is achieved (Gillman and Noble, 2005).

Column Leaching Experiment

A 5 g sample of aged NO_3-HT was mixed with 500 g of sand, and the mixture placed in a 70 mm diameter Perspex column with a filter paper in the bottom supported by a silk screen. A filter paper was also placed on top to evenly distribute distilled water added at about 2.5 ml/minute, a rate that maintained unsaturated flow conditions. Leachate was collected in 25 ml aliquots for the first 20 pore volumes, and thereafter in 250 ml aliquots until 70-75 pore volumes had been collected. Besides analysing each aliquot for nitrate-N, Mg was also determined to allow estimation of the rate of HT breakdown, as was NH_4^+, to estimate the amount of residual nitrate associated with NH_4NO_3 which is a by-product in HT synthesis.

There was a flush of nitrate from the column in the first 4-5 pore volumes, representing about 40% of the nitrate added as HT product (Figure 2). The uppermost curves show the cumulative total amount of added nitrate recovered, while the curve marked ‘Breakdown’ refers to the nitrate fraction associated with HT dissolution, and was calculated from the Mg determination (1 mole of nitrate would be released from HT for every 2 moles of Mg). The ‘Soluble’ curve, prepared from the NH_4^+ analyses, represents the nitrate associated with residual NH_4NO_3 not washed from the HT product after synthesis. Finally, the difference between the total amount of nitrate recovered and the sum of breakdown and soluble nitrate, is considered to be the nitrate removed from exchange sites of the relatively stable fraction of the HT.

The relatively high initial nitrate removal rate from the HT (50% at 15-20 pore volumes) is accounted as 22% from HT exchange sites, 20% from residual ammonium nitrate, and about 8% from the dissolution of HT particles. It would appear from these results that

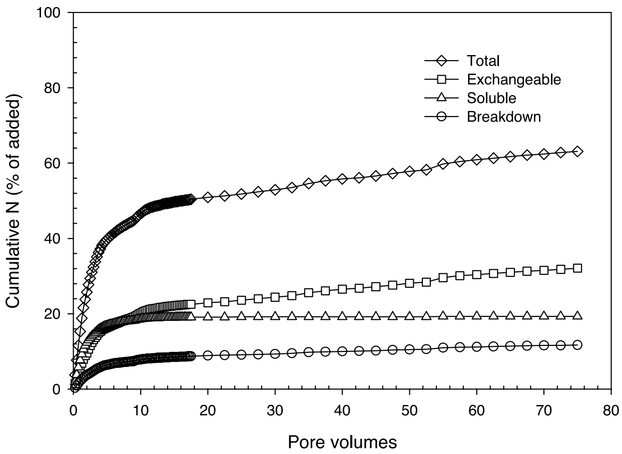

Figure 2. Cumulative amounts of nitrate (% of that applied) leached from a column of sand containing nitrate-saturated hydrotalcite

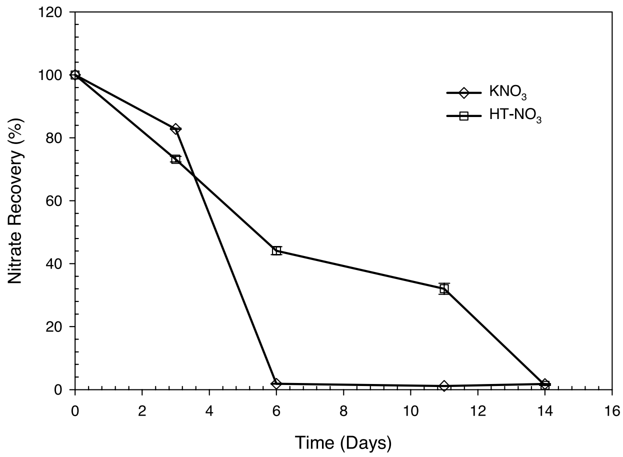

Figure 3. The recovery of nitrate when nitrate was added as nitrate-saturated HT(□), and as potassium nitrate (♢), to a saturated sandy soil with sucrose added as energy source, and stored under vacuum. Vertical bars are the standard error of the mean

NO_3-HT added to soil would act as both a ready source of N at the early stage of plant development, and as a reserve source of N at later stages of the growth cycle.

De-nitrification Studies

An aged HT slurry was dried to a point (dough consistency) where it could be rolled into balls of 4-5 mm diameter, that were then dried at 80°C. Approximately 0.1 g of material was added to pre-weighed tubes for the accurate recording of particle mass. 50 g of sandy soil from a wheat field, 5 ml of 12 g/l sucrose solution, and 11 ml of water were then added, effecting an N concentration of approximately 100 kg N/kg soil and a C concentration of 500 mg C/kg soil. Forty tubes were prepared in this way to allow 10 tubes to be extracted at four time periods, i.e. after 3, 6, 11, and 14 days, for determination of nitrate remaining. A parallel set of tubes were prepared where 4 ml of 1 mg N/ml of KNO_3 solution was substituted for NO_3-HT and only 7 ml of water added to keep soil:water ratio constant, but with only 16 tubes to allow 4 tubes from this treatment to be extracted at each sampling occasion. Finally, 8 control tubes with no added N were included to allow 2 controls to be examined each time. The tubes were placed in a desiccator, the air evacuated, and stored at room temperature for the required intervals, at which times the tube contents were extracted with 2M KCl for nitrate analysis of the extracts.

The results of this de-nitrification experiment is summarized in Figure 3. It is clear that the location of nitrate in the HT inter-layers affords some protection, though the mechanism has not been investigated.

The conditions of high vacuum, saturated soil, and adequate energy source were ideal for de-nitrification to occur, so that the rates of loss of nitrate might not be as rapid under some field conditions. The obvious retarding effect of HT warrants further investigation of the use of NO_3-HT for the growth of crops such as lowland rice, produced under de-nitrifying conditions. It should be remembered, however, that even in sandy soils, conditions can still exist for de-nitrification to occur when soil is temporarily saturated.

Greenhouse Trials with NO_3-HT

This trial compared the use of nitrate saturated HT and urea as sources of N for the growth of tropical maize, and consisted of 4 rates of N (25, 50, 75, 100 kg N/ha) and a control with zero N. The experiment was conducted in 5 kg freely draining plastic pots using a coarse-textured alluvial sand. The two nitrogen sources were applied as granules, drilled as a band across the diameter of the pot. After germination the maize plants were thinned to 4-5 per pot, and the pots were freely watered daily throughout the 9 week growth period. Macronutrients (except N) and micronutrients were applied as required. At harvest, the above ground biomass was dried and weighed to assess Dry Matter production.

The response of forage sorghum to nitrogen added as NO_3-HT and as urea growing in a sandy soil under freely-draining conditions is summarized in Figure 4. For N application rates greater than 40 kg/ha, significantly higher yield was achieved with the

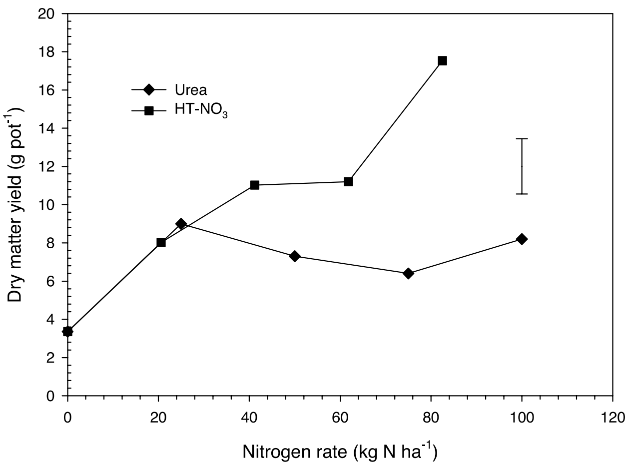

Figure 4. Response to nitrogen applied as urea and as nitrate-saturated HT of tropical maize growing in sandy soil placed in freely-draining pots. Vertical bar represents LSD between two treatment means

NO_3-HT application. Unfortunately, N content of the herbage was not determined but the plants that received nitrogen as NO_3-HT were greener and healthier in appearance than those fertilized with urea.

Stabilization of Feedlot Wastes

The rapid expansion of Confined Animal Feedlot Operations (CAFOs), more commonly known as Feedlots, has led to huge problems relating to disposal of wastes exiting these facilities. The organic matter and plant nutrient content of the materials make them prime candidates for use as fertilizers and soil ameliorants, but their generally high water content and/or intractable physical properties present major difficulties in respect of handling and storage, transport, and land application. Odour is often a problem if the facilities are located near residential areas. The above-mentioned problems result in concentration of applications of feedlot manure on relatively small areas close to the feedlot.

Nitrogen and phosphorus in the manures are of particular concern because applications of manure in excess of the plants' capacity to adsorb these elements pose a threat of their escape to waterways, and the subsequent development of anoxic and/or eutrophic conditions. Since a plant's P requirement is generally much less than that for N, regulatory authorities are devoting increasing attention to the rates of soluble P that can be applied to land.

Hydrotalcite has a high specificity for phosphate, and in this section, the possibility of stabilizing soluble P in feedlot wastes and using the treated material as slow-release fertilizer is canvassed.

Swine lagoon sludge

One of the more common practices for treating the effluent from swine feedlots is to pond the effluent in dams to allow settling of solids for aerobic/anaerobic digestion, and evaporation of some water. The excess supernatant liquid can be re-cycled with additional fresh water to the facility, or it can be used for fertigation of nearby areas. The jelly-like sludge that slowly accumulates in the bottom of the dam has to be removed at intervals, but is difficult to handle owing to its gelatinous nature and its objectionable odour. Also, because of its relatively high soluble P content, there are grave environmental problems associated with applying it too liberally on surrounding land.

Swine lagoon sludge (1 kg) having 89% water content was mixed with 100 g of chloride-HT in a blender for 30 minutes to allow the HT to adsorb soluble P. An amount of powdered bentonite (350 g in this case) was then blended in until a workable 'dough' was produced, and this was forced through a perforated plate to form 'noodles' that were dried at 80ºC. This product could be easily broken down into granules (Figure 5). A foul-smelling intractable sludge had been converted into an odourless, easily-handled material that had a water soluble phosphate content of 0.2 ppm P, whereas the equivalent dry weight amount of original sludge contained 47.5 ppm P in soluble form.

Figure 5. Conversion of swine lagoon sludge to granular fertilizer by addition of hydrotalcite and bentonite, with reduction in water soluble phosphate content from 47.5 mg P kg^{-1} to 0.2 mg P kg^{-1}

Chicken battery manure

The manure from a chicken battery usually contains far less water than effluent from other animal feedlots, and in fact can be retrieved in a relatively dry form from the battery floor under particular management conditions. The soluble phosphate content is generally high owing to the large amounts of phosphate fed to battery chickens.

To demonstrate the capacity of HT to stabilize this soluble phosphate, increasing amounts of chloride-HT, viz. 0, 0.2, 0.8, and 2.0 g were added to 4 g aliquots of dried chicken manure, and the resultant mixes shaken with 10 ml of distilled water for 18 hours. As evident in Figure 6, the HT was able to greatly reduce P concentration in the extracts, soluble P being converted to an exchangeable form that would be suitable as a slow-release fertilizer.

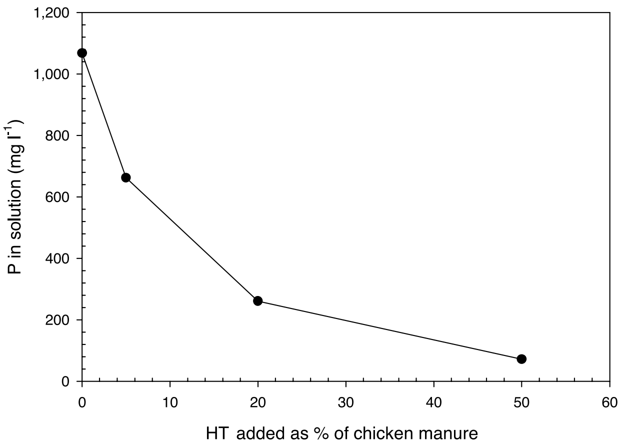

Figure 6. Reduction in water soluble phosphate content in chicken manure extract following incremental additions of hydrotalcite

Stabilization of phosphate in feedlot wastes is of particular benefit when the waste is to be applied to light-textured soils, where the benefits of addition of untreated material would be quickly lost via leaching. Also, production of dry granules allows economic transport over longer distances and easier land application. To achieve a more valuable product, however, other nutrient ingredients, either synthetic or natural, could be introduced at the blending stage to achieve higher and more balanced nutrient contents. In keeping with the overall theme of this paper, it would be preferable if all resultant nutrients were in slow-release form either as exchangeable or sparingly soluble species.

Conclusion

The use of technical grade hydrotalcite as a fertilizer platform, whether carefully designed to deliver specific amounts of anionic nutrients, or incorporated into nutrient-rich wastes to extend their effectiveness, offers great benefits with respect to economic efficiency and environmental protection, especially where agricultural enterprises are established on light-textured soil landscapes. In combination with a similar platform (e.g. bentonite) for delivering exchangeable cations, a complete system of leaching-retarded soil fertilization can be envisaged.

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Assessment of salinity hazard by Time Domain Reflectometry in flooded sandy paddy soils

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Keywords: Salinity, Time Domain Reflectometry, Sandy soils, Rice field, Northeast Thailand

Abstract

Since the 1960's salinity has become an increasing constraint for rainfed rice production in the sandy lowlands of Northeast Thailand. In salt-affected areas, during flooded periods, very sharp gradients in salinity occurred inside the soil solutions from the soil surface to 20 cm depth. On the soil surface, water from precipitation and runoff maintain the salt contents at values that are not detrimental to the growth of rice. Inside the matrix of the soil, salt enrichment was found to be related to the ascent of the saline water from the aquifer. During the flooded period, survival of rice depends on the behaviour of a thin (less than 10 cm) fresh water lens. Previous field survey methods for assessment of salinity hazard have relied predominantly on soil conductivity measurements by electromagnetic induction. Although this method has been found useful in this context, its low vertical resolution prevented the detection of sharp salinity gradients at depth that is required to enhance the assessment of saline flooded sandy soils. The objective of the present study was to test the use of TDR measurements to describe the spatial distribution of the fresh water lens and mean conductivity of the top layer soil (0-20 cm) during the flooded period. A survey of water measurements with vertical uncoated waveguides was performed in a salinity contrasted flooded area leading to the measurement of average salinity of the surface soil layer (0-20 cm) and an estimation of the depth of fresh water lens. Surveys with TDR measurement of average salinity of the plough layer and determination of the salinity contrasts inside the first centimeters of the flooded sandy soil was demonstrated to be an effective method of the assessment of salinity hazard.

Introduction

Time Domain Reflectometry (TDR) has been widely used with the objective of measuring the water contents of soils and the method has been found particularly efficient and reliable in sandy soils. The method is based on the measurement of the time delay between an electrical impulse and its reflection at the end of waveguides implanted in the soil. This delay is related to the permittivity of the soil and then to the water content (Topp *et al.*, 1980). The effect of salinity has been shown to be a limitation of this method, because of its influence on the signal. However, under particular conditions the salinity effect will allow simultaneous measurement of conductivity and permittivity (Castaglione and Shouse, 2003). Several authors have focused on the responsiveness of TDR probes when the wave guide is implanted across a multilayered media (Nadler *et al.*, 1991; Feng and Lin, 1999; Todoroff and Sun Luk, 2001; Lin, 2003a and 2003b, Oswald *et al.*, 2003). In the case of a soil with contrasting water contents, the apparent permittivity could be computed by summing the propagation times (Topp *et al.*, 1982). This method is known as "refractive index mixing". Recently, Schapp *et al.* (2003) demonstrated that "refractive averaging was mostly prevalent when a small number of thick layers are oriented perpendicular to the probe" and arithmetic averaging was found to be more appropriate for multiple small layers systems.

Ploughed layers of sandy soils in flooded rice represented a particular media that is homogenous with respect to saturation in water and uniformity of texture. In salt-affected areas during flooded periods, very

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sharp gradients in salt contents occurred within the soil solution from the soil surface to 20 cm depth (Quantin *et al.*, 2005; Hammecker *et al.*, 2005). At the soil surface, water from precipitation and runoff maintained the salt content at values that are not detrimental to the growth of rice. However, inside the soil matrix, salt enrichment was found to be related to the ascent of the saline water from an aquifer. During the flooded period, survival of the rice crop was dependent on the behaviour of a thin (less than 10 cm) fresh water lens. Because of the low vertical resolution and the presence of the surface water, electromagnetic induction measurement appeared to be inappropriate to delimitate the fresh water lens. A destructive sampling performed using soil coring under water was likely to modify the fresh water lens behaviour. The objective of the present study was to evaluate the use of TDR measurements to describe the spatial distribution of fresh water lens and mean conductivity of the top layer soil (0-20 cm) during the flooded period in a sandy salt-affected paddy soil under cultivation.

Methods

All experiments were undertaken at the same site, near Khon Kaen in Northeast Thailand (N 16º 22′ 24.3′′E 102º38′43.3′′). The experimental field was selected in order to be representative of rainfed cultivated paddy fields common to the region that are affected by salinity.

Sodium and chloride make up approximately 98% of the soluble components of the soil solution (Saejew *et al.*, 2004).

Salt patches were defined as areas covered with salt crusts in dry season and low yields of rice during the flooded period. Two pairs of soil profiles where studied inside and outside two salt patches. The main characteristics of soil samples in the dry season and ranges of electrical conductivity measurements of soil solution when flooded are presented in Table 1. The ploughed layer was a sandy loam with no significant increase in clay content with depth. In the dry state, bulk density values increased with depth, but development of the high soil strength are not evident during the flooded period. Inside the saline patch, (profiles L25-S and L14-S), the conductivity of soil solution in dry season at 10cm were above 10dSm $^{-1}$ which is known to be detrimental to rice production (Zeng and Shannon, 2000), in contrast with outside the saline patch (L25-NS and L14-NS) were the conductivity of solutions were suitable for rice production.

TDR measurements were performed using a Trase field system connected to a 20 cm uncoated waveguide with three rods. The time window of the trace acquisition was generally settled to 40 ns which is the maximum value for this type of device. In order to establish conductivity calibration, TDR

Table 1. Selected characteristics of four soil profiles used in the study

Profile	Depth	Saturated paste conductivity [a]	Conductivity of solutions[b] (Flooded period 2003)		Texture[e]			Bulk Density[f]
		(Dry season 2003)	Average	standard error	Sand	Silt	Clay	
	cm	dS m^{-1}	dS m^{-1}		g.kg^{-1}			
L14-S	Surf.[c]	–	1.31	0.16	–	–	–	–
	0-10	54.1	**24.71**	2.05	591	356	52	1.72
	10-20	15.6	**19.65**	0.90	623	305	72	1.84
L14-NS	Surf.[c]	–	1.19	0.14	–	–	–	–
	0-10	6.4	3.49	0.43	598	353	49	1.69
	10-20	2.7	**8.14**	0.36	622	324	54	1.81
L25-S	Surf.[c]	–	1.09	0.14	–	–	–	–
	0-10	27.1	**16.04**	1.40	627	311	63	1.61
	10-20	19.7	**27.03**	0.82	700	246	54	1.75
L25-NS	Surf.[c]	–	1.01	0.14	–	–	–	–
	0-10	12.9	6.41	0.34	679	259	62	1.55
	10-20	6.5	**10.68**	0.73	703	241	56	1.81

[a]: Electrical conductivity of saturated paste in dry season, [b]: Conductivity of surface water and soil solutions from plastic cups at different soil depths (0.1 m and 0.25 m) in bold values indicates conductivity levels that are not suitable for rice production; [c]: Surface water [e]: Pipette method, f: 100 cm^3 cylinder method (average of 5 replications) in dry season 2003.

measurements were performed in a set of solutions with increasing conductivity (Ec_s) that were previously measured with a laboratory conductimeter. Calibration of the salinity measurements were based on the method given by Nadler, (1991) with an adaptation due to the larger ranges of values. Equations developed by Dalton *et al.* (1984) were found to be imprecise for the high and low conductivity values observed in the field. The impedance of the transmission line (R_L) was computed from the characteristic impedance of the cable (Z_0 = 50 Ω) and the total reflection coefficient (ρ_t).

$$R_L = -Z_0(1+ \rho_t) / (\rho_t -1) \quad [1]$$

where ρ_t was computed from the initial voltage value of the traces (V_0) and the last value of the response outside the influence of the reflections (V_f).

$$\rho_t = (V_0-V_f) / V_0 \quad [2]$$

R_L is linked to the Ec_s of the solution by the geometric constant K_c defined as

$$K_c = Ec_{s*} R_L \quad [3]$$

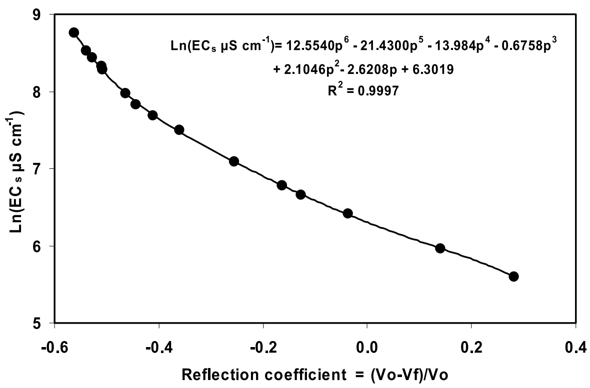

Figure 1. Measurements of the reflection coefficients of TDR traces with the waveguide immersed in solutions of in contrast to Nadler (1991), K_c was founded to be higher for low values of conductivity (Ec_s <1 dS m^{-1}) and lower for high values of Ec_s (Ec_s >3 dS m^{-1}). Between 1 and 3 dS m^{-1}, K_c was found comparable with the values indicated by the authors [K_c = 30-45]

This difficulty was overcome by adjusting a polynomial expression between the logarithm of Ec_s and the total reflection coefficients observed (Figure 1).

$$\ln(Ec_s) = 12.55\rho_t^6 - 21.43\rho_t^5 - 13.98\rho_t^4 - 0.68\rho_t^3 + 2.10\rho_t^2 - 2.62\rho_t + 6.30 \quad [4]$$

with Ec_s in µS cm^{-1} known electrical conductivity. Fitted polynomial expression used as calibration curve in this study (Eq. 4).

For survey purposes, measurements where spaced 2.5m apart. The waveguide, 0.2m long, was entirely driven into the soil between rice plants, in a vertical position under the water of the rice field. The conductivity for the entire length of the probe was converted introducing the reflection coefficient in equation 4. In the profiles described in Table 1, instead of a simple measurement of the entire depth of the probe, 5 measurements were performed at the same point. Firstly, measurement was performed inside the surface water, the waveguide was then driven vertically into the soil, with measurement record at depths 0.05, 0.1, 0.15, 0.2 m. Last measurement was then performed over the entire length of the probe inside the soil. When the depth of the surface water was less than 0.15m the first measurement at 0.05m was not possible. The reflection coefficients (ρ_{twater} ρ_{t5cm}, ρ_{t10cm}, ρ_{t15cm}, ρ_{t20cm}) were calculated from the traces and computed into conductivity values using the equation 4 (Ec_{sw}, Ec_{5cm}, Ec_{10cm}, Ec_{15cm}, Ec_{20cm}). A four layer approach was applied to compute the conductivity layer by layer assuming additive behaviour of conductivity parameter.

$$Ec_{[0-5cm]} = [0.20Ec_{5cm} - 0.15Ec_w] / 0.05 \quad [5]$$

$$Ec_{[5-10cm]} = [0.20Ec_{10cm} - 0.10Ec_w - 0.05Ec_{[0-5cm]}] / 0.05 \quad [6]$$

$$Ec_{[10-15cm]} = [0.20Ec_{15cm} - 0.05Ec_{[5-10cm]} - 0.05Ec_{[0-5cm]} - 0.05Ec_w] / 0.05 \quad [7]$$

$$Ec_{[15-20cm]} = [0.20Ec_{20cm} - 0.05Ec_{10-15cm} - 0.05Ec_{[5-10cm]} - 0.05Ec_{[0-5cm]}] / 0.05 \quad [8]$$

Results

TDR measurements of two soil layers are presented in Figure 2. Traces presented typical shapes for the depths of implantation 0.1, 0.15, 0.20 m. The transition from the cable to the rods caused a decrease of voltage. This decrease was associated with the thickness of the water layer. Sharp increases in voltage were observed because of the transition from a liquid to a saturated porous media. A time shift corresponding to the time necessary for the pulse to reach and return from contact with the water layer and the surface of the soil. Relative increases of voltage ranged from 3.8 to 12.8%. If only 0.05m of the waveguide were inserted in the soil, the influence of the transition between water and saturated soil was combined to the reflection that took place at the end of the probes and only a small effect on voltage was perceptible allthought a clear shift in time (almost 1 ns) was observed due to the

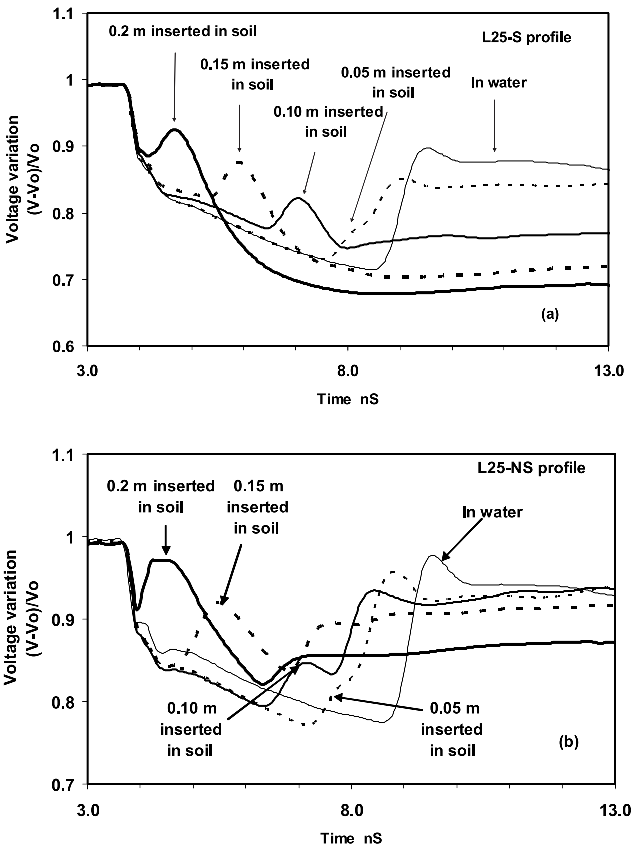

Figure 2. Traces of TDR measurements in L25-S (a) and L25-NS (b) profiles for different positions of the probe relative to the surface of the soil (totally inserted, 0.05, 0.1, 0.15 m out of the soil, inside the field water). Arrows are pointing to the effect of a resistive layer representative of the transition between water and soil

permitivity effect. In the 4 profiles, the speed of reflection impulse values were between 3.9 10^7 ms $^{-1}$ and 4.010 ^{7} m s^{-1}. The application of the equation of Topp *et al.* (1980) indicated volumetric water contents of 0.64 and 0.57 cm^3cm^{-3} in the 0-0.2 m layer.

Conductivity estimates using equations from 1 to 8 are presented in Figure 3. Near the surface conductivity values of the soil were found to be in a narrow range [0.5-0.8 dS m^{-1}]. Profiles L14-NS and L25-NS showed slight increases in conductivity with depth in the ploughed layer reaching 1 dS m^{-1}. On the contrary, both profiles located in the saline patch (L25S and L14S) showed a strong increase in conductivity with depth since the conductivity of the 0.05-0.1 m layer reached values higher than 1.7 dS m^{-1}.

Conductivity map of the first layer was constructed using equations 1, 2, 3 and 4 and values were interpolated and are presented in Figure 4. The result was compared to a classical salinity survey map using the same locations but developed 3 months latter.

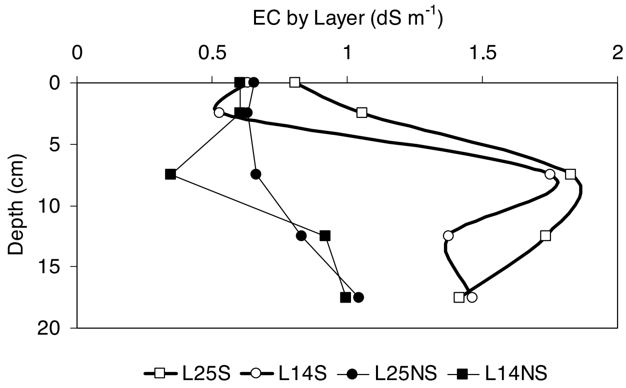

Figure 3. Estimation of the conductivity values by layer for four profiles

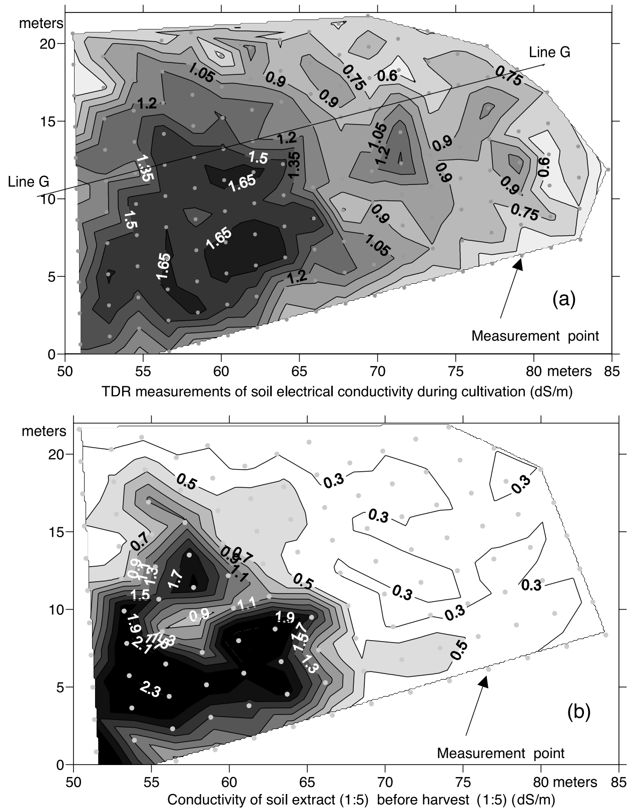

Figure 4. Survey of soil electrical conductivity measured by TDR (dS m^{-1}) (a) compared to conductivity of 1:5 soil extracts (dSm $^{-1}$) (b) using triangulation with linear interpolation. Line G traces

It is to note that the two maps are comparable in that they both highlight the presence of the saline patch.

The shape of the traces are likely to provide suplementary information of the existence of a relatively resistant layer at the soil surface. For example, points along the line G, presented in Figure 4, had their corresponding traces depicted in Figure 5.

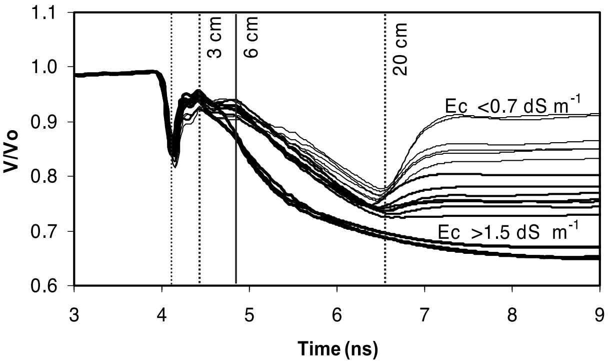

Figure 5. TDR traces along the line G, as indicated in Figure 4. (3 cm, 6 cm and 20 cm are indicating the distances along the waveguides assuming a constant permittivity, illustrating the main changes in reflection coefficient)

Two groups of traces were clairly identified.

a) Traces of soil profiles with conductivity values higher than 1.5 dS m^{-1} could be used to determine the water content. The sharp voltage peak of short duration indicated the thiness of the resistive layer at the surface, which was found to have a thickness less than 0.03 m.

b) Traces of soil profiles with conductivities between 0.7 and 1.5 dS m^{-1} could be used to determine soil water contents. A wider peak in voltage at the beginning of the curve indicated that, after the transition from water to soil, the conductivity stayed low in the first layer with a thickness that could be greater than 6 cm.

Conclusions

Estimation of bulk conductivity by TDR of the upper surface layer of a saline sandy soil could be performed during the flooding period. The method was quicker than 1:5 soil and water extracts and was far less destructive. Unlike determination of conductivity by electromagnetism induction, the measurements achieved using TDR traces were representative only of the ploughed layer.

Inside the saline patches, the water content measurement could not be performed because of the lack of reflection at the end of the waveguides. The four profiles studied by measurements at incremental depths indicated that inside the saline patch the fresh water lens thickness was less than 0.05m. The shape of the TDR traces suggested that similar circumstances existed inside the saline patch. In contrast outside the saline patch, the low conductivity layer was thicker and the trace had distinctive characteristics. The shape of the traces could be used to identify the distribution of salinity over a given depth.

Surveys with TDR measurement of average salinity of the ploughed layer and qualitative determinations of salinity inside the few first centimeters of the flooded sandy soil has been demonstrated to be an effective method for the assessment of salinity hazard. Further developpement will require a simulation model to test the sensibility of the relation between the traces and the evolution of salinity with depth.

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Effects of land use changes on soil chemical properties of sandy soils from tropical Hainan, China

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Keywords: soil chemical properties, sandy soils, Hainan, changed land use

Abstract

Data on soil quality properties including soil organic matter, nutrient contents, cation exchange capacity (CEC), base saturation (BS) and pH of sandy soils developed from granite and gneiss in tropical Hainan were collected from previous research and other published literature. An analysis was undertaken using the Tukeys t test and the boxplot method. The primary forest was taken as a reference to assess the extent of the change resulting from land use changes (from tropical primary forest to secondary forest, plantation forests, rubber tree plantation, orchards, dry land and rice field). The results show that the clearing of the primary forest led to a dramatic decrease in soil organic matter, total N, and cation exchange capacity. Other than a decrease in soil organic matter for the secondary forest, orchard and rice fields, and a decrease in soil total N for orchard and rice fields that fall within the same range as primary forest, the decreases in soil organic matter, total N and cation exchange capacity for all the other land use forms do not fall within the natural ranges defined by primary forest. However, land use patterns had no significant effect on total P and K, available P and K, pH and base saturation.

Introduction

Hainan Island is the southernmost part of China, rising from the vast South China Sea, with an area of approximately 34,000 km^2. It occupies 42% of the tropical area of China with an annual average temperature of 22º-26ºC and an annual rainfall of 1,500-2,000 mm. Highly weathered ferralsols and ferrisols are the predominant soils on the island. Land use patterns have dramatically changed in the last decades due to deforestation and exploitation for agricultural and forestry production. Natural tropical rainforests covered 35% of the island in the early 1950s. However, it has declined to 18% at present as a result of the “rubber plantation fever” in the 1950s, the “land reclamation fever” in the 1960s, the “crop breeding fever” in the 1970s and the “opening to the outside world fever” in the 1980s. Changes in land use patterns have disturbed natural nutrient cycles and the balance within native ecosystems that have significantly modified soil quality (Lin and Zhong, 2002; Ma et al., 2000; Zhao et al., 2005).

Soils derived from coarse texture materials including granite, sandstone, shallow-sea and coastal deposits, river alluvium, and purple sandstone, amount to more than 84% (granite accounts for 46.7%, sandstone for 20%, and sea deposit 12.1%, respectively) of the area of Hainan Island, resulting in these soil being predominantly of a sandy texture. Data on soil nutrient content, organic matter contents, cation exchange capacity (CEC), base saturation (BS) and pH of such sandy soils were analysed with the goal of understanding the consequences of the changes in land use patterns.

Material and method

Data collection

In Hainan Island, after the primary forest (PF) is cleared, the land becomes a secondary forest (SF), an artificial forest (AF), rubber tree plantations (RP), orchards (OC), dry land (DL) or rice fields (RF). Soil chemical properties in the topsoil of sandy soils developed from granite and gneiss from different land use patterns were collected from our databases and published materials, including the Second National Soil Survey, which was conducted in the early 80s at county, provincial and national level (Gong et al., 2004; Soil and Fertilizer Experimental Station, Agricultural Department, Hainan Province, 1993). The number of samples collected for each land use pattern and the main characteristics of each land use pattern are shown in Table 1.

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Table 1. Data sample collected and description

Land use pattern	Numbers of samples	Land use description
Primary forest (PF)	9	Tropical rainforest or evergreen broadleaf forest, undisturbed by human activity, with canopy coverage near 100%
Secondly forest (SF)	9	Auto-generated tropical rainforest or evergreen broadleaf forest, with canopy coverage 30~90%
Artificial forest (AF)	13	Mainly artificial short-rotation eucalypt forest with coverage 60~90%
Rubber tree plantation (RP)	7	Rubber tree plantations with canopy coverage 50~90%
Orchard (OC)	8	Grown with tropical fruit (litchi, mango, longan, banana and other fruits)
Dry land (DL)	8	Different vegetables, sweet potatoes, sugarcane and other vegetable crops
Rice field (RF)	9	Rice cultivation 2~3 times annually

Data analysis

The initial stage of the analysis was to compare the soil chemical properties using the Tukey Test. The results of the statistical comparisons were further examined using boxplots for the range of values from the individual samples. These plots are used in a manner analogous to the control charts discussed by Larson and Pierce (1994); basically the range of values for the primary forest provides a measure of the undisturbed or natural range of variability for the local soil quality indicators. The range of values of land use patterns can then be compared to this natural range to assess the possible severity of the observed differences (Pennock and Kessel, 1996).

Results and discussion

The first stage of analysis was to compare the soil chemical properties under the different land use patterns in the studied area. The second stage was to compare the soil quality.

Soil organic matter and total N

Soil organic matter and total N decreased after primary forest was cleared for other land uses. There were significant differences in soil organic matter and

Table 2. Comparison of soil organic matter and total N contents of different land use patterns

Soil organic matter				Soil total N			
	Mean (g/kg)	5% sig. lev.	1% sig. lev.		Mean (g/kg)	5% sig. lev.	1% sig. lev.
PF	39.84	a	A	PF	3.16	a	A
OC	16.59	b	B	OC	1.64	b	B
SF	15.53	b	B	RF	1.27	bc	BC
RF	17.78	b	B	SF	1.10	bc	BC
DL	9.49	b	B	AF	0.77	c	BC
AF	9.20	b	B	RP	0.72	c	BC
RP	8.54	b	B	DL	0.55	c	C

total N contents between the primary forest and the other land use types, SF, AF, RP, OC, DL and RF (Table 2).

The crude statistical assessment of changes in soil organic matter and total N contents for land use patterns can be placed in a larger context by examining the observed changes relative to the range of values of the primary forest. This was done by comparing the boxplots for different artificial land use types with those for primary forest. For soil organic matter contents, the median levels for the land use patterns SF, OR and RF are clearly falling into the range defined by the highest and lowest median levels of the primary forest, hence these land use type levels are clearly within the natural or ecological range defined by the local primary forest (Figure 1). However the other three land use types, AF, RP DL are below the minimum of primary forest, indicating that they are outside of the range of primary forest. When total soil N was assessed by using the boxplot method, it can be seen in Figure 2 that OR and RF are well inside of the range defined by primary forest, while SF, AF, RP and DL are below the lowered limit of the range.

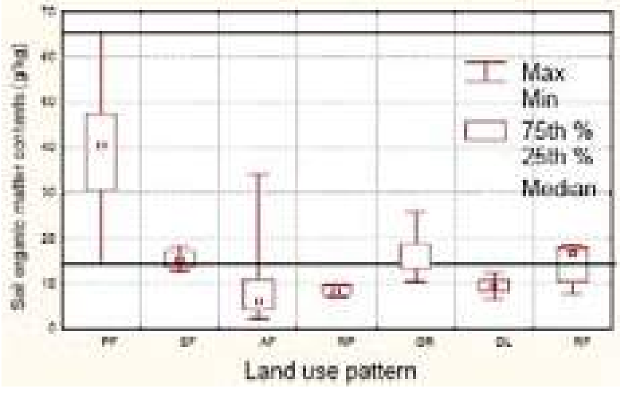

Figure 1. Boxplots of soil organic matter contents of different land use pattern

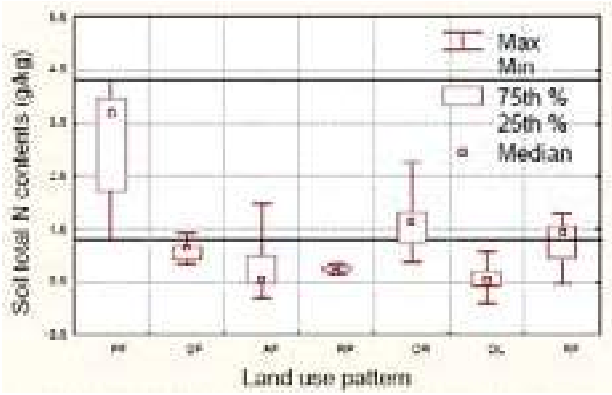

Figure 2. Boxplots of soil total N contents of different land use patterns

Soil P and K

Results of statistical analysis shows that there are no remarkable changes in total soil P and K content after primary forests were changed to SF, AF, RP, OC, DL and RF (Table 3). When they were compared with the defined range of primary forest, the median values of them are not outside its maximum and minimum limits (Figure 3 and Figure 4).

Table 3. Comparison of soil total P and K contents of different land use patterns

	Total soil P				Total soil K		
	Mean (g/kg)	5% sig. lev.	1% sig. lev.		Mean (g/kg)	5% sig. lev.	1% sig. lev.
OC	1.04	a	A	RP	30.53	a	A
PF	0.81	ab	AB	SF	29.16	a	A
RF	0.65	b	B	OC	27.49	a	A
DL	0.57	b	B	PF	26.57	a	A
AF	0.50	b	B	RF	25.81	a	A
SF	0.49	b	B	AF	25.60	a	A
RP	0.46	b	B	DL	24.79	a	A

Tukey t tests indicated no significant difference in available soil P contents between SF, AF, RP, OC and PF, but show an increase for RF and DL (p <1%) (Table 4). However, the boxplots method in Figure 5 indicates no median values of available P for SF, AF, RP, OC, DL and RF exceed the defined range for PF (Table 5). For available soil K, no significant differences appeared when all other land use patterns were compared with PF (Table 4) and the medians of them are also limited within the defined limits by PF (Figure 6).

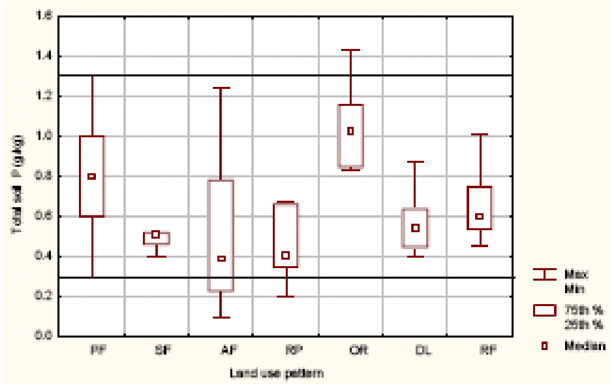

Figure 3. Boxplots of total soil P for different land use patterns

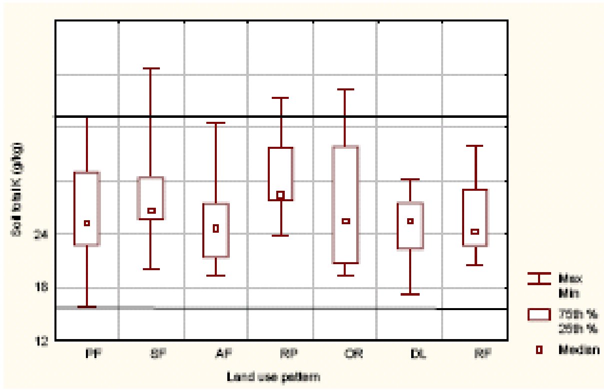

Figure 4. Boxplots of total soil K for different land use patterns

Table 4. Comparison of soil available P and K contents of different land use patterns

	Available soil P				Available soil K		
	Mean (g/kg)	5% sig. lev.	1% sig. lev.		Mean (g/kg)	5% sig. lev.	1% sig. lev.
DL	16.21	a	A	OR	111.44	a	A
RF	14.18	ab	AB	PF	91.97	a	A
OC	8.87	abc	ABC	RF	78.64	a	A
PF	6.43	bc	ABC	SF	77.17	a	A
AF	4.52	c	BC	DL	71.68	a	A
SF	2.84	c	C	AF	70.00	a	A
RP	2.37	c	C	RF	62.02	a	A

Table 5. Comparison of soil CEC of different land use patterns (cmol$_c$/kg)

	Available soil P		
	Mean (g/kg)	5% sig. lev.	1% sig. lev.
PF	15.19	a	A
SF	10.22	b	B
OR	6.57	c	BC
RF	6.10	c	BC
RP	5.26	c	C
AF	5.14	c	C
DL	4.80	c	C

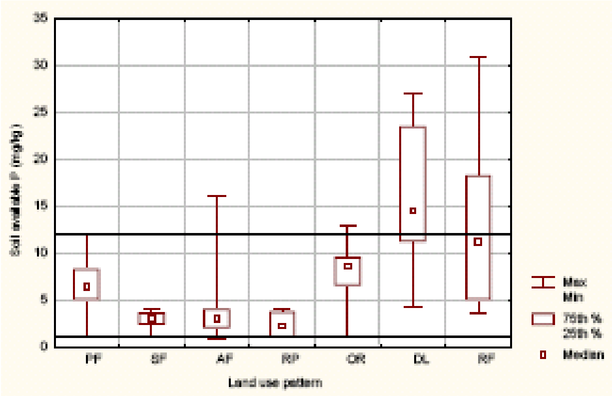

Figure 5. Boxplots of available soil P contents of different land use patterns

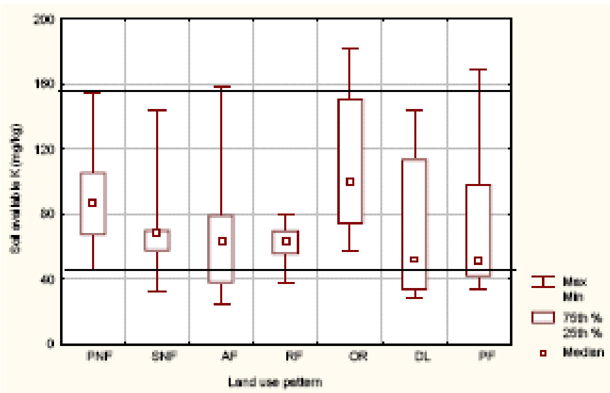

Figure 6. Boxplots of available soil K contents of different land use patterns

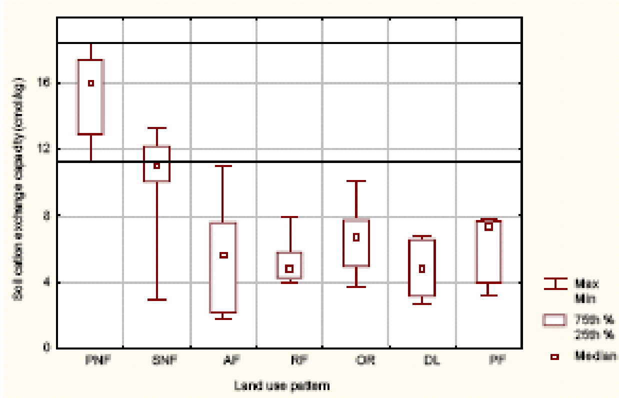

Figure 7. Boxplots of soil cation exchange capacities of different land use patterns

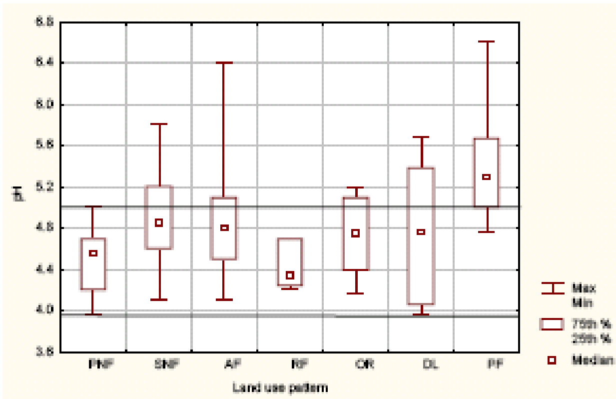

Figure 8. Boxplots of soil pH of different land use patterns

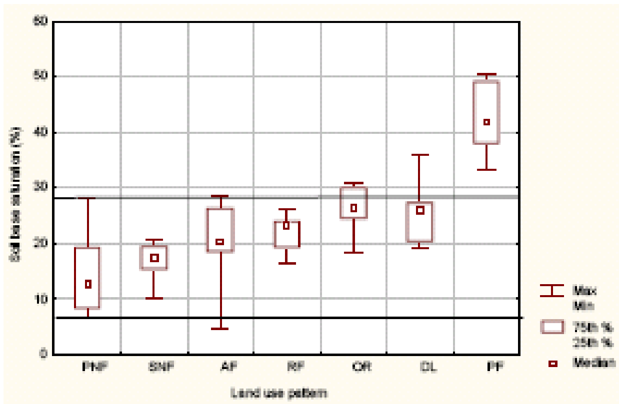

Figure 9. Boxplots of soil base saturations of different land use patterns

Soil chemical quality properties

Soil cation exchange capacities for SF, AF, RP, OC, DL and RF are significantly lower (p <1%) than that for PF (Table 5). The former are all below the minimum range defined by PF (Figure 7). There were no obvious differences both in soil pH and base saturation between SF, AF, RP, OC, DL and PF, except for RF, which is significantly higher (p <1%) than PF in them (Table 6). Figure 8 and 9 also show that the medians for pH and base saturation for SF, AF, RP, OC, DL are plotted within the maximum and minimum range for PF, while that for RF are above the maximum limits of the ranges.

Table 6. Comparison of soil pH and BS of land use patterns

	Soil pH				Soil Bs (%)		
	Mean (g/kg)	5% sig. lev.	1% sig. lev.		Mean (g/kg)	5% sig. lev.	1% sig. lev.
RF	5.43	a	A	RF	42.39	a	A
AF	4.95	ab	AB	OR	30.25	ab	AB
SF	4.92	ab	AB	AF	26.35	bc	AB
DL	4.76	ab	AB	DL	26.36	bc	AB
OR	4.73	ab	AB	RP	21.93	bc	B
PF	4.49	b	AB	SF	16.92	bc	B
RP	4.41	b	B	PF	14.43	c	B

Conclusions

Change in land use pattern from primary forest to others leads to remarkable decrease (p <1%) in soil organic matter, total N, and cation exchange capacity in sandy soils developed from granite in tropical Hainan. Except for the decrease in soil organic matter for the secondly forest, orchard and rice field, and the decrease in soil total N for orchard and rice field that do not go out of the defined range for primary forest, the decreases in soil organic matter, total N and cation exchange capacity for all the other land use forms bring them out of their natural range defined by primary forest.

Succession in land use pattern from primary forest to human influenced land use types does not lead soil total P and K, available P and K, pH and base saturation being outside the defined range for primary forest, except for dry land that its soil available P is above the upper limit of the range and for rice field that its pH and base saturation are higher than the maximum for primary forest.

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Improvement of the saline sandy soil in Northeast Thailand using polyvinyl alcohol (PVA)

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Keywords: aggregate, desalinization, Northeast Thailand, polyvinyl alcohol (PVA), salt-affected soil

Abstract

Improvement of the salt-affected infertile sandy soil has been regarded as a key issue in the sustainable development of agriculture in Northeast Thailand. An important attribute that needs to be addressed using new ameliorative technology is aggregate stability using polyvinyl alcohol (PVA) for suppressing salt-accumulation by capillary rise from saline groundwater in the dry season and for the enhancing desalinization with rain water in the rainy season. Laboratory experiments revealed: (1) Among PVAs examined, GH-20 (Nippon Gohsei Ind. Co., molecular weight 100,000) was most effective in aggregating soil particles: GH-20 at an application rate as low as 0.02% (w/w) was enough to generate stable aggregates. (2) Aggregated soils suppressed capillary rise of saline water and were stable against disruption by osmotic pressure during desalinization. A preliminary field experiment conducted over 1.5 year on a strongly salt-affected soil with an elevated water table suggested: (1) Combination of PVA with cow dung was necessary for the establishment and growth of plants because the plants needed nutrients supplied from cow dung. (2) Cow dung enhanced capillary rise of saline water in the dry season. (3) PVA weakened the undesirable effect of cow dung on the capillary rise and somewhat suppressed microbial decomposition of cow dung. (4) The undesirable effect of cow dung was weakened in the second year. Field experiments conducted for 3 years on the highly salt-affected area confirmed all the results of the preliminary field experiments and gave the following further results: (1) The desirable effects of PVA remained for at least 3 years. (2) PVA + cow dung should be applied at the beginning of the rainy season.

Introduction

In Thailand, the Northeastern region is less successful in terms of economy. This is because the economy of this region is supported by agriculture which has been kept undeveloped by both hostile climate and very poor soils. Climate of this region is tropical monsoon with clear alternation of rainy and dry seasons. Surrounding mountain ranges are obstacles of the rain-laden cloud. Rainfall in this region is low and erratic, accordingly. Arable soils are sandy, infertile and acid. A rather large part of the soils are salt-affected, leading to bare lands as shown in Figure 1.

Figure 1. Salt-affected soil in Northeast Thailand

Improvement of those salt-affected soils has been regarded as a key issue for the development of agriculture and economy of this region. Accordingly, Thai scientists alone or in cooperation with foreign scientists have worked for many years in surveying and characterizing the salt-affected soils. This has resulted in several ameliorative technologies (McGowan International Pty. Ltd. 1983, Arunin 1984, Takai et al. 1987, Puengpan 1992, Subhasaram 1994). However, appropriate ameliorative technologies are still lacking for the most degraded sites characterized by 1) an elevated groundwater table, during the rainy season (where the desalinization with percolating ran water is thus suppressed) and 2) accumulation of salt by capillary rise from saline groundwater in the dry season.

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The current study aims at establishing a new technology for ameliorating the salt-affected infertile sandy soil with elevated groundwater tables by conducting both laboratory experiments and field experiments. The cardinal point of the new technology is to aggregate the soil with polyvinyl alcohol (PVA) for promoting the leaching out the salt from the soil with rainwater and for suppressing the salt-accumulation by capillary rise. PVA is a non-ionic water-soluble synthetic polymer with high ability of aggregating clay soils irrespective of ambient salt concentrations (Carr and Greenland 1975): We expected PVA could aggregate even the salt-affected sandy soil in Northeast Thailand.

Materials and methods

1. Laboratory experiment

At first, three kinds of PVA were compared in their ability to aggregate two kinds of sandy soils collected in Northeast Thailand for selecting a suitable PVA and for clarifying the effective way of its application. Then, the selected PVA was examined by several methods in its effects on capillary rise of saline water and on hydraulic conductivity through the column of the aggregate.

1.1 Ability of PVA to form stable aggregate

Soil: Two sandy soil samples were collected from the plow layers of 2 upland fields identified as Korat series (Kt) (fine-loamy, siliseous, isohyperthermic Oxic Paleustults) and Yasothon series (Yt) (fine-loamy, siliseous, isohyperthermic Oxic Paleustults) which were end members of a common catena in the undulating region in Northeast Thailand. They were air-dried and passed through a sieve with 2 mm mesh.

PVA: Three kinds of PVA of different molecular weight (MW) were used. They were a chemical reagent (MW: 88,000, Wako Pure Chemical Industries Ltd. Japan) and 2 industrial products (Gohsenol, Nippon Gohsei Industry Co. Ltd.), GH-20 (MW: 100,000) and GL-30 (MW: 15,000).

Preparation of aggregate: Ten grams of each soil sample was added with 2 ml of the aqueous solution of each PVA of varying concentrations (0, 0.1, 0.25, 0.5, 1.0%). They were manually handled to make aggregates of about 2-5 mm diameter. A part of the aggregates were kept moist, the remaining part being air-dried.

Stability of aggregate: These aggregates were measured for stability against both slaking and shaking in water. A few air-dried aggregates were placed in a Petri dish and were added with a few drops of distilled water. Stability of the aggregates against slaking was judged by the immediate degree of disintegration estimated by naked eye. Ten grams of each aggregated soil were place in a 50 ml beaker and added with 50 ml of distilled water. The beaker was shaken by a rotary shaker for 30 min. and kept at a standstill on a laboratory table for 2 hrs. The amount of the dispersed clay was estimated by measuring turbidity of the solution pipetted from the supernatant in the beaker. The amount of the stable aggregates against the shaking was estimated by measuring the weight of the aggregates of 3 fractions (>500, 500-250, 250-1,501 μm) separated by wet sieving.

1.2 Properties of PVA-amended aggregate formed from the salt-affected soil

Soil: Two soil samples were collected from the surface sandy cover (sand 87.8%, silt 10.6%, clay 1.6%) and the underlying dark colored somewhat clayey semi-impermeable layer (sand 58.3%, silt 34.2%, clay 7.5%) at a salt-affected area identified as Satuk series saline variant, a member of the above mentioned catena (Puengpan 1992). Both soil samples were air-dried and passed through the sieve.

PVA: GH-20 was used.

Preparation of aggregate column: Aggregates of each soil sample were prepared by the above-mentioned way. Each of the aggregates was packed in a respective stainless core (height: 5 cm, diameter: 5 cm, capacity: 100 ml) to prepare a column of the aggregate.

Measurement: The aggregate-columns were saturated with 1 N NaCl solution by capillary rise. The rate of the capillary rise was recorded. Then the aggregate-columns were percolated at first with the saline water and then with fresh water for measuring 2 kinds of hydraulic conductivity.

2. Preliminary field experiment

Before doing a full-scale field experiment, a small-scale field experiment was conducted.

Experimental site: The site was located at a place of an elevated groundwater table in a depressed part of a salt-affected area. The site was divided into 2 sections for 2 Series of experiment at slightly different groundwater table: the groundwater table at

Series 1 was about a few 10 cm lower than that for Series 2.

Plot: Eight beds (50 cm high, 1 × 6 m) were prepared for each Series with 4 different plots (T1, T2, T3 and T4) for avoiding flooding. T1 was the control plot. T2 was the plot applied with cow dung (1%) and PVA (0.2%). T3 was the plot applied with cow dung (1%). T4 was the plot applied with cow dung (1%) and PVA (0.05%). All the plots were mulched with rice straw and halved into 2 subplots. One subplot was cultivated with *Panicum repens*, a perennial grass, and the other with *Sesbania rostrata*, an annual legume.

Monitoring: The experiment started at the end of a rainy season and terminated at the middle of the next dry season. During this period, the surface soil (5 cm), the groundwater tables and the plants were monitored.

3. Field experiment

To confirm and to supplement the results of the preliminary field experiment, a full-scale field experiment with the 4 plots, which were the same as those in the preliminary field experiment, was conducted near the site of the preliminary field experiment. The field experiment differed from the preliminary field experiment in: (1) Every 4 plot (1 × 1.5 m) was replicated 4 times. (2) Three kinds of vegetables (baby corn, *Ipomoea aquatica* var. *reptans*, and tomato) were successively cultivated at every plot in every rainy season for 3 years. (3) Low beds (15 cm high) instead of the tall beds were prepared so that the beds were temporarily flooded every year. (4) The experiment started at the beginning of a rainy season.

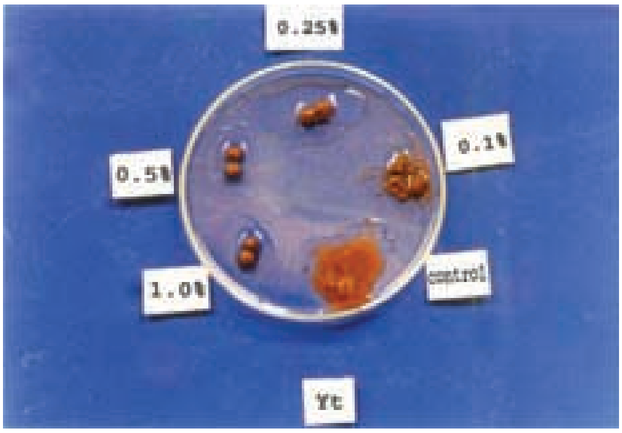

Figure 2. Slaking decrease with increasing amount of PVA

Results and discussion

1.1 Ability of PVA to form stable aggregate

The stability tests demonstrated the following facts: (1) All the PVA formed stable aggregates from the 2 sandy soil samples. (2) In stabilizing the aggregates, the chemical reagent was similar to GH-20 and GH-20 was more effective than GL-30. (3) The air-dried aggregate was more stable than the moist aggregate. (4) GH-20 at an application rate as low as 0.02% (w/w) was enough to generate fully stable aggregate (Figure 2 and Tables 1, 2).

Table 1. Dispersion of clay particles (Turbidity, % Absorbance)

Treatments		Yt			Kt		
		Chemical	GH-20	GL-03	Chemical	GH-20	GL-03
	Control	0.120	0.122	0.136	0.262	0.096	0.091
PVA	0.1%	0.013	0.009	0.106	0.041	0.020	0.136
	0.25%	0.007	0.001	0.039	0.026	0.004	0.019
	0.5%	0.010	0.005	0.031	0.020	0.004	0.020
	1.0%	0.011	0.001	0.064	0.019	0.003	0.020

Table 2. Size distribution of aggregates (Yt soil)

Treatments		Chemical			GH-20			GL-03		
		>500	500-250	250-150	>500	500-250	250-150	>500	500-250	250-150
		<----------µm---------->			<----------µm---------->			<----------µm---------->		
	Control	0.09	1.05	6.73	0.14	1.10	5.30	0.13	1.32	5.84
PVA	0.1%	3.81	1.87	3.32	4.66	1.80	2.67	0.15	1.86	5.67
	0.25%	8.40	0.32	0.87	8.11	0.44	1.25	0.21	2.60	5.24
	0.5%	8.64	0.18	0.60	8.24	0.33	0.79	0.42	3.80	4.35
	1.0%	9.51	0.11	0.22	9.69	0.02	0.08	0.63	3.93	3.74

These results implies, (1) almost all the sandy soils in Northeast Thailand can be fully aggregated with PVA, (2) the stability was unaffected by purity of PVA, (3) high molecular weight of PVA was desirable for stabilizing the aggregate and (4) air-drying the aggregates enhances the effect of PVA. Accordingly, GH-20 was selected for further study.

1.2. Properties of PVA-amended aggregate formed from the salt-affected soil

These experiments revealed the following facts (1) PVA remarkably increased stability of the aggregates of both soil samples. (2) Capillary rise of the saline water through the aggregate-columns of 2 soil samples was evidently suppressed with PVA. (3) Hydraulic conductivity through the aggregate-columns of 2 soil samples for both the saline and the fresh waters became high by amending with PVA (4) Without PVA, hydraulic conductivity of the dark colored somewhat clayey soil was higher than that of the sandy soil in the saline solution and the reverse was true in the fresh water, most probably due to dispersion of Na-clay in the fresh water (Tables 3, 4).

Table 3. Rate of capillary rise of NaCl solution

	Rate of capillary rise (mm/min.)*
Sandy aggregate (Water)	0.70
Sandy aggregate (PVA)	0.13
Dark aggregate (Water)	0.14
Dark aggregate (PVA)	0.02

* period of wetting of surface soil column divided by height of soil column in NaCl solution.

Table 4. Percolation rate of NaCl solution and of distilled water

	1 N NaCl Ksat. (cm/sec.)	Distilled H_2O Ksat. (cm/sec.)
Sandy aggregate (Water)	2.78×10^{-3}	3.92×10^{-3}
Sandy aggregate (PVA)	0.036	0.036
Dark aggregate (Water)	Very quick*	9.40×10^{-4}
Dark aggregate (PVA)	Very quick*	Very quick*

* too quick to be measured.

These results confirm PVA is promising for desalinizing the salt-affected sandy soil in Northeast Thailand by suppressing capillary rise of saline water and by promoting leaching of the salt contained in the soil without disruption of the aggregates against the osmotic pressure during the desalinization.

2. Preliminary field experiment

The following facts were recognized:

1) Moisture content in the soil decreased in the dry season, slightly increased in the initial period of rainy season, decreased in the dry spell, then increased rapidly in the late rainy season and decreased again in the next dry season. The groundwater tables of both Series fluctuated in a similar way.

2) In the first dry season, EC increased with decreasing moisture content till at a certain point then decreased in spite of that moisture content still tended to decrease. The increase in EC during the dry season was enhanced with cow dung. The undesirable effect of cow dung was somewhat suppressed with PVA. In the next dry season, the undesirable effect of cow dung was weakened and the effect of PVA was strengthened. These results advance the following suggestions: (1) Small and sporadic rain in the late dry season is responsible for desalinization without increasing moisture content. (2) Plant debris included in the cow dung provides long straight capillaries for capillary rise of saline water from below. (3) PVA generates aggregates containing the plant debris, resulting in weakening of the promoting effect of cow dung on salt-accumulation in the dry season. (4) The effect of cow dung diminishes when the plant debris is comminuted by microbial decomposition in the rainy season.

3) EC of any plot of Series 1 was lower than that of the corresponding plot of Series 2. This should be caused by the difference in the groundwater tables between 2 Series.

4) Low bulk density was accompanied by low soil hardness as expected. They were decreased in the following order: T1 > T3 ≈ T4 > T2. Both low density of cow dung and the ability of PVA to aggregate soil particles may contribute to make the soil more porous and friable. In addition, soil hardness as well as bulk density changed with time. Their changes were associated with changes in moisture content and soil management.

5) Among 4 plots of Series 1 with low EC, growth of 2 plants deceased in the following order: T4 > T3 > T2 > T1. This result suggests: (1) The supply of nutrients from the cow dung, which is decomposed by microorganisms, is a more

limiting factor of growth of both plants than salinity and (2) the microbial decomposition of the cow dung is somewhat suppressed with PVA probably because particles of the cow dung is coated with an uneatable film of PVA.

6) Growth of *S. rostrata* in any plot of Series 2 was markedly worse than that corresponding plot of Series 1. This should be caused by higher EC in Series 2 than in Series 1 and low tolerance of this plant against salinity. In addition, the order of growth of the plant among 4 plots of Series 2 was different from that of Series 1. This suggests both EC and the supply of mineral nutrients from the cow dung control the plant growth in Series 2.

7) Growth of *P. repens* in Series 2 was not much different from that in Series 1. This may be a reflection of fairly high tolerance of the plant against salinity. However, order of growth of the plant among 4 plots was somewhat different from that in Series 1. Probably, some unknown factors other than EC and the nutrient supply contribute to control growth of the plant under salt stress (Figures 3-6 and Table 5).

3. *Field experiment*

The field experiment confirmed most of the results of the preliminary field experiment. In addition, the following further information was obtained:

1) The undesirable effect of cow dung to increase EC in the first dry season was less remarkable than that in the preliminary field experiment. This must be resulted from that the capillary of the plant debris included in the cow dung was somewhat destroyed by microbial decomposition of the cow dung during the first rainy season.

2) Effect of PVA to decrease EC became evident with time. PVA may remain rather intact even after 3 years.

3) Order of 4 plots in terms of the plant growth changed year by year: T4 > T3 ≈ T2 > T1 (1st year), T2 ≥ T4 ≥ T3 > T1 (2nd year), T2 >> T4 ≈ T3 ≈ T1 (3rd year). This may be caused by gradual loss of the suppressing effect of PVA on the microbial decomposition of cow dung. In other words, this effect appears to be almost completely lost before the 3rd year for T4. On the contrary, this effect still remains even in the 3rd year for T2 (Tables 6-8).

Figure 7 illustrates assumed roles of PVA in the salt-affected infertile sandy soil in Northeast Thailand: to promote the desalinization by generating stable aggregates and to timely supply nutrients from cow dung to the plants by suppressing too rapid microbial decomposition of the cow dung.

Conclusion

On the basis of the present study, application of PVA mixed with cow dung in the beginning of the rainy season is recommended for ameliorating the salt-affected infertile sandy soil at the place with high groundwater table. However, further studies are necessary for extending this recommendation to the farmers in Northeast Thailand. This is because the rate and time of the application of PVA and cow dung should vary according to nature of both the soil and the plant.

In addition, the present study revealed the following new findings: (1) Decrease in EC in the middle to late dry season. (2) The enhancing effect of cow dung on accumulation of salt in the dry season. (3) The suppressing effect of PVA on microbial

Table 5. Fresh and dry weights (g) of *S. rostrata* and *P. repens*

Plot no.	Treatments	*S. rostrata*		*P. repens* 1st Harvesting		*P. repens* 2nd Harvesting	
		Fresh wt.	Dry wt.	Fresh wt.	Dry wt.	Fresh wt.	Dry wt.
P1	Control	980	214.2	939.4	382.9	2,100	597.14
	0.2% PVA + 1% CD	2,150	480.1	1,421.5	523.9	2,360	862.10
	1% Cow dung	3,250	774.3	1,710.2	651.7	2,840	967.69
	0.05% PVA + 1% CD	3,550	839.4	1,500.7	590.4	2,200	843.88
P2	Control	230	40.4	785.2	311.8	1,970	640.02
	0.2% PVA + 1% CD	1,050	255.0	600.2	265.7	640	203.89
	1% Cow dung	330	63.5	299.5	131.3	1,120	371.69
	0.05% PVA + 1% CD	600	134.1	683.5	282.1	2,800	897.37

decomposition of cow dung. These findings should be thoroughly examined to understand their underlying principles. This effort may contribute to the integration of 3 research fields of soil science (soil physics, soil chemistry and soil microbiology).

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Impact of agricultural practices on the biogeochemical functioning of sandy salt-affected paddy soils in Northeastern Thailand

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Keywords: Soil salinity, land management, organic matter, paddy systems

Abstract

Most lowlands in Northeast Thailand are cultivated to rainfed rice. The main constraint for rice production is drought associated with sandy and acid soils that are also often saline. Efficient water management and organic matter (OM) inputs are low-cost solutions used by farmers to limit salinity effects and to enhance the physico-chemical properties of paddy soils where yield is very low. Field monitoring was conducted during the 2003 rainy season to explore the interactions between land management (i.e. water management and OM incorporation), salinity and soil function. Several parameters (Eh, pH, EC) were continuously measured inside and outside saline patches in two adjacent contrasting plots, differing in management (high management i.e. water management and OM addition vs low management no OM input limited water management). Soil solution was regularly sampled at three depths and analysed for Mn and Fe.

High reducing conditions appeared after flooding in all sites, but were limited inside the saline patch without OM addition. Anoxic processes lead to the reduction of Fe- and Mn-oxides, especially when OM was added. Oxide reduction led to the consumption of H+ and the greater the degree of Fe reduction, the larger the increase in pH. Where OM was not incorporated, high salinity prevented the establishment of the reduction processes and pH stabilised around 4. Even under high reduction conditions, Fe concentrations in the soil solution were below commonly observed toxic values. Moreover, amended plots had better rice production yield.

Water management and availability of organic carbon, which maintain saturation and control the extent of the reduction, are processes of major importance for pH regulation and rice production. Moreover, these practices were able to counteract the toxic effects that occurred in salt-affected paddy fields.

Introduction

Most lowlands in Northeastern Thailand are cultivated with rice, but among them, 8.5% have been classified as severely salt-affected (Arunin, 1984) due to the rising of the water table since land clearing. Water rises to the surface by capillary action and evaporates, so salts accumulate at the soil surface and a saline crust can be observed during the dry season. Therefore, salinity drastically affects soil fertility and rice productivity, already affected by the acidity of these sandy soils. Then, farmers focus their efforts on cultivating less affected soils, so the result is that the salt-affected soils become more damaged. However, in Isaan, efficient water management and organic matter addition or green manuring are low cost solutions used by farmers to supply nutrients to these poorly fertile soils.

In paddy soils, incorporating rice straw or green manure can be an useful way of adding organic matter and thus increasing carbon storage and providing nitrogen, phosphorus, potassium and other nutrients to soils (Vityakon et al., 2000). However, a poorly controlled incorporation of OM can be responsible of the appearance of strong reducing conditions that may have adverse effects on rice cropping, as for instance the production of sulphide and the subsequent formation of black roots (Gao et al., 2004) or organic

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acid toxicity (Saenjan, 1999). The addition of organic matter or the incorporation of crop residues increases the organic matter availability and thus the anaerobic bacterial activity. This can lead to a high transfer of electrons from organic matter to oxides, especially amorphous or poorly crystallised ones, leading to the reduction of both manganese and iron, and also to the establishment of strongly reducing conditions. Solubilisation of these elements is a function redox conditions driven by bacterial activity, organic matter availability, soil moisture and thus agricultural management. Moreover, reduction processes control the pH and the ionic composition of the soil solution, both acting on soil fertility (Ponnamperuma, 1976). Thus, Mn and Fe are key indicators for understanding the reduction processes and thus the biogeochemical functioning of rice paddy soils.

In order to quantify the impact of realistic low cost agricultural practices on the biogeochemical functioning of paddy fields in N.E. Thailand, we have studied the interactions between agricultural management (i.e. organic matter addition, water level control), salinity and redox processes, during the 2003 rainy season. Field measurements included pH, Eh, EC and major elements in the soil solution, with a particular focus on Fe dynamics.

Materials and methods

The field investigation was carried out in 2003, from July to November. Two rainfed lowland paddy fields of a rice cropped watershed in Isaan, close to Phra Yun in the Khon Kaen district (E 102º38′- N 16º22′) were selected, as representative of two types of farming practices: an intensively managed plot (L25 plot, 599 m^2) and a poorly managed one (L14, 718 m^2). The first plot was characterized by organic matter addition (buffalo, poultry and pig manure mixed with sawdust), of around 170 kg $plot^{-1}$ $year^{-1}$, corresponding to 2.4 t ha^{-1} $year^{-1}$ wet weight, and efficient water control with a high bund system that allows an almost continuous flooding. The second one did not receive any particular treatment, i.e. neither organic matter addition nor water management.

Saline patches were observed during the dry season inside each plot, and monitoring points were selected to reach the maximum contrast of salinity over a short distance (i.e. 8 meters). In each plot, one monitoring point was located inside an area were the production of rice was affected by high salt contents (soil conductivityobtained by EM38 higher than 250 $mS.m^{-1}$, labelled S for saline) while the other monitoring point was located in an area where rice yield was non affected by salinity (soil conductivity around 150 $mS.m^{-1}$, labelled NS for non saline).

Soils were sandy loam from the soil series Kula Ronghai (Natraqualf), which predominates in salt affected zones of Northeast Thailand lowlands. Main characteristics are summarised in Table 1.

The composition of flooding water, groundwater and soil solution was monitored during the entire rainy season. Flooding water was sampled close to each monitoring point and groundwater in piezometers. The free soil solution was sampled every week or every two days, inside and outside the saline patches, at 10, 25 and 45 cm depth in polypropylene pierced boxes

Table 1. Bulk soil analysis

		Salinity[a]		Organic matter		Exchangeable Cations[d]				Texture[e]			Bulk	Elemental analysis[g]			
Profile	Depth	Ec s.p.	pH	OC[b]	N[c]	Na^+	K^+	Ca^{2+}	Mg^{2+}	Sand	Silt	Clay	density[f]	Al	Mn	Fe	Fe_o[h]
	cm	$dS.m^{-1}$	(KCl)	$g.kg^{-1}$		$cmolc.kg^{-1}$				$g.kg^{-1}$			$g.kg^{-1}$				% Fe tot
L14-S	0-10	54.1	4.12	3.2	0.28	1.92	0.03	0.94	0.07	591	356	52	1.72	5.65	0.217	3.02	19.00
	10-20	15.6	3.98	1.8	0.16	0.97	0.03	0.71	0.07	623	305	72	1.84	8.33	0.289	6.71	12.00
	40-50	7.6	3.85	1.1	0.09	1.41	0.04	1.24	0.19	609	262	129	1.63	18.60	0.731	6.41	6.00
L14-NS	0-10	6.4	3.67	4.1	0.36	1.32	0.05	0.67	0.08	598	353	49	1.69	5.51	0.022	3.34	12.60
	10-20	2.7	3.76	1.6	0.14	0.97	0.04	0.88	0.12	622	324	54	1.81	6.98	0.025	5.01	10.50
	40-50	1.1	4.04	0.5	0.05	2.68	0.05	1.91	0.39	496	371	133	1.70	20.20	0.306	9.02	2.29
L25-S	0-10	27.1	3.85	4.7	0.41	3.09	0.15	0.92	0.13	627	311	63	1.61	6.83	0.000	3.59	21.30
	10-20	19.7	3.90	2.7	0.24	3.13	0.07	0.74	0.08	700	246	54	1.75	5.97	0.000	4.89	22.20
	40-50	30.0	4.15	0.9	0.08	1.06	0.03	0.54	0.08	728	196	76	1.62	8.68	0.000	4.14	5.60
L25-NS	0-10	12.9	4.28	3.8	0.33	0.53	0.15	0.95	0.10	679	259	62	1.55	5.89	0.046	3.50	18.30
	10-20	6.5	3.80	3.1	0.27	1.28	0.08	1.16	0.11	703	241	56	1.81	6.65	0.036	3.85	15.40
	40-50	2.9	3.71	1.0	0.09	1.76	0.05	1.34	0.28	612	236	152	1.62	26.90	0.014	7.83	3.25

a: Electrical conductivity of saturated paste, b: Organic C by Walkey and Black method, c: Kjeldahl method, d: Ammonium acetate method, e: Pipette method, f: 100 cm^3 cylinder method (average of 5 replications), g: acid attack ($HF + HClO_4$; $HCl + HNO_3$), h: Tamm extraction buried in soil, as described by Boivin et al. (2004). These devices allowed the soil solution to enter by free drainage and the sampling was carried out under a N2 atmosphere.

pH and EC were measured in the field as soon as possible after filtration of the soil solution, in order to prevent strong re-oxidation. Another aliquot was acidified for cation analysis by ICP-OES.

Eh was measured in situ during the entire cropping season, inside and outside the saline patches in the two plots, at 10 and 25 cm depth. In L25 plot, Eh was measured continuously every hour, whereas in L14, measurement was performed manually once a week.

Results

Flooding water did not vary in composition during the cropping period, except a slight increase in EC at the end of October, mainly due to increasing Na concentration (Table 2). The groundwater salinity was very high and the aquifer was not chemically homogenous (Table 2).

In the L25 plot, strong reducing conditions prevailed. In L25NS and L25S, Eh rapidly decreased after transplanting and stabilised around -200 to -250 mV at 10 cm depth. At 25 cm depth, Eh also decreased quickly in L25S, reaching -180 to -200 mV before increasing and stabilising at around -100 mV. In L25NS, this decrease was slower, and Eh stabilised at around -100 mV. Oxidation peaks occurred at different times, corresponding to rainfall events. Eh rapidly increased to oxidised values when plots were drained in November.

In L14NS, the Eh pattern was close to that observed in L25NS. In L14S, Eh was significantly higher than in L14NS, and higher at 25 cm than at 10 cm depth. Eh values were practically always above +100 mV, apart from an occasional rapid decrease to -45 mV at 10 cm depth.

In all locations except in L14S, EC increased with depth. Outside the saline patches, EC remained almost constant with time with slight fluctuations, around 6.4 ± 1.5 dS.m^{-1}, 10.7 ± 3.2 dS.m^{-1} and 11.6 ± 0.8 dS.m^{-1} in L25NS at 10, 25 and 45 cm depth, respectively, and around 3.5 ± 1.9 dS.m^{-1}, 8.1 ± 1.5 dS.m^{-1} and 8.3 ± 0.6 dS.m^{-1} in L14NS at 10, 25 and 45 cm depth, respectively. Electrical conductivity values and variations were larger inside the saline plots. In L14S, EC at 10 cm depth was higher than EC at 25 and 45 cm depth.

pH changes in the soil solution differed depending on the management practices and on the depth. After transplanting, pH at 10 cm depth in L25NS increased from 5 to 6.5 in a few days A similar increase, with a time lag, occurred at 25 cm (Figure 1). At 45 cm depth, pH remained low at 4.1 ± 0.5 during the entire cropping period. In L25S, pH at 10 cm depth showed the same trend as in L25NS, stabilising around 6.5. At 25 and 45 cm depth, pH remained very low, around 4.8 ± 0.5 and 3.8 ± 0.1, respectively (Figure 1). In L14NS, pH increased from 4.8 to 6.7 at 10 cm depth, much slower than in L25 and remained quite high until harvesting. At all other depths and also at 10 cm in L14S, pH remained constant around 4.

The main cation in the soil solution was Na, ranging from 14-80 mmol.l^{-1} at 10 cm, 60-10 mmol.l^{-1} at 25 cm and 50-135 mmol.l^{-1} at 45 cm depth in L25NS and L14NS plots. Inside the saline patches, Na concentrations were significantly higher and more variable with time with most of the values ranging from 150 to 450 mmol.l^{-1}.

As for pH, Fe and Mn concentrations in the soil solution differed depending on the management practices and on the depth. Fe solubilisation was significantly higher in L25 than in L14 (Figure 2),

Table 2. Flooding water and groundwater analysis

		salinity		cation concentrations (mmol.l^{-1})							
		pH	EC (dS.m^{-1})	K	Al	Ca	Fe	Mg	Mn	Na	Si
L14S	flooding water	6.11 ± 0.71	1.41 ± 0.64	0.04 ± 0.02	0.14 ± 0.27	0.25 ± 0.15	0.03 ± 0.06	0.09 ± 0.05	0.01 ± 0.00	8.5 ± 2.6	0.32 ± 0.46
	groundwater	5.68 ± 1.77	26.0 ± 0.6	0.64 ± 0.08	0	5.5 ± 0.1	0	2.7 ± 0.1	0.04 ± 0.01	323 ± 38	0.30 ± 0.20
L14NS	flooding water	6.26 ± 0.49	1.2 ± 0.42	0.04 ± 0.03	0.22 ± 0.43	0.21 ± 0.07	0.05 ± 0.10	0.08 ± 0.02	0.01 ± 0.00	8.2 ± 2.0	0.48 ± 0.71
	groundwater	4.17 ± 1.61	7.94 ± 0.55	0.05 ± 0.02	0.03 ± 0.03	0.96 ± 0.15	0.60 ± 0.32	0.24 ± 0.03	0.09 ± 0.01	74 ± 3	0.31 ± 0.03
L25S	flooding water	5.84 ± 0.33	0.86 ± 0.46	0.03 ± 0.01	0.05 ± 0.08	0.17 ± 0.07	0.01 ± 0.02	0.10 ± 0.04	0.02 ± 0.01	4.9 ± 1.3	0.20 ± 0.15
	groundwater	3.63 ± 0.47	31.1 ± 0.8	0.28 ± 0.05	2.3 ± 0.1	6.5 ± 0.4	0	3.6 ± 0.2	0.80 ± 0.12	359 ± 55	0.32 ± 0.02
L25NS	flooding water	5.92 ± 0.49	0.81 ± 0.42	0.03 ± 0.01	0.08 ± 0.11	0.16 ± 0.07	0.02 ± 0.03	0.10 ± 0.04	0.02 ± 0.01	4.8 ± 1.4	0.24 ± 0.22
	groundwater	6.25 ± 0.74	23.0 ± 3.8	0.37 ± 0.02	0	4.7 ± 0.3	0	2.18 ± 0.15	0.10 ± 0.02	287 ± 34	0.61 ± 0.17

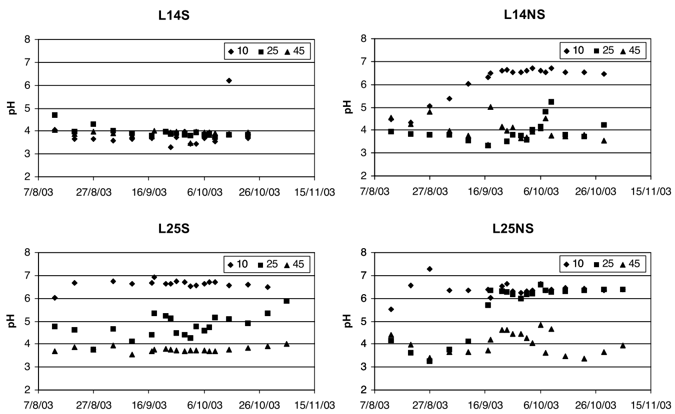

Figure 1. Changes in soil solution pH at 10, 25 and 45 cm depth, in the four monitoring points

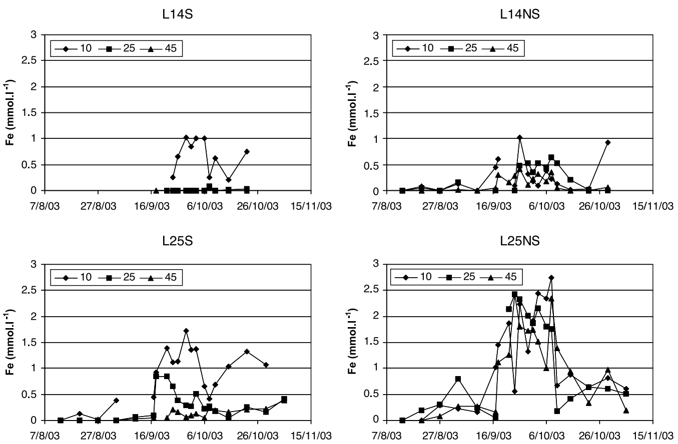

Figure 2. Fe content of the soil solution at 10, 25 and 45 cm depth, in the four sampling points

particularly outside the saline patch. Fe reduction increased with rice growth and Fe concentrations reached 2.74 and 2.5 mmol.l^{-1} in L25NS and 1.72 and 0.85 mmol.l^{-1} in L25S at 10 and 25 cm depth, respectively. At 45 cm depth, Fe solubilisation was also high in L25NS, with the same trend as at the other depths, while it remained low in L25S, less than 0.2 mmol.l^{-1}. After 55 days, Fe concentrations decreased dramatically until the rice harvesting. In L14, Fe reduction was low (Fe concentration 0 to around 1 mmol.l^{-1}), or even nil, inside the saline patch at all depths.

Discussion

Flooding leads to major chemical changes in the soil that affect element mobility. Within a few hours to days after submergence, O_2 is consumed by aerobes, which is reflected by the rapid decrease in Eh after flooding. Moreover, the controlled flooding limited, even decreased, the salinity in the top-soil layer, especially at 10 cm depth, i.e. in the root zone. The salt concentrations inside the saline patches decreased with flooding, mainly due to dilution.

The almost continuous submerged conditions induced anaerobic conditions, which were maintained during the cultural cycle. At 10 cm depth, i.e. in the rooted soil in well managed plot (L25NS and S) and also in L14 outside the saline patch, Eh reached very low values, lower than in deeper horizons, and topsoil remained highly reduced during almost the entire growth period.

Anaerobiosis leads to the establishment of reducing conditions, particularly strongly when organic matter is incorporated into the soils. Thus, other electron acceptors than O_2 are sequentially reduced: NO_3^-/N_2, Mn(III, IV)/Mn(II), Fe(III)/Fe(II), SO_4^{2-}/HS^-, and CO_2/CH_4 (Sposito, 1989), by facultative anaerobes followed by strictly anaerobes in order to oxidise organic matter (Ehrlich, 1996, Madigan et al., 2000). As a result, the concentration of reduced compounds like Fe^{2+} increases in the soil solution, and the changes in the soil solution composition are closely related to the metabolic activity of the microbial communities involved. Ferric iron is commonly the dominant electron acceptor in anoxic systems and may contribute considerably to organic matter biodegradation (Thamdrup, 2000, van Bodegom and Stams, 1999).

The reduction of oxidised compounds depends both on their availability and the presence of microbial communities in soils. Iron release increased with rice growth and was stimulated by organic matter addition, i.e. with high organic carbon availability, as observed by other authors (Tanji et al., 2003, van Asten et al., 2004). Both organic matter addition and high reducible Fe contents may increase the intensity of reduction. High concentrations of dissolved organic carbon, originating from the organic matter added, from root exudation and from the anaerobic biodegradation of root materials, were measured in L25, higher than in L14 at 10 and 25 cm depth (data not shown). These high dissolved organic carbon concentrations suggest there is no limitation in electron donors to sustain Fe reduction, particularly in the well-managed plot. Nevertheless, Fe release was highly limited under saline conditions. Salinity drastically affects microbial biomass and specific metabolic activities (Rietz and Haynes, 2003) and it can be argued that Fe reduction capabilities are also reduced. The number of active anaerobic iron-reducing bacteria is probably lower inside the saline patches and, even if organic substrates are added, their activity is probably strongly inhibited. Thus, by affecting the reducing activity inside the saline patches, salinity drastically affects the pH of the soil solution, even if organic matter is incorporated (see below).

In flooded anaerobic soils, Fe is highly available for plants and Fe toxicity may occur (Marschner, 1995; Becker and Asch, 2005). Even if lowland rice is adapted to such anaerobic conditions, Fe^{2+} can become toxic at high concentrations or when other nutrient deficiencies occur. Fe toxicity seems to appear when Fe concentration is high in the rhizosphere (Montas Ramirez et al., 2002) and when multiple deficiencies occur. In the four studied profiles, Fe concentrations were well below the concentration mentioned by Vizier (1978), so Fe toxicity seems not to be a major risk in these fields. Organic matter addition may also enhance sulfide toxicity resulting in black roots symptom (Tanji et al., 2003), but this can be counteracted by the precipitation of sulfide minerals like FeS when Fe^{2+} concentration is high (Gao et al., 2004). Even though we did not observe retarded plants having such symptoms, the conditions favouring both Fe solubilisation and sulfide accumulation need further investigations in amended plots especially if we want to propose alternative farming practices to farmers.

It is commonly observed that pH of submerged acid soils increases with time to fairly stable values close to neutrality (Ponnamperuma, 1976, Genon et al., 1994, Scott et al., 2003, Kirk et al., 2003, Kirk, 2004). pH greatly influences soil fertility as it controls several parameters like chemical equilibria and surface charges, microbial processes, plant absorption of nutrients, organic matter biodegradation, and also the availability of toxic substances (Sposito, 1989). The pH increase was quicker when organic carbon was highly available as in the L25 plot. Where organic matter was not added to soil, i.e. in low management plot, high salinity prevented high reduction in the top layer. Therefore, no pH increase occurred and pH remained unfavourable for rice growth. The two-stage pH vs time profile observed in paddy soils is mainly explained by the Fe systems. The initial pH rise is explained by the reduction of Fe oxides and the $Fe(OH)_3/Fe^{2+}$ couple. The further pH stabilisation around 6.5, when observed, may be explained by the formation of a mixed Fe(II)-Fe(III) hydroxide. Indeed, ion speciation computations revealed that the soil solutions were oversaturated with respect to an hydroxy-green rust in the intensely managed plot particularly (data not shown).

The alternation of oxic and anoxic conditions produce redoximorphic features, which were observed in the soil profile. Fe- and Mn oxide nodules were observed at 30-40 cm depth, particularly in non saline profiles. During the dry season, red coatings and iron sheaths could be observed around rice roots. They provide evidence of the biogeochemical redox processes occurring in the soil profile. Iron sheaths usually limit phosphorus availability for rice (Berthelin and de Giudici, 1993). The reduction process also may affect the CEC of the soil, especially because of the reduction of coatings that may neutralise negatively charged sites on clay minerals. Such poorly crystallised or amorphous Fe oxides, which represented a large proportion of iron in the studied soils, are preferentially reduced in hydromorphic soils (Munch and Ottow, 1980, Francis and Dodge, 1988). Moreover, structural Fe can also be reduced, thus increasing CEC (Stucki et al., 1987, Favre et al., 2002).

Conclusion

Intensive management of rainfed lowland rice soils in Northeastern Thailand has great impact on the biogeochemical functioning of these soils. It leads to the establishment of strong reducing conditions in the topsoil and to pH increase to near neutrality. Organic matter input seems to counteract salinity effects on soil chemistry and soil microbial activity. Moreover, the proportion of Fe released from the reductive dissolution of amorphous or poorly crystallized Fe oxides depends on such organic management. Thus, water management and availability of organic carbon, which maintain saturation and control the extent of the reduction, are processes of major importance for pH regulation and rice production. While strong reducing conditions appear to be favourable for pH, Fe toxicity could occur for sensitive rice cultivars as the Fe concentration in the root zone reaches high values. Repeated incorporation of organic matter could enhance the risk of Fe toxicity, particularly in such degraded and low buffered soils.

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Remediation of soil acidification by form of nitrogen fertilizer on grass swards of Australia and Thailand

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Keywords: acid soils, nitrate leaching, alkalinity generation, grass species, legume species

Abstract

Acidification of soil profiles from legume and N fertilized crops is a serious sustainability threat. Under tropical conditions of Northeast Thailand and Northern Australia, acidification to >90 cm has been recorded in ***Stylosanthes*** *and* ***Leucaena*** *based pasture systems. Acidification has also been measured in other Australian cropping systems fertilized with urea or ammonium forms of N. The major processes contributing to what could be termed anthropogenic acidification are removal of base cations in the harvested product and leaching below the root zone of nitrate from ammonium and urea N fertiliser or legumes resulting in an accumulation of protons in surfaces horizons. If prophylactic applications of lime are not undertaken, acid generation in surface horizons will progressively move down the profile inducing subsoil acidification. Subsoil acidity is often difficult to correct using conventional applications of liming products.*

Field experiments with pastures on Acrisols in Northeast Australia (two sites) and Northeast Thailand (one site) compared the rates of alkalisation or acidification from N applied as nitrate or as urea (Australia) or ammonium sulphate (Thailand). Soil pH increased where N was applied as nitrate and decreased where N was applied as urea or ammonium sulphate. At one of the sites in Australia, regular applications of N as nitrate at 350 kg N ha^{-1} year^{-1} were made to irrigated ***Digitaria melanjiana*** *cv Jarra. This significantly increased soil pH (1:5 0.01 M $CaCl_2$) by up to 0.5 units to a depth of 0.90 m over a period of 4 years when compared to bare soil. The alkalisation of the profile was equivalent to 2.7 t/ha of calcium carbonate distributed evenly down the profile. Urea at the same rate of N decreased soil pH at 20-50 cm by 0.2 units. Similar but smaller changes were measured at the other Australian site (****Brachiaria decumbens****) and the site in Thailand (****Andropogon gayanus*** *cv Carimagua (Gamba grass). Treatment effects at these sites were restricted by time (1 year) or seasonal conditions that limited the number of N applications that could be applied (290 kg N/ha over 3 years) at the Thai site.*

The research has clearly demonstrated that nitrate N fertilizer can rapidly correct soil acidity down the soil profile to 0.9 m and this is attributed to the release of alkali from roots as nitrate is taken up. Such a strategy may be an effective approach to addressing subsoil acidification where surface applications of lime are ineffective and profile modification is cost prohibitive.

Introduction

Acidification of soil profiles from legume and N fertilized crops is a serious sustainability threat. It is associated with specific limitations to plant growth such as toxicity of aluminium and manganese and deficiency of calcium and molybdenum as well as a reduction in cation retention capacity. Under tropical conditions of Northeast Thailand and Northern Australia, acidification to >90 cm has been recorded in *Stylosanthes* and *Leucaena* pastures (Noble *et al*. 1997). Acidification has also been measured in other Australian cropping systems fertilized with urea or ammonium forms of N (Moody and Aitken 1997). The major processes contributing to anthropogenic acidification are removal of base cations in the harvested product and leaching below the root zone of nitrate from ammonium and urea N fertiliser or

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legumes that result in a net accumulation of protons in surface horizons. Subsoil acidity is often not corrected by conventional application of liming products to the soil surface (Moody and Aitken, 1997), although cost prohibitive in most cropping systems and invasive, practices such as deep placement of lime can be effective (Farina and Channon 1988). The processes of soil acidification from C and N cycles are additions of NH_4^+ and NO_3^- (alkalising), leaching of NO_3^-, export of organic anions (calculated from the amount of crop removed and its ash alkalinity) and changes in soil organic matter (Helyar and Porter 1989).

The supply of nitrate to plants has been shown to alkalise soil, in contrast to acidification when supplied with ammonium in pot experimentation (e.g. Jarvis and Robson, 1983). The current study examines the rate, quantity and extent of alkalisation by grasses supplied with nitrate under field conditions.

Materials and methods

Field experiments with pastures on Acrisols in Northeast Australia and Northeast Thailand compared the rates of alkalisation or acidification from N applied as nitrate or as urea (Australia) or ammonium sulphate (Thailand) (Table 1). The plots were cultivated, sown with seed and allowed to establish before N treatments started in October 2000, July 2002 and September 2001 at sites in Mareeba and Tully (Australia) and Chiang Yuen (Thailand), respectively. Rates and forms of N in each application are detailed in Table 1.

Mareeba

Nitrogen treatments were applied during 4 growing seasons (October to May) and irrigation applied as required. Plots were harvested by hand cutting to 75 mm above ground with a 0.25 × 0.25 m quadrant. The remaining plot area was mown and the clippings removed to simulate a cut-and-carry system. N fertilizer at a rate of 50 kg N ha^{-1} was applied to the soil surface after each harvest on 7 occasions per year, as either urea (N_{urea}) or a combination of $Ca(NO_3)_2$, KNO_3 and $NaNO_3$ (N_{nit}) (Table 1). Irrigation equivalent to 25 mm of rain was immediately applied after fertilizer application. Potassium and Ca applications were the same regardless of N source but SO_4-S varied from 100 to 355 kg S ha^{-1}. Other fertilizer applied at planting supplied P 30, Mg 70, Cu 2, Zn 1.5, B 0.4 and Mo 1.7 kg ha^{-1}, respectively. Additional P was applied in October 2000 (30), October 2001 (30) and December 2003 (40 kg P ha^{-1}) to correct low extractable soil P concentrations. Rainfall varied from 443 to 1,248 mm (long term average 840 mm, with 88% falling between December and April).

Soil water samples were collected from 3 replicates of each N treatment with barrel lysimeters (diameter of 31 cm). They contained 3 ceramic cups and were installed at a depth of 1 m before sowing. Water was extracted from the soil profile via the ceramic cup at a negative pressure equivalent to natural drainage. The pressure was generated by a falling head of water that was maintained between fixed heights by

Table 1. Selected site and agronomic practices implemented at the three experiment sites

Site	Mareeba, Australia	Tully, Australia	Chiang Yuen, Thailand
Climate/average annual rainfall (mm)	Semi-arid tropical (840)	Wet tropical (4300)	Semi-arid tropical (1210)
Lat/long	17ºS, 145º25′E	17º53′S, 146ºE	16-24′N, 103º01′E
Clay (%, 0-30 cm)	13	20	5
pH buffer capacity ($mmol^+$/kg.pH unit, 0-30 cm)	20	16	10
Control (s)	Bare plot (without plants or fertilizer)	Unfertilized grass	Bare plot (without plants or fertilizer) and unfertilized grass
Plot size (m)	4 × 4	6 × 3	10 × 5
Species	*Digitaria melanjiana* cv Jarra	*Brachiaria decumbens*	*Andropogon gayanus* cv Carimagua (Gamba)
N sources	Urea or K, Ca, Na nitrates	Urea or K, Ca, Na nitrates	Ammonium sulphate or potassium nitrate
N rate per application/experiment total (kg N/ha)	50/1,400	25-75/225-675	40/290
Average yield from N fertilized grass (t/ha)	13	36	25

a pump. The cups were connected to individual 5 L water traps also located at a depth of 1 m. Samples were collected at a minimum of weekly intervals, after being stored at soil temperature in the light-proof water traps, and more frequently as drainage events dictated. The samples were chilled after extraction and then frozen on delivery to the laboratory until the time of analysis. Volumes of water extracted were calculated from the height of the water in the calibrated external sampler. Water samples were analysed for ammonium- and nitrate-N (Methods 7C2 and G3b, Rayment and Higginson, 1992). The amount of N leached on 136 occasions between November 2000 and June 2004 was calculated from the concentration and volume for each sample.

The harvested grass was dried at 65ºC, weighed and a sub-sample ground for chemical analysis. Samples were digested by a micro-Kjeldahl procedure and N determined by a continuous flow analyser procedure. Composite soil samples from 3 cores per plot were collected in June-July (mid dry season) at depths of 0-10, 10-20, 20-30, 30-50, 50-70, 70-90 and 90-120 cm (2004 only) and bulked. Samples were dried at 40ºC, sieved to <2 mm and analysed for pH (1:5 in water and in 0.01 M $CaCl_2$, Methods 4A1 and 4B2 in Rayment and Higginson 1992), mineral N (ammonium- and nitrate-N, Method 7C2) Colwell (bicarbonate extractable) P (Method 9B2) and total organic C (2003 only, Method 6B2). pH in $CaCl_2$ (pH_{Ca}) data are presented because of their more consistent trends from year to year.

Similar harvest and analytical procedures were used at the other sites although lysimeters were only installed at Mareeba.

Tully

After establishment, the plots were fertilized and harvested for 11 months (June 2002 – April 2003) and received N as urea (N_{urea}) or $Ca(NO_3)_2$, KNO_3 and $NaNO_3$ (N_{nit}) at 3 rates (25, 50 and 75 kg N ha^{-1} per application for at total of 9 applications). Applications of K and Ca increased proportionally to rate of applied N with 1.15 kg K/kg N and 0.9 kg Ca/kg N. Soil samples were collected to 90 cm after plant establishment and before the application of N treatments in April 2002 and 1 year later. Rainfall during the experiment was 1,815 mm compared to average annual rainfall of 4,300 mm.

Chiang Yuen

Plots were planted in September 2001 and fertilized shortly after with 41 kg N ha^{-1} as potassium nitrate (KNO_3) or ammonium sulphate (N_{ammon}). These applications were repeated 4 times in 2002 (May to September) and 2 times in 2003 (June, August). K was applied to the ammonium sulphate treatments at each N application and P was applied regularly as triple superphosphate (92 kg P ha^{-1}). Soil samples were taken at depths of 0-10, 10-20, 20-30, 50-60 and 100-110 cm at 1 year intervals. Harvests were undertaken 6 times over the duration of the study from 50 m^2. Rainfall was 1,219 mm between September 2001 and August 2002.

Results

Mareeba

There were no differences among treatments in pH_{Ca} before the N treatments were imposed in 2000 (mean profile pH_{Ca} 4.84 for 0-90 cm). Mean profile pH_{Ca} N_{nit} increased to 5.47 in 2004, while the N_{urea} pH_{Ca} remained similar in all 4 years (4.86-4.93). In both 2001 and 2002, pH_{Ca} for N_{nit} between 0 and 50 cm was higher by up to 0.8 than the control and N_{urea} treatments, which were similar ($P < 0.05$). The same trends were measured in 2003 (N_{nit} up to 0.7 pH_{Ca} units higher) although the differences extended deeper in the profile to 90 cm. In 2004, pH_{Ca} for N_{nit} between 10 and 90 cm was higher by up to 0.5 units than N_{urea} and control treatments, which were similar for all depths (Figure 1).

Soil mineral N concentrations in 2000-2003 were always low (<2 mg N kg^{-1}) throughout the profile during the dry season at 68 to 107 days after N application. Mean total OC for 0-30 cm in 2003 was slightly higher in N treatments (0.7-0.9%) than in the bare soil (0.6%).

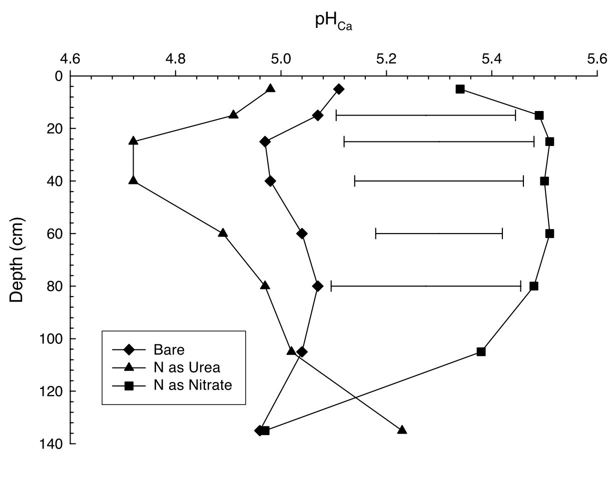

Figure 1. pH_{Ca} in soil profile after 4 years of N treatments to grass pasture at Mareeba, Australia. The horizontal lines represent the lsd (P = 0.05) for the depths where there were significant differences

Mean dry matter yields (DM) from 4 years were higher (P <0.01) for N_{nit} (2.3 t ha^{-1} $harvest^{-1}$) than for N_{urea} (1.9 t ha^{-1} $harvest^{-1}$). The mean annual yield was 13.8 and 11.8 t ha^{-1} for N_{nit} and N_{urea} treatments, respectively. N uptake was generally higher for N_{nit} (mean 235 kg N ha^{-1} yr^{-1}) than N_{urea} (204 kg N ha^{-1} yr^{-1}) but these differences were not significant (P >0.05). Mean N concentration was 1.79% for both N treatments.

Mean inorganic N concentrations in soil water samples at a depth of 1 m were very low during the 3.5 years of measurement. NH_4-N concentration was 0.06 mg L^{-1} (range <0.01-2.5 mg L^{-1}) and NO_3-N concentration was 0.3 mg L^{-1} (range <0.01-32 mg L^{-1}). Losses of inorganic N by leaching were correspondingly low. Average annual losses were <1 kg ha^{-1} for NH_4-N and 2 to 4 kg ha^{-1} of NO_3-N when 350 kg N ha^{-1} was applied.

Tully

After N applications for 1 year, pH_{Ca} was significantly higher (P <0.05) in the N_{nit} treatment than all other treatments at 0-10 cm depth only (Figure 2). There was a trend for pH_{Ca} in this treatment to be higher than all other treatments down to the 20-30 cm depth but this was not significant. Soil mineral N concentrations at the final plant harvest during the dry season in 2003 were low (NH_4-N <3 and NO_3-N <1 mg kg^{-1}) throughout the profile, 35 days after N application.

There were 5 harvests between September 2002 and April 2003. N treatments significantly increased DM compared to the control for 3 harvests, but yields where there were no statistical differences were not obviously constrained (6.1 and 5.1 t/ha for harvests on 15/1/2003 and 29/4/2003, respectively). For both forms, the lowest rate of N (25 kg N ha^{-1} $application^{-1}$) doubled the yield of the control to an average of 26 t ha^{-1}. Further increases in N application produced large increases in DM. Applications of 50 and 75 kg N ha^{-1} $application^{-1}$ produced average DM of 33 and 37 t ha^{-1}, respectively, but differences among rates of N were significant for only 3 harvests (P <0.05). For all rates of N, the N_{nit} treatments had slightly higher DM yields (by 6-10%) than the N_{urea} treatments, although this difference was not significant. N concentrations generally increased with rate of applied N. Mean concentrations for 0, 25, 50 and 75 kg N ha^{-1} $application^{-1}$ were 0.73, 0.86, 1.13 and 1.27%, respectively. N concentration for the highest rate of N (75 kg N ha^{-1} $application^{-1}$) was significantly higher than N at 25 kg N ha^{-1} $application^{-1}$ at each harvest for N_{nit} and for 3 harvests for N_{urea} (P <0.05). N uptake for all harvests also generally increased with rate of N application. Mean uptake for 0, 25, 50 and 75 kg N ha^{-1} $application^{-1}$ were 97, 216, 379 and 471 kg N, respectively. N uptake for the highest rate of N (75 kg N ha^{-1} $application^{-1}$) was significantly higher than N at 25 kg N ha^{-1} $application^{-1}$ at each harvest for N_{nit} and for 3 harvests for N_{urea} (P <0.05).

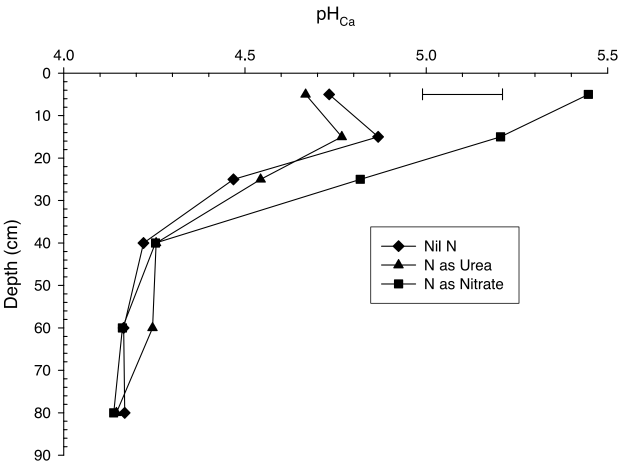

Figure 2. pH_{Ca} in soil profile after 1 year of N treatments (675 kg N/ha) at Tully, Australia. The horizontal line represents the lsd (P = 0.05) for the depths where there were significant differences

Chiang Yuen

At the first soil sampling in December 2001 after one N application, there were no differences in pH_{Ca} in the profile (mean pH_{Ca} 4.01) among N treatments. In 2002 after another three N applications (total of 123 kg N ha^{-1}), pH_{Ca} for the ammonium treatment was lower in the 0-10 and 10-20 cm layers (3.99 and 3.89, respectively) than all other treatments, which were similar to each other (4.13-4.27 and 3.97-4.06, respectively). In 2003 after a total N application of 289 kg N ha^{-1}, pH_{Ca} for unfertilised grass and nitrate fertilised grass was higher (P <0.05) in the 0-10 cm layer than the bare and ammonium fertilized treatments (Figure 3).

The plots were harvested 6 times between December 2001 and November 2003. Mean DM was 4.2 t ha^{-1} for unfertilized Gamba grass. N increased DM by 180% to an average of 7.7 t ha^{-1} $harvest^{-1}$. This difference was significant for 5 of the harvests (P <0.05). Sources of N produced similar DM except in November 2003 when DM N_{ammon} was higher than N_{nit} (P <0.05). Plant N concentration and N uptake for the N treatments were usually similar (P >0.05) but higher than the nil N treatment for 5 harvests. N application increased N concentrations in grass from

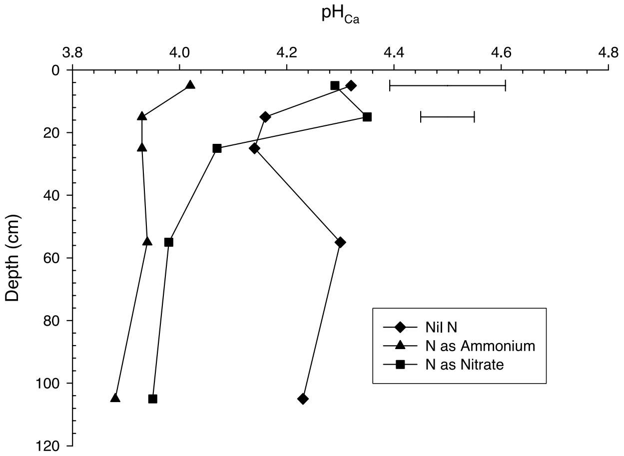

Figure 3. pH$_{Ca}$ in soil profile after 2 years of N treatments at Chiang Yuen, Thailand. The horizontal line represents the lsd (P = 0.05) for the depths where there were significant differences

a mean of 0.39% (s.e. ± 0.05) in unfertilized treatment to 0.58% (s.e. ± 0.14) in both N_{nit} and N_{ammon} treatments. N uptake over the 6 harvests increased from 102 kg N ha^{-1} in the unfertilized treatment to 283 kg N ha^{-1} in the N fertilized treatments.

Discussion

N fertilizer applied in the nitrate form increased the soil pH at each site. The depth and magnitude of alkalisation was greatest at the Mareeba site, presumably due to the high rate of N (1,400 kg ha^{-1}) applied over 4 years. N_{nit} increased pH$_{Ca}$ by as much as 0.5 units to a depth of 90 cm over this time. This is equivalent to 2.7 t ha^{-1} of lime but relatively uniformly distributed down the profile. The pH increase was attributed to alkali (OH^- and/or HCO_3^-) extrusion by roots accompanying NO_3^- uptake (Jarvis and Robson, 1983). Leachate measurements with the lysimeter system showed that very little N was leached below 1 m, thus maximising the opportunity for plant uptake. Leaching data were not available at the other sites, but may have been important at Tully because of high rainfall (1,812 mm during the experiment) and some high N application rates. It is not clear why the pH$_{Ca}$ of unfertilized grass increased to the same extent as the nitrate fertilized grass at Chiang Yuen.

An important result is the ability of nitrate fertilizers to remediate soil acidity to considerable depth in the profile. This is not usually the case with liming products applied to the soil surface. For example, Moody and Aitken (1997) found that regular applications of lime (2.5 t/ha/yr) in a hot, wet environment similar to the Tully site did not prevent acidification in 4 of 5 banana soils to >100 cm. In contrast, Noble and Hurney (2000) found that surface lime applied 18 years earlier increased pH to 100 cm in a Yellow Dermosol. They attributed this to ion pairs of Ca^{2+} and Mg^{2+} with NO_3^- moving through the profile, subsequent uptake of nitrate by roots and secretion of an excess of bases by roots to increase pH.

Nitrate fertilizers are more expensive than urea and there are now restrictions on their purchase in Australia. Calcium nitrate and potassium nitrate cost respectively 8 and 10 times more than urea per unit of N, although these obviously also supply other important plant nutrients. The increased cost of using nitrate-N may be partially offset by significantly higher yields at Mareeba (an increase of 17%) and a trend to higher yields at Tully (an increase of 6-10%).

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Influence of afforestation with eucalypts in Congolese savannas on long-term nutrient availability in the soils

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Keywords: Eucalyptus, savanna, biogeochemical cycles, nutrient budget, sustainability, Congo

Abstract

Fast growing forest plantations managed in short rotations in order to maximize biomass production are likely to deplete soil nutrient reserves. The effects of ***Eucalyptus*** *stands on long-term nutrient availability in sandy soils were studied in the coastal plains of Congo, using a biogeochemical cycle approach. Atmospheric deposition, canopy exchange and transfer through the soil were estimated on the whole rooting depth (6 m) over three years, in an experimental design installed in a native savanna and an adjacent 6-year-old* ***Eucalyptus*** *plantation. Complementary measurements during 3 years after planting the same* ***Eucalyptus*** *clone in the experimental savanna made it possible to establish input-output budgets of nutrients for the whole rotation and to compare them with the native savanna ecosystem.*

Even if the nutrient fluxes in the savanna ecosystem were affected by afforestation, the biogeochemical cycles remained highly conservative after planting eucalypts. The main outputs of nutrients from the soil occurred during burning in savanna and with biomass removal at the harvest in the ***Eucalyptus*** *stand. Both ecosystems were efficient in preventing losses by deep drainage (<5 kg ha^{-1} year^{-1} for N, P, K, Ca, and Mg). After afforestation, weeding in the* ***Eucalyptus*** *stands eliminated the leguminous species responsible for N input by symbiotic fixation of about 20 kg ha^{-1} year^{-1}. Whereas the budgets of P, K, Ca and Mg were roughly balanced, the current silviculture led to a deficit of about 140 kg N ha^{-1} in the soil, throughout a 7-year rotation. This deficit was large relative to the pool of total N in the upper soil layer (0-50 cm), which was about 2 t ha^{-1}. The nutrient budgets were consistent with field trials on fertilization, showing that the sustainability of Congolese plantations will require an increase in N fertilizer inputs over successive rotations.*

Introduction

Large areas of native vegetation have been replaced by monospecific *Eucalyptus* stands for several decades, and this genus is nowadays the most represented in tropical plantation forests. The ecological impact of *Eucalyptus* plantations has been widely discussed around the world (Cossalter and Pye-Smith, 2003). This issue has been studied in littoral plains of Congo, after afforestation with *Eucalyptus* clones in native savannas (Loumeto and Huttel, 1997; Mboukou-Kimbatsa et al., 1998; Bernhard-Reversat et al., 2001; Ranger et al., 2004).

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Paired comparisons of soil chemical properties in the top soil under savannas and adjacent *Eucalyptus* stands showed that 20 years of short-rotation silviculture did not modify carbon stocks but decreased N and Ca contents (Bouillet et al., 2001). To gain insight into the processes governing the mineral functioning of these ecosystems, the biogeochemical cycles of nutrients have been compared in a clonal *Eucalyptus* stand and an adjacent savanna over three years: modifications of the chemical composition of solutions throughout their transfer were investigated in the two ecosystems (Laclau et al., 2003a, b), as well as the dynamics of biomass and nutrient accumulation in the plants (Laclau et al., 2002; Laclau et al., 2003c). The flux dynamics is an important parameter to consider, because nutrient availability and demand should coincide both in time and space under conditions of high rainfall and permeable soils.

The present study aimed at establishing input-output nutrient budgets for the whole *Eucalyptus* rotation in order to assess the long-term effects of silvicultural practices on nutrient availability and to elaborate sustainable management practices.

Material and methods

1. Site characteristics

The study site was located on a plateau at an elevation of about 80 m and a distance from the sea of 10 km (4ºS 12ºE). The mean annual rainfall over the last 50 years was 1,200 mm, with a dry season between May and September, and the mean temperature was 25ºC with seasonal variations of approximately 5ºC. The geological bedrock is composed of thick detritic formations of continental origin, dated from plio-pleistocene. An experimental design monitoring the biogeochemical cycles was installed in 1997 in a *Eucalyptus* stand and a native savanna. The area was flat and the distance between the two designs was about 500 m. Soils were ferralic arenosols (FAO classification), acidic ($pH_{H2O} \approx 5$) and characterized by a sandy texture (sand content >85% down to a depth >12 m) and a low amount of available nutrients (CEC <0.8 $cmol_c\ kg^{-1}$, even in the upper layers). The organic matter content of soils decreased in both stands from about 1.3% in the surface layer (0-5 cm) to about 0.15% below a depth of 2 m. Concentrations of exchangeable elements were of the same order of magnitude in the two stands. Nevertheless, in the topsoil (0-5 cm layer), the concentration of Ca in the eucalyptus stand was lower than in the savanna and the concentrations of available P and Al were higher (Laclau et al., 2005).

2. Plant material

The *Eucalyptus* clone studied here comes from natural crosses in Congo between a few individuals of *Eucalyptus alba* Reinw. ex Blume (mother tree) and a group of poorly identified *Eucalyptus* hybrids (father tree). The stand was planted in January 1992 on savanna, at a stocking of 530 trees per hectare, and a starter fertilization (150 g per cutting of NPK 13:13:21) was applied. Manual weeding in the planting row and chemical weeding in the inter-row were made in the early stages of stand development. The stand was 6 years old at the onset of the study, with a mean height of 26 m and a mean over-bark volume of 158 $m^3\ ha^{-1}$. Other studies dealing with the dynamics of nutrient fluxes throughout a 7-year rotation were performed in this area, using a chronosequence approach for the same clone (Laclau et al., 2003c).

The grass *Loudetia arundinacea* (Hochst.) Stend represented 80% of the total aerial biomass of the savanna, which reached about 5 t ha^{-1} of dry matter at the end of the rainy season. This savanna was burnt every dry season (August) like most savannas in Congo (Laclau et al., 2002).

3. Methodology

Climatic data, soil moisture and solution chemistry were measured in both ecosystems from January 1998 to December 2000. Methods used to assess input-output fluxes were described by Laclau et al. (2005). In brief:

Atmospheric depositions. Lack of reliable measurement methods for dry deposition made it necessary to use a calculation approach based on the comparison of nutrient fluxes in an open area and beneath the canopy. We considered Na^+ as a tracer, assuming that canopy exchange was negligible for this element compared with dry deposition of marine aerosols in this coastal area (Parker, 1983). Dry deposition of nutrients was considered proportional to that of Na^+.

Weathering of soil minerals. Soil minerals were considered to be external to the available soil nutrient reservoir where trees take up their nutrients. Mineralogy of the different particle size fractions and mineral bearing nutrients were quantified using identification of mineral by X ray diffraction, total and selective chemical analysis, thermogravimetric analysis and normative calculation. The geochemical Profile model developed by Sverdrup and Warvfinge (1988) was calibrated for the site to estimate the magnitude of this flux, overlooking weathering processes for the very stable accessory minerals.

Accumulation in the aerial ligneous biomass. Twelve trees were sampled in the *Eucalyptus* stand at age 6.5 years and 10 trees at age 8 years. Selected trees were cut down, and the major components were isolated: stemwood, living and dead branches, stembark, and leaves. The fresh stem weight was measured and disks of wood and bark of constant thickness were taken every 3 meters. Samples were dried (65ºC) and the dry biomass of the components in each tree was calculated proportionally. All the branches and leaves were collected and samples of these components were dried. One composite sample for each component of each tree was ground, homogenized and sent to the laboratory for chemical analyses. Tables were established and applied to the stand inventories to quantify the stand biomass and nutrient content per hectare.

Nutrient losses by drainage. Nutrient fluxes were calculated multiplying the water fluxes at each soil depth (assessed from hydrological model) by the mean concentration of nutrients in gravitational solutions. Run off solutions were collected from 4 replicates of 1 m^2 collectors in the two ecosystems. Soil solutions were sampled in both ecosystems from 4 replicates of ceramic cup lysimeters installed at various depths between 15 cm and 6 m and connected to a vacuum pump maintained manually (daily checking) at a constant suction of about – 60 kPa. A complete description of the lysimetry design was presented by Laclau et al. (2003b). Three to five replicates of TDR probe (Trase System I) were installed at the depths of 15, 50, 100, 200, 300, 400 and 500 cm in the *Eucalyptus* stand, and at the same depths down to 3 m in the savanna. Volumetric water content was measured automatically every 3 hours from July 1998 to December 2000 in the *Eucalyptus* stand and once or twice a week in the savanna. A model based on the Richard’s equation for simulating one-dimensional water flows (Hydrus 1D) was calibrated in the *Eucalyptus* ecosystem and in the experimental savanna to quantify water flows at the depths where lysimeters were installed (Laclau et al., 2005). All the equations used in the model were established from measurements performed in 1998 and 1999. The ability of the model to predict the fluxes was checked during the year 2000.

Chemical analyses

Once a week, after volume measurements and sampling, the solutions were collected and carried to the laboratory where they were kept at +4ºC. Pooled volume weighted samples were made every 4 weeks for chemical analyses. Each replicate of soil solution collected was analyzed separately. The solutions were filtered (0.45 µm) in the Congo and measurements of pH (HI 9321) and SO_4^{2-} by colorimetry (ANA 8 Prolabo) were performed as quickly as possible. The samples were then acidified with H_2SO_4, sent to the CIRAD laboratory in France where nitrate and ammonium were measured by colorimetry (INTEGRAL PLUS – Alliance instruments). Total P, K, Ca, Mg were determined by ICP emission spectroscopy (JY 50).

In plant samples, N was determined by thermal conductivity after combustion (FP-428) and P, K, Ca, Mg, by a sequential spectrometer ICP (JY 24) after digestion by hydrofluoric acid and double calcination.

Input-output budgets

Current annual and seasonal input-output budgets were established between 1998 and 2000 from the measurements performed, considering losses by deep drainage at a depth of 4 m under savanna and 6 m under *Eucalyptus*. Indeed, previous studies showed the absence of roots beyond the depth of 3 m under savanna, and extremely low densities in this *Eucalyptus* stand (Laclau et al., 2002). The nutrient uptake by plants considered in the current budgets was the permanent uptake: immobilization in stemwood for the *Eucalyptus* stand and transfers to the atmosphere during burning in the savanna.

The calculation of nutrient budgets over the whole rotation required assessing the nutrient fluxes during the first years after afforestation. To measure losses by drainage during the early growth of the stand, the experimental savanna was planted with the same *Eucalyptus* clone in May 2001. Soil solutions were collected and analyzed for 2 years with the same methodology. Losses were assessed every 4 weeks, multiplying the average concentration in soil solutions at a depth of 4 meters by the simulated water flow (Unpublished data). Dry deposition was adjusted proportionally to the foliar biomass of the stand throughout stand rotation (Laclau et al., 2000). From 2 years onward, annual fluxes in the *Eucalyptus* ecosystem were considered identical to values measured at the end of the rotation. Indeed, a chronosequence approach showed that the main fluxes of the biological cycle are roughly constant (Laclau et al., 2003c).

Results and discussion

1. Main changes in nutrient cycling after afforestation

Planting *Eucalyptus* in the native savanna modified the inputs of nutrients to soil through the following processes:

A filter effect of the canopy at the end of the *Eucalyptus* rotation led to dry depositions of nutrients of the same order of magnitude as wet deposition, whereas the pattern of Na^+ concentration in wet depositions and throughfall suggested that this flux was negligible in the savanna (Laclau et al., 2003a). Atmospheric deposition was in the range of values given in the literature for forest stands. However, this flux was determined with high degree of uncertainty which influence the accuracy of determination of input-output budgets at the ecosystem level (Laclau et al., 2005).

Fertilizers are usually applied in *Eucalyptus* plantations. This flux was considered in the budgets calculated for the whole rotation (Figure 1) but not in Table 1, because fertilizers were applied only at planting in the stand studied.

Biological N_2 fixation is necessary to explain the sustainability of savannas in littoral areas of Congo for about 3,000 years showed by isotopic studies (Trouvé, 1992), despite large losses of N during annual fires. The input of N by symbiotic fixation, assessed roughly to balance the N budget in savanna, amounted to about 22 kg ha^{-1} year^{-1} (Table 1). The legume species *Eriosema erici-rosenii* R.E. Fries (Papilionoideae) was found in all the savannas of the region. Chemical weeding during the early growth of the *Eucalyptus* stand led to the disappearance of this flux.

Calculations performed with the Profile model suggested that the amounts of P, Ca and Mg released by the weathering processes were negligible in this Ferralic Arenosol. The amount of K released on a soil depth of 6 m in the *Eucalyptus* ecosystem was about 0.3 kg ha^{-1} year^{-1} and half on a depth of 3 m under savanna. This flux was consistent with the extremely low nutrient concentrations in soil solutions sampled

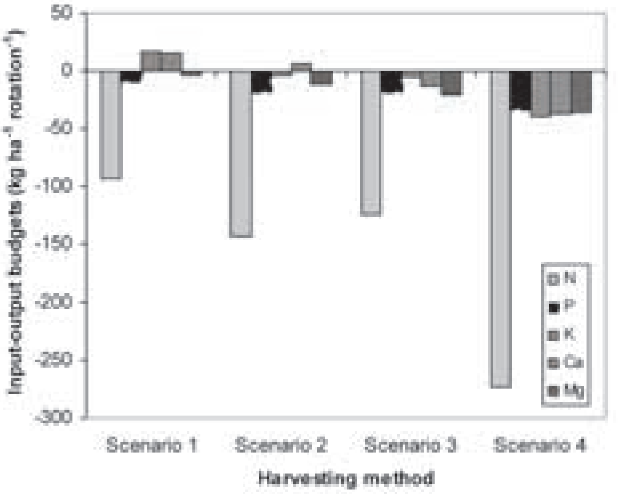

Figure 1. Input-output budgets (kg ha^{-1}) of N, P, K, Ca and Mg for the whole *Eucalyptus* rotation, and for different harvesting scenarios
***Scenario 1:* de-barked pulpwood harvest**
***Scenario 2:* de-barked pulpwood and firewood harvest**
***Scenario 3:* pulpwood with bark harvest**
***Scenario 4:* whole tree harvest**

by tension lysimeters below the rooting zone (Laclau et al., 2003b).

Outputs of nutrients also were modified by afforestation:

Transfers of plant nutrients to the atmosphere during burning were a major output of nutrients in this

Table 1. Mean input-output fluxes of nutrients in the soil under the *Eucalyptus* stand at the end of the rotation, and under the savanna, from 1998 to 2000 (kg ha^{-1} year^{-1})

	Savanna					*Eucalyptus* stand				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg
ANNUAL FLUXES										
Wet deposition	4.8	0.3	2.7	3.3	1.4	4.8	0.3	2.7	3.3	1.4
Dry deposition	0.0	0.0	0.0	0.0	0.0	6.5	0.3	3.8	4.5	1.8
Symbiotic Fixation[1]	21.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Weathering	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.3	0.0	0.0
Total inputs	26.4	0.3	2.8	3.3	1.4	11.4	0.6	6.8	7.8	3.2
Surface runoff	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.4	0.1
Deep drainage	3.0	0.1	0.6	0.4	0.2	4.3	0.3	2.1	1.1	1.2
Immobilization[2]	–	–	–	–	–	32.7	3.7	4.8	3.9	2.5
Burning	23.4	1.5	2.4	2.6	2.9	0.0	0.0	0.0	0.0	0.0
Total outputs	26.4	1.6	3.0	3.0	3.1	37.0	4.1	7.1	5.4	3.8
ANNUAL BUDGETS										
Mean over 3 years	**0.0**	**-1.3**	**-0.2**	**0.3**	**-1.7**	**-25.6**	**-3.5**	**-0.3**	**2.4**	**-0.6**
Inter-annual range:										
Min	**0.0**	**-1.4**	**-0.4**	**-0.1**	**-1.8**	**-29.7**	**-3.9**	**-2.4**	**1.6**	**-0.3**
Max	**0.0**	**-1.2**	**0.0**	**0.5**	**-1.6**	**-21.6**	**-3.0**	**1.3**	**3.4**	**-0.7**

[1] Calculated to balance the nitrogen budget in the savanna,
[2] Nutrient immobilization in stemwood.

savanna. They amounted to 23.4, 1.5, 2.4, 2.6 and 2.9 kg ha^{-1} year^{-1} for N, P, K, Ca and Mg, respectively (Laclau et al., 2002). They represented, respectively, 85%, 25%, 39%, 21%, and 28% of the N, P, K, Ca and Mg contents in the above-ground biomass before the fire. This output of nutrients was avoided after afforestation.

Nutrients immobilized in stemwood were exported from the ecosystem at the harvest. They amounted to about 30 kg ha^{-1} year^{-1} of N, and from 3 to 5 kg ha^{-1} year^{-1} of P, K, Ca and Mg, at the end of stand rotation (Table 1). Nutrient exportation with biomass removal does not occur in most of Congolese savannas owing to the absence of cattle.

Losses of nutrients by surface runoff were negligible in savanna and represented very low amounts in the *Eucalyptus* stand (<0.5 kg ha^{-1} year^{-1}). At the end of the rotation, the *Eucalyptus* stand was as efficient as the native ecosystem of savanna to prevent losses of nutrients by deep drainage. The losses of N, P, K, Ca and Mg amounted to 4.3, 0.3, 2.1, 1.1 and 1.2 kg ha^{-1} year^{-1}, in the *Eucalyptus* stand, respectively, and 3.0, 0.1, 0.6, 0.4 and 0.2 kg ha^{-1} year^{-1} in savanna (Table 1). Losses of nutrients by deep drainage observed over the first two years after afforestation of the experimental savanna remained low. Although the mineralization of savanna residues occurred when the root system of the trees was not completely established, the fluxes of N, P, K, Ca and Mg at a depth of 4 m were lower than 3 kg ha^{-1} year^{-1} on average (Unpublished data). Rainfall amounts were much lower during this period than from 1998 to 2000 which may explain the very low losses by drainage observed. Therefore, it cannot be excluded that nutrient outputs by drainage would be higher, and consequently the N budget more unbalanced, if afforestation occurred during a period with a more normal precipitation distribution.

Moreover, afforestation led to great changes in the internal nutrient cycling within the ecosystem (Laclau et al., 2003a, c). Foliar leaching of cations observed in savanna decreased after planting eucalypts. Plant uptake of nutrients from the soil increased sharply after afforestation. Internal retranslocations of nutrients occurred in the savanna but were not quantified. This process supplied about 30% of the annual requirements of N and P in the *Eucalyptus* plantation from 2 years of age onwards, and about 50% of K requirements. Litter fall and litter decomposition were negligible in the savanna ecosystem and became important nutrient fluxes from age 2 years onwards, in the *Eucalyptus* stands.

The biogeochemical cycle of N was the most affected by afforestation. In particular, both mineralisation and nitrification rates permanently increased after planting eucalypts (Ranger et al., 2004). The immediate increase in nitrification rate observed after the destruction of the savanna was interpreted as a drastic change in the control of the nitrifying populations. Savanna vegetation was known to inhibit the activity of nitrifiers by allelopathic processes not yet completely elucidated. Investigations made in Ivory Coast showed the role of grass ecotypes on the control of nitrifiers (Abbadie et al., 2000). Allelochemicals responsible for the inhibition of nitrifiers were not yet identified in the savannas, contrarily to other specific forest situations (Paavolainen et al., 1998).

2. *Input-output budgets*

Harvesting method had a great influence on the nutrient budgets (Figure 1). The range of variation between the most conservative harvesting method (scenario 1) and the most costly in nutrients (scenario 4) was about 180 kg ha^{-1} for N, 25 kg ha^{-1} for P, 55 kg ha^{-1} for K, Ca, and 30 kg ha^{-1} for Mg. De-barking the stems on site retained at the soil surface 31, 9, 21, 28 and 16 kg ha^{-1} of N, P, K, Ca and Mg, respectively. These values represented about 10% of the amount of N accumulated in the above-ground part of the trees at harvest, 20% of that of P and K, and 35% of that of Ca and Mg. The removal of firewood for surrounding populations in Congo (scenario 2) led to further losses of 50, 8, 20, 9 and 7 kg ha^{-1} of N, P, K, Ca and Mg, respectively, relative to the most conservative method where only de-barked pulpwood is harvested. The current silviculture in Congo led to a deficit of 144 kg ha^{-1} of N for the first rotation after afforestation. This deficit represented about 7% of the initial amount of total N in the A_1 horizon (0-50 cm) under savanna. In highly-weathered sandy soils, the long-term sustainability of these plantations is therefore greatly dependent on the reliability of fertilization practices.

Even if certain fluxes were assessed with large uncertainty, input-output budgets demonstrate clearly that *Eucalyptus* plantations take advantage, during the first rotation after afforestation, of a N soil fertility inherited from the previous vegetation of savanna. Unfavourable qualitative changes add further to the quantitative deficit of the N budget: savanna organic matter is progressively replaced by *Eucalyptus* organic matter poor in N (Trouvé et al., 1994), and whose chemical composition (tannins, lignin, polyphenols) leads to a slower mineralization (Bernhard-Reversat et al., 2001). For the other elements, the budgets for the whole rotation were well balanced relative to the amounts of available elements in the soil. This behaviour is consistent with fertilizer field trials in this area, which show that tree responses to N inputs increase over successive rotations, whereas no response to P and K inputs is observed, even in replanted sites 20 years after savanna conversion (Bouillet et al., 2003).

3. Consequences for sustainable silivicultural practices

Low amounts of nutrients in the soils of this area (P excepted), and the high cost of fertilizer inputs make it essential to strictly limit nutrient losses throughout stand rotation. Several modifications in silvicultural practices were proposed to achieve this goal:

- *Field trials of fertilization.* The quantitative data from the budgets show that field trials should focus on N fertilization. Future plantations, with much more productive clones of the hybrid *E. urophylla* × *E. grandis*, might lead to unbalanced budgets of K, Ca and Mg in the soils. It would then be important to determine whether these elements become limiting after several rotations.
- *Soil preparation and weed control.* Minimum cultivation is recommended to limit nutrient losses by erosion and planting must occur as quickly as possible after harvesting to reduce nutrient losses by drainage. Moreover, weed control must be planned to take advantage of the temporary fixation of nutrients in the biomass of weeds during the early growth of the stands (Nambiar and Sands, 1993).
- *Harvesting method.* The effects of various harvesting scenarios on nutrient budgets were quantified. They show that current practices including de-barking on site is fundamental owing to the chemical paucity of the soil. This feature was confirmed by an experiment dealing with organic matter management in Congolese *Eucalyptus* plantations (Nzila et al., 2002).
- *Fire prevention.* Nutrient budgets provide new light on the negative effects of fires in these plantations. Large losses of N by volatilization during burning have clearly detrimental consequences on the long-term production in this area where N is the first nutritional limiting factor. Effective fire prevention is therefore crucial for the sustainability of these plantations.
- *Introduction of a legume understorey.* Numerous studies show that mixed plantations between *Eucalyptu*s and legume species can have beneficial effects on soil N fertility (*e.g.* Binkley et al., 2003). In the Congo, mixed plantations cannot be established because the growth of N fixing trees is much lower than that of *Eucalyptus*. In this case, experiments were set up recently introducing an understorey of *Acacia* in *Eucalyptus* stands to enhance soil fertility, through inputs of organic matter and atmospheric N.

Conclusion

Quantification of nutrient fluxes throughout a rotation of *Eucalyptus* in the Congo demonstrated that the influence of silvicultural practices varied greatly according to the elements. Whereas the amounts of P, K, Ca and Mg in the soil were roughly stable throughout stand rotation, current silvicultural practices led to a deficit of about 140 kg ha^{-1} of N in the soil. The budgets were strongly dependent on the harvesting method because this period accounted for the major output flux from the system. Input-output budgets suggested that *Eucalyptus* stands benefit from a N fertility inherited from the previous ecosystem of the savanna. Weeding destroyed a legume species responsible for N input in the savanna ecosystem estimated at around 20 kg ha^{-1} $year^{-1}$.

Therefore, the sustainability of *Eucalyptus* plantations in this area will require an increase in N fertilizer inputs over successive rotations. Another option to improve the N status in these soils might be to introduce a biological nitrogen fixing species, compensating for the destruction of the native legume species in the savanna. Several experiments have been set up recently in the Congo to assess the influence of various *Acacia* species introduced as understorey in *Eucalyptus* stands. Further research is necessary to investigate silvicultural practices providing a positive influence of a leguminous understorey on soil N availability in the long term, without competing significantly with eucalypts during the early growth of the stands.

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Session 4

"Physical properties of tropical sandy soils"

Physical properties of tropical sandy soils: A large range of behaviours

Bruand, A.[1]*; C. Hartmann*[2] *and G. Lesturgez*[2, 3]

Keywords: Sandy soil, bulk density, structure, porosity, particle size distribution, clay, hydraulic properties, compaction

Abstract

Sandy soils are often considered as soils with physical properties that are easily defined however they are far from being simple. This is particularly the case for sandy soils in the tropics where they are subjected to a cycle of wetting and drying associated with seasonality. In this respect small changes in composition lead to significant differences of physical properties. One of the major soil characteristics to be taken into account is the size distribution of the sand grains. Fine sand induces greater porosity, water retention and resistance to penetration than coarse sand, they exhibit lower permeability. Porosity decreases when the heterogeneity of the sand grain distribution increases leading to an increase in resistance to penetration and decreases in permeability. The presence of silt particles leads to similar consequences. Thus, silty sands are more compact than sandy soils, most silt particles occupying the voids between sand grains thereby reducing porosity and consequently permeability. Size distribution and mineralogy of silt and clay sized particles that are associated with sand grains are also responsible for variations in physical properties of tropical sandy soils. Under tropical environments, sandy soils undergo significant weathering to depth thus resulting in a mineralogy where quartz is the dominant mineral in the sand and silt fraction and forms a significant proportion of the clay sized fraction. On the other hand, sandy soils can be present in the lower part of the landscape where clays or salts form during the dry season. As a consequence, sandy soils with similar particle size distribution but due to differences in mineralogy of the clay sized fraction that represents not more than a few percent of the soil mass, show very different physical properties. Finally, in sandy soils unlike other soils, the elementary fabric is easily affected by tillage practices. If greater porosity can be produced through tillage operations, the stability of these systems is very weak and compaction by wheels or other actions can in return produce a dense structure. Thus, compaction results from a variation of the structure at all scales, i.e. from the macroscopic to microscopic scales.

Introduction

Sandy soils are characterized by less than 18% clay and more than 68% sand in the first 100 cm of the solum. In the World Reference Base (WRB) soil classification system (ISSS Working Group R.B. 1998), sandy soils may occur in the following Reference Soil Groups: Arenosols, Regosols, Leptosols and Fluvisols. These soils have developed in recently deposited sand materials such as alluvium or dunes. They are weakly developed and show poor horizonation. Soils characterized by a high proportion of sand in the first 100cm can also correspond to the upper part of highly developed soils formed in weathered quartz-rich material or rock, as evidence by the development of a highly depleted horizon. In the following discussion consideration will be given to a range of soils including sandy soils of the WRB and those with sandy horizons in the upper 100cm of the profile.

Sandy soils are often considered as soils with physical properties easy to define: weak structure or no structure, poor water retention properties, high permeability, highly sensitivity to compaction with many adverse consequences. However, analysis of the literature shows that their physical properties are far from simple. This is particularly true in the tropics where sandy soils are subjected to a cycle of wetting and drying that greatly affects the soil with small differences in composition leading to significant differences of physical properties.

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Structure, porosity and bulk density

Sandy soils are characterized by a lack of structure or that it is weakly development. Coquet (1995) measured the shrinkage properties of two soils in Senegal with different texture. On the sandy soil, results obtained in the field and in the laboratory (on cores originating from the same horizons), showed very small shrinkage: bulk volume variation was only 0.05%. When they dried, sandy soils develop very few thin cracks organised in a loose network. The meagre shrinkage properties of these soils are related to the low clay content and the high proportion of low activity clays of many tropical sandy soils.

A large range of porosity

Sandy soils in the tropics show a large range of porosities and consequently bulk density (D_b). Porosity ranges from 33% (D_b = 1.78 g cm^3) to 47% (D_b = 1.40gcm $^{-3}$) are commonly recorded (Figure 1). The porosity in sandy soils is usually smaller than in clayey and silty soils.

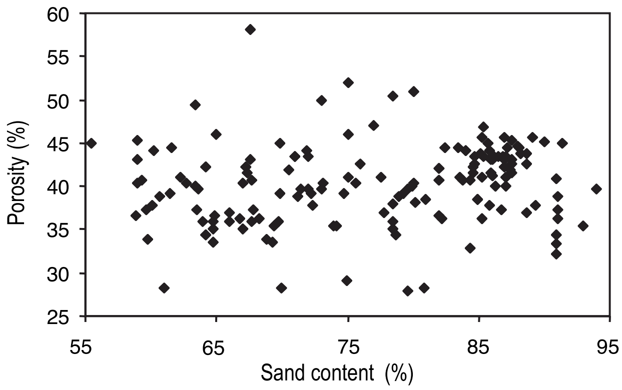

Figure 1. Variation of porosity according to the sand content in tropical sandy soils (after Nicou, 1974 and 1976; Chauvel, 1977; Coquet, 1995; Lamotte *et al.*, 1997a; Burt *et al.*, 2001; Nyamangara *et al.*, 2001; Feng *et al.*, 2002; Bortoluzzi, 2003; Bruand *et al.*, 2004; Lesturgez, 2005; Osunbitam *et al.*, 2005)

Very small changes in porosities are generally observed in sandy soils of the tropics. Lamotte *et al.* (1997a and b) observed a porosity of 28% (D_b = 1.91 gcm $^{-3}$) between 35 and 45 cm depth in the Northern Cameroon’s in very old cultivated fields. Lesturgez (2005) measured a porosity of 28% between 20 and 30 cm depth in a soil belonging to the Warin-Satuk series in Northern Thailand in cultivated soils. Deeper in the soil, similar small porosities were recorded by Burt *et al*. (2001) in sandy soils developed in a saprolithe derived from granitic rocks in Zimbabwe. These small porosities were recorded in sandy soils with no gravel or stones thus indicating a close packing of elementary soil particles in soils that have been subjected to continuous cultivation.

However, under native vegetation with intense biological activity or after recent tillage operation (wheel tracks excluded), greater porosity of 60% (D_b = 1.10 gcm $^{-3}$) have also been recorded (Bortoluzzi, 2003; Lesturgez, 2005). Such a large porosity is related to the presence of numerous macropores that results from both faunal activity and root development. Bruand *et al*. (2004) have also observed greater porosity in the subsoil of intensively cultivated soils, this being related to a loose assemblage of elementary soil particles unaffected by farming practices.

Significance of sand and silt grain size distribution

Porosity varies with time after tillage operations thus making it difficult to attribute to soil composition alone. Osunbitan *et al*. (2005) showed a continuous decrease in the porosity of the 0-5 cm layer of a Nigerian loamy sand soil. Porosity ranged from 47.7% (D_b = 1.30 gcm $^{-3}$) to 60.4% (D_b = 1.05 gcm $^{-3}$) according to the tillage system and time after tillage. If we exclude the topsoil horizons from the dataset used in Figure 1, Figure 2 indicates that the finesand: coarsesand ratio ranges from 0.5 to 6.1 for the data collected in the literature and the porosity tends to decrease when ratio increases (R^2 = 0.40, n=55). The fine sand particles occupying the voids resulting from the packing of the coarse particles would result in the porosity decreasing when the proportion of fine sand particles increases up to a value that would correspond to the total infilling of that void. With a greater proportion of fine sand, the porosity would start again to increase. An increase in the silt-sand ratio would

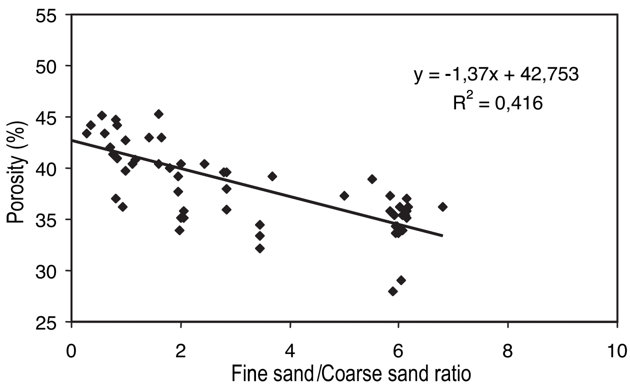

Figure 2. Relationship between the fine sand and coarse sand ratio (after Nicou, 1974; Chauvel, 1977; Coquet, 1995; Lamotte *et al*., 1997a; Nyamangara *et al*., 2001; Feng *et al*., 2002; Bortoluzzi, 2003; Bruand *et al*., 2004; Lesturgez, 2005)

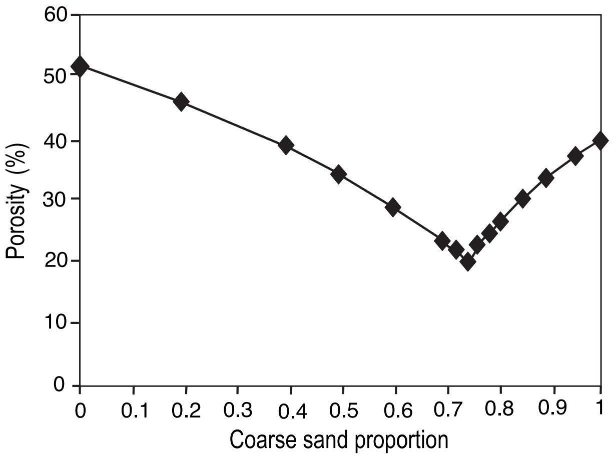

Figure 3. Porosity recorded for a mixture of silt (20-50 µm) and coarse sand (2 mm) particles according to the coarse sand proportion (modified after Fiès *et al*., 1972)

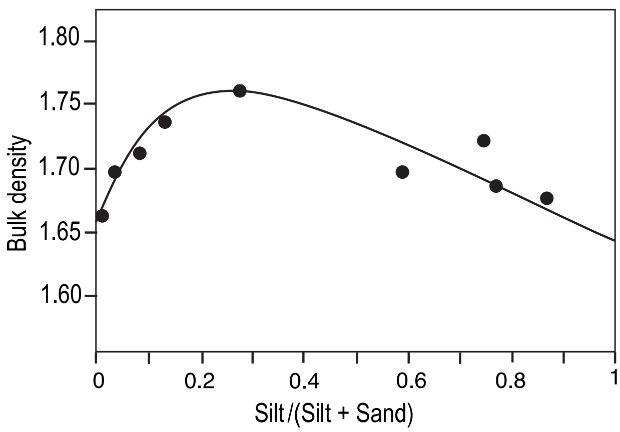

Figure 4. Bulk density recorded by Fiès and Stengel (1981) according to the proportion of silt (20-50 µm) relative to the silt and sand particles (200-2,000 µm) in soils with clay content <20% and no macroporosity

also result in a decrease in the porosity as discussed by Agrawal (1991) for Indian loamy sand and sandy loam soils.

These data recorded with soils samples are consistent with those obtained earlier with models and artificial mixtures in the laboratory (Fiès, 1971; Fiès *et al*., 1972; Panayiotopoulos and Mullins, 1985). Fiès *et al*. (1972) studied the porosity of granular binary mixture and modelled porosity according to the proportion of coarse and fine fractions. They showed that for a mixture of 20-50 µm material with grains 2 mm in diameter, the porosity is minimum (P ≈0.20) for 20-50 µm material content close to 25% (Figure 3). That proportion of fine material is consistent with the theory developed by Westman and Hugill (1930). They calculated an optimum ratio of 3.46 parts by mass of coarse sand to one part of very fine sand (i.e. 22.4% on mass basis of very fine sand) was required to obtain a mixture with the lowest porosity. Fiès and Stengel (1981) showed good concordance between porosity measured on small aggregates resulting from soil fragmentation and theoretical porosity computed with a model of binary mixtures. In particular, they showed that the porosity was at a minimum for a mixture of 2-20 µm and 200-2,000 µm when 2-20 µm content was close to 20% (Figure 4). These data indicate that the loose relationship shown in Figure 2 between the porosity and the fine sand and coarse sand ratio would be valid for a limited range of fine sand and coarse sand ratio.

Role of the clay fraction characteristics

The large range of porosity (Figure 1) is related to the small cohesion forces between elementary particles thus enabling the formation of a large range of assemblages from very loose to very compact. This is specific to sandy soils because of the small amount of clay that can act as inter-grain cement. In the tropics, clay is often low activity clay (mainly kaolinite) and for similar clay content, tropical sandy soils show usually much smaller inter-grain cohesion than sandy soils in temperate and Mediterranean regions (van Wambeke, 1992). In these deeply weathered soils, the clay-sized fraction may in part consist of quartz as observed by Hardy (1993) in soils that developed in sandy colluvial deposits in Northern Vietnam. Hardy (1993) showed that 10 to 40% of the <2 µm fraction was quartz in the soils studied. Bruand *et al.* (2004) studied sandy soils belonging to the Nam Phong series in Northeast Thailand and found that 25 to 35% of the <2 µm fraction was quartz. The presence of quartz in the <2 µm fraction contributes to its low activity. In some sandy soils, however the presence of smectitic clays can lead to very different physical soil properties. In the semi-arid tropics, Lamotte *et al*. (1997) studied soil hardening in sandy soil with contrasting loose topsoil and underlying hard horizons. The horizons had similar particle size distributions and the hardness was closely related to a fabric with clay coatings on the sand grains and clay wall-shaped bridges linking the latter. This induced a strong continuity of the solid phase with only a minimum clay content of 6%.

Hydraulic properties

Water retention properties

Sandy soils retain little water at high water potentials and water content decreases rapidly with the water potential. Panayiotopoulos and Mullins (1985) studied the water retention properties of pure sand materials varying in size (Figure 5). They showed that most water was released between -0.1 and -1kPa for a coarse sand (2,000-710 µm) and between -15 and -30 kPa for a very fine sand (125-45 µm). The limited water release osbserved for the very fine sand between saturation and -0.5 kPa was not discussed by Panayiotopoulos and Mullins (1985). Mullins and Panayiotopoulos (1984) showed that the water retention curve was only very slightly affected by the clay content for a clay content <20%. The clay used was a kaolinite. With sandy soils, two thirds of the water present at saturation is usually released at -30 kPa as recorded by Obi and Ebo (1995) in a sandy soil in Southern Nigeria. Water contents ranging from 0.20 to 0.30cm ^{3}cm $^{-3}$ and from 0.04 to 0.12cm ^{3}cm $^{-3}$ are often recorded at -33 and -1500kPa, respectively in tropical soils belonging to the sand, loamy sand and sandy loam textural class (Hodnett and Tomasella, 2002). In sandy soils, there is very little water available at matric potential <-100 kPa. Kukal and Aggarwal (2004) measured a water content of 0.16 and 0.10 cm^3 cm^{-3} at -33 and -1500kPa, respectively in a sandy loam topsoil (% clay = 10%) in India. The water content significantly increased with a slight increase in the clay content and was 0.22 and 0.13 cm^{3}cm $^{-3}$ at -33 and -1500kPa, respectively when the clay content was 14%. Osunbitam *et al*. (2005) showed in Nigeria an averaged water loss in sandy soils of 0.006mm $^{-3}$ between -100 and -150kPa, the water content at -150 kPa being 0.017mm $^{-3}$. Several studies have shown that the available water increases with the silt content (Kapilevich *et al*., 1987; Agrawal, 1991).

Tomasella and Hodnett (1998) compared the measured volumetric water content at different matric potentials and those estimated with the pedotransfer

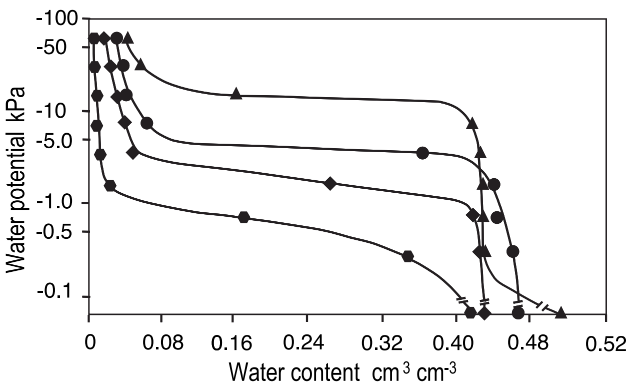

Figure 5. Water retention curves recorded for a coarse sand (hexagon, 2,000-710 µm), medium sand (diamond, 500-180 µm), fine sand (circle, 220-105 µm) and very fine sand (triangle, 125-45 µm) (modified after Panayiopoulos and Mullins, 1985)

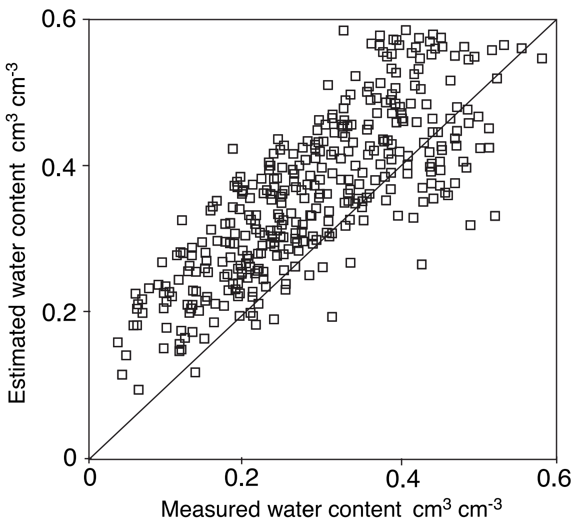

Figure 6. Comparison between measured values of volumetric water content at -33 kPa water potential and those estimated by the pedotransfert functions of Rawls *et al*. (1982) (modified after Tomasella and Hodnett, 1998)

functions (PTFs) developed by Rawls *et al*. (1992) from the USDA soil data base. They showed that these PTFs greatly overestimate the volumetric water content when applied to sandy soils of Brazilian Amazonia (Figure 6). The available water capacity measured between -5 and -1,500 kPa by Nyamangara*et al*. (2001) in Zimbabwe for topsoils with a sand content close to 90% ranged from 0.159 to 0.174 m^{3}m $^{-3}$ according to cattle manure management options.

Hydraulic conductivity

The saturated hydraulic conductivity (K_s) of sandy soils in the tropics varies within a range of values covering several orders of magnitude ($10^{-7} < K_s < 10^{-3}$ ms $^{-1}$). In a Brazilian sandy soil with very low clay contents (average content in the whole profile of 0.25%), Prevedello *et al*. (1995) measured $1.1 \times 10^{-6} < K_s < 7.5 \times 10^{-5}$ m s^{-1}. Contrasting this in another Brazilian sandy soil with only a slight change in clay content (average content in the whole profile of 6%), Faria and Caramoni (1986) measured $1.5 \times 10^{-5} < K_s < 2.8 \times 10^{-4}$ m s^{-1}.

In soils, K_s varies according to the development of the macroporosity. As a consequence, K_s variation is more closely related to the macroporosity development rather than to soil texture. Thus, most studies try to relate K_s to part of the macroporosity that is called effective porosity (Φ_e) and defined as total porosity, Φ minus the water content at -33 kPa (Ahuja *et al*., 1984). K_s and Φ_e are related as following:

$$K_s = B(\Phi_e)^n$$

with *B* and *n*, are two parameters varying with the soil characteristics. These parameters were obtained by Tomasella and Hodnett (1997) for Brazilian tropical soils. They found log *B*=4.752 and *n*=4.536 for the soils studied by Predevello *et al*. (1995) and log *B*=4.758 and *n*=4.532 for soils studied by Faria and Caramoni (1986). These soils were also used by Tomasella and Hodnett (1997) to derive parameters of the Brook-Corey/Mualem model for unsaturated hydraulic conductivity.

However when cultivated, the macroporosity of sandy soils is very unstable and collapses rapidly in the presence of water. Thus, the measurement of K_s becomes difficult to perform without modifying the macroporosity that have a tremendous effect on K_s. This probably explains why many studies do not report a large range of K_s variation between field experimental treatments and with time as expected. Thus Osunbitan *et al*. (2005) recorded $5.5 < K_s < 7.5 \times 10^{-5}$ ms $^{-1}$ in a topsoil under different tillage treatments. The K_s difference recorded by these authors between the different treatments (1×10^{-5} ms $^{-1}$) was small and similar to the differences recorded under the same tillage treatment over a period of 8 weeks.

Unsaturated hydraulic conductivity (K_θ) of Brazilian sandy soils was also discussed by Tomasella and Hodnett (1997) (Figure 7).

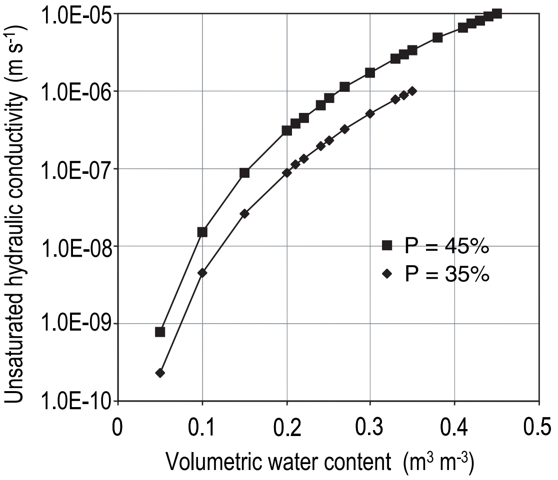

Figure 7. Unsaturated hydraulic conductivity for a sandy soil with a porosity of 45 and 35% (computed after the data published by Tomasella and Hodnett, 1995)

Surface crusting and water infiltration

Because of the very small inter-particle cohesion that results in a very small aggregate stability, sandy soils are highly sensitive to surface crusting, thus explaining the large number of papers in this area (e.g. Chartres, 1992; Casenave and Valentin, 1992; Isbell, 1995; Bielders and Baveye, 1995a; Valentin and Bresson, 1998; Malan Issa *et al*., 1999; Duan et al., 2003; Eldridge and Leys, 2003; Janneau *et al*., 2003; Goossens, 2004;). Crusts protect the soil surface from wind and interrill erosion but they also favour runoff and consequently rill and gully erosion (Valentin and Bresson, 1998). Two main types of structural crusts were recognised in sandy soils depending on the dominant forming process (Casenave and Valentin, 1992; Valentin and Bresson, 1992; Janeau *et al*., 2003): (i) sieving crusts made of well sorted micro-layers with average infiltrability of approximately 30 mmh $^{-1}$, (ii) and packing crusts made of sand grains closely packed with average infiltrability of 10 mmh $^{-1}$. Bielders and Baveye (1995b) studied in the laboratory the processes of structural crust formation on coarse textured soils. They proposed that the formation of clay-band in sieving structural crusts would be initiated by the displacement of micro-aggregates or other small particles from the above washed-out layer, followed by their accumulation due to mechanical straining. Erosion crusts that result from smoothening and erosion of structural crusts and depositional crusts that result from sedimentation were also described (Valentin and Bresson, 1998). They exhibit more restrictive infiltrability (2-5 mm h $^{-1}$) than structural crusts.

The development of crusts leads to runoff that can be quite significant. Sombatpanit *et al*. (1995) measured between 300 and 400mm of runof f that corresponded to about 35% of the rainfall on bare sandy soils in Thailand with 25 to 70 tha $^{-1}$ of soil loss. Runoff was still between 10 and 20% of the rainfall under different agricultural treatments.

Surface infiltrability can also be reduced in sandy soils by repellency. Indeed, sandy soils are particularly susceptible to water repellency and susceptibility increases with the duration of the dry season. Repellency is responsible for vertical fingered flow in sandy soils because of the presence of repellent soil volumes with hydrophobic organic matter (Roberts and Crabon, 1972; Dekker and Ritsema, 1994; Ritsema and Dekker, 1994). Study of repellent soils in arid and humid climates showed that repellency would be much more related to the type of organic matter than to the duration of the dry period (Jaramillo *et al*., 2000).

Compaction

Sensitivity to soil compaction

Unlike other soils, the structure of sandy soils can be easily affected by mechanical compaction over a large range of scales. Usually mechanical compaction preferentially affects large pores (i.e. macropores that result from tillage and biological activity) but in sandy soils it affects these large pores down to the small pores that result from the arrangement of the skeleton particles (sand and silt) within the clay fraction. That re-arrangement when submitted to mechanical compaction is possible because of the small cohesion between the skeleton particles. For narrowly graded pure sand materials, Panayiotopoulos and Mullins (1985) showed that these air-dry and nearly saturated sands were always found to pack more closely under a given load than the same sand at any water content.

Very small porosity can be recorded under wheel tracks and just underneath the tilled layer. Thus, Bennie and Botha (1986) recorded $1.7 < D_b < 1.8 gcm^{-3}$ in the 0-20 cm layer under wheel tracks and in the 20-40 cm layer. Because of this small inter-particle cohesion, high bulk density is also recorded when sandy soils are puddled in rice-wheat cropping systems. Thus, Aggarwal *et al.* (1995) recorded $1.75 < D_b < 1.82 gcm^{-3}$ in the 15-20 cm layer after several years of high puddling in a sandy loam soil.

Smith *et al*. (1997a) studied the effect of soil compaction on a large range of South African forestry soils. They showed on soil cores in the laboratory that the porosity after compaction of sandy loam and loamy sand soils was related to the size distribution of the sand fraction and tended to decrease with the increase in the clay and silt content. Smith *et al*. (1997b) showed for loamy sand that increases in compaction were almost independent of the water content and then almost entirely due to increasing applied pressure alone. Smith *et al*. (1997c) also recorded a high compactibility for sandy soils derived from sandstone, granite and aeolian sands. The maximum bulk density was related to the loss in mass after ignition at 450°C.

Penetration resistance

Increases in bulk density invariably results in an increase in the penetration resistance with significant consequences for root development although there no clear relationship with the penetration resistance (Mullins *et al*., 1987; Bengough and Mullins, 1991). Critical values that severely restrict root growth have been estimated to vary from <1 to >4 MPa depending on the soil, water content and crop type (Greacen *et al*., 1968). Indeed, the penetration resistance varies within a large range of values according to the soil water content without any variation of the other soil characteristics (e.g. particle size distribution, mineralogy, porosity, assemblage of the elementary particles). It is significantly inversely related to water content. Many penetration resistances published in the literature for sandy soils range between 0.1 and 0.8 MPa but the water content at which they were determined often remains unclear (Osunbitan *et al*., 2005). Bruand *et al.* (2005) recorded a penetration resistance ranging from 0.35 to 0.55MPa in the subsoil of a sandy soil in Thailand when the water content ranged from 0.03 to 0.09kgkg $^{-1}$ (Figure 8). In South African sandy soils that developed in aeolian sand, Du Preez *et al*. (1981) measured penetration resistance >1.5MPa, at field moisture capacity, in a ploughed layer under wheel tracks. In these soils Bennie and Botha (1986) confirmed the presence of such values of resistance to penetration in the subsoil and showed that they result from compaction because of traffic that leads to an increase in the penetration resistance that restricts root development for wheat and maize. Kukal and Aggarwal (2003) measured much greater penetration resistance in a sandy loam soil after puddling because of subsurface compaction. Indeed, these authors recorded at field capacity a penetration resistance ranging from 3.0 to 4.5 MPa in the compacted layer.

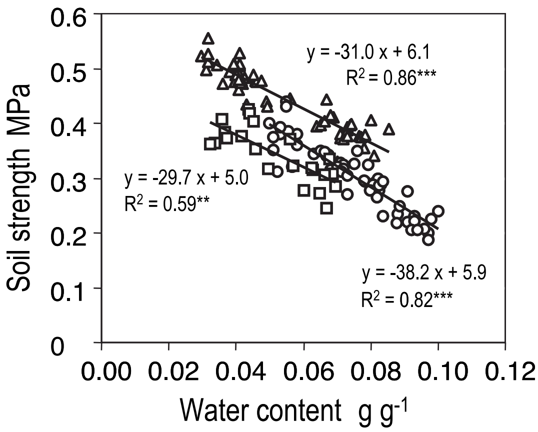

Figure 8. Resistance to penetration expressed as unconfined strength with respect to water content in the Ap (square), E (circle) and Bt (triangle) horizons. (modified after Bruand et al., 2005)

In their study, Smith *et al*. (1997a) showed on compressed soil cores only small differences in strength development across a wide range of water content for a loamy sand soil. This would be related to the contribution of frictional rather than cohesion forces to resistance to penetration (Smith *et al*., 1997a). On the other hand, results also showed somewhat different behaviour for a sandy loam soil, resistance to penetration increasing from 1 to 5 MPa over a range of water content of only 4% by mass. This large range of resistance to penetration would result from the contribution of cohesion forces that are partly related to the water content. Thus, a decrease in water content would increase frictional and cohesion forces from field capacity to intermediate water content, smaller water contents increasing the frictional forces alone, the cohesion forces disappearing, thus explaining the results recorded in Nigeria by Ley *et al*. (1995) on a large range of soils including sandy soils.

Effect of combined deep tillage and controlled traffic on penetration resistance and its consequences for root growth has been studied in several countries. In their one-year study, Bennie and Botha (1986) showed that deep ripping and controlled traffic led to a significant increase in rooting depth, rooting density in the subsoil, water use efficiency and yield increases of 30% for maize and 19% for wheat. Increased yields were recorded in many earlier studies after deep tillage (e.g. Reicosky *et al*., 1976; Bennie *et al*., 1985) but the duration of the positive effects of deep tillage is still under discussion. Slotting was also used to loosen the subsoil in sandy soils of Northeast Thailand and thus promoted rooting (Jayardanne *et al*., 1995). Hartmann *et al*. (1999) showed that rooting depth and yield of various crops were increased for two successive years after slotting. Lesturgez (2005) recorded a significant increase in root density in the slot that enables a better subsoil exploitation. Lesturgez *et al*. (2004) also investigated the potential use of forage legume *Stylosanthes hamata* (stylo) to ameliorate the structure of compact layers in sandy soils of Northeast Thailand. They showed that after 24 months of continuous stylo, roots were able to penetrate the compact subsoil, resulting in an improvement of its macroporosity. They also showed that a subsequent maize crop developed a deep and extensive root system using the macropores.

Hardsetting in sandy soils

Many tropical sandy soils are potentially hardsetting soils, i.e. they can become compact, hard with apparently apedal condition prevailing on drying (Northcote, 1979). In these soils, a significant increase in soil strength is recorded over very narrow water content changes within the plant available range of soil water potential (-10^2 to -10^3kPa) with resulting adverse effects on root growth and crop production (Mullins *et al*., 1990). Thus, Chan (1995) measured strength characteristics in sandy loam hardsetting soil in the semi-arid region of Australia and showed that in the cultivated soil strength increased from 0.02 to 0.09 MPa with decreasing water content from 0.11 to 0.04 kgkg^{-1} when there was no strength variation under permanent pasture. McKyes *et al*. (1994) studied the cohesion and friction in two sandy-loam hardsetting soils from Zimbabwe. They showed that the cohesion changed from nearly zero at saturation to well over 0.1 MPa in the field dry state. Young and Mullins (1991) suggested that the amount of <60 µm particles rather than solely the <2 µm is important in causing the development of hardsetting properties.

High soil strength in sandy soils can be also partly related to the development silica precipitation that forms globules and silica flowers over the sand grains (Lesturgez, 2005). These precipitations would not be responsible for a cementation of the sand and silt grains but would lead to an increase in particle contacts and frictions, thus explaining the increase in soil strength recorded.

Controlled compaction

Compaction in sandy soils was also discussed as a possible water and nutrient management to improve water retention properties and reduce nutrient leaching in Indian sandy soils (Agrawal and Kunar, 1976; Agrawal *et al*., 1987; Agrawal, 1991; Arora *et al*., 2005). Indeed, according to these authors, compaction that reduces the volume and continuity of large pores, would increase water retention and reduce water infiltration and saturated hydraulic conductivity in highly permeable deep sandy soils. Compaction would save irrigation water by 15-36% and increase productivity by 30-50%.

Puddling is also used to reduce high percolation losses of irrigation water and nutrient leaching when cultivated for rice production (Aggarwal *et al*., 1995; Arora *et al*., 1995). Sharma and Bhagat (1993) showed that puddling was effective in reducing percolation losses when sand was less than 70%, and finer fractions were dominated by clay (13-20%). Puddling has been reported to decrease saturated hydraulic conductivity of the puddled layer (0-10cm) of sandy loam soil from 1.810^{-7}ms^{-1} in unpuddled to 4.210^{-8}ms^{-1} with medium puddling and 2.510^{-8}ms^{-1} with highly puddle soils (Kukal and Aggarwal, 2002). Kukal and Aggarwal (2003b) showed in a sandy loam soil that puddling reduced percolation losses by 14-16% with the increase in puddling intensity from medium to high, whereas the amount of irrigation water required decreased by 15-25%. Similar results were recorded by Kukal and Sidhu (2004) in another sandy loam soil in India.

However, puddling in rice-wheat cropping systems leads to some adverse effects for the following wheat crop that requires to be managed with appropriate tillage techniques (Aggarwal *et al*., 1995; Kukal and Aggarwal, 2003a; Arora *et al*., 2005).

A yield decline of wheat is often recorded because of subsurface compaction (1.70 <D_b <1.75 gcm $^{-3}$) at 14-20 cm depth under normal puddling at normal depth. Kukal and Aggarwal (2003a) showed in India for a sandy loam soil that puddling at shallow depth (5-6 cm) led to the development of a compact layer at 10-12 cm depth that was loosened (1.50 <D_b <1.55 g cm^{-3}) during normal cultivation for wheat seedbed preparation

Conclusion

In the tropics, physical attributes of sandy soils are particularly sensitive to both the sand and silt size distribution and mineralogy of the clay fraction. Because of the presence of low activity clay in most sandy soils, the assemblage of elementary skeleton particles is highly unstable resulting in a high instability with respect to structure from the microscopic to macroscopic scale. When for a variety reasons, the assemblage collapses, the resulting porosity and penetration resistance would be all the greater as the skeleton particle distribution is heterometric.

In contrast, in sandy soils unlike other soils, the elementary fabric can be easily loosened by tillage practices. Thus greater porosity can be produced easily by tillage but its stability is very weak and compaction by wheels or other actions can produce a dense structure with adverse physical properties. This leads to a decrease in the water retention properties and hydraulic conductivity, an increase in the resistance to penetration and sensitivity to surface crusting.

More generally, tropical sandy soils, more than other soils, require careful management in an environmentally friendly manner. Indeed, even if most physical degradation processes are more easily reversible in tropical sandy soils than in other soils, the physical fertility of these soils is weak. These soils require very little tillage operations in the wrong way to produce significant adverse consequences for plant development and consequently for crop yield and environment.

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Compaction processes in a tilled sandy soil

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Keyword: sandy soil, oedometer, compaction, hydrocollapse, rearrangement

Abstract

Sandy soils are often considered as structurally inert because of their massive structure and the absence of shrink-swell properties. Frequent and severe compaction observed in agricultural fields raises the question of the processes and factors that control soil compaction and its reversibility. In the sandy upland soils of Northeast Thailand, subsoil compaction (20-40 cm) is a common feature that impairs root development and therefore is responsible for low crop production. The objective of this study was to determine the processes and factors that control soil compaction in order to improve soil management practices. Oedometer tests were conducted on aggregate beds. An initial loose layer was prepared and was subsequently submitted to a compression pressure. Two parameters were controlled: (i) the mechanical compression pressure, and (ii) the water content. A first series of experiments was carried out on aggregate beds (i) under dry conditions, (ii) under wet conditions, and (iii) by wetting dry samples under constant compression pressures. A second series of experiments dealt with the application of compression-relaxation pressures to understand their role on soil particle re-arrangement and to characterize soil elasticity.

Wet and dry compression curves appeared as envelopes delimiting the subsidence range. Results showed that soil structure collapsed almost entirely under low pressure and the phenomenon started at very low water content. The subsequent compression-relaxation curves showed the absence of soil elasticity.

We used theses results as a framework to understand sandy soil behaviour in the field. The results can explain why sandy soils are easily and inevitably compactable even under reduced traffic load. Because of low soil elasticity and the close contact between the soil particles after compaction, we suggest that a small bulk density increase can result in a high increase in penetration resistance, even in wet conditions. We conclude that alternative and adapted techniques such as slotting or biological drilling are options to manage the sandy soils in order to preserve or even improve their physical properties.

Introduction

Soil compaction in agricultural systems is a worldwide concern and has received considerable attention over the past decades (Soane and van Ouwerkerk, 1994; Hamza and Anderson, 2005). Soil compaction is defined as: “the process by which soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density” (Soil Science Society of America, 1996). The vast majority of soil compaction in modern agriculture is often attributed to heavy machinery and traffic load (Flowers and Lal, 1998). However other processes can be involved and soil compaction may occur without traffic load on soil surface. For example, the formation of a dense subsoil layer known as “fragipan” is interpreted by soil collapse under its own weight. This process occurs when a metastable arrangement of particles is wetted under a constant confining pressure (weight of the top layer in the case of natural collapse) (Assallay *et al.*, 1997; 1998).

Sandy soils are often considered as structurally inert because of their weak structure and the absence of shrink-swell properties but frequent and severe compaction observed in agricultural fields raises the question of the processes and factors that control soil compaction and its reversibility. In the sandy upland soils of Northeast Thailand, subsoil compaction (20-40 cm) is a common feature that impairs root

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development and therefore is responsible for low crop production (Bruand *et al.*, 2004). Comparisons between forest and adjacent cultivated area have proved that the compact layer commonly observed in agricultural fields was induced by intensive agriculture of the last decades (Lesturgez, 2005). Sandy soils of the region have developed mainly from light textured aeolian material (Boonsener, 1991) well known for its problematic characteristics for engineering works (Udomchoke, 1991; Kohgo *et al.*, 2000). On the other hand, deep ploughing and subsoiling have always been inefficient in overcoming this compaction in agricultural systems since soil re-compacts after the first heavy rain. This suggest that collapsibility is a key factor not only in deep profiles but also in the superficial and tilled layers (Hartmann *et al.*, 1999; Hartmann *et al.*, 2002).

Compaction of aggregates beds in a dry state, hydrocollapse (also known as hydroconsolidation) and load-upload cycles under the same pressure (traffic load conditions), can be involved in the formation or the reformation of a compact layer. The objective of the study was to investigate the processes of soil compaction in a tilled sandy soil subjected to non-flooding rains and evaluate their respective contribution to total soil compaction. Experiments focussed on uniaxial compactability, hydrocollapse and rearrangement under traffic load.

Material and methods

Soil characteristics and sampling

The samples were collected in a sugarcane field located in Ban Phai District, 40-km from Khon Kaen City, Northeast Thailand (16°08′N, 102°44′E). The choice of the site was based on a previous investigation that highlighted the presence of a compact layer located at 20-40 cm depth that was representative of the general situation of subsoil compaction (Lesturgez, 2005). The soil has a sandy texture with no or very weak structure. It belongs to the Nam Phong soil series (Imsamut and Boonsompoppan, 1999) and was classified as a loamy, siliceous, isohyperthermic Arenic Haplustalf (Soil Survey Staff, 1998) or Arenic Acrisol (FAO, 1998). Three undisturbed samples were collected from the vertical face of a pit, respectively in the topsoil (0-15 cm), in the compact subsoil (15-25 cm) and underneath the compact layer (40-50cm). Selected chemical and physical characteristics of the samples are presented in Table1. Mineralogical characteristics of the studied soil were investigated using X-ray diffraction. When the sand and silt fractions were exclusively constituted of quartz, the clay fraction included kaolinite, traces of illite and a significant proportion of small quartz particles. The three samples were identical in their mineralogy and the particle size distribution of the sand fraction. They differed only in their clay content (from 70gkg $^{-1}$ in the topsoil to 136 g kg^{-1} in the deepest layer). A last sample (pure sand material) was prepared from the topsoil horizon by sieving the >50 µm material from the whole soil after dispersion in sodium hexametaphosphate.

Sample preparation

The samples were manually crumbled in the laboratory in order to produce small aggregates similar to tillage-induced aggregates. The aggregates were poured into a ring 50mm in diameter, and 18mm in height placed on a porous plate using a small funnel fixed 5-cm above the middle of the ring. The ring was overfilled, then the surface was carefully levelled off, and the assemblage thoroughly cleaned with a small brush. The assemblage was then installed in the oedometer and the top cap gently positioned. Preliminary tests had shown that the preparation of the aggregate beds using this method allowed the formation of a metastable arrangement of aggregates with a bulk density similar to that of the topsoil after ploughing.

Design of the oedometer apparatus

The oedometer test is classically used for consolidation and compression studies of fine-grained soil samples, such as clays and silts, since it recreates the conditions of volume change with zero lateral strain (i.e. one-dimensional compression). The oedometer apparatus used (Figure 1) allows the application of an axial load that ranges from 0 to 1,500 kPa. We applied a range of 29 pressure steps (2, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 150, 200, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,100, 1,300 and 1,500 kPa), with 5 minutes interval between each step (minimum duration to reach equilibrium). The change in volume of the samples was recorded continuously by measuring the vertical displacement of the rigid top platen used to apply the load. The design of the apparatus allows the injection of water on the top of the sample. Drainage was free through the porous plate located below the sample. The volume of water injected into and drained from the samples can also be recorded. Bulk density and average water content were derived from these measurements. The background noise of the oedometer originating from internal deformation (porous plates) and elasticity of the

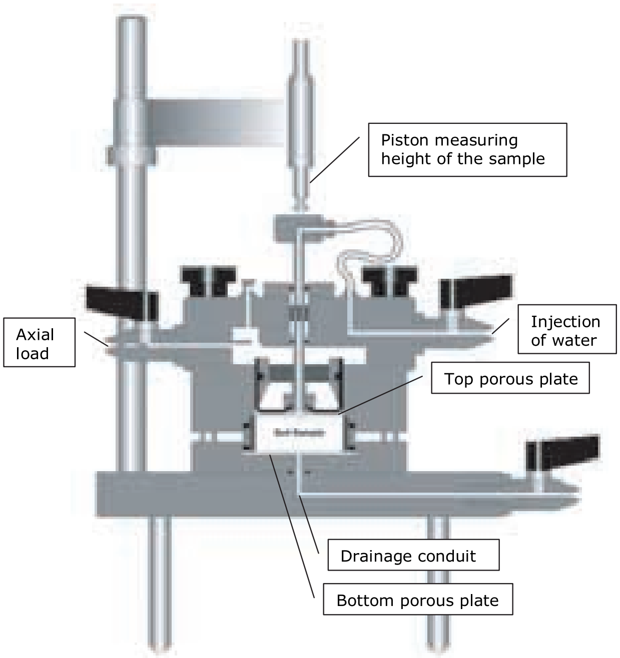

Figure 1. Oedometer apparatus

membrane was estimated during preliminary tests on uncompressible Plexiglas cylinders and results were corrected accordingly.

We used the following experiment to characterize the compaction in dry and wet conditions:

(a) To characterize the behaviour in dry conditions, an air-dried aggregate bed of the control and the three horizons was prepared with five replicates. The series of pressure steps was applied and the changes in bulk density recorded.

(b) To characterize the behaviour in a wet state, an identical set of aggregate beds was prepared. The beds were saturated by injecting water under no load until drainage began at the bottom of the samples. The series of pressure steps was then applied while the samples were kept saturated in a free draining state. The changes in bulk density were continuously recorded.

Hydroconsolidation tests

Hydroconsolidation is characterised by an abrupt change in bulk density of samples loaded at their *in situ* water content and then flooded. Hydroconsolidation under a constant load P_w was studied in a three-stage test:

(a) Air-dried samples (5 repetitions for each depth) were loaded step by step to a constant load P_w of 2, 100, 500 and 1,500kPa.

(b) While the axial load P_w was maintained on the sample, water was injected at 50mm ^{3}min $^{-1}$ through the porous plate located on the top of the sample until drainage started at the bottom of the porous plate.

(c) The load was then increased step by step on the wet samples from P_w to 1,500kPa. Water continued to be added freely at no pressure to keep the sample wet until the end of the test.

Compression-relaxation tests

The purpose of this test was to characterise subsequent compaction (i.e. rearrangement processes) under a series of identical axial loads in wet conditions. The test consisted of a series of compressions/ relaxations applied on wet samples:

(a) Five samples of each horizon were saturated and then loaded step by step to create stresses P_R of 100, 500 and 1,500kPa. Water was added freely at no pressure to keep the samples wet throughout the test.

(b) A series of 70 cycles of compression (P_R) and relaxation (0 kPa) was applied on the wet samples. Bulk density was continuously recorded.

Results

Figure 2 presents the compaction curves using the classical compaction approach. Both dry and wet bulk density measurements are presented as a function of axial load. For the pure sand, compaction due to axial load was very low over the range of pressures and there was no significant difference between dry and wet curve (Figure 2-a). Compaction was low and highly heterogeneous between replicates for the three soil samples up to 25kPa. There was no significant difference between the dry and wet samples in this range of pressures (Figure 2-b, c, d). Bulk density increased sharply above 25kPa and became more homogeneous. Beyond 100 kPa, the bulk density increased with depth for any given load all soil samples (Figure 2-b, c, d). At 1,500kPa the dry bulk densities reached 1.60, 1.63 and 1.69 Mg.m^3 for the 0-15, 15-25 and 40-50cm depths, respectively .

Figure 3 presents the results of the hydro-consolidation test on the pure sand material. The compaction either in the dry or wet state was almost insignificant and there was no significant difference between the dry curve and the wet curve at any pressure. Therefore, the collapse was insignificant.

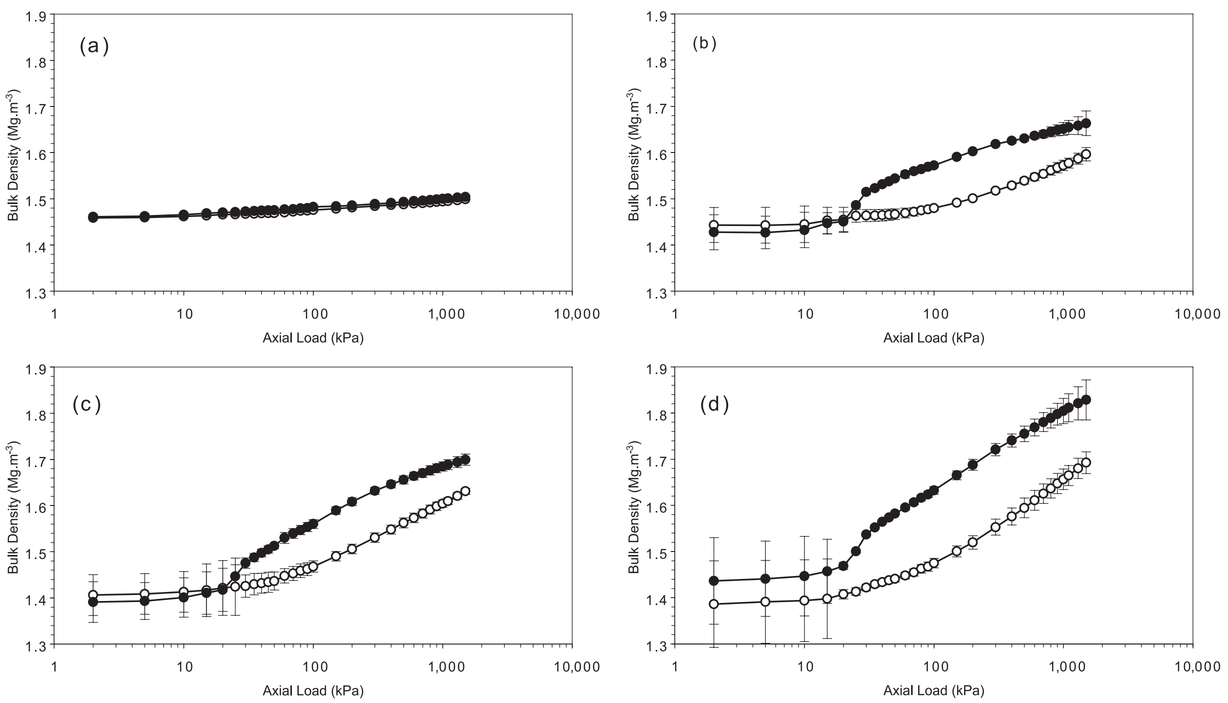

Figure 2. Air-dried (–○–) and wet (–●–) compaction curves for (a) sand fraction, (b) 0-15 cm, (c) 25-35 cm, and (d) 40-50 cm. Average and standard deviation (n = 5)

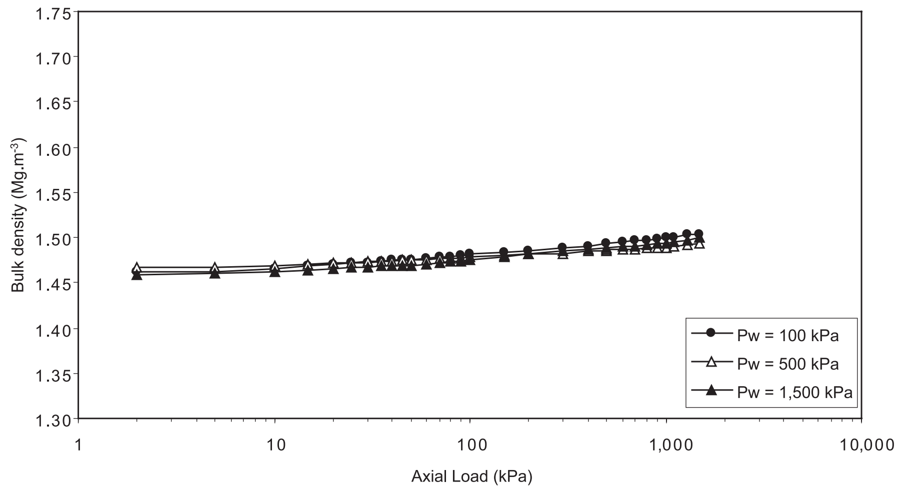

Figure 3. Hydrocollapse curves for pure sand material

Figure 4 presents the results of the hydroconsolidation test together with the results of the compaction test for the 25-35cm depth layer. Collapse resulting from water injection (represented on the chart as white arrows), always resulted in a final bulk density between the dry and the wet compaction values. The increase in bulk density as a result of hydrocollapse was quite similar over the range 50 <Pw <1,500kPa, even though the largest bulk density change was recorded for an axial load of 100kPa. The bulk density after hydrocollapse was sometimes significantly lower than that of the wet curve ($P < 0.05$). However, the difference was no more significant when the loads were increased after hydrocollapse had occurred. As the dry and wet compaction curves tend to get closer at high pressure, we can assume that for very high loads, no more collapse will occur.

Figure 5 presents the changes in bulk density with increasing water content at constant load (P_w= 1,500 kPa) for the three soil horizons.Two replicates are presented for each depth as a means to highlight heterogeneity. In agreement with the compaction in wet conditions, the lowest collapse was recorded for the 0-15cm depth sample, and the intensity of collapse increased with depth. Collapse always occurred in a range of gravimetric soil moisture between 5 and 15%.

Figure 6 presents the compression-relaxation curves. The bulk density increased by at least 0.1T .m^{-3} at P_R=1,500kPa from the initial compaction to the end of rearrangement cycles. The soil samples presented significant elasticity. The material recovered a significant proportion of the porosity when the axial pressure was relaxed but some of the deformation is

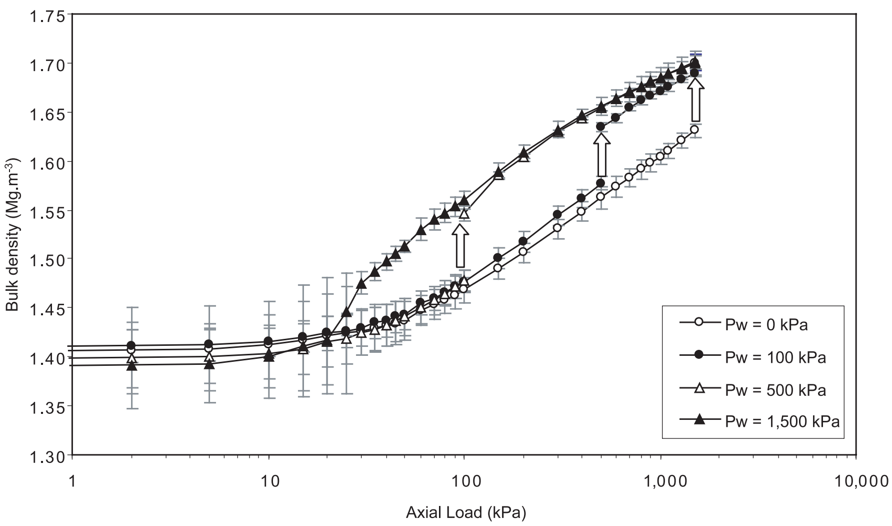

Figure 4. Hydrocollapse curves for 23-35 cm soil sample

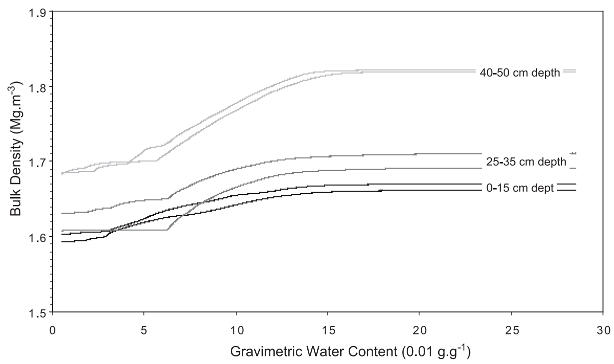

Figure 5. Bulk density versus depth during collapse at Pw = 1,500 kPa

non-reversible and the bulk density increased for each cycle. The deformation intensity decreased as the number of cycles increased. The rearrangement intensity increased with depth. Similar results were obtain at P_R=100 and 500kPa (data not shown).

Discussion

Compaction of the pure sand

For the pure sand, the sensitivity to compaction, in dry and in wet conditions as well, was very small and can be considered as being independent of the applied pressure (Figure 4). The sand grains did not reorganize under pressure, even when wet. This result suggests that the lubricant effect of the water was ineffective in the case of this material. Two factors can explain this unusual behaviour. Firstly, the bulk density was already 1.46T m $^{-3}$ at the beginning of the experiment, probably because the size of the sand grains was distributed over a large range (Table 1). Secondly, most sand grains had a jagged shape according to them aeolian origin, that probably resulted in interlocking between the grains (Lesturgez, 2005).

Compaction of soil samples

In contrast, the compaction curves recorded with the soil samples in wet condition proved that the same sandy material mixed together with clay and silt was highly compactable. In dry conditions compaction started at around 25kPa and increased with increasing pressure until 1,500kPa. In the case of aggregate beds, collapse was in part the consequence of the deformation of the aggregates (Faure, 1976). This process was not active in the pure sand material under study because aggregates were absent. Dry compaction may in part result from the deformation of clay particles. However, the contribution of this process must be limited, given the low clay content of the material (Table 1) and the high proportion of quartz grains within the clay fraction (Bruand *et al.*, 2004). The major contributing factor associated with compaction was probably due to lubrication, the planar-shaped clay minerals helping the sand grains slip against each other.

Hydrocollapse

When water is injected in the samples, hydrocollapse proved to be a phenomenon that

Table 1. Selected physical and chemical properties of the soil at the study site

	Particle size distribution (g kg^{-1}) *mesh equivalent diameter in µm*							pH	CEC ($cmol_c$ kg^{-1})	BD (Mg m^{-3})	
	<2	2-20	20-50	50-200	200-500	500-1,000	1,000-2,000			Mean	SD
10-15 cm	70	81	122	614	100	11	2	6.1	3.2	1.61	0.13
25-35 cm	86	87	122	601	94	8	2	5.6	3.0	1.75	0.04
40-50 cm	136	88	115	565	86	8	2	4.6	3.9	1.67	0.02

CEC is cation-exchange capacity measured in cobalt-hexamine, BD is dry bulk density measured in the field using cylinders and SD is standard deviation (n = 5).

developed fully under constant pressure and at any given pressure (Figure 3). Indeed, whatever the initial pressure, the final bulk density was almost identical to the bulk density obtained by compaction in wet conditions. This result, consistent with the observations of Assallay *et al.* (1998) on loess materials, has a direct application in predicting the collapse. Maximum collapse under any load can indeed be estimated by the difference between the dry and wet compaction curves under the considered load. Maximum hydrocollapse was recorded for P_w=200kPa, close to the value of 100kPa observed by Assouline *et al.* (1997) on aggregate beds. It has been shown in aeolian deposits that collapse needed a small amount of clay to develop (Rogers *et al.*, 1994), and that collapse intensity increased with clay content up to 25% clay (Assallay *et al*., 1998). The same increase in hydrocollapse with clay content was observed in this experiment, but the range of clay content covered by the three samples was not sufficient to determine a maximum value. The increase in water content with clay content for hydrocollapse to develop (Figure 5) suggests that the process is related to the hydration of the clay minerals. Faure (1976) mentioned the importance of the clay fraction in compaction of sandy soil and introduced the notion of water potential and clay hydration. In the three horizons hydrocollapse started between 3 and 7% of gravimetric water content. This low water content proves that the phenomenon becomes active in any horizon as soon as it gets wet. The samples presented a mechanical behaviour similar to metastable deposits (Assallay et al., 1997). These properties, usually associated with loess and loess-like deposits (Jefferson et al., 2003), are therefore not confined to silty materials and develop also in sandy soils.

Compression-relaxation cycles

The mathematical description of soil compaction is based on relationships between bulk density and applied stress (Assouline, 2002). This approach assumes that after a sample has been consolidated under a pressure P_1, the consolidation would resume only for a pressure $P_2 > P_1$ (Guérif, 1982). This theory is not applicable to the results of this study as a series of successive stresses under the same axial load resulted in a substantial increase in bulk density (Figure 6). The relaxation between successive stresses allowed the internal friction between sand grains to decrease and therefore permitted the network of forces to reorganise during the next axial load, leading to increased bulk density. The asymptotic shape of the curve showed the development of the soil structure towards the highest possible bulk density. The

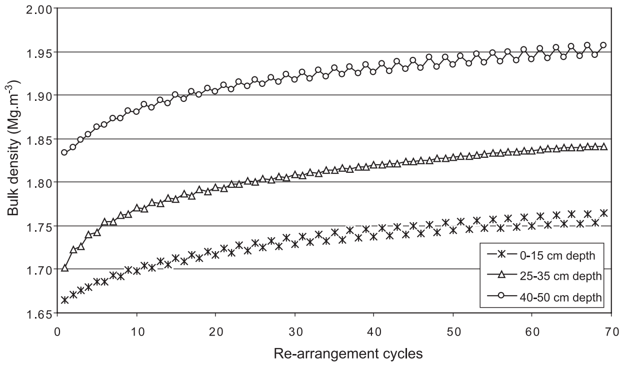

Figure 6. Bulk density during compression-relaxation cycles (0-1,500kPa)

rearrangement test in a wet state is probably the most representative test to simulate vehicle traffic load as it models as series of confined uniaxial stresses under the same pressure.

Contribution of the different processes to total soil compaction

The contribution of dry compaction, hydrocollapse and compression-relaxation cycles to bulk density increase was estimated from our results at a load of 1,500kPa. The last series, namely “field” is the bulk density measured in the field using cylinders (Figure 7). The effect of the three processes on bulk density increased with clay content. However, the contribution of the three processes to bulk density increase remained similar in relative value whatever the clay content. Dry compaction represented around 50% of total compaction, when hydrocollapse and rearrangement ranged between 20 and 30%. In the field dry compaction and hydrocollapse under low pressure (weight of the upper soil horizons) are the first two processes to develop after tillage. The many tillage operations usual in the region induce through a succession of traffic loads, rearranges the fabric to produce the usual massive aspect of the soil with high bulk density. The close lay out of grains, with small particles filling the voids left between bigger ones, has been described by Bruand *et al.* (2004) as the main factor of high resistance to penetration of the compact layer. Finally, as soil sensitivity to compaction increases with clay content and clay content increases with depth, the most sensitive horizons are the deepest. As a consequence the deeper the soil tillage, the higher is the risk of compaction and the final density. The bulk density is highest in the 20-40cm layer probably because this layer supports the wheels of the tractors during ploughing (at least three times a year). Surface axial load due to vehicle traffic may also be transmitted to subsoil horizons through the massive and often dry

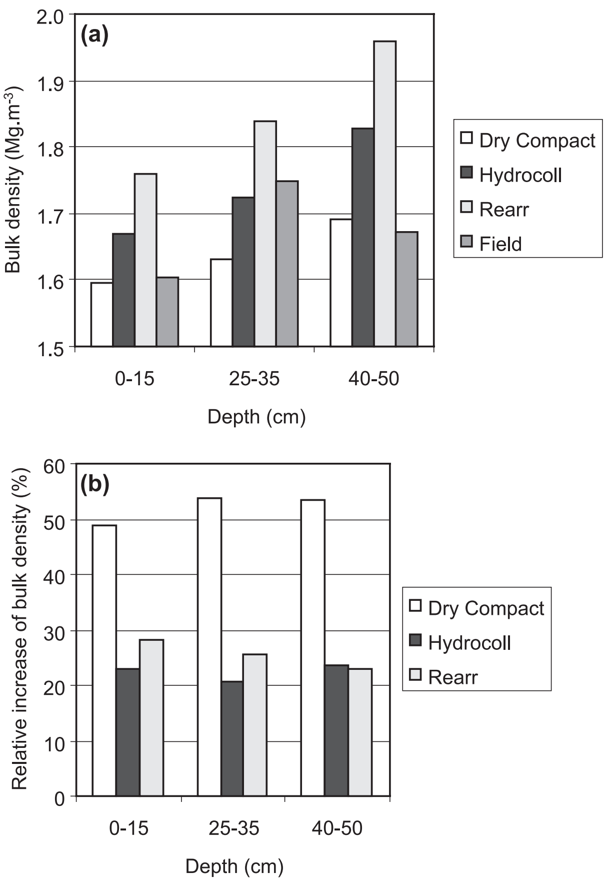

Figure 7. Dry compaction, hydroconsolidation and rearrangement (compression-relaxation cycles for each depth at Pw = 1,500 kPa

topsoil, increasing bulk density through rearrangement processes. In the field the highest bulk density values were recorded in the 20-40 cm (Figure 7) depth interval despite the higher sensitivity to compaction of the lower horizon (Figure 2). Two kinds of tillage operations are to distinguish: frequent tillage of the 0-20 cm interval depth and some punctual deep tillage operations with the objective to break the compact layer. As the soil is highly collapsible and sensitive to rearrangement, the density of the post-tilled layer reach inevitably high values as a function of time. The frequency of tillage in the topsoil (0-20cm) does not allow high density as in the 20-40cm interval depth as the structure return frequently to the tilled state. However, the 20-40cm interval depth benefits as it has the enough time to accumulate the combine effect of the traffic load. As for the lower layers (>40 cm depth), tillage operation have never change organisation of the structure and if aggregates beds from this layer are highly sensitive, the actual weakly developed structure is stable. It has been shown that tilled layers are much more sensitive to compaction than massively structured or already compacted subsoil (Schäfer-Landefeld *et al.*, 2004). Porosity of this layer is mainly constituted of biopores which are usually stable because they develop in a stable structure (Dexter, 1987; Bruand *et al.*, 1996). These results suggest that the deeper the soil is tilled, the higher is the risk in obtaining high bulk densities. Deep tillage is therefore not an option to rehabilitate compact subsoils due to the instability of the resulting structure. However, alternative techniques such as slotting (Hartmann *et al.*, 1999) or biological drilling (Lesturgez *et al.*, 2004) have proved to be efficient is such unstable soils. These techniques ensure the development of pathway for the roots through the compact layer and preserve the massive and stable structure surrounding them.

Conclusions

The compaction of the sandy material studied under uniaxial load was trivial, even in wet conditions. The same material was highly sensitive to compaction when mixed with silt and clay. The sensitivity to compaction increased with increasing clay content. Compaction in the dry state, hydrocollapse (collapse under increasing water content at constant pressure) and rearrangement under a series of successive loads were more pronounced when clay content increased. However, the contribution of each phenomenon to final bulk density was approximately constant whatever the clay content. Most part of soil compaction (around 50%) was due to dry compaction. Hydrocollapse explained about half of the remaining compaction. Hydrocollapse was responsible for sharp increases in bulk density as a result of small increases in water content (gravimetric water content between 3 and 7%), even under low pressure. The rearrangement under successive loads explained 20 to 30% of the final bulk density, even though the bulk density was already higher than 1.65Mgm $^{-3}$ after dry compaction and hydrocollapse. As clay content increased with depth, the deeper horizons were the most sensitive to compaction. The highest bulk densities were however measured in the 20-40cm layer in the field. The direct traffic load resulting from the many ploughings a year usual in the region is probably a part of the explanation but the structural effect of deep ploughing (which changed the massive structure of the layer into a metastable organisation of aggregates very sensitive to densification) is probably the main factor. Deep tillage is therefore not an option to rehabilitate compact subsoils due to the instability of the resulting structure and alternative techniques conserving part of the initial stability are recommended.

Acknowledgments

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Physical reorganization of sand due to the motion of a solid intruder

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Keywords: model granular media, reorganizations of grains, force chains

Abstract

The sandy soil can be considered as an example of fragile matter from a physical point of view; our approaches are to identify the most simple elementary mechanisms responsible for the instability and the reorganization of the sandy structure and thus to characterize the physical parameters involved in the weakness of this type of soil. We thus use a very simple model of granular soil without any biological or chemical influences. The ability of an intruder to move in such a model granular media is a test of the resistance to reorganisation of a granular soil.

Introduction

Sandy soils are very unstable or evolving materials, whose properties are not well known, making it thus difficult to manage for agricultural purposes. Due to the low content of clay, the cohesion between grains of the soil is low and the sandy soil can be particularly sensitive to any external perturbation, whatever the origins are: climatic (intense rain, capillary rise) or anthropogenic (ploughing, mechanical vibrations) for example. In this work, we are considering the sandy soil as an example of fragile matter from a physical point of view; our approaches are to identify the most simple elementary mechanisms responsible for the instability and the reorganization of the sandy structure and thus to characterize the physical parameters involved in the weakness of this type of soil. We thus use a very simple model of granular soil without any biological or chemical influences. This approach aims to test the part of the physical influence in the instability of real soils.

In a first section, we will describe how we reduce the problem to model physical experiments and mention the characteristic features of dry granular media. In the second section we will describe in more details a particular experiment for testing the instability of a granular media. In particular the resistance to reorganisation of a granular medium is characterised by the ability of an intruder to move in it. The strength needed to displace it and the size of the reorganisation around critically depends on the original packing of grains and could give information on the ability of a worm or a root to penetrate this type of medium.

I – Model granular media for experiments

Granular matter we use in physics are collections of grains of controlled dispersity, simple form and known grain density (Fontainebleau sand made of rounded grains of 300 µm of diameters, monodisperse glass beads or metallic ball-bearing beads…). Their diameters are always larger than the micrometer, so that the thermal agitation does not play any role in the motion of the grains. Moreover, we choose large diameters (of the order of 100 µm to several millimetric sizes) to minimize for example drag forces produced by the interstitial fluid (generally air in the porosity of the granular network) so that the interactions are mediated through the direct contacts between grains. In the case of non-cohesive grains, these interactions are limited to collisions and contact forces, according to the duration of contact between grains.

Despite these drastic simplifications which seem to be very naive from a practical point of view, the variety of phenomena observed with model granular media is very rich and still complex. We will describe below the main features of a granular structure which could play a role in a real sandy soil.

The heterogeneity of forces

In granular materials, force is rarely transmitted uniformly, but rather preferentially along a network

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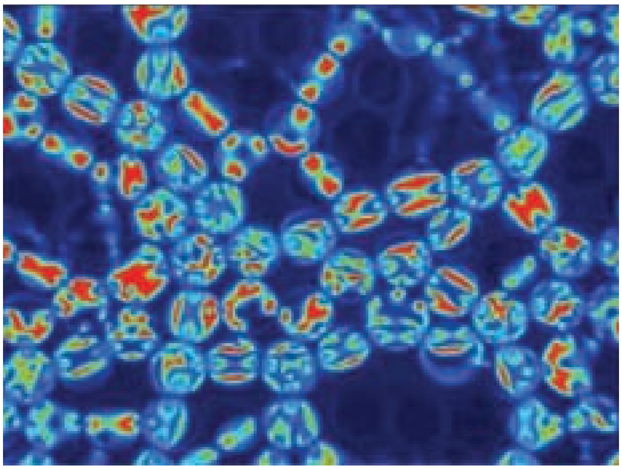


Figure 1. Force distribution network as observed in a photoelastic system with birefringent discs placed in between circular polarizers (Behringer)

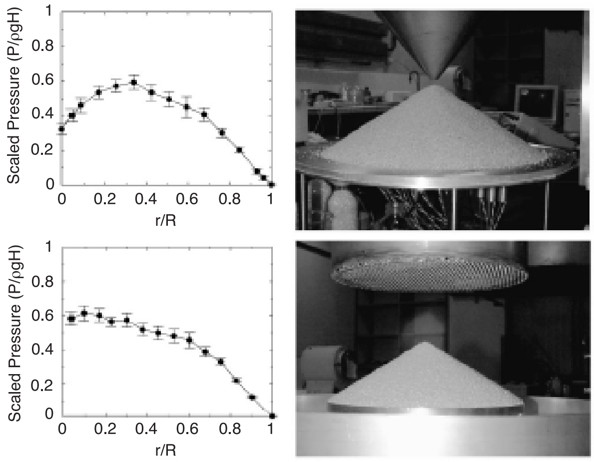


Figure 2. Dimensionless normal stress profiles *P/ρgH* versus dimensionless radial distance *r/R* beneath conical piles of sand of height *H* and radius *R*. The preparation techniques are illustrated by the corresponding photos on the right side (top: point source; bottom: pluviation) (Vanel et al., 1999)

forming force chains. The network of contact forces can be observed by photoelastic measurements (**Figure 1**) (Behringer). It appears to be very heterogeneous, forming chains along which the forces are particularly intense encompassing regions bearing relatively small loads. Then the description of the transmission of forces inside a granular medium is quite a great challenge where the inhomogeneity of the material leads to unexpected behaviours.

The spatial distribution of forces is large, with fluctuations of the order of the mean force. According to (Radjai et al., 1997) the network of contact forces can be divided into 2 parts: the large network for forces larger than the mean force bears most of the load with a stress tensor and angular distribution of contact directions which is suited to oppose external constraints. On the other hand, the small force network (forces smaller than the mean force) shows isotropic contact direction and a weak anisotropy of the stress tensor with the major principal axis oriented in such a way that it opposes the buckling of large force chains (Clément, 1999).

These chains play an important role in many of the properties of the granular material, such as the transmission of sound and the fragility of the packing along particular directions (Cates et al., 1998). Generally the mesh size of the large force network is of the order of 10 grains, which is also the typical size of a shear band.

The history dependence

The protocol of preparation is particularly important for granular materials and determines the subsequent mechanical properties. For example preparing a dry sand pile by using a point source (sand falling from a funnel) or a pluviation technique (sand falling from a grid) leads to the same macroscopic pile with a repose angle (angle between the slope of the pile and the horizontal) which is around 30° for both piles (**Figure 2**). However the measured pressure profiles on the bottom below the sand piles are rather different. When the sand pile is built from a point source, there is a dip of pressure below the apex of the pile, while there is a maximum of pressure when the pile is prepared by pluviation (Vanel et al., 1999). This drastic difference in the pressure profiles can not be inferred from macroscopic properties like the angle of repose and therefore the internal coefficient of friction is not sufficient for describing the mechanical properties of a sand pile. Some microscopic parameters have to be taken into account.

The importance of preparation can act on packing fraction but also on finer parameters like the directions of contacts between grains and the orientations of the force network (De Gennes et al., 1999). The evolving nature of the mechanical properties of a granular medium can be illustrated by the following experiment (**Figure 3**) where some photoelastic discs are placed into a shear box. Initially before applying the shear the medium is isotropic (there is no anisotropy in the orientations of contact directions) and the response to a point force on top of the box is maximal along the direction of the force (applying a point force is a way to test the mechanical properties). However if the box is submitted to an

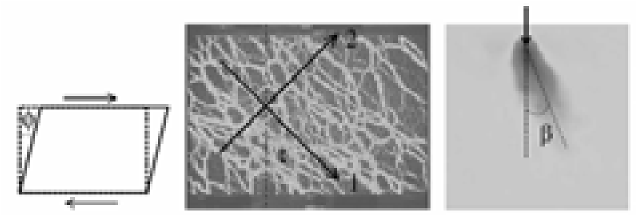


Figure 3. Importance of the microscopic scale on the mechanical properties
Left: schematic of the shear box.
Middle: Visualisation of contact forces between grains by use of photoelastic grains.
Right: Mean response to a point force applied along the direction of the arrow. The intensity of the mean stress grows when it is darker (Atman et al. 2005).

initial preshear some new force chains are created along direction 1 which tend to oppose the shear. A new “texture” is formed and the mechanical properties have changed, as it can be observed on the shift of the response to a point force (Atman et al., 2005).

The fragility

Granular materials as other particulate materials are examples of fragile matter. For non-cohesive grains there is a lack of resistance of contact forces to any extension. The internal structure (the contact and force networks) can evolve and adapts itself to support the applied load as we have seen before. Then the incremental response can be elastic only to “compatible” loads. Incompatible loads like the one produced for example by a change of compression axis, even if small, will cause finite, plastic reorganizations: irreversible rearrangements will be produced in the structure (Cates et al., 1998).

The different scales

The approach used at a macroscopic scale in soil mechanics is usually based on standard compression experiments like triaxial tests, from which constitutive relations between stresses, deformations and directions of deformations are obtained. In this approach, the soil can be considered as an effective continuum medium but the constitutive elasto-plastic relations between stresses and strains inferred from these tests are mostly non-linear, piece-wise, anisotropic and crucially depend on the history of the loading/unloading cycles (Clément, 1999).

The problem of granular materials is that there is no clear separation between microscopic and macroscopic scales, from the size of the micrometric asperities in the surface area of contact of grains to the mesoscopic scale of force chains and till the macroscopic size of the bulk material of soil. Therefore many scales are involved in the resulting mechanical properties and microscopic rearrangements can have a drastic effect on macroscopic properties. This is the reason why we perform the following experiment.

II – Experiment on reorganizations in a granular medium due to a solid intrusion

In this part we describe in more details a conceptually simple experiment (Kolb et al., 2004). It consists in testing the local resistance of a granular material by moving an intruder in it. From a practical point of view it bears similarities with standard penetrometry tests currently used in soil mechanics.

However we want to focus here on the microscopic perturbation introduced by the measurement itself, which is a consequence of the fragile nature of granular material. The network of contacts between grains is not permanent and the perturbation induced by the motion of an intruder (which can be a rough model for the growth of a root or the progression of a worm) can open or close some contacts and produce some irreversible rearrangements that change the nature of the granular structure itself and thus of the complementary porous matrix, what affects its mechanical properties at a larger scale. Therefore we want to characterize the rearrangements induced by the displacement of the intruder and the range of the effect of perturbation inside the granular material. Thus we apply a local and cyclic perturbation inside the granular packing for both detecting the displacements of grains in the vicinity of the perturbation and characterizing the evolution of the structure by investigating the irreversible displacements after a given number of cycles of perturbation.

Experimental setup

For this purpose we use a 2 dimensional (2D) granular media. That means the motions of grains can only occur inside a plane, there is no influence of the third dimension. Once again it is an oversimplification of a real sandy soil but it gives some hints on the micro-reorganizations of granular material because the 2D geometry allows to directly follow the motion of each grain by simply using a camera above the setup. More precisely the grains are not beads but small metallic hollow cylinders whose form is adapted to the 2D geometry: the axis of the cylinders are perpendicular to the plane of motion (see **Figure 4 right part**) The cylinders have two different outer diameters d_1 = 4 mm and d_2 = 5 mm. Mixing 2 types

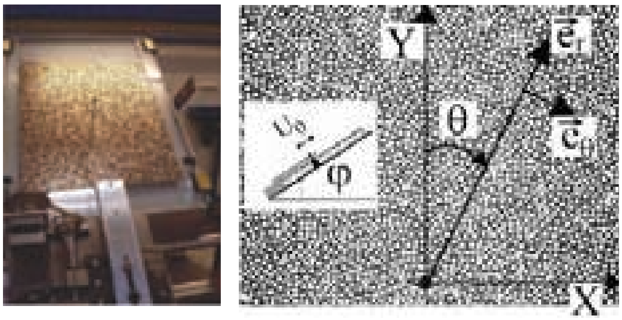


Figure 4. Left: Experimental setup. Right: typical frame of observation of the piling. The intruder is below the black point (inset: sketch of the experimental setup viewed from the side)

of grains leads to a disordered granular media by avoiding crystallization, i.e. regular stacking of the grains. This is done in purpose for obtaining generic results. The inner diameters of the cylinders are also different, which allows a proper determination of the type of grains for further image analysis.

Around 4,000 such grains in an equal proportion in mass of the two types of cylinders are piled up onto an inclinable plane (**Figure 4 left part**). All cylinders have a 3-mm height and lye on this plane (a low frictional glass plate allowing a backward illumination) without rocking. The lateral and bottom walls are made of Plexiglas and delimits a rectangular frame of L = 26.8 cm (54 d_2) width and an adjustable height of typically H = 34.4 cm (70 d_2). The 2D packing fraction c defined as the ratio of the surface of grains to the total surface they occupy is then c = 0.749 ±0.004.

For the experiment the bottom plane is tilted at an angle $ø$ (see **Figure 4 inset of the right part**) such as to control the confinement pressure inside the granular material by an effective gravity field $g\sin ø$ where g is the gravity acceleration. A value of $ø$ = 33° is chosen for being larger than the static Coulomb angle of friction between the grains and the glass plate which is around $\theta = 20°$ ($\mu_{\text{grain/glass}} = \tan\theta$ is the static friction coefficient between grains and glass). Therefore the grains spontaneously move downward if they have the possibility to find a place below.

The intruder is a big grain of diameter d_2 located in the median part of the container at a 21.2 cm (i.e. 42 d_2) depth from the upper free surface. The intruder is attached to a rigid arm in Plexiglas (reinforced by metallic parts) moved by a translation stage and a stepping motor driven by a computer. The arm motion takes place along the median axis Y of the container and is parallel to the plane. In this report we use an intruder displacement value U_0 of a fraction of a grain diameter (U_0 = 1.25 mm ≈ $d_2/3$) giving a typical strain less than 10^{-2}, far above the elastic limit but also far below the usual fully developed plasticity domain where shear bands appear. The intruder is moving up then down to its first position and then again up and down and so on with always the same amplitude of displacement U_0, thus performing cycles of displacements in a quasi-static way. The up and down motions along the Y-axis are separated by rest periods during which pictures with a high resolution CCD camera (1280*1024 pixels^2) are taken. The image frame is centered slightly above the intruder and covers a zone of area 39 d_2*31 d_2 (see **Figure 4 right part**).

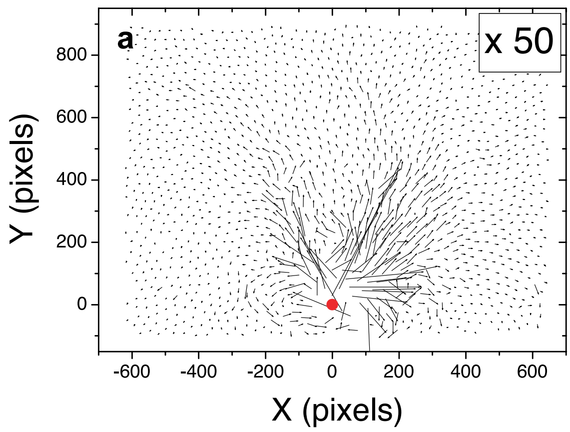
In the following, we use the notation i for the index corresponding to the i^{th} image just before the i^{th} displacement of the intruder (upward or downward) and n for the cycle number with n = int[{i+1}/2] where int is the integer part. For each image i, the center of each grain is determined with precision using the computation of the correlation on grey-levels between an image of the packing and two reference images corresponding to both grain types (d_1 and d_2). Note that the inner diameter of the cylindrical hole, which is different for each grain type (small or big), helps crucially for the proper determination of the centre and of the grain type. Hence, we obtain, for each image, the locations of more than a thousand grains with a resolution down to 0.05 pixels. The displacement of each single grain is then calculated by the difference between its position in image i and in image j. This method allows a precision of less than 10 μm ($d_2/600$) for the displacements. Thus we obtain 2 types of informations:

- the displacement field in response to an upward or downward intruder motion (also called the response function) by comparing images i and $i+1$.
- the irreversible displacement field by comparing images i and $i+2$. (Between images i and $i+2$ the intruder has accomplished a cycle of displacement but some grains don't come back to their first positions; they have undergone irreversible displacements).

Experimental results

Displacement fields as a response to the motion of the intruder

The displacements fields have been computed for 16 independent realizations prepared in the same



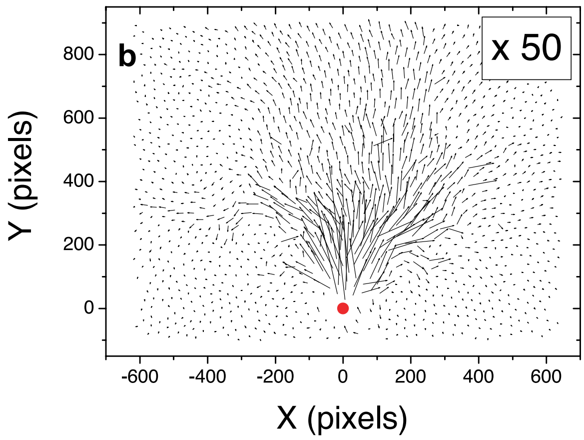


Figure 5. Displacements fields observed for the second upward motion of the intruder (*i* = 3 or *n* = 2) for two independent realizations a and b. The point corresponds to the location of the intruder. All displacements have been magnified by a factor of 50 and the scales are given in pixels. The intruder is initially located in *X* = 0, *Y* = 0 before its upward motion

way. We plot in **Figure 5** the displacement of grains induced by an upward motion of the intruder (the figure presents the response obtained in the case of the second upward motion of the intruder, for example). We observe that the amplitudes of displacements are very small and that there is some redirection effect towards the lateral walls, but the most important point is that the grains that move are not obligatory close to the intruder and that the perturbation due to the solid intruder has a long range effect. The second point is that the displacement field is very sensitive to the particular organization of grains and probably linked to the force network of each configuration.

We can extract from these results a mean behaviour by averaging over the 16 realizations inside little binning cells of size 1.2 d_2*1.2 d_2 regularly located in the Cartesian coordinates *(O, X, Y)* reference frame.

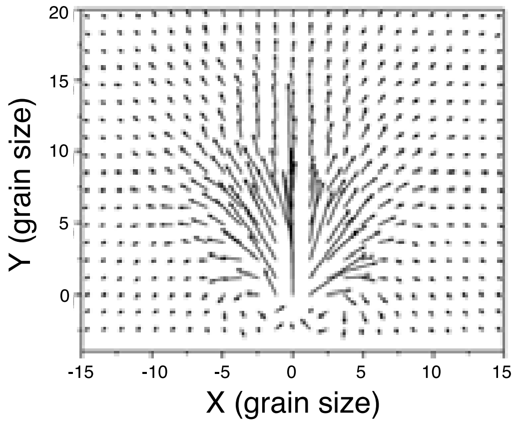


Figure 6. Mean upward displacement field for the second upward motion of the intruder (*i* = 3 or *n* = 2). All displacements have been magnified by a factor of 70. The coordinates are expressed in unity of a big grain size d_2

This gives the mean displacement field presented in **Figure 6**. We clearly notice that the granular motion is not localized in the vicinity of the intruder and that this small perturbation of only one third of a grain diameter indeed produces a far field effect. Furthermore, the presence of two displacement rolls is observed near the intruder. They are located symmetrically on each side of the intruder but turn in opposite directions. Besides this near field effect, the main response principally occurs above the intruder with displacement vectors that tend to align along the radial directions from the intruder.

The typical decay of the response with the radial distance *r* from the intruder is analysed. After several cycles the response to an upward perturbation exhibits a $1/r^a$ dependence where *a* is close to 1, what can be modelled by the following relation (eq.1):

$$\vec{u}_i^{\uparrow} \approx b_i U_0 d_2 \frac{f(\theta)}{r} \vec{e}_r \qquad \text{(eq.1)}$$

This relation is valid in the upper part above the intruder for a distance larger than 7 d_2 (far enough from the rolls). The function $f(\theta)$ of the polar angle θ (defined in **Figure 4**) has a typical bell shape with its maximum value for $\theta = 0$ corresponding to the direction of the intruder motion. The dimensionless parameter b_i gives the amplitude of the response for the i^{th} intruder motion.

Evolution of the response with the number of cycles: reversibility/irreversibility

We followed the evolution of the response (via the parameter b_i) with the number of cycles or

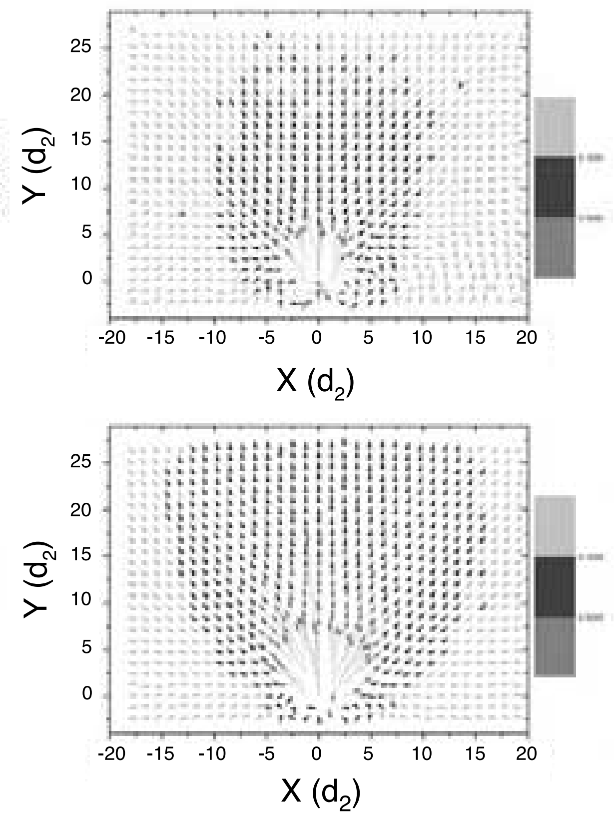


Figure 7. Mean upward displacement field for normal (above) and tapping (below) preparations for the 9th cycle. The grey-level code corresponds to different amplitude of displacements given in pixels. 33 pixels correspond to the diameter of a big grain d_2

equivalently with i: the parameter b_i decreases progressively with i and then saturates to a constant value after about 60 displacements, i.e. 30 cycles. Each cycle of motion of the intruder produces some irreversible displacements of grains, and then the structure of the material changes and the following response to the next motion of the intruder is different. Note that in spite of these irreversible displacements mainly downward in the direction of gravity, there is no detectable increase of the mean packing fraction (averaged over the 16 experiments) with the number of cycles n: it stays constant with a relative error of 0.1%. But after $n \approx 30$ cycles, both mean responses for upward and downward motions of the intruder are almost identical: a quasi-stationary regime or "limit cycle'' is obtained and the packing seems to be more stable with regard to the perturbation.

Dependence on preparation

We now compare 2 modes of preparation: the original one obtained by random initial mixing of grains inside a specific surface and the so called "tapping one'' consisting in tapping the walls of the inclined container just before beginning the experiment. Note that the initial mean packing fraction is $c = 0.750 \pm 0.002$ for tapping preparation so that there is no significant change of $ø$ compared with the first preparation described before (called the normal one).

However the effects on the subsequent response observed by mean of the displacement field are quite visible as it can be observed on **Figure 7** with grey-levels corresponding to different amplitudes of displacements. We clearly observe that the response is enhanced and more directive in the direction of gravity for the tapping preparation. In both cases, changes in mean packing fraction along the experiments are less than 1/1,000 and they certainly would not explain such differences in the evolution process. It is then natural to look for the influence of local configuration parameters such as the evolution of contact direction distribution or other texture parameters at the level of the grains. This analysis reveals that a difference could be observed between the 2 types of preparation only if we compare the mean coordination number (the mean number of contacts per grain), which is a microscopic parameter at the level of the contact size.

Conclusion

We experimentally determine the reorganisation field due to a small localised cyclic displacement applied to a packing of hard grains under gravity modelling the physical parameters that could be involved in a sandy soil. We surprisingly find that the displacement fields in response to the small local perturbation are quite long range in the direction of the perturbation and quite evolving. We also propose here new results on the effect of a slight difference in the preparation procedure: We compare the evolution of the response function along the cycling procedure and we show that the initial configurations prepared either by random mixing of grains at constant surface or under a weak tapping have a clearly different response even though the mean packing fraction obtained in these two cases are extremely close. Not only the first response but also the further evolution during the cycling procedure is different, showing that there is still a memory effect of the initial preparation after many cycles. With this experiment we want to emphasize the role of microscopic rearrangements in the stability of a granular packing.

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Wind and water erosion of non cultivated sandy soils in the Sahel: a case study in Northern Burkina Faso, Africa

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Keywords: wind erosion, water erosion, crust, grazing area, Sahel

Abstract

In the Sahel, sandy soils are widespread and support not only most of pearl millet production, the major staple crop in the region, but also forage production for livestock. Parent sediments of these soils have an aeolian origin and hence are prone to wind erosion. However, the clay content, albeit very low, results in the formation of crusts during rainfall, thus leading to runoff and water erosion. Squall lines, major rainfall events of the rainy season, are usually preceded by intense wind. Wind and water erosion is thus closely associated both in time and in space, but they are rarely studied simultaneously. Erosion measurements were carried out during two years (2001, 2002) on a small catchment of grazing land (1.4 ha) at Katchari, Burkina Faso, typical of the Sahel area under 500 mm annual rainfall. Wind erosion occurred at the onset of the rainy season, when soil cover is the lowest, from May to 15^th^ of July, before vegetation growth. Water erosion occurred throughout the rainy season, but some intense events produced most of the total annual erosion.

Wind caused the largest sediment fluxes leading to both erosion (up to 20 Mg ha^{-1} yr^{-1}) and deposits (up to 30 Mg ha^{-1} yr^{-1}) according to the area of the catchment. Water erosion is one order of magnitude lower than wind erosion, and is more intense where wind erosion is the highest. Thus the same area is eroded both by wind and water. Conversely, in areas where there are aeolian deposits, water erosion is low and these areas correspond to fertile islands where vegetation grows. At this study scale, there is no land degradation, but intense dynamics leading to a high spatial variability typical of the Sahelian environment. On this uncultivated area, the dynamics were similar to those recorded in other Sahelian cultivated millet fields.

1. Introduction

In the Sahel, sandy soils are dominant. In Niger, for example, they represent more than 80% of the agro-pastoral zone (Gavaud, 1977). They support most of the annual vegetation growth, pearl millet, the main staple crop, and forage for livestock. Consequently, they play a major role for the farmers who represent more than 80% of the Sahelian population (Thiombiano, 2000; Guengant and Banoin, 2003). On these soils, both wind and water erosion occurs, but these two forms of erosion are rarely studied simultaneously. Wind erosion data, scarcer than than that on water erosion, can be found in the literature for cultivated areas (fields and fallows). At the field scale, soil loss due to wind erosion is found to reach very high levels (more than 25 Mg ha^{-1} yr^{-1}, Bielders et al. 2001). However, very few studies concern uncultivated areas where grazing is the only land use. Soil losses by water erosion in the Sahel seem to be lower (Collinet and Valentin, 1985), but, as measurements were not carried out on the same surface (same surface features and same surface area), they are difficult to compare. However a recent study (Visser, 2004) addressed estimation and comparison of wind and water erosions based on field work and modeling in the same area as the present work. Her results confirm those of previous studies, i.e. sediment and nutrient fluxes associated with wind are generally several orders of magnitude larger than those due to runoff. Her data were obtained at the erosion event scale on plots installed on two cultivated fields and one degraded surface with bare gravelly soil, but no measurement was performed in the grazing area. The objective of our work was to quantify wind and water erosion simultaneously in small grazing catchments with different surface features, over 2 seasonal cycles (2001 and 2002).

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2. Materials and methods

2.1 Study area

The study area is located in the North of Burkina Faso (UTM30, WGS84, 809847 m East, 155093 m North), near Dori, 250 km Northeast of Ouagadougou (Figure 1). The climate is of the Sahelian type, with a long dry season and a short rainy season from May to September. Average annual rainfall recorded in Dori from 1925 to 1998 was 512 mm. The grazed areas of the village lands are located on a low longitudinal slope (about 1%). They show two main soil types: i) large areas of bare crusted clayey soil patched with ii) areas of sandy soil that have developed on aeolian sand deposits (microdunes less than 0.7 m thick) where annual vegetation, shrubs and trees grow (Ribolzi *et al.*, 2000). Within this zone a small representative catchment (1.4 ha) was selected composed of five main soil surface types according to the classification of Casenave and Valentin (1992) (Figure 1): (1) bare erosion surfaces (ERO) accounted for 33.6% of the total catchment area, (2) pavement surfaces (G), which were also bare, covered 0.4% of the catchment area, (3) sedimentation surfaces (SED) covering the bottom of ponds and depressions, accounted for 1.2% of the catchment area, (4) runoff type surfaces (RUN) consisting mainly of laminated materials of various textures, represented 4.2% of the catchment area, and (5) the drying surfaces (DRY) which covered the leeward area of sandy microdunes represented 59.9% of the catchment area. Microdune soils accounted for 69% of the total catchment area and constituted almost exclusively the support for annual vegetation, shrubs and trees. The windward sides of microdunes accounted for 14.3% of the total catchment area; they were characterized by a steep fragmented ERO surface (i.e. crumbling of the laminated structure of plasmic and sandy layers called ERO/S) resulting from wind deflation. These observations served ground to the selection of three sub-areas homogeneous in terms of surface feature combinations (Figure 1).

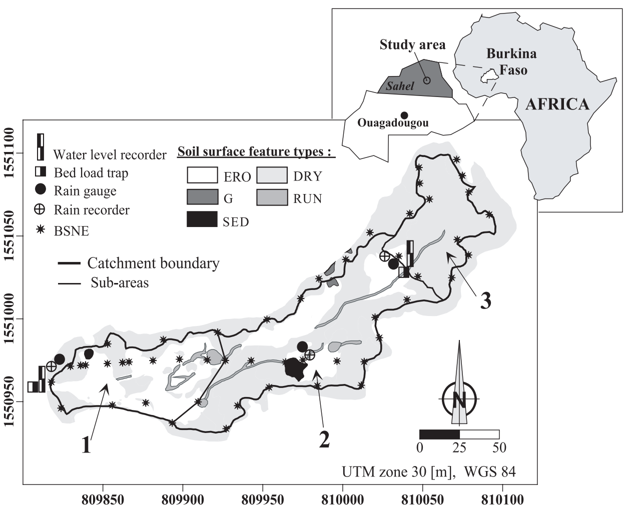

Figure 1. The study area, map of soil surface features, experimental design and boundaries of the 2 catchments for which water erosion was calculated and of the 3 sub-areas for which wind budget was calculated

Measurements of both wind and water erosion were undertaken from the 1st of June 2001 to the end of September 2002.

2.2 Water erosion measurements

In this study, it was not possible to use classical water erosion plots because artificial boundaries act as windbreaks, causing significant aeolian sand deposits. To avoid such disturbances, water erosion was measured on two natural nested catchments. The upstream catchment (0.3 ha) corresponds to sub-area 3 on Figure 1.

Rainfall was monitored using three simple rain gauges and three rainfall recorders. The stream discharge of each catchment was measured using flow recorders. Suspended matter fluxes at the outlets were estimated from discrete 1-litre water samples collected throughout runoff events with a time interval varying from 2 to 5 minutes. Bedload was collected in sediment traps after each event. The totality of these materials was dried and then weighed.

2.3 Wind erosion measurements

Unlike cultivated land where field/fallow transitions have to be taken into account in wind erosion studies (Bielders *et al.*, 2002), in Sahelian grazing land there is no clear boundary acting on wind erosion. Thus, the limits of the areas under study are determined by those of water erosion (main catchment and upstream catchment [sub-area 3] boundaries) and by surface feature patterns (sub-areas 1 and 2) (Figure 1).

Wind-blown sediment fluxes were obtained using 50 masts equipped with 3 BSNE sand catchers (Fryrear, 1986) of 0.05, 0.15 and 0.3 m in height. The masts were placed 1) on the sub-area boundaries approximately every 20-m and 2) along a transect in the western side of the catchment (Figure 1).

Wind-blown sediments caught in BSNE were collected if possible after each erosion event from June to September and each month from October 2001 to May 2002. The horizontal fluxes were calculated at each mast by integrating the sediment flux density profile between 0 and 0.4 m height. Wind speed and direction were measured using an automatic weather station. An acoustic saltation sensor (Saltiphone, Span and Van den Abeele, 1991) indicated the period during which the fluxes were significant. With this information, it was possible to estimate the mean direction of wind during each storm event, and to determine the upwind and downwind limits of catchments; the incoming and outgoing mass fluxes along the boundaries of the catchments were then calculated by linear interpolation of sediment mass fluxes measured at each mast. The mass budgets within the sub-areas 1, 2 and 3 were calculated by subtracting outgoing from incoming wind-blown sediments.

Along the E-W transect, the BSNE masts were setup at each major surface feature change. When erosive wind direction corresponded to the transect direction (95 ± 15º), which was assumed to correspond to the more intense wind erosion events, it was possible to compute a budget by subtracting downwind from upwind fluxes and dividing the result by the distance between the two measurement locations.

Measurements of wind-blown sediments along the E-W transect were taken during the rainy season 2001.

3. Results and discussion

3.1 Dynamics of wind-blown sediment flux

Sand catchers were collected 57 times during the measurement period. Some data correspond to mixed events occurring at close intervals, or during the monthly period of collection. From meteorological measurements, it is possible to estimate that sixty-eight wind erosion events occurred during the 16 months of measurement. For the common period of measurement (June to September), there were 33 and 21 events in 2001 and 2002, respectively. The flux density at a height of 30 cm, averaged for the 50 BSNE masts (called FD_{30} below), accumulated over 2001 and 2002 was 25 and 22 g cm^{-2} , respectively. The inter-annual variability was lower than that measured in Niger from 1996 to 1998 (Rajot, 2001).

Only three events occurred during the dry season from October to March. These latter events represented less than 0.3% of the cumulative FD_{30} for the whole period. The first event of 2002 occurred on the 6th of April and was linked to the first rainfall of the year. As in a cultivated field in Niger (Rajot, 2001), the Harmattan wind did not produce wind erosion in this grazing area of the Sahel.

For the whole period, eight events produced 53% of the cumulative FD_{30}. Five of them occurred in June, two in July, and one in April. A few events at the onset of the rainy seasons produced most of the wind erosion.

Figure 2 shows the cumulative FD_{30} according to wind direction classes. 75% of the flux corresponded to wind blowing from the East to the Southeast (between 75º and 165º). This result corresponds closely with the local morphology of the microdune showing a higher slope on the windward side.

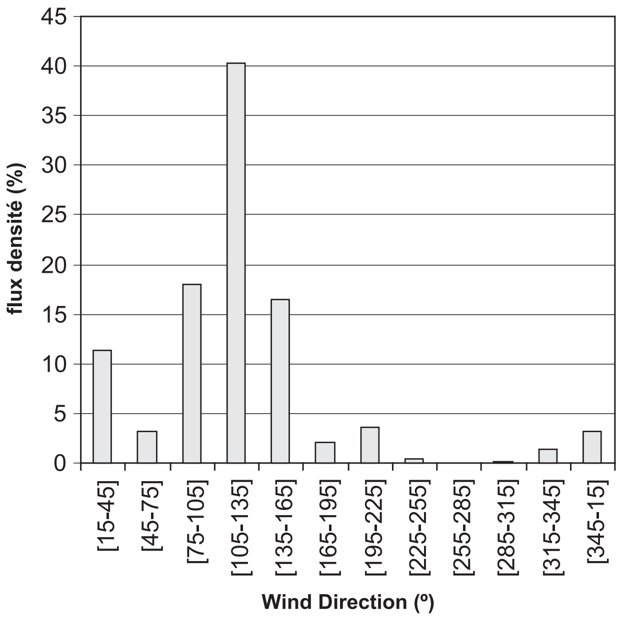

Figure 2. Percentage of flux density at 30 cm height averaged on the 50 BSNE masts and accumulated over the measurement period versus wind direction of events

All these observations correspond closely to other measurements suggesting a similar wind dynamic throughout the Sahel (Bielders *et al.*, 2004).

3.2 Wind-blown sediment budget within sub-areas

From the 68 events producing wind-blown sediment flux during the study period, it was only possible to calculate the mass sediment budget for a subset of forty-two events owing to mixed events or important variations in the wind direction for the other twenty-six. The cumulative FD_{30} for these forty-two computed events represented 87% of the total FD_{30} blowing out on the catchments during the entire measurement period. There was no major event, i.e.

with high sediment transport, among those events that were not considered. Thus, it will be assumed that the results obtained with these 42 events provide a good image of wind erosion on the catchments.

A Monte Carlo procedure was used for one major erosive event to estimate the standard deviation on budget result taking into account all the uncertainties affecting the computation, namely: the height of catchers, the surface of the opening, the fit of the theoretical equation for the calculation of horizontal flux, the position of the catcher on the area under study and the wind direction. The variation coefficients obtained ranged from 20% to 150% according to the sub-area and the differences between the sub-area budgets always remained highly significant.

Figure 3 shows the cumulative mass balances of aeolian sediment over the period of measurement for the three sub-areas. These areas behaved very differently: the budget is almost systematically positive for the upstream sub-area (#3) whereas it is systematically negative for the downstream one (#1), amounting to about +65 $Mg.ha^{-1}$ and -35 $Mg.ha^{-1}$, respectively, over the measurement period. Both erosion and deposition occurred in the centre sub-area (#2), but the budget remained positive over the measurement period (+27 $Mg.ha^{-1}$). At the catchment scale, these different behaviours of the sub-areas led to an almost balanced budget until the beginning of June 2002 (+3 $Mg.ha^{-1}$), and a really positive budget at the end of the measurement period (+16 $Mg.ha^{-1}$).

A high level of wind-blown sediment deposits was also reported by Bielders et al. (2001) for fallow land in Niger which presented similar surface features as sub-area 3 (dry crust with annual and perennial vegetation). The deposits were ascribed to the high surface roughness of these areas. In Niger, the sources of wind-blown sediments were pearl millet fields (Bielders et al., 2001). In this study, net wind erosion occurred on complex natural areas where all the different surface features encountered in the catchment are represented (Figure 1). Thus the surface features from where wind-blown sediments originate are still unclear and need to be assessed.

3.3 Wind-blown sediment budget along the transect

The transect measurements taken across sub-areas 2 and 3 (Figure 1.) enabled a better description of the processes occurring in relation with soil surface features. Only five events required the wind direction to be computed from the transect, but two of them were the more intense events of the 2001 season. General trends appeared and can be summarized from the budget computed from the sum of these five events (Figure 4). First of all, the transect revealed the high spatial variability of wind erosion at the meter scale. There was no systematic behaviour on the 2 main surface features with regards to the budget: erosion may occur on the DRY surface and deposits may occur on the ERO surface. Nevertheless, the larger deposits occurred on the DRY surface whereas the more intense erosion occurred on the ERO surfaces covering windward slope of sandy microdune (ERO/S) or areas where such a surface was present (between 70 and 85 m), as well as on the RUN surface.

ERO/S surfaces are closely associated to DRY surfaces and develop on the same sandy soil. If one considers these 2 surfaces together (between 0 and 9 m and between 25 to 37 m) the sediment budget is

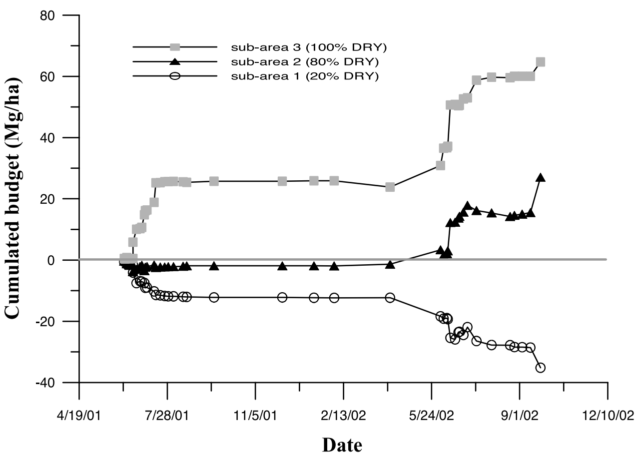

Figure 3. Wind-blown sediment mass budget ($Mg.ha^{-1}$) accumulated over the study period for the 3 sub-areas selected because of their surface feature distribution

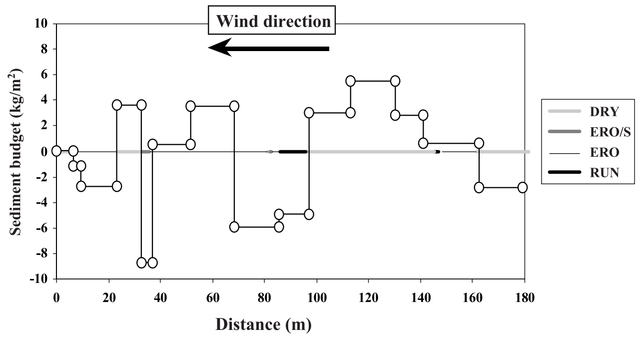

Figure 4. Accumulated wind-blown sediment budget for the five events with easterly winds (parallel to the transect orientation) versus distance from the western border of catchment. The various types of surface features (see text for description) are indicated by different shades of gray on horizontal axis

negative i.e. the small patches of sandy soil are currently subject to net erosion as suggested by Casenave and Valentin (1989) during drought conditions.

The fact that net deposits may occur on ERO surfaces whereas sand deposits were not observed suggests that these sediments are mobilized by water erosion which often follows wind erosion in the Sahel (Visser et al., 2004). Similarly, the high susceptibility of RUN surfaces to wind erosion shows that water erosion produces sediments that are easily mobilized by wind erosion.

3.4 Dynamics of water erosion

The annual rainfall levels were 325 mm in 2001 and 345 mm in 2002. Both years showed a deficit compared to the mean annual level (512 mm for the reference period of 1925-1998). Rainfall generated 16 floods in 2001 and 13 in 2002. The number of water erosion events was less than half the number of wind erosion events. Although the amount of rain was lower in 2001, more heavy events were observed during this year: rainfall levels exceeded 25 mm for only two events in 2002 compared to four events in 2001 (Figure 5). For the whole catchment, water erosion was twice as high in 2001 as in 2002, but it was the reverse for the upstream catchment (Figure 5). Water erosion, unlike wind erosion, occurred throughout the rainy seasons and did not show a period of clearly higher intensity. As for wind erosion, some events were responsible for a large part of the annual erosion. In 2001, the four most important rainfall events (level >25 mm) were responsible for 60% of water erosion

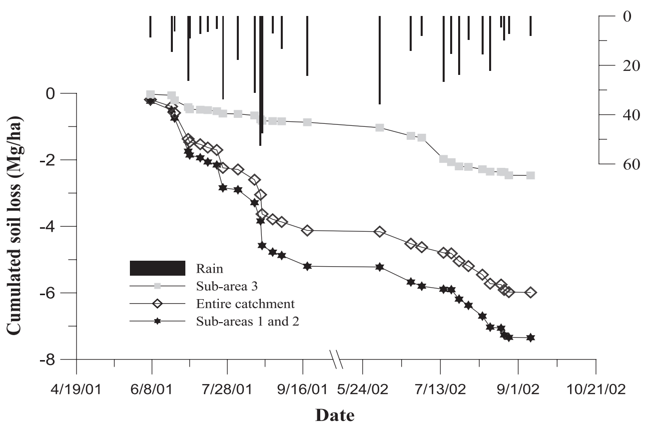

Figure 5. Rainfall depth and accumulated soil loss due to water erosion over the study period (rainy seasons 2001 and 2002) for the entire catchment, sub-area 3 (i.e. 100% DRY) and sub-areas 1 and 2 (between 20 and 80% DRY)

(Figure 5). Karambiri et al. (2003) already showed the similar behaviours in the same catchment for the period 1998-2000.

3.5 Water erosion within sub-areas

Cumulative soil losses by water for this period were estimated at 6.0, 2.5 and 7.3 Mg ha^{-1} yr^{-1} for the entire study area, the upstream zone (sub-area 3) and the downstream part of the catchment (sub-areas 1 and 2), respectively (Figure 5). Soil losses by water were lower upstream than downstream. These results conform closely to observations of Karambiri *et al*. (2003) in the same area (1998, 1999 and 2000 rainy seasons). They attributed the different behaviours of the two catchments to the soil surface characteristics: Drying surfaces, which are more permeable and supported herbaceous plants, covered the entire sub-area 3 and hence favoured infiltration rather than runoff. In contrast, the downstream zone was patched with impervious-prone erosion crust, which is more susceptible to erosion.

Particle size distribution of sediment exported varies according to the catchment. On the upstream sub-area, the exported sediments were composed mainly of sandy bedloads, while silty-clay suspended particles were dominant downstream (i.e. sub-areas 1 and 2). These results suggest that the clayey erosion crust could be a major source of sediment for water erosion; they correspond closely to the results reported by Karambiri *et al.* (2003) in the same study area.

3.6 Combined water and wind sediment budget

At the catchment scale, taking into account both wind and water erosion, and considering the whole study period, we estimated a positive cumulative budget of 10.2 Mg/ha. This result masks high spatial and interannual variabilities of the sediment budget (Table 1). There was a high positive budget on sub-area 3 due to wind sediment deposits (65 Mg/ha). Sandy sediments accumulated on sub-area 3 and were partially removed by water erosion (-2.5 Mg/ha) mainly in the form of bedload. Conversely, there was a negative budget on the downstream part of the catchment due to both wind (-0.4 Mg/ha) and water (-7.3 Mg/ha) erosion. For this sub-area, we observed a net wind erosion in 2001 (-6.4 Mg/ha), which was compensated by wind deposits in 2002 (6.0 Mg/ha). Such high spatial variability due to wind erosion in the Sahel was pointed out by Bielders et al. (2001) in a cultivated area. It also appears to be very high in grazing areas.

Table 1. Accumulated soil (Mg/ha) due to water and wind for the entire catchment, sub-area 3 and sub-areas 1 and 2

	water	wind	sum	water	wind	sum	water	wind	sum
		2001			2002			Cumulative totals	
Entire catchment	-4.1	1.1	-3.0	-1.9	15.1	13.2	-6.0	16.2	10.2
Sub-area 3	-0.9	25.7	24.8	-1.6	39.0	37.4	-2.5	64.7	62.2
Sub-areas 1 and 2	-5.2	-6.4	-11.6	-2.1	6.0	3.9	-7.3	-0.4	-7.7

In these areas, water erosion can locally reach the same order of magnitude as wind erosion and can move higher quantities of sediments (table 1). This result differs from that of Visser (2004) obtained for a cultivated field where wind erosion dominated.

4. Conclusions

For the first time in the Sahel, wind and water erosion was measured from the same surface areas of grazing lands, composed mainly of sandy soils. The main conclusions of this study can be summarized as follows:

1. Annual wind erosion dynamics for this grazing area are typical of the Sahel and are the same as observed for a cultivated field in Niger.
2. Wind erosion has a clearly oriented direction and is responsible for the asymmetric morphology of the microdune.
3. Wind erosion events are more numerous than those of water erosion and at the smallest scale are more intense, moving higher quantities of sediments.
4. There is a high spatial variability at the local scale with areas of net deposits, where vegetation grows and areas of net erosion where bare soils predominate.
5. Both wind and water erosion is more intense downstream and appears to be related to the type and size of surface features.

These results revealed the difficulties in estimating land degradation in the Sahel that depends heavily on the study scale. They suggest a strong linkage at the scale of a few meters between sediment source areas where degradation occurs and sediment sink area where vegetation develops in “islands of fertility”. They emphasize the necessity of taking into account both wind and water erosion in order to assess the current land degradation in the Sahel.

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Surface crusts of semi-arid sandy soils: types, functions and management

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Keywords: soil crusting, semi-arid region, runoff, wind erosion, water erosion

Abstract

Soil crusting is increasingly recognized as a major form of soil degradation; it impedes seedling emergence, restricts infiltration and favours rill and gully erosion. Most research on soil crusts has concentrated on the loess belts in Europe and the United States where the soils are both highly productive and very prone to crusting. In comparison, studies on sandy soil crusts remained limited, mainly because these soils are considered as marginal, especially under semi-arid conditions. The objective of this paper is to review studies on surface crusts of semi-arid sandy soils in terms of forming processes, soil-crust types, hydrological and ecological functions, and agricultural management.

Most of these studies have been based on macro- and micro-morphological approaches associated with field rainfall simulation, these methods being more appropriate than laboratory structural stability tests. The analysis of the main soil and climatic factors showed that predicting crusting can rarely be based on a unique factor but requests a combination of factors (e.g. textural properties and organic carbon content).

Soil-crusts types (structural, erosional, depositional, biological) have been related to forming processes and hydrological and erosive properties. Identifying the prevailing role of surface crusts on runoff generation in the semi-arid regions has led to hydrologic models based more on surface conditions than on soil properties. Soil crusts have ambivalent impacts on soil erosion; they protect the soil surface from wind and interrill erosion but favour rill and gully erosion. Surface crusts are inherent to semi-arid sandy ecosystems and favour the concentration of resources, which is pivotal to pastoral and agricultural activities in the semi-arid regions. Due to soil crusts, runoff and runon are important components of the water balance. It is therefore essential for water and land management of the semi-arid sandy regions to account for the spatial and temporal distribution of soil crusts.

Introduction

Although soil crusting has been mixed up for a long time with its causes (e.g. dispersion) or with its effects (e.g. surface compaction), it is increasingly recognized as a major form of soil degradation (e.g. Auzet et al., 2004). It impedes seedling emergence (e.g. Valenciano et al., 2004; Voortmana et al., 2004), restricts infiltration (e.g. Janeau et al., 2003) and favours rill and gully erosion (e.g., Valentin et al., 2005). Most research on soil crusts has concentrated on the loess belts in Europe (e.g. Bresson and Cadot, 1992) and the United States (e.g. Ruan et al., 2001) where the soils are both highly productive and prone to crusting. In comparison, studies on sandy soil crusts remained limited, because these soils are considered not only as marginal for crop production but also because most scientists have assumed that that are resistant to crusting (e.g. FAO, 1984). By contrast, these last two decades, a significant body of evidence has pointed to the high sensitivity of coarse-textured soils to surface crusting in Northern Senegal (Valentin, 1985), in Northern Niger (Valentin, 1991), in Southern Togo (Bielders et al., 1996), in Southern Niger (e.g. Rockström and Valentin, 1997; Esteves and Lapetite, 2003; Valentin et al., 2004), in Northern Burkina Faso (e.g. Karambiri et al., 2003; Ribolzi et al. 2003, 2005), in Northeastern Thailand (e.g. Hartmann et al., 2002) and in many other parts of the world as Northern China (Duan et al., 2003; Shirato et al., 2005), Zimbabwe (Burt et al., 2001) and Australia (e.g. Chartres, 1992; Isbell, 1995).

The objective of this paper is to review studies on surface crusts of semi-arid sandy soils in terms of

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factors, processes and soil-crust types, hydrological and ecological functions, and agricultural management.

Materials and methods

Because of the very thin structure of the crusts, generally less than 1 mm thick, many scientists characterized crust types based on micromorphological analysis (e.g. the review by Bresson and Valentin, 1994). A growing number of authors consider that instability tests are unsatisfactory to predict the soil sensibility to crusting (e.g. review by Valentin and Bresson, 1998). Field rainfall simulation has proved an invaluable tool to monitor crust forming processes and their impact on soil infiltrability (e. g. Valentin, 1991; Wace and Hignett, 1991; Casenave and Valentin, 1992; Bielders et al., 1996, Hartmann et al., 2002). Only few authors coupled rainfall micromorphology and rainfall simulation to monitor the various stages of crust forming in sandy soils (e.g., Valentin, 1991; Bielders and Baveye, 1995).

Crust types, processes and properties

The structural crusts are formed *in situ* while depositional crusts consist of sedimentary microlayers (Chen et al., 1980). Depending on the dominant forming process, two main types of structural crusts have been identified in sandy soils: the sieving crusts (Valentin and Bresson, 1992) and the packing crusts (Janeau et al., 2003). The sieving crusts are made of three well sorted microlayers: a top microlayer of loose coarse sand, a middle microlayer of fine sand with vesicular porosity and a lower dense microlayer of thin particles (Valentin, 1991; Bielders and Baveye, 1995). Packing crusts consist of sand grains or stable micro-aggregates tightly packed at the soil surface with very few macropores. Both types of crusts are influenced by kinetic energy of rainfall (e.g. Valentin, 1986). Sieving crusts develop on very sandy soils with very low organic matter content <1% while packing crusts develop on soils containing more organic matter and fine materials (but with silt <40%; Valentin, 2004).

They consist of a smooth, very dense, hard and thin (of the order of 0.1 mm) microlayer (Valentin and Bresson, 1992).

Structural crusts develop mainly upslope, erosion crusts mid-slope and sedimentation crusts down-slope (e. g., d’Herbès and Valentin, 1997). When these are not removed or destroyed by erosion, tillage or trampling, they tend to be colonized by cyanobacteria, algae, lichens, moses, microfungi, etc. As a result, several authors considered biological crusts as a typical category of surface crusts (e.g. Belnap and Lange, 2001; Eldridge and Leys, 2003) without considering the original physical crusts on which they develop. These underlying crusts greatly determine their hydrological behaviour (e.g., Bresson and Valentin, 1994; Malam Issa et al., 1999; Valentin, 2002) because abiotic (or ‘physical’) soil crusts differ not only in their main morphological characters (Table 1) but also in infiltrability (Table 2). Hence the interest of hydrologists for this classification to predict

Table 1. Main characteristics and properties of soil crusts in sandy soils
Sources: Casenave et Valentin, 1992; Valentin et Bresson, 1992, 2002; Janeau et al., 2003;Valentin, 2004)

Crust type	Thickness (mm)	Other characteristics	Forming process	Main factors	Mean infiltrability (mm h^{-1})#
Structural Packing	1-3	Tightly packed sands or stable micro-aggregates	Compaction under rainfall impact	Silt <40%, Soil organic matter >1% Heavy storms	32 (10-54) n = 14
Sieving	1-3	Vertical textural sorting with coarse particles at the top and thin particles at the bottom. Vesicular porosity	Particle sieving under rainfall impact. Air trapping (hence vesicles)	Very sandy soils, Soil organic matter >1% Heavy storms	10 (0-20) n = 31
Erosion	<1	Smooth, very dense and hard microlayer made of thin particles	Smoothening and erosion of structural crusts	Pre-existing structural crusts Runoff or/and wind.	3 (0-10) n = 20
Depositional	2->50	Vertical textural sorting with thin particles at the top and coarse particles at the bottom. Vesicular porosity	Sedimentation is still water	Pre-existing structural crusts Accumulation of water	2 (0-4) n = 9

(Range of values), n = number of samples

infiltration and runoff in the semi-arid regions from field observations and thus improve models (e.g., Casenave and Valentin, 1992; Tauer et Humborg, 1993; Bromley et al., 1997; Peugeot et al., 1997; Estevesi and Lapetite, 2003; Ndiaye et al., 2005). Because soil crusting can be identified by significant reflectance changes on the soil’s surface, soil crust-related properties such as water infiltration can be remotely sensed and mapped in semi-arid regions (e.g. d’Herbès and Valentin, 1997; Goldshleger et al., 2004).

Soil crusts have ambivalent impacts on soil erosion; they protect the soil surface from wind and interrill erosion but favour rill and gully erosion. Loose sands of the sieving structural crusts are more easily removed by wind (e.g. Goossens, 2004; Hupy, 2004), and water than the more resistant erosion crusts (e.g. Valentin, 1994). The superimposition of a biotic crust tend to make the underlying crust more resistant to erosion (e.g., Malam Issa et al., 2001; Eldridge and Leys, 2003; Valentin et al., 2004; Neff et al., 2005). Runoff produced by soil crusts tends to concentrate and form gullies even in sandy soils (e.g., Peugeot et al., 1997; Leduc et al., 2001; Descloitres et al., 2003; Esteves and Lapetite, 2003). Sandy soils are therefore generally eroded not only by sheet but also by gully erosion, even for very gentle slope gradients (Valentin et al., 2005).

Implications for land and water management

In the semi-arid zones, farmers need to weed several times during the cropping season not only to remove weed covers (e.g., de Rouw and Rajot, 2004) and limit thus competition for nutrients and water resources, but also, and often primarily to destroy the surface crust and increase water intake into the soils (Valentin et al. 2004). However, surface crusts quickly re-establish as a result of the cumulative kinetic energy of the following rainfalls. Table 2 indicates that this critical cumulative rainfall necessary for the crust to form again after tillage tends to increase with mean annual rainfall. Although a part of rainfall is lost through runoff during crust formation, and despite its short-lived positive effect, tillage is therefore essential to increase the amount of water available for crops in semi-arid sandy soils (e.g. Graef and Stahr, 2000). Tillage explains why infiltration is greater in cropped soils than in pasture soils (e.g., Casenave and Valentin, 1992; Burt et al., 2001; de Rouw, 2005).

Because crusts in sandy soils result mainly from the direct impact of raindrops, mulching of crop residues or branches is generally recommended. Since available residues are primarily used for other purposes as livestock feed or roof thatching, mulch is generally restricted to patches covered with erosion crusts. In addition to the effect of sand and seeds accumulation, mulch attracts termites that perforate pre-existing crusts and increases infiltration by a mean factor 2-3 (e.g., Casenave and Valentin, 1992; Mando et al., 1996; Léonard and Rajot, 2001). Manure application and livestock corralling on the most severely crusted patches are also valuable alternatives to restore soil surface properties (e.g. Graef and Stahr, 2000; de Rouw and Rajot, 2004; Schlecht and Buerkert, 2004; de Rouw, 2005).

The proportion of fine particles in the top layer decreases during cultivation (e.g. Ambouta and al., 1996) and increases once the land is returned to fallow (e.g., Ambouta, 1994; Abubakar, 1996). This enrichment in fine particles is primarily due to atmospheric dust deposition (e.g. Orange and Gac, 1990; Valentin et al., 2004). These textural variations influences greatly crusting processes because no erosion crust could develop when clay + silt contents falls below 5% (Ambouta, 1994), which is often the case for cropped sandy soil. By contrast, in the fallow soils, clay + silt content can approach the optimal content of 10% (e.g., Poesen, 1986; Casenave and Valentin, 1989). In the desert regions of China, straw of wheat, rice, reeds, and other plants is half buried and the other half is exposed to fix dunes. This decreases the intensity of sand flux by as much as 99.5%. Where the sand is fixed, fine particles are accumulated and a hard soil crust is formed on the dune surface, improving the stability of the dune surface (Qiu et al., 2004). Once formed, the crusts, which are neither tilled not subjected to trampling, are gradually colonised and

Table 2. Mean annual rainfall (MAR, mm) and critical cumulative rainfall necessary to form a new crust after tillage (CCR, mm) in sandy soils of the arid and semi-arid zones of West Africa

Location	Soil texture	MAR (mm)	CCR (mm)	CCR/MAR (%)	Source
Agadez, Northern Niger	Sandy	150	25	17	Valentin, 1991
Banizoumbou, Southwester Niger	Sandy	560	150	27	Röckstrom and Valentin, 1997
Bidi, Northern Burkina Faso	Sandy	620	200	32	Lamachére, 1991
Thysse Khaymor, Central Senegal	Sandy loam	660	160	24	Ndiaye et al., 2005

consolidated mosses and y green algae (e.g., Li et al., 2002) and protected from further water and wind erosion (Malam Issa et al., 2001; Valentin et al., 2004). As a result, Peugeot et al. (1997) observed in South-western Niger a much higher mean runoff coefficient (MRC) from a fallow (MRC = 23%) than from an adjacent the millet field (MRC = 5%). Most of the runoff concentrates into gullies. Since the bottom of these gullies are highly permeable (Peugeot et al., 1997; Esteves and Lapetite, 2003) a large proportion of the runoff in these gullies contribute to the water table recharge (Leduc et al., 2001).

In Northern Senegal, most severe crusting was observed in sandy exclosures where the vegetation but also soil crusts were protected from tillage and trampling (e. g. Valentin, 1985). This process has also been observed during a long-term fencing experiment in a sandy desert of Turkmenistan where crusts extended while bush and herbaceous biomass decreased (Orlovsky et al., 2004). These authors concluded that in this environment, undergrazing, as well as overgrazing, should be considered as a desertification factor. A biological soil crust with high contents of soil organic carbon and fine particles (clay + silt) was also formed within 3 years on sand dunes in an exclosure in a semi-arid, sandy grassland located in Northern China (Shirato et al., 2005).

In semi-arid areas, using mean landscape characteristics leads to a considerable underestimation of infiltration-excess surface runoff (e.g. Güntner and Bronstert, 2004). Re-infiltration and lateral redistribution of surface runoff between adjacent landscape patches need therefore to be accounted of. For instance, the mosaic of runoff generating fallows or pastures and runon-fields can be part of an efficient water-harvesting system (Rockström and de Rouw, 1997; Rockström and Valentin, 1997; Rockström et al., 1999).

Although surface crusts can hamper seedling emergence, they have overall positive effects on plant production in semi-arid sandy soils. Where rainfall input is insufficient for a continuous plant cover, vegetation benefits from the concentration of water. Such concentration is made possible only because crusts generate runoff. Crusts, especially erosion crusts, are thus inherent to the semi-arid ecosystems where they regulate scarce resources (e.g., Valentin and d'Herbès, 1999).

Conclusions

(1) Crusts form on sandy soils with silt + clay content exceeding 5%. Most severe crusting is observed for a silt + clay content of 10%.

(2) Crusts develop on sandy soils where they hamper seedling resistance and often generate runoff despite the pervious nature of the underlying soil.

(3) Accounting soil crust types improve predicting hydrological models.

(4) Crusts and associated concentrated runoff explain gully erosion of sandy soils even on gentle slopes.

(5) In the semi-arid and sandy regions, crusts must not be regarded as detrimental for the ecosystems but rather as an essential component to concentrate the poor water resources.

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An estimation of water retention properties in sandy soils of Southern Brazil

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Keywords: water retention, water potential, electric charges, organic matter, clay minerals

Abstract

Soil fabric and soil structure are sensitive to land use and management and their role in water retention properties have to be estimated in order to evaluate soil degradation or remediation. Undisturbed soil blocks were sampled on the campus of the Federal University of Santa Maria in Rio Grande do Sul State – Brazil, on a soil classified as Typic Paleudalf. Soil sampling was carried out on A1, A2, E and B horizons of five soil profiles representing different soil management practices. Their water retention and bulk density were measured from -1 to -107,000 kPa and their cation exchange capacity at soil pH (CEC_E) and at pH 7 (CEC_7) were determined. The contribution of organic carbon and clay minerals to CEC was evaluated according to the model developed by Bortoluzzi et al. (2005). A multiple regression was developed to estimate water retention properties in relation with bulk density and the contribution of clay and organic matter at different water potentials. Bulk density explains part of the water content at high water potentials. In contrast, soil CEC_7 provides a satisfactory explanation of the water retention properties at all water potentials studied. At high water potentials, the water retention reported to the organic carbon (OC) charge is considerably higher than that of clay charge, i.e. 60 g $cmol_c^{-1}$ and 30 g $cmol_c^{-1}$ for instance at -1 kPa. The amount of water per charge unit of carbon and of clay was similar at ~ -50 kPa, and the CEC can be used to predict water retention as a single parameter. At higher water potentials, taking into account the clay and organic carbon parameters improves the prediction of water retention properties. These results can be used to evaluate soil structure and therefore the impact of land use and management practices on soil physical properties.

Introduction

In subtropical areas, the amount of soil water available for plant uptake can be limited and is determined by a number of factors, including climatic conditions but also pore space characteristics. Available water content varies widely depending on soil composition and especially soil texture and organic carbon content as reported by Bauer and Black (1992). Agricultural management can also exert a considerable influence on soil fabric and pore space (Wander and Bollero, 1999), and on soil strength. This evolution can be associated to a decrease in organic carbon content and the effects of various stresses including mechanical compaction (Assouline et al., 1997, Bruand and Tessier, 2000).

Although sand particles are mainly responsible for determining soil pore space, the fine fractions control part of the water retention properties. For instance, in French loamy soils, Bigorre et al. (2000) showed the additive effect of clay and organic carbon content on water retention properties at low water potentials (-1,600 and -107,000 kPa).

The objective of this paper is to determine the role of soil structure and electric charges associated with clays and organic carbon content on water retention properties in a wide range of water potentials for sandy soils in Southern Brazil, in relation to soil management practices.

Materials and methods

Soil location and characteristics

The study site was located on the Federal University Campus of Santa Maria in Rio Grande do Sul State, Brazil (29º42′52′′S and 53º42′10′′W) at an altitude of about 90 m. The parent material is a sandstone of the Santa Maria Formation. The soils are Typic Paleudalfs (USA, 1994). They are well drained and present a strong vertical clay gradient (Bortoluzzi, 2003).

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Originally, the natural vegetation was a prairie. Five sites were used in this study: 1) a natural prairie (P); 2) a natural re-vegetation, i.e. a forest (F) corresponding to little human activity, when the other three sites have different management techniques, i.e. 3) conventional tillage (CT) for the past 30 years; 4) 18 years of conventional tillage followed by 12 years no-tillage (NTCT); and, 5) five years of no-tillage after prairie (NTP).

Soil sampling

At each site a trench 2.5 m long, 1 m wide and 1.7 m deep was opened when the soil was close to its field capacity. Blocks of about 1,700 cm^3 and soil cores of 70 cm^3 were sampled from the A1a (0-7.5 cm) and a A1b (7.5-15.0 cm) horizon, in the A2 (~15-30 cm), E (~40-55 cm) and Bt (~80-95 cm) horizons.

Analytical techniques

Soil core water content (*W*) and bulk density measurements were determined at field conditions. From blocks, clods (~3-5 cm^3) were prepared in the laboratory for water potentials ranging from -1 to -1,600 kPa. At low potential values, i.e. lower than -1,600 kPa and up to -107,000 kPa, the samples were equilibrated with controlled hygrometry in contact with saturated salt solutions. Water retention and bulk density measurements were carried out using the kerosene method according to Afnor (1996).

The pH_{H2O} was measured in a 1:1 soil/solution proportion with a potentiometer. The Effective Cation Exchange capacity (CEC_E), measured at soil pH, was determined by exchange with cobalt hexamine trichloride at a concentration of 0.01666 M. The CEC at pH 7.0 (CEC_7) was determined by exchange with 1 M NH_4^+-acetate, buffered at pH 7.0 (Afnor, 1996). The total organic carbon content (OC) was measured by a CN elemental analyser (Fison Carlo Erba).

Results

The main soil characteristics are shown in Table 1. The pH_{H2O} ranged from 3.9 to 6.1. The total organic carbon content (OC) ranged from 0.003 to 0.0137 kg kg^{-1}. CEC values measured at soil pH

Table 1. General soil properties and contribution of Clay and OC charges to CEC_7

Site	Hz	Particle-size distribution (μm) <2	2-50	50-2,000	ρ^a/Mg m^{-3}	OC^b/ kg $kg^{-1}\times 100$	pH_{H2O}/ unit	CEC_E	CEC_7	Contribution of charges to CEC_7^c Clay	OC
		------/kg $kg^{-1}\times 100$------						--------------/$mmol_c$ kg^{-1}	--------------		
P	A1a	16.2	24.8	59.0	1.45 (0.10)	1.37 (0.09)	6.1 (0.09)	65.7 (6.4)	65.7 (5.0)	30.2	35.4
	A1b	16.2	24.8	59.0	1.58 (0.01)	0.94 (0.05)	5.9 (0.18)	54.0 (4.4)	58.3 (2.1)	32.3	26.1
	A2	81.4	22.4	59.0	1.51 (0.00)	0.82 (0.04)	5.0 (0.28)	45.0 (4.0)	52.3 (5.5)	32.5	19.9
	AB	76.5	21.1	55.4	1.46 (0.04)	0.69 (0.01)	4.5 (0.07)	43.0 (1.0)	65.7 (3.8)	45.5	18.5
	BT	46.8	18.4	34.8	1.33 (0.04)	0.56 (0.02)	4.4 (0.02)	74.3 (1.5)	105.0 (2.6)	89.0	15.0
F	A	11.8	20.6	67.6	1.11 (0.20)	1.27 (0.07)	4.8 (0.52)	40.7 (5.7)	53.7 (1.5)	21.5	32.2
	A	11.8	20.6	67.6	1.51 (0.09)	0.69 (0.06)	4.5 (0.35)	23.0 (1.0)	36.3 (0.6)	20.0	16.3
	A	12.8	23.0	64.2	1.53 (0.05)	0.69 (0.02)	4.4 (0.16)	27.7 (3.2)	35.3 (4.0)	20.3	15.1
	E	9.5	37.4	53.1	1.61 (0.09)	0.30 (0.01)	4.6 (0.10)	14.3 (1.5)	27.3 (1.5)	18.1	7.9
	BT	42.0	17.2	40.8	1.54 (0.05)	0.52 (0.04)	4.6 (0.09)	69.0 (2.6)	91.0 (2.0)	77.9	13.1
CT	Ap	11.0	24.3	64.7	1.70 (0.06)	0.77 (0.03)	5.3 (0.27)	38.0 (4.0)	41.7 (0.6)	21.0	20.7
	Ap	11.0	24.3	64.7	1.72 (0.01)	0.70 (0.04)	5.8 (0.17)	39.3 (5.8)	40.0 (1.0)	21.3	18.7
	A2	13.6	26.3	60.1	1.65 (0.01)	0.59 (0.04)	5.4 (0.04)	39.0 (2.0)	38.3 (5.8)	24.2	14.2
	E	9.5	30.7	59.8	1.75 (0.01)	0.37 (0.01)	4.8 (0.25)	24.7 (0.6)	29.3 (2.3)	20.9	11.2
	BT	39.7	19.2	41.1	1.56 (0.01)	0.49 (0.07)	4.5 (0.06)	69.7 (6.7)	84.7 (5.0)	67.8	12.2
NTP	Ap	11.9	24.7	63.4	1.34 (0.06)	1.04 (0.17)	4.9 (0.16)	38.3 (7.5)	47.7 (7.2)	21.1	26.5
	Ap	11.9	24.7	63.4	1.59 (0.06)	0.78 (0.09)	4.4 (0.12)	30.3 (2.3)	45.3 (1.2)	23.7	21.7
	A2	13.6	26.2	60.2	1.48 (0.05)	0.71 (0.02)	4.4 (0.14)	32.7 (1.5)	42.3 (4.2)	24.6	17.8
	E	16.1	24.6	59.3	1.57 (0.03)	0.46 (0.01)	4.3 (0.03)	25.3 (1.5)	36.7 (2.1)	28.1	10.9
	BT	46.9	18.4	34.7	1.30 (0.03)	0.53 (0.03)	4.0 (0.08)	72.3 (4.5)	93.3 (0.6)	80.4	12.7
NTCT	Ap	13.0	20.0	67.0	1.58 (0.06)	0.79 (0.03)	3.9 (0.02)	25.3 (0.6)	43.3 (1.5)	22.4	21.0
	Ap	13.0	20.0	67.0	1.72 (0.00)	0.64 (0.03)	4.1 (0.08)	25.3 (2.1)	41.0 (1.0)	24.4	16.6
	A2	14.9	23.6	61.5	1.61 (0.08)	0.61 (0.02)	4.4 (0.17)	28.7 (2.3)	37.3 (5.9)	23.9	13.5
	E	12.6	14.3	73.1	1.58 (0.04)	0.40 (0.03)	4.4 (0.04)	17.3 (1.5)	34.7 (3.1)	26.4	11.6
	BT	30.9	17.9	51.2	1.55 (0.04)	0.48 (0.01)	4.5 (0.03)	48.7 (14.3)	76.0 (12.0)	52.7	11.3

[a] Bulk density, [b] Organic Carbon. [c] Clay and OC charge contribution obtained by solving of the equation 1, where the relative contribution (%) from each constituent was applied in the measured CEC_7 values. The data in parenthesis are standard deviations of means with three replicates.

(CEC_E) ranged from 14.3 to 74.3 mmol$_c$ kg^{-1}. The values of CEC at pH 7.0 were higher and ranged from 27.3 to 105.0 mmol$_c$ kg^{-1}.

Physical properties

The bulk density (ρ) varied from 1.11 Mg m^{-3} to 1.72 Mg m^{-3} (Table 1). The greatest bulk density variations were observed close to the surface at 0-15 cm depth. Below, the soil can be divided into two groups: (i) under prairie or under no-tillage after prairie where the bulk density ranged from 1.30 to 1.33 Mg m^{-3} and (ii) under forest or under conventional tillage and under no-tillage after conventional tillage where bulk density was close to 1.55 Mg m^{-3}.

The results also showed that the relationship between water content and bulk density at conditions close to field capacity was poorly correlated for cores (R^2 = 0.22) (Table 2). On clods, this relationship between water content and bulk density at -1 kPa was improved (R^2 = 0.84). Furthermore, the quality of the prediction decreased from high water potentials to low water potentials (0.84 <R^2 <0.22).

In order to distinguish the contribution of soil structure and fabric, i.e. the arrangement of soil particles, we used the CEC_7 to predict soil water content (Table 2). There is a adequate relationship between water content and CEC_7 for water potential varying between -3.2 to -1,600 kPa with determination coefficients higher than R^2 = 0.86. The determination coefficients are lower on cores at field conditions (R^2 = 0.72) and for clods at -1 kPa (R^2 = 0.66) and -107,000 kPa (R^2 = 0.69). These relationships were improved when the water was estimated by the CEC reported to the soil volume (cmol$_c$ dm^{-3}) and not by mass (cmol$_c$ kg^{-1}) (Table 2).

Relevance of soil charges on water retention properties

We used a multiple linear regression equation to evaluate the contribution of clay and organic carbon content to water retention properties (Table 3). For organic carbon, water retention reached 16.34 and 1.58 g g^{-1} at -1 and -1,600 kPa, respectively. This is in agreement with the water retained per g of carbon reported by Emerson (1995). The clay contribution is considerably lower than organic carbon since the water content at -1 kPa is 0.49 g g^{-1}. This water content is quite stable from -1 kPa to -1,600 kPa (0.49 to 0.35 g g^{-1}). At high water potentials the water content per negative electric charge unit of organic carbon was higher than that of the clay (61.3 and 28.9 at -1 kPa; 46.3 and 28.2 at -3.2 kPa; 34.4 and 27.4 at -10 kPa), while at low potential range, it was the contrary (19.5 and 24.8 at -100 kPa; 11.5 and 22.3 at -320 kPa; 4.3 and 21.3 at -1,600 kPa). At -107,000 kPa the organic carbon and clay contribution, per electric charge unit, in water content was lower and similar (3.5 and 2.0, respectively).

Table 2. Linear regression equations between bulk density and cation exchange capacity and water content at different water potentials

Water potential in kPa	Multiple linear regression equations	R^2	n[b]
Field conditions[a]	W = 0.451 - 0.185 ρ	0.22**	25
-1	W = 0.829 - 0.394 ρ	0.84*	25
-3.2	W = 0.809 - 0.397 ρ	0.76*	25
-10	W = 0.726 - 0.359 ρ	0.56*	25
-100	W = 0.577 - 0.288 ρ	0.46*	25
-320	W = 0.646 - 0.339 ρ	0.42*	25
-1,600	W = 0.380 - 0.188 ρ	0.24**	25
-107,000	W = 0.049 - 0.022 ρ	0.22**	25
Field conditons	W = 0.043 + 0.024 CEC_7 mass	0.72*	25
-1	W = 0.107 + 0.021 CEC_7 mass	0.66*	25
-3.2	W = 0.072 + 0.022 CEC_7 mass	0.86*	25
-10	W = 0.044 + 0.023 CEC_7 mass	0.87*	25
-100	W = 0.007 + 0.022 CEC_7 mass	0.87*	25
-320	W = -0.007 + 0.021 CEC_7 mass	0.86*	25
-1,600	W = -0.035 + 0.022 CEC_7 mass	0.89*	25
-107,000	W = 0.004 + 0.002 CEC_7 mass	0.69*	25
Field conditons	W = 0.061 + 0.030 CEC_7 vol	0.74*	25
-1	W = 0.115 + 0.030 CEC_7 vol	0.79*	25
-3.2	W = 0.087 + 0.030 CEC_7 vol	0.92*	25
-10	W = 0.059 + 0.031 CEC_7 vol	0.91*	25
-100	W = 0.023 + 0.030 CEC_7 vol	0.90*	25
-320	W = 0.006 + 0.028 CEC_7 vol	0.87*	25
-1,600	W = -0.020 + 0.030 CEC_7 vol	0.89*	25
-107,000	W = 0.004 + 0.003 CEC_7 vol	0.77*	25

[a] In field conditions, samples are soil cores. At given water potential values, the samples are clods (3-5 cm^3); [b] n = number of observations used in regression equations; ρ is bulk density (Mg m^{-3}); CEC_7 is cation exchange capacity measured at pH 7 in mass (cmol$_c$ kg^{-1}) and in volume (cmol$_c$ dm^{-3}); W is water content (g g^{-1}). * Significant at P <0.01, ** Significant at P <0.05 and ns = no significant.

Discussion and Conclusion

CEC value and modelling

The Effective Cation Exchange Capacity (CEC_E) and the CEC at pH 7.0 (CEC_7) were used to estimate the electric charges of the soil constituents according to the following equation (Bortoluzzi et al., 2005):

$$CEC_{\text{given pH}} = a_{\text{clay}} + \{b_{(\text{pH}-c)\text{clay}}\} + \{d_{(\text{pH}-e)\text{OC}}\}, \quad (1)$$

Table 3. Multiple linear regression equations between organic carbon and clay and water content at different water potentials

Water potential in kPa	Multiple linear regression equations	R^2	n^a
-1	W = 0.49 Clay + 16.34 OC	0.62*	25
-3.2	W = 0.48 Clay + 12.46 OC	0.77*	25
-10	W = 0.46 Clay + 9.41 OC	0.82*	25
-100	W = 0.42 Clay + 5.45 OC	0.88*	25
-320	W = 0.37 Clay + 3.58 OC	0.83*	25
-1,600	W = 0.35 Clay + 1.58 OC	0.90*	25
-107,000	W = 0.003 Clay + 0.93 OC	0.73*	25
-1	W = 28.9 CVP Clay + 61.3 CV carbon	0.63*	25
-3.2	W = 28.2 CVP Clay + 46.3 CV carbon	0.82*	25
-10	W = 27.4 CVP Clay + 34.4 CV carbon	0.87*	25
-100	W = 24.8 CVP Clay + 19.5 CV carbon	0.90*	25
-320	W = 22.3 CVP Clay + 11.5 CV carbon	0.93*	25
-1,600	W = 21.3 CVP Clay + 4.3 CV carbon	0.96*	25
-107,000	W = 2.0 CVP Clay + 3.5 CV carbon	0.73*	25

[a] *n* = number of observations used in regression equations; *W* is water content (g g^{-1}); Clay and OC are clay and organic carbon content; CV carbon and CVP clay are the surface charges due to carbon and clay soil constituents. * Significant at P <0.01, ** Significant at P <0.05 and ns = no significant.

where a is the permanent charge density kg^{-1} clay, $mmol_c$ kg^{-1}, b is the pH-dependent charge density per unit of pH and kg^{-1} clay, $mmol_c$ kg^{-1} pH^{-1}, c is the pH value at ZPC (zero point of charge) of the clay, expressed in units of pH, d is the pH-dependent charge density per unit of pH and kg^{-1} OC, $mmol_c$ kg^{-1} pH^{-1}, e is the pH value at ZPC (zero point of charge) of the organic carbon, expressed in units of pH and pH is the pH_{H2O} of the soil sample. Clay and OC are expressed in kg kg^{-1}.

The equation 1 was simplified for solving the clay and OC relative contribution to the $CEC_{7.0}$. Thus, the charges due to clay and OC are shown in the Table 1.

Contribution of structure and fabric to water retention properties

The results show that we can estimate the contribution of the CEC due to organic carbon and clay fraction on water retention properties. In Figure 1, the CEC does not completely explain the water retention at high water potential values, for instance at -10 kPa in sandy horizons, while in Bt horizons the estimation was better. This means that part of the water retention properties is due to grain packing voids in sandy material. On the contrary, at low water potential, namely -1,600 kPa, there is very good agreement between estimated water and measured water content in all horizons.

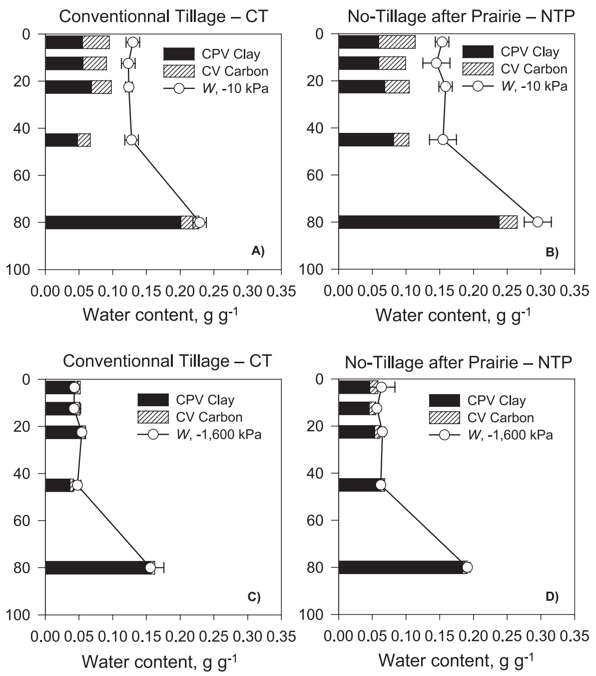

Figure 1. Contribution of clay (CPV clay) and organic carbon (CV carbon) charges to water content in two soils subjected to contrasting soil management practices, i.e. conventional tillage, CT and no-tillage after prairie, NTP, where A and B are the water potential at -10 kPa and C and D at -1.600 kPa

Clay and organic matter fractions have very different properties, especially at high water potential values of organic carbon. One of the possible explanations is the specific fabric of organic matter at high water content, whereas its hydration properties at low water potentials appeared to be related to its molecular structure (Feller et al., 1996). In contrast, the clay fabric is mainly an assemblage of kaolinite crystals or domains, mainly face-to-face (Ben Rhaïem et al., 1987). In this case, the clay fabric does not vary to a large extent in the high-water-potential range.

It is also interesting to notice that the water content per negative electrical charge unit of clay and organic carbon was similar at a specific water potential value close to -50 kPa. This value is obtained by the intersection between clay and organic carbon water retention curves. This means that the CEC can be used to predict the soil water content alone on the basis of this specific value. This result confirms other data previously reported by Bigorre et al. (2000). Furthermore, because the water content of the clay was rather constant from -1 kPa to -1,600 kPa, this means that water associated with clay fraction is mainly residual water. This would also suggest that organic carbon is the major component of soil water uptake and release at higher potential.

For our soils, the value of CEC can be used to predict water retention properties due to clay and organic carbon, and water potential. The water retention of clays was very constant within a large range of water potentials and can be considered as residual water content since little water was released or taken up over a large water potential range. This may be due to the specific structure of sandy soils where the fine fractions filling the sand matrix can fully express their water retention properties as a result of the available volume for hydration and swelling.

There is a specific water potential of -50 kPa, where the water content related to the charge unit of the clay and organic carbon. At this water potential in the soils under study, the CEC can be used to predict water retention as a single parameter. For other water potential values, a better prediction was obtained by taking the contribution of clay and organic carbon to the CEC and its contribution to water content.

It is shown that land use and soil management practices orient water retention properties. Close to -10 kPa, the prediction must take the structure of the soil into consideration and is thus associated with changes in packing voids and soil structure due to practices.

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Hydraulics of rill initiation on a low-slope sandy soil

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Keywords: rainfall simulation, water erosion, erosion models, rill, Senegal

Abstract

Most sandy soils in West Africa have low slopes, typically of less than one percent. They however are prone to water erosion because of their susceptibility to crusting and their weak cohesion. This study presents a rainfall-simulation experiment. It consisted of a 2 hrs rainfall event at a constant intensity of 75 mm h^{1}, on a smooth bare soil with a 1 percent slope with the objective of forming a rill. After the rill was formed, soil elevation was measured at a horizontal resolution of 2.5 cm. Flow velocities were measured at 62 locations on the plot with the Salt Velocity Gauge technology, an automated, miniaturized device based on salt tracing. Measured velocities ranged from 0.006 m s^{1} to 0.26m s^{-1}. Three hydrological models were tested using these experimental data and their ability to simulate the velocity fields was studied. The first model solved the Saint-Venant equations in 2D. The second model used a kinematic wave in 1D in the slope direction coupled with a 2D flow-routing algorithm. The third model involved an empirical runoff algorithm close to the diffusion wave equation in 2D. The Darcy-Weisbach friction factor was calibrated in all cases. The comparison of simulated to observed velocities indicated that the full Saint-Venant equation gave better results than either the kinematic or the diffusion-wave equation. This result is attributed to the low slope angle of the plot, which is in part attributed to the fact that at low slopes, the local variations of water depth are of the same order of magnitude to that of variations in soil elevation. All models underestimate the velocity in the rill and overestimate velocities in the interril area. These results demonstrate that the Darcy-Weisbach friction factor used in the models should vary with the Reynolds number while all models considered it constant.

Introduction

Rill erosion is a major contributor to sediment removal from agricultural fields. Other erosion processes such as interrill erosion, splash erosion or tillage erosion preferentially lead to translocation of soil within the field (cf. Parsons *et al.*, 2004). Thus, rill erosion has not only a crucial importance for on-site effects of erosion, but also for off-site effects and environmental concerns. It is therefore critical to understand the occurrence of dynamics of flow in rills and their controls on the pattern and timing of erosion.

Rill density has been thoroughly measured and related to landscape properties (*e.g.* Desmet and Govers, 1997). Hydraulics in rills has also been studied (Gimenez and Govers, 2001; Govers, 1992; Nearing *et al.*, 1997). These studies have highlighted a number of interactions between flow and bed roughness. A first kind of interaction involves grain roughness and Reynolds number *Re* ($Re = 4 \cdot u \cdot r / \nu$), where u is average velocity, r is hydraulic radius and ν is the fluid kinematic viscosity; This formula is classically used to estimate Re in shallow free surface flows; *e.g.* Savat, 1980, Gilley *et al.*, 1990, Abrahams *et al.* 1995, Pilotti and Menduni, 1997). Grain roughness does not affect flow velocity the same way in laminar and turbulent flow. As a result, the friction factor *ff* in the Darcy-Weisbach equation decreases with increasing values of *Re*. This interaction was shown experimentally by Nearing *et al.* (1997) on bare sandy soils, where grain size is small with regard to flow depth. At greater grain size and/or when natural vegetation interacts with the flow, the relationship between *ff* and *Re* is even more complex, as shown by Abrahams *et al.* (1995).

A second type of interaction involves channel roughness and Froude number *Fr* ($Fr = u / \sqrt{g \cdot h}$,

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where u is the average velocity, g is gravitational acceleration and h is flow depth). Grant (1997) provided the first assessment of such an interaction on high-gradient alluvial channels. He showed that *Fr* could not be higher than unity over long distances or long periods of time. The same interaction was demonstrated by Gimenez and Govers (2001) on eroding rills. Finally, Gimenez *et al*. (2004) hypothesized that critical flow was a necessary condition for rill initiation. Interaction with *Fr* lies on the development of small hydraulic jumps along the rill when the flow velocity is critical. At the jump location, localized erosion occurs due to turbulence in the jump, with the result of eroding the channel, enlarging it and finally lowering the average velocity above the critical speed.

This knowledge of rill initiation and development is however underexploited in most erosion models. Rill density is either predefined (one rill per metre for WEPP: Gilley *et al.* 1988) or as an input parameter (Siepel *et al.*, 2002). A few models are aimed at dynamically developing a rill network (RillGrow model, Favis-Mortlock *et al.*, 2000; PSEM_2D model, Nord and Esteves, in press) However, these models use uniform friction factors. Finally little attention had been paid to the reliability of *Re* and *Fr* values simulated by erosion models.

This study presents a rainfall-simulation experiment carried out at Thies, Senegal (14º45′43″N, 16º53′16″W), on a 40-m^2 plot with sandy soil and low slope (1%). Flow velocity was measured at 58 individual points on the plot with a miniaturized version of the salt velocity gauge (SVG) technology (Planchon *et al*. 2005). SVG is an automated salt-tracing technique which provides reliable point velocity data over a wide range of flow speeds and with no lower limit on flow depth. Measured velocities have been compared with simulated data from three models and the consequences on the simulation of *Re* and *Fr* are assessed and discussed. The results allow us to draw some research perspectives for the modelling of rill initiation.

Material and methods

The new generation of SVG

The SVG technology has been presented in Planchon *et al.* (2005). It consists of injecting salty brine into the flow and recording the conductivity peak simultaneously at two locations downstream. A new generation of SVG has been developed for this experiment. Each conductivity sensor consisted of two aluminium pins spaced 1-cm apart, which allowed for measuring the velocity of a narrow flow path. The inter-probe distance was 10cm. The flow velocity was calculated by fitting a 1D convection-dispersion model for velocity and dispersion coefficients (Eq. 1). Hayami (1951), reported by Henderson (1966), gave Eq. 2 as the solution of Eq. 1 when C(0,t) is the Dirac function, *i.e.* injection is instantaneous. Eq. 3 describes the least-squares sum that is minimized in the model used by the SVG.

$$\frac{\partial C}{\partial t} = -V\frac{\partial C}{\partial x} + D\frac{\partial^2 C}{\partial x^2} \tag{1}$$

$$C = \frac{x}{2\sqrt{\pi \cdot D \cdot t^3}} \exp\left(-\frac{(V \cdot t - x)^2}{4D \cdot t}\right) \tag{2}$$

$$ssq = \sum_t \left[\left(C_1 \otimes \overline{C}\right) - \left(a \cdot C_2 + b\right)\right]^2 \tag{3}$$

where C is salt concentration (g· l^{-1}); C_1 is measured at the upper probe; C_2 is measured at the down probe; t is time (s); x is length (m); V is flow velocity (m·s^{-1}); D is dispersion (m^2·s^{-1}); ⊗ is the convolution product; $\overline{C}$ is Hayami’s solution from Eq. 2 with x being the inter-probe distance, i.e. 0·1m; a and b are coefficients that account for salt losses between the two probes (due to infiltration or other cause); *ssq* is the quadratic sum that is minimized by fitting V, D, a and b for each pair of peaks.

The new generation of SVG requires two operators. The first is located on the plot to place the probes in the measuring locations and to do the injections manually. The brine was coloured with potassium permanganate to allow for visual control of the tracing process. Four probes were multiplexed to the datalogger, allowing four locations to be measured simultaneously. The second operator was at the computer. At a given signal, the data acquisition was triggered when the first operator injected the brine a few centimetres upstream of the probes. Conductivity was measured at 200 Hz during 2·5s and the model was then automatically fitted to the data. The measurement was replicated until clear peaks were seen on the software graphical interface and the model gave satisfactory results.

Rainfall-simulation experiment

The rainfall-simulation site was located at Thies, Senegal. The plot was 10m long by 4m wide, with a 1% slope, and sandy soil (1% clay, 7% silt, 43% fine sand, 49% coarse sand). The rainfall simulator was as described by Esteves *et al.* (2000a). It allowed for rainfall at constant intensity of 70mm $\cdot hr^{-1}$ in average. In order to limit wind effects, which may cause noticeable variations of rainfall intensity, simulations were carried out at a maximum wind speed of 1 $m \cdot s^{-1}$. Six tipping-bucket rain gauges with electronic recording were placed along the plot borders for monitoring the actual rainfall intensity. The flow discharge was collected in a trough and alternately directed, via a 4-inch flexible hose, into two 150-litre cylindrical buckets, one being filled while the other was drained. The volume in the filling bucket was monitored by recording the rise of a float. The resolution of this apparatus was 2·5litres. The typical flow discharge at steady state was 0·5l $\cdot s^{-1}$.

On day 1 of the experiment, a wetting rainfall of 20mm was applied and the plot was manually ploughed to a depth of 50cm. The surface was then raked in order to form a slight V shape, with 1% slope longitudinally and 1% slope towards the median axis of the plot. The purpose of the V shape was to prevent a rill from forming by the edge of the plot.

The experiment detailed in this article was held on day 7. The days before, a total of six hours of rainfall had already been applied on the plot for others experiments that are not reported in this article. The consequence of these successive experiments was an already ‘old’ surface with a well organized flow pattern. The longitudinal slope had evolved from straight to slightly concave (Figure1) with thick sand deposits in the concave downstream part.

Days 6 and 8 (*i.e.* the day before the experiment, and the day after) were used to carry out microrelief measurements. The relief-meter was the same as described by Planchon *et al.* (2001). It consists of a vertical rod with a sensor at the end that detects the soil surface. Stepper motors allow the apparatus to move in small increments in all directions. The horizontal resolution is 2·5cm transversally to the plot and 5cm longitudinally. The vertical precision is 0·5mm. With a maximum acquisition rate of 1·6 point·s^{-1}, the 16,000 measured points of the entire plot required a full day.

The experiment on day 7 consisted of a 2h15′-long continuous rainfall at constant rainfall intensity (69 mm·h^{-1} on average). After the discharge had stabilized, flow velocity was measured at 72 locations with three to six replications, which led to a total of 348 individual velocity measurements. Among this set, 122 individual measurements, covering 68 locations, have been selected for further analysis. The other data were discarded for various reasons: in particular because of the poor quality of either one of the two conductivity peaks or poor quality of the modelled peaks.

At the end of the experiment, a series of digital pictures of the plot were taken from a height of 6 metres above the plot. The pictures have been mounted in a single file and geometrically corrected so that each pixel corresponds to one square millimetre in the field. The resulting image can be combined with a DEM to calculate virtual pictures. Figure1 shows one of these views with the relief magnified ten times and the colour contrast enhanced. The native soil appears in black (its natural colour is a yellowish light brown). White and reddish colours correspond to various types of sand deposits.

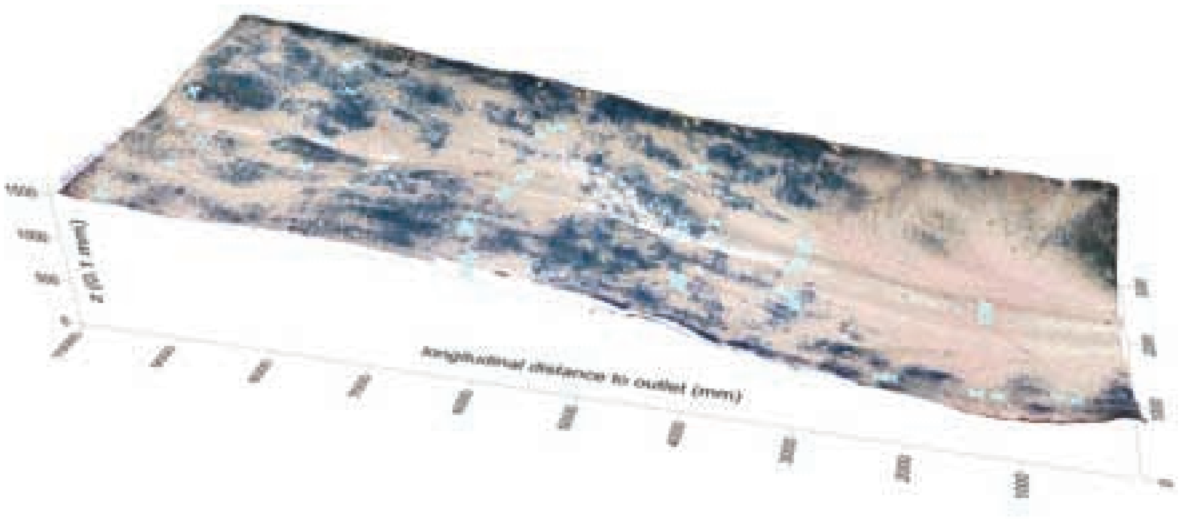

Figure. 1. Location of the velocity measurements showed on a virtual picture of the plot. Vertical axis has been magnified ten times. Colour contrast has been enhanced. The native soil appears in black. White and reddish colours correspond to various types of sand deposits

The models

PSEM 2D (Plot Soil-Erosion Model 2D; Nord and Esteves, in press; Esteves *et al.*, 2000b) is a soil erosion model dedicated to small experimental plots, typically of less than 100m ^{2}.

Overland flow is described by the depth-averaged two-dimensional unsteady flow equations commonly referred to as the Saint-Venant equations (Zhang and Cundy, 1989). The friction slopes are approximated using the Darcy-Weisbach equation (Eq. 4.) derived for uniform steady flow. The second-order explicit scheme of MacCormack (1969) is used for solving the overland flow equations. Infiltration is computed at each node using a Green-Ampt model (Green and Ampt, 1911).

$$S_{fx} = ff\frac{u_x^{\ 2}}{8gh}, S_{fy} = ff\frac{u_y^{\ 2}}{8gh} \tag{4}$$

where *ff* is the calibrated Darcy-Weisbach friction factor. A constant value is assuming during the simulation.

NCF (New Conceptual Framework; Parsons *et al.*, 1997, Wainwright *et al.*, 1999) is a flexible model that can be used for experimental plots as well as small watersheds. The hydraulics consists of solving the kinematic wave equation in 1D along the flow direction derived from a DEM which depressions have been previously filled (using the algorithm from Planchon and Darboux, 2001). The kinematic wave simplification uses the continuity equation from Eq. 5, together with the Darcy-Weisbach equation in one dimension (Eq. 6). The numerical scheme used with this model is the Euler simple backward difference (Scoging, 1992).

$$\frac{\partial q}{\partial x} + \frac{\partial d}{\partial t} = e_x \tag{5}$$

$$v = \sqrt{\frac{8gds}{ff}} \tag{6}$$

where g is gravitational acceleration ($m{\cdot}s^{-2}$), d is flow depth (m), q is unit discharge ($m^2 s^{-1}$) and s is the slope ($m{\cdot}m^{-1}$).

The flow is routed from each cell to one of its four adjacent cells in a finite difference grid using a topographically based algorithm based on the greatest difference in altitude of the cells. Overland flow is generated as Hortonian (infiltration excess) runoff by determining the difference between the rainfall and infiltration rate. The latter is predicted using the Smith-Parlange model with modifications to allow runon infiltration and temporally variable rainfall.

RillGrow2 (Favis-Mortlock, 1998; Favis-Mortlock and Boardman, 2000) is a model dedicated to the numerical simulation of emerging rill patterns. Space is discreticized at very small scale so that any cell is supposed to be entirely inside, or entirely outside a rill. Each cell is eroding independently to each other. Cells lower while eroding. Eroding cells thus attract more water flow, subsequently increasing the erosive power of the rill. Because of its high computational needs, applications of RillGrow2 are limited to experimental plots of a few tens of square metres.

RillGrow2 hydraulics consists of calculating a ‘potential flow velocity’ with a Manning-type equation, based on the water depth: $u = w{\cdot}d{\cdot}R^n$, where u is ‘potential flow velocity’, w is an empirical roughness coefficient, d is water depth, R is the hydraulic gradient and $n = 0{\cdot}5$. The RillGrow2 numerical scheme is unique in soil-erosion modelling: at each time step, the model checks a single cell, chosen at random, and processes it. The check consists of calculating u and determining if outflow is possible from this cell. If the answer is yes, an outlet cell is chosen among eight neighbours according to the steepest descent of the free surface. The required amount of water is then passed from the source cell to the destination cell in order to level the free surface between the two cells. This procedure is then repeated until all cells have been chosen at the particular time step.

Results

Surface-feature patterns

Figure2 shows the left bank of the rill viewed from downstream. The coloured arrows represent the flow velocities as computed by the best model result (to be detailed below). At this point of the result presentation, the model results are used as a convenient illustration of the various flow conditions on the plot and their relation to surface features.

Table 1 summarizes the qualitative information detailed in this section.

Location A represents a high point with a convex soil surface. No visible flow could be seen and the model actually predicts a flow velocity lower than $0{\cdot}02\ m{\cdot}s^{-1}$. Because of their higher position, these locations were sediment sources with regards to splash erosion: sediments occasionally splashed onto these

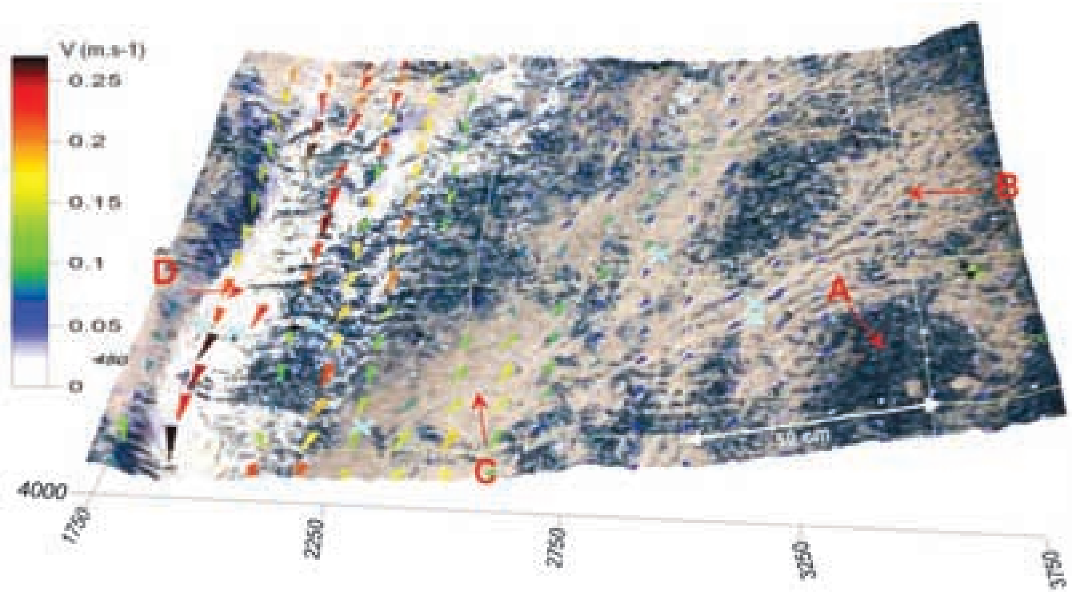

Figure 2. Detail of the left bank of the rill viewed from downstream. Light blue crosses show velocity measurement locations. Coloured arrows are modelled flow velocity. Capital letters show the four surface features that develop on the plot (comments in text). Axis labels are in mm

Table 1. Qualitative information on flow condition deduced from field observation during rainfall and from surface feature description after the experiment

<table>
<tr><th>Location</th><th>Surface feature</th><th>Velocity ($m.s^{-1}$)</th><th>Turbu-lence</th><th>Flow regime</th></tr>
<tr><td>A</td><td>Native soil, light brown</td><td><0·02</td><td rowspan="2">Laminar</td><td rowspan="3">Sub-critical</td></tr>
<tr><td>B</td><td>Discontinuous sand deposit</td><td>0·02 <0·05</td></tr>
<tr><td>C</td><td>Continuous reddish sand deposit</td><td>0·1 <0·2</td><td rowspan="2">Turbulent</td></tr>
<tr><td>D</td><td>Continuous white sand deposit with crossed wavy features</td><td>>0·2</td><td>Super-critical</td></tr>
</table>

areas were sooner or later splashed back to the lower areas. The soil surface at A had therefore the colour of the native soil, which is a yellowish light brown.

Location B represents the first visible flow. It is characterized by small undulating furrows, ~10 mm wide and 2mm deep. Flow velocity was still slow (~0·05 $m{\cdot}s^{-1}$ according to the model). The transport capacity was subsequently negligible. However, uneven sand grains could be observed in these tiny channels, slowly creeping downstream until a raindrop hit them and splashed them away. The only turbulence in the flow was caused by raindrop impacts.

At location C, a well established stream was flowing at 0·1 to 0·15 $m{\cdot}s^{-1}$. The soil surface was covered by a continuous layer of reddish sand that was slowly creeping downstream. Flow was turbulent, but still subcritical. Turbulent flow could easily be determined from the observation of the fate of the coloured brine. In laminar flow, the brine left the injection point very gradually, thus forming a long colourer tail. This fate indicates a vanishing flow velocity at the bottom of the flow, which is typical to laminar flows. In turbulent flows, the tracer left the injection point in a fraction of seconds, indicating a very sharp vertical velocity profile that did not allow the tracer to ‘stick’ to the soil surface, as it did in laminar conditions.

Location D is characterized by white sand deposits with crossed wavy features typical to supercritical flow. The white colour of the sand indicates that the sand grains were washed up by turbulence until all clay and organic particles had detached. These field observations indicate that the flow was certainly turbulent and supercritical. Modelled as well as measured velocities were all above 0·2m $\cdot s^{-1}$.

Qualitative results

RillGrow2 used 5-cm cells in order to follow its requirement that a given cell should be entirely inside or entirely outside a flow path. NCF used 50-cm cells for the opposite reason: because the 1-D hydraulics does not allow for lateral flow movement, NCF requires that the same flow path will not be divided into multiple cells, otherwise the modelled free surface may be unrealistic, which leads in practice to numerical instabilities. PSEM_2D used 10-cm cells, which was the smallest cell size the model could simulate without numerical oscillations. Only RillGrow2 was able to run the raw DEM. Both PSEM_2D and NCF needed a smoothed and depression-free DEM.

Each model was calibrated from the hydrograph. The infiltration parameters were calibrated from the total runoff and the steady infiltration rate. The friction factor was calibrated from the hydrograph rise (Figure3).

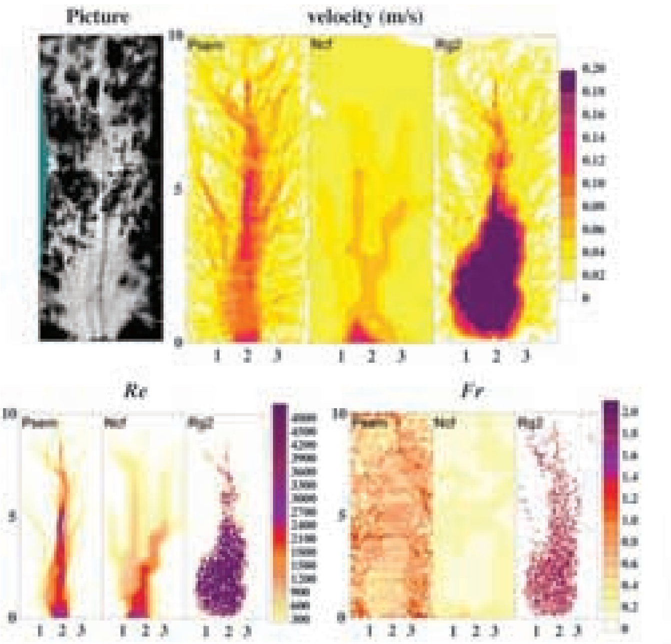

Figure 3. Picture of the plot (with contrast magnified) compared to the velocity, Re and Fr maps predicted by the models. Calibrations were done from the hydrograph

The velocity field from PSEM_2D is very similar to what can be estimated from the picture at the left of the figure. One can notice for example the location of the predicted maximum velocity. It corresponds to the white sands at the centre of the plot, which we interpreted as a mark of supercritical flow. The pattern from NCF is similar to PSEM, with a noticeable loss of precision due to the coarser grid. RillGrow2 predicts a wide area of high velocity in the bottom part of the plot which corresponds fairly well to the concave area of reddish sands deposits that can be seen either on Figures 3 and 1.

The *Re* predictions follow approximately the same pattern as the flow velocity. However, according to the threshold of 2000 commonly used for the transition between laminar and turbulent flows, the spatial extension of turbulent flow is underestimated with regard to observations made by eye during the velocity measurement (as explained in the previous section). *Fr* is even more problematic since no pattern at all is predicted by PSEM_2D or NCF while the pattern predicted by RillGrow2 does not fit to the field observations reported in Table 1.

Models results: Comparison with measured velocity

Figure 4 shows the modelled velocity *vs* the observed ones. All models have a better fit at low velocities than at higher ones. PSEM_2D and NCF slightly overestimate the low velocity and strongly underestimate the high ones. RillGrow2 simulates very well the slowest flows (*i.e.* v<0 ·05m ·s^{-1}) and underestimates the other cases. Results from NCF are not exactly comparable to measured data because while measured velocities are point data, the model results represent a 0·25 m^2 cell. Localized maxima or minima cannot be expected to figure in NCF results.

Modelling the interaction between friction factor and flow conditions

The velocity modelled by PSEM_2D (Figure 4) fits Eq. 8, which can be used to estimate ff_1, the true value of ff at each cell. This is done by solving, at each cell, the set of equations 8 to 11 for ff_1, which Eq. 12 gives the solution. Eq. 9 states the unit discharge at the cell location will not change after ff is corrected from ff_0 to ff_1. Eq.10 and 1 1 are the Darcy-Weisbach equation before and after correction, respectively.

$$v_0 = b \cdot v_1^{\,a} \qquad (8)$$

$$v_0 \cdot h_0 = v_1 \cdot h_1 \qquad (9)$$

$$v_0 = \sqrt{\frac{8gh_0 s}{ff_0}} \qquad (10)$$

$$v_1 = \sqrt{\frac{8gh_1 s}{ff_1}} \qquad (11)$$

$$ff_1 = ff_0 \cdot v_0^{\left(3-\frac{3}{a}\right)} \cdot b^{\left(\frac{3}{a}\right)} \qquad (12)$$

where a = 0·5; b = 0·28; ff_0 = 0·26; (*h0, v0*) are flow depth and flow velocity read at a given cell in the PSEM_2D results shown in Figures3 and 4; *v1* is the observed velocity; *h1* is the corresponding flow depth according to the modelled unit discharge.

ff_1 was calculated from Eq. 12 at each cell. The resulting map was then smoothed to prevent the model

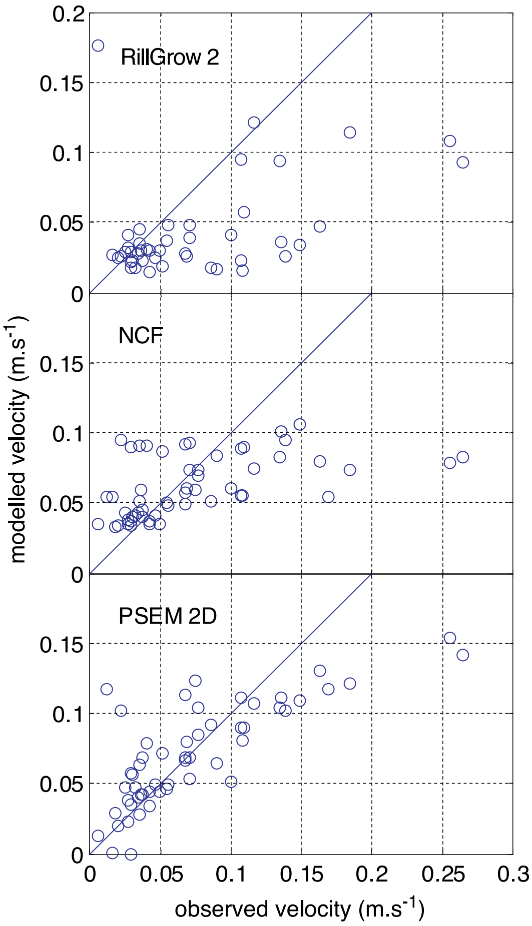

Figure 4. Modelled velocity against measured values

from producing numerical instabilities. A threshold of *ff*<2 was finally applied to account for inconsistent velocities predicted at very small water depths, whereas the value of this threshold proved to have little influence on the final result. PSEM_2D is the only model which allows for spatially non uniform values of *ff*. It was therefore used for validation. Figure5 shows the resulting maps for *V*, *Re* and *Fr*. The *Fr* >1 limit is in fair agreement with the white sands that has been interpreted as the mark of supercritical flow. The *Re* >2,000 limit is wider (albeit still limited to the central channel). Figure 6 shows the graph of modelled vs observed velocity. Results are scattered around the one-one line, which was the expected result of the use of Eq. 12. Figures 5 and 6 show that the results with varying *ff* are far more realistic, and closer to the field observations, than those obtained from homogeneous *ff*.

Figure7 relates *ff* with *Re* in logarithmic co-ordinates. It shows that *ff* is high at low Reynolds numbers and decreases with increasing *Re*. This is the same kind of relationship as previously obtained by Nearing *et al.* (1997). Figure8 compares the two experiments. Each line was drawn inside the data limits of the corresponding experiment. Results from Nearing et al. (1997) are therefore extended from rill flow and high *Re* values to interrill flow at the transition between laminar and turbulent conditions.

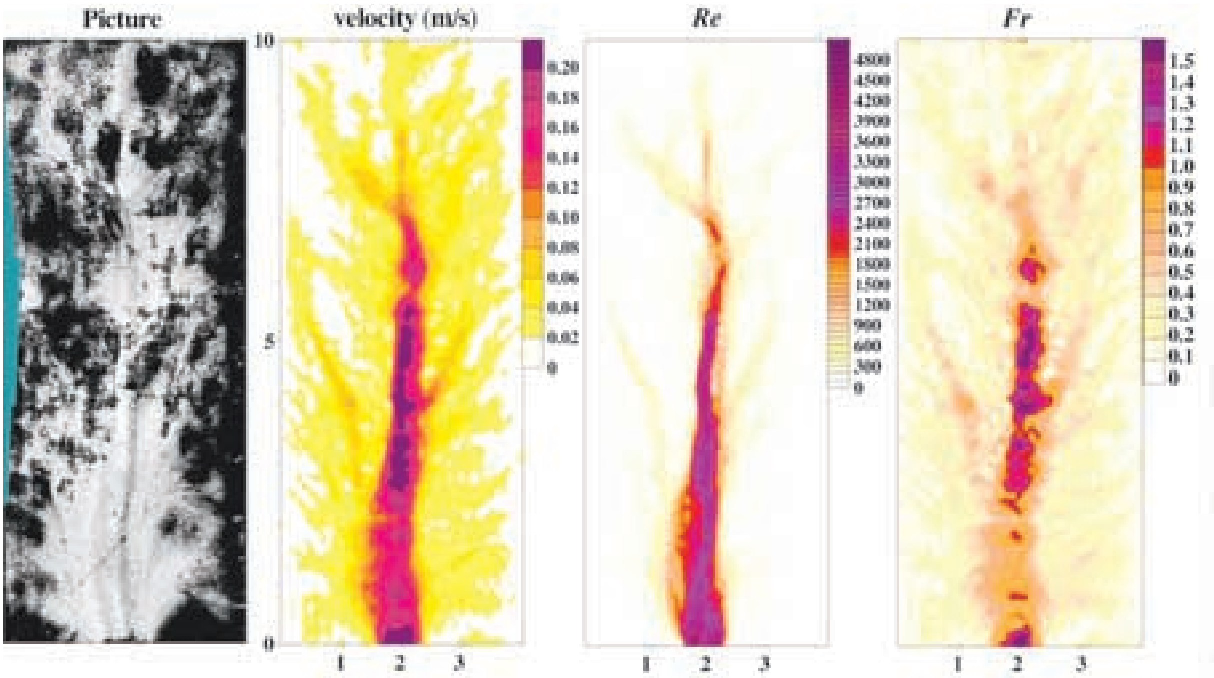

Figure 5. PSEM_2D results with *ff* calculated from Eq. 12: output maps compared with the picture of the plot

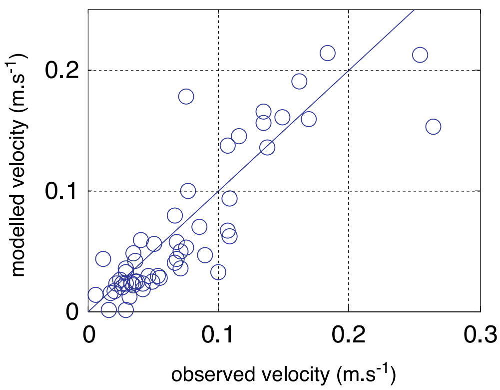

Figure 6. PSEM_2D modelled velocity with *ff* calculated from Eq. 12

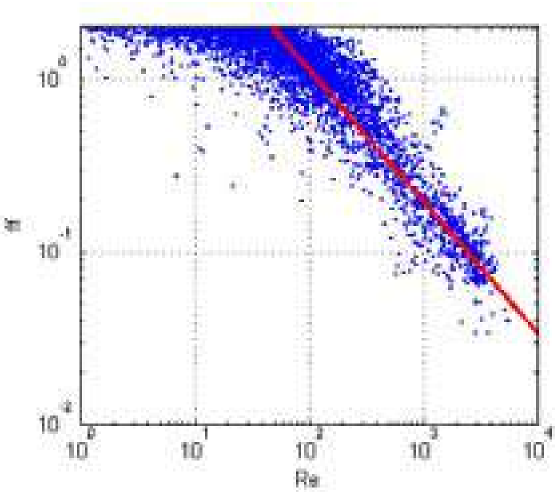

Figure 7. Relationship between Friction factor *ff* and Reynolds number *Re* simulated by PSEM_2D with friction factor calculated from Eq. 12

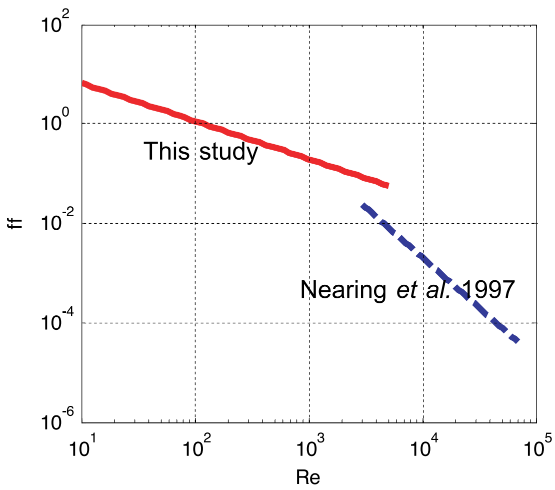

Figure 8. Relationship between Friction factor *ff* and Reynolds number *Re*: comparison with results from Nearing et al. (1997)

Discussion and Conclusion

The SVG technology has allowed flow-velocity measurement in a wide range of flow speeds (from 0·006m $\cdot s^{-1}$ to 0·27$\cdot s^{-1}$ in this experiment). The use of salty brine as a tracer makes SVG suitable for measuring very shallow flows. The only limitation was the probe size, which was 1-cm wide and 10-cm long. Thanks to this technology, we were able to measure velocity in a wide variety of flow conditions, from unconcentrated to concentrated in a small rill, from laminar to turbulent, and from subcritical to supercritical. The data obtained have been used to test three hydrological models (PSEM_2D, NCF, and RillGrow2) which were very different to each other, having only in common the use of a Manning/Darcy-Weisbach-type hydraulic equation with a constant, homogeneous friction factor. The main results were the followings:

- PSEM_2D, NCF and RillGrow2 to a lesser extent, simulated satisfactorily the patterns of flow velocity and Reynolds number *Re*. However, both patterns and values of the Froude number *Fr* were incorrectly predicted by the three models.
- Low velocities were overestimated (PSEM_2D NCF). High velocities were largely under-estimated (all models).
- *Re* values estimated by the models are realistic. However, the classical threshold of *Re* = 2,000 for the transition between laminar to turbulent flow, would predict laminar flow everywhere on the plot but in the central channel, while field observation described turbulence even in the tributaries of the main channel.
- A heterogeneous friction factor *ff* was calculated to fit the modelled velocity with the whole range of observed values. Running PSEM_2D with the new *ff* led to an improvement of *Re* and *Fr* patterns. Moreover, *ff* appeared to be related to *Re* via a power law similar to the one observed by Nearing *et al.* (1997) on sandy bare soil (albeit the range of *ff* and *Re* differed in the two studies).

  These results lead to the following conclusions:

- The hydrograph alone is an insufficient source of information to calibrate *ff*. Other source of data such as the measured velocity field is therefore highly desirable to calibrate any hydrological model dedicated to be coupled to an erosion model.
- *ff* decreases with increasing *Re*, which we interpreted by the fact that the flow becomes less sensitive to the grain roughness when its

turbulence increases. This result confirms the conclusion of Nearing *et al.* (1997) for sandy bare soils and extends them to lower values of *Re* than in their study.

- The usual procedure in soil-erosion models is the calibration, from the hydrograph, of a single value of *ff* for the whole plot. Our results show that this procedure will correctly calibrate the friction factor for the cells at low to moderate velocity, which dominate the hydrological response of the plot. Contrarily, the hydrograph will not be significantly affected by an even dramatic underestimation of the highest velocity because these maxima occur on short distances, so that the corresponding error in terms of travel time will be small.
- Uniform *ff* leads to erroneous *Fr*. However, when measured velocities are used to recalculate *ff*, *Fr* patterns and values are satisfying. Gimenez *et al.* (2004) have demonstrated the importance of *Fr* in the initiation and the development of rills. Any future model aimed at simulating rill initiation on the basis of these findings will first have to account for the *ff-Re* relationship in order to have realistic simulations of *Fr* for using at predicting rill initiation.

Acknowledgements

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The co-composting of waste bentonites from the processing of vegetable oil and its affect on selected soil properties of a light textured sand

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Keywords: Co-composted waste acid bentonite, waste bentonite, soil amelioration, degraded soils

Abstract

Waste acid bentonite is a byproduct from vegetable oil bleaching that is both acidic (pH <3.0) and water repellent (hydrophobic). These materials are currently disposed in landfills and are an environmental hazard due to the aforementioned properties. A study was undertaken using three different sources of waste oil bentonites collected from processing plants within the Bangkok metropolitan area. These wastes included soybean oil bentonite (SB), palm oil bentonite (PB) and rice bran oil bentonite (RB), each of which was co-composted with rice husk, rice husk ash, and chicken litter in order to eliminate their acid reactivity and hydrophobic nature. The chemical and physical characteristics of acid activated bentonites before and after bleaching and the co-composted materials after addition to a degraded light textured soil were assessed and are reported herein. The organic carbon (OC) content, pH, exchangeable cations and cation exchange capacity (CEC) of the waste oil bentonites increased significantly after the co-composting phase. In addition, the hydrophobic nature of these materials as measured using the Water Drop Penetration Test (WDPT) decreased from 10,800 seconds to 16-80 seconds after composting. Furthermore, when these composted materials were incorporated into a degraded light textured sandy soil positive impacts to soil physical attributes in terms of specific surface area, total porosity and available water content for crop growth were observed. The results from this study demonstrate the positive impact of the waste products when modified through composting on the physical and chemical properties of a light textured sandy soil.

Introduction

Sandy light textured soils are common throughout the globe and it is estimated that they cover approximately 900 million hectares (Driessen *et al*., 2001). Whilst these soil types (Arenosols) predominate the arid and desert regions of the world, these soils occur extensively within the semi- and humid-tropics and support the livelihoods of large populations. Within Thailand, the upland regions of the Northeast (Isaan) occupy approximately one third of the entire land area of Thailand. The soils in this region are dominated by light textured soils with clay contents of <15%. These soils are aeolian in origin and have formed under a rainfall regime that exceeds 1,200 mm per annum (Lesturgez, 2005). In addition, these soils are predominantly acid in reaction with low soil organic matter (Kheoruenromne and Suddhiprakarn, 1998). Under their native *Dipterocarp* forests, these soils are highly productive and support large amounts of biomass in association with closed and highly efficient nutrient cycling. However, when these soils are cleared for agricultural production a rapid decline in fertility occurs in association with a loss in soil organic matter, which is reflected in a concomitant decrease in cation exchange capacity (CEC) (Noble *et al*., 2000). Further, the combination of inappropriate land management and over-exploitation of these limited natural resources has resulted in significant soil degradation. Hence these degraded soils are often regarded as marginal for crop production.

An important step in addressing the low productivity of these degraded soils is to address the fundamental problem of diminished nutrient holding capacity (as indicated by CEC) associated with a decline in soil organic matter. A possible approach to addressing the aforementioned issue is through the application of natural materials (Noble *et al*., 2004; Noble *et al*., 2001) or industrial waste products that are easily available to resource poor farmers.

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Bentonite is a 2:1 layer silicate containing smectite minerals, usually montmorillonite. It is used in a large number of applications ranging from foundry moulds, drilling muds, pet litter adsorbent to stock feed supplementation. The annual production is estimated to be 8 million tonnes (Mt) (Virta, 2001). Bentonite is also used to remove a variety of impurities in the vegetable oil industry including phosphotides, fatty acids, gums, and trace metals. This results in the production of light-colored and stable oils acceptable to consumers (Foletto, *et al*., 2002). Acid activated calcium-bentonites are the preferred form of clay used as an absorbing agent during the decolorizing, clarification and refining process in the manufacture of vegetable oil. Acid activated clays are produced by treating calcium bentonites with mineral acids (i.e. hydrochloric or sulphuric acids). In their natural non-activated state bentonites have a limited absorbing capacity. However, when bentonites are acid activated as a result of treatment with hot mineral acid solutions, hydrogen ions attack the aluminosilicate layers via the inter layer spacing (Taylor and Jenkins, 1987 in Foletto *et al*., 2002; Falaras, *et al*., 1999). This alters the structure, chemical composition and physical properties of the clay and significantly increases the adsorption capacity (Mokaya *et al*., 1993 in Foletto *et al*., 2002).

The reuse of waste oil bentonites is an area of potential opportunity for cost savings in the oil processing industry that would have the added benefit of protecting the environment. The application of either modified or naturally occurring bentonites have been shown to increase the soils cation exchange properties and increase crop productivity (Noble, *et al.*, 2001; 2004). However, a significant problem in the re-use of waste acid activated bentonites from vegetable oil processing is their hydrophobic nature due to the presence of fats and oils on the surfaces of the spent clay as well as their acidic nature. This reduces the ability of these materials to adsorb nutrients and water. Croker *et al.* (2004) applied waste oil bentonite to a degraded light textured soil at rates up to 40 t ha^{-1} and observed increases in CEC from 0.6 to 1.9 $cmol_c$ kg^{-1}. However, due to nutrient insufficiencies (nitrogen and potassium) and the acidic nature of these materials, overall productivity of a maize test crop was limited.

The objectives of the study were (i) to determine whether composting of waste oil bentonite with rice husk, rice husk ashes and chicken litter, could remediate the hydrophobic and acidic nature of the waste bentonite, and (ii) to assess the potential of these composted materials on soil properties.

Materials and Methods

Chemical characterization of acid activated bentonites before and after bleaching:

Samples of the raw acid activated bentonite prior to and post bleaching were obtained from three oil processing companies (Morakot, King and Tip) in the Bangkok metropolitan region, Thailand. Samples were air dried and passed through a 2-mm mesh sieve. Soil electrical conductivity (EC) and pH were measured in water and 0.01 M $CaCl_2$ at a clay:solution ratio of 1:5. Exchangeable cations (calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+)) and cation exchange capacity (CEC) were determined using 1 M NH_4-acetate buffered at pH 7.0 (Rayment and Higginson, 1992). Organic carbon was determined by wet oxidation using the Walkley and Black method as modified by Rayment and Higginson (1992) and total N by Kjeldahl steam distillation. In addition, the co-compositing materials, namely chicken litter, rice husk and rice husk ash were similarly assessed.

Co-composting of waste acid bentonite with chicken litter, rice husk and rice husk ash:

A total of 9 composting treatments were imposed (Table 1). Ratios of the different components making up the composting material were mixed air dry. In addition, 4, 5, or 6 kg of dolomitic lime was applied to each treatment (1-9) in order to neutralize the residual acidity associated with the acid activated bentonite as based on the amount of chicken litter added. The mixed treatments were then placed in concrete composting bins with drainage holes placed at the base of bins to avoid excess water at the bottom of the bins. The amount of water added to each bin varied depending on the treatment. However, all bins that received water had the same consistency. A further set of control treatments (10-12) were assessed where the waste acid bentonites were placed in composting bin with no additions. These treatments were subject to the same mixing routines as previously described. Temperature within the composting bins was monitored on a daily basis at 3 points within the pile. The compost materials were turned every 2 weeks and water re-applied to maintain the desired moisture. Samples from each of the bins were collected on three occasions during the composting period, air dried, subjected to chemical analysis and water repellency assessment. Water Drop Penetration Time (WDPT) was assessed on all samples at each sampling date using the methodology of Bisdom *et al.* (1993).

Table 1. Composted treatment combinations imposed on three source of acid waste bentonite with rice husk, rice husk ash and chicken litter

Treatment Code	Treatment description	Ratio*
1. SB01	Waste soybean oil bentonite + Rice husk + Rice husk ash + Chicken litter + water.	1:1:1:1
2. SB02	Waste soybean oil bentonite + Rice husk + Rice husk ash + Chicken litter + water	1:1:1:2
3. SB03	Waste soybean oil bentonite + Rice husk + Rice husk ash + Chicken litter + water	1:1:1:3
4. PB01	Waste palm oil bentonite + Rice husk + Rice husk ash + Chicken litter + water.	1:1:1:1
5. PB02	Waste palm oil bentonite + Rice husk + Rice husk ash + Chicken litter + water.	1:1:1:2
6. PB03	Waste palm oil bentonite + Rice husk + Rice husk ash + Chicken litter + water.	1:1:1:3
7. RB01	Waste rice bran oil bentonites + Rice husk + Rice husk ash + Chicken litter + water.	1:1:1:1
8. RB02	Waste rice bran oil bentonites + Rice husk + Rice husk ash + Chicken litter + water.	1:1:1:2
9. RB03	Waste rice bran oil bentonites + Rice husk + Rice husk ash + Chicken litter + water.	1:1:1:3
10. P-SB	Rare waste soybean oil bentonite	
11. P-PB	Rare waste palm oil bentonite	
12. P-RB	Rare waste rice bran oil bentonite	

* Ratio of waste oil bentonite: rice husk: rice husk ash: chicken litter mixed on a volumetric basis.

Pot experiment

A pot experiment was established in the Kasetsart University Central Laboratory greenhouse, Bangkok, Thailand. The twelve composted materials generated from the first phase of the study were evaluated (Table 1). To undertake the experiment, over 400 kg of degraded light textured sandy soil (0-15 cm) was collected from an experimental site established at the Animal Nutrition Development Station, Department of Livestock, Chiang Yuen, Mahasarakham Province, Northeast Thailand. The soil was classified as a Satuk series or isohyperthermic Oxic Paleustult (LDD, 1993; Soil Survey Staff, 1990). The soil was air dried, sieved to pass a 2-mm sieve and thoroughly mixed to ensure homogeneity. All laboratory analysis was undertaken at the Land Development Department, Soil Chemistry Laboratory. The soil used in this study was acid in reaction (pH_{Ca} 4.04) with a low CEC (1.76 $cmol_c\ kg^{-1}$) and organic carbon content (0.5%). The values indicate the low nutrient supplying capacity of the test soil as evidenced through comparison with the composted materials. In addition, the gravimetric soil moisture content of the air dried soil used in the current study was 0.01 kg kg^{-1} (water/oven dry soil). With respect to the texture of the soil, sand, silt, and clay content were 834, 55, 111 g kg^{-1}, respectively.

The design of the experiment was a 4 x 12 + 1 incomplete factorial design consisting of 4 application rates of 0, 15, 30, 60, and 120 t ha^{-1}, 12 sources of materials and a single control replicated 3 times. The resultant 147 pots were placed in a complete randomized block design on six benches within an evaporatively cooled greenhouse. Soil chemical properties were determined on all samples using the methodology previously described.

Water retention and porosity

In order to determine changes in the water retention and porosity of soils associated with the application of co-composted (PB, SB, and RB) and non-composted (P-PB, P-SB, and P-RB) waste oil bentonites, rates equivalent to 0, 15, 30, 60, and 120 t ha^{-1} were applied to 3 kg of the air dried soil, thoroughly mixed and placed in a free draining PVC pot. Annually, the Northeast of Thailand experiences several rainfall events >50 mm (Noble *et al*., 2004). Therefore, to simulate such an event, deionized water was applied to the soil surface and allowed to drain freely through the pot at room temperature for 3 days. At the conclusion of this equilibration period, three soil samples were collected from each pot using a stainless steel cylindrical core (47 mm in diameter and 30 mm in height). The soil cores were capillary-saturated using deionized water and the matric potential of samples was adjusted to -10 kPa (approximately equivalent to the field capacity θfc) by the suction table method. Thereafter the volumetric moisture content and bulk density of the samples were determined by oven drying at 110ºC for 24 hrs. The total porosity of the samples was derived from the bulk density and particle density of the soil using the following relationship;

$$\theta p = 1 - \rho d / Gs \quad (1)$$

where, θp is total porosity ($m^3\ m^{-3}$), ρd is bulk density ($Mg\ m^{-3}$) and Gs is particle density (assumed to be 2.65 $Mg\ m^{-3}$).

Using soil samples collected from the pots (following the removal of the soil cores), the matric potential of the soil was measured over the range of -6.1 MPa to -0.2 MPa during the desorption process from saturation using the freezing point depression method (Suzuki, 2004). This facilitated the determination of the volumetric moisture content at the permanent wilting point (i.e. -1.5 MPa in matric potential, θpwp). The available water content for crop growth (θawc) was derived from the difference between θfc and θpwp.

Statistical analysis

The analysis of variance (ANOVA) was used to estimate the significance of treatment effects using GENSTAT 5 release 3.22 statistic program.

Results and Discussion

Chemical characterization of acid activated bentonites before and after bleaching

For brevity, the results and discussion are confined to soil chemical and physical changes. Although detailed assessment of the composting process and productivity of two consecutive maize crops on the amended soils was conducted, the reader is referred to Soda *et al*. (2005) for further details.

Selected chemical attributes of the acid activated bentonites before and after the bleaching process of the three contrasting vegetable oil bentonites along with materials used in the composting process are presented in Table 2. As expected, the initial pH_w of the acid activated bentonites was low (range: 3.10-4.13) thereby enabling these materials to absorb fats and oils during the bleaching process. After undergoing the oil bleaching processing, the pH_w of the waste soybean oil (SB) decreased slightly whilst the palm (PB) and rice bran (RB) waste oil bentonites increased slightly (Table 2). The largest changes in chemical characteristics of the acid activated bentonite associated with bleaching was a dramatic decline in exchangeable Ca^{2+} in all materials and in exchangeable Mg^{2+} in the soybean waste oil bentonite (Table 2). Contrasting this, there was an increase in exchangeable Mg^{2+} in the waste rice bran oil bentonite after the bleaching process whilst the waste palm oil bentonite remained unchanged. It is of note that the EC in the bentonites before and after processing was relatively high this being due to a high level of dissolved salts that are not associated with the exchange complex. Confirmation of the high level of soluble salts can be found if one compares the CEC as measured in buffered ammonium acetate with the sum of exchangeable bases, the latter being considerably larger than the former (Table 2). Both exchangeable Na^+ and K^+ were low although for all samples exchangeable Na^+ increased with bleaching and exchangeable K^+ increased in the case of the rice bran oil waste bentonite (Table 2).

The absorption of fats and oils associated with the bleaching of vegetable oils resulted in an increase in the organic carbon content of the waste oil bentonites (Table 2). In general the organic carbon content increased by the same amount regardless of the oil source. Total N content on the both the acid activated and bleached spent bentonite remained unchanged after processing except for the palm oil bentonite where the N content increased from 0.06% to 0.13% with bleaching (Table 2).

Table 2. Selective chemical properties of acid activated bentonite before and after bleaching of selected vegetable oils, chicken litter, rice husk and rice husk ash

Source	pH_w	pH_{Ca}	EC	CEC	Exch. Ca^{2+}	Exch. Mg^{2+}	Exch. Na^+	Exch. K^+	Sum bases	Total N	OC	WDPT
			($dS\ m^{-1}$)			$cmol_c\ kg^{-1}$				(%)	(%)	(sec)
Acid activated soybean bentonite	3.26	3.24	5.35	51.04	120.70	22.39	0.78	0.69	144.56	0.05	0.25	nd
Waste soybean oil bentonite	2.98	2.97	5.06	47.46	28.08	4.88	2.73	0.44	36.13	0.05	36.13	25
Acid activated palm bentonite	4.13	4.26	3.49	52.13	97.97	18.26	0.49	0.65	117.37	0.06	0.21	nd
Waste palm oil bentonite	4.46	4.48	2.38	42.58	69.24	17.51	1.72	0.60	89.07	0.13	23.88	>10,800
Acid activated rice bentonites	3.10	3.06	3.26	35.60	88.84	3.54	0.62	0.77	93.77	0.06	0.15	nd
Waste rice oil bentonite	3.60	3.54	1.40	19.18	9.90	21.21	2.82	2.76	36.69	0.05	21.16	9,000
Chicken litter	6.84	6.85	23.80	50.58	69.14	36.02	25.47	77.31	207.94	2.55	18.44	nd
Rice husk	6.03	5.54	1.58	1.25	12.50	18.03	1.33	1.86	33.72	0.29	43.78	nd
Rice husk ash	8.02	7.37	3.12	6.72	4.09	5.22	12.42	5.36	27.09	0.07	5.09	nd

The other components used in the composting process, namely chicken litter, rice husk and rice husk ash had variable nutrient compositions (Table 2). As expected, rice husk pH increased with ashing, this being associated with the formation of oxides, and the chicken litter had a neutral to slightly acid reactivity (Table 2). Exchangeable cations in the rice based materials were low when compared to the chicken litter. Of importance with respect to the chicken litter is the elevated K^+ level (77 $cmol_c\ kg^{-1}$). It is of note that most of the cations extracted from the chicken litter, rice husk and rice husk ash were in a soluble form as evidenced by the elevated EC and difference between CEC and sum of bases (Table 2). This implies that these nutrients are readily available for plant uptake as well as being potentially subject to leaching (Table 2). Chicken litter had the highest total N content (2.55%) compared to all materials and hence would be an effective source of N in the composting process.

Changes in chemical attributes with composting

Changes in chemical characteristics after the 84 days of the composting phase are presented in Table 3. The pH_w of the co-composted spent bentonites increased with composting when compared to the original waste bentonites (Tables 2 and 3), these increases being associated with the addition of the rice husk ash, chicken litter and dolomitic lime. The mean pH of the co-composted spent bentonite increased to 7.18 compared to an initial mean pH of 3.68. Significant increases in pH within an individual spent bentonite treatment were observed with increasing additions of chicken litter (Table 3). For example, with the ratio of constituents increasing from 1:1:1:1 to 1:1:1:3 in the case of spent palm oil bentonite, pH_w increased from 6.95 to 7.72 (Table 3). Associated with the increase in pH of the co-composted materials there was an increase in EC of the materials due to the mineralization of organic constituents with the concomitant release of cations (Table 3). K^+ concentrations increased with increasing additions of chicken litter resulting in its dominance on the exchange complex in the co-composted treatments (Table 3). Contrasting this, organic carbon declined from the initial values observed in the individual constituents, suggesting losses of CO_2 associated with the mineralization of organic matter. In general, the quality of the compost material with respect to available nutrients increased in those treatments receiving chicken litter, rice husk and rice husk ash. Calcium and Mg^{2+} concentrations increased along with the CEC (Table 3). A cursory assessment of CEC and the sum of basic cations indicates that a significant proportion of the exchangeable cations are not associated with the exchange complex and are therefore in a soluble and mobile form.

Treatments that did not receive additions of rice husk, rice husk ash and chicken litter did not undergo significant changes in chemical properties (Tables 2 and 3). They remained acidic with little change in their chemical characteristics from their original state (Tables 2 and 3).

One of the main reasons for undertaking co-composting with readily available agri-waste products was to reduce the hydrophobic nature of the waste oil bentonites associated with the deposition of oils and fats on the surface of these materials. The WDPT for the waste materials prior to and after 84 days co-composting are presented in Tables 2 and 3. Prior to the co-composting process the WDPT ranged from 25 to >10,800 seconds for the soybean and palm oil wastes respectively (Table 2). Through the co-composting process the WDPT declined significantly

Table 3. Selective chemical characters of co-composted treatments 84 days after the initiation of the composting process

Treatment	pH_W	pH_{Ca}	EC (mS cm^{-1})	CEC	Exch. Ca^{2+}	Exch. Mg^{2+}	Exch. Na^+	Exch. K^+	Total N (%)	OC (%)	WDPT (sec)
				($cmol_c\ kg^{-1}$)							
SB01	6.45	6.32	7.59	39.68	44.95	30.13	10.20	23.57	0.67	12.92	16.0
SB02	6.79	6.65	9.97	39.17	37.12	29.54	13.75	36.26	0.97	13.67	22.0
SB03	6.96	6.83	11.59	45.60	35.00	27.35	14.86	46.62	1.06	15.33	28.2
PB01	6.95	6.73	5.75	45.01	15.55	19.61	11.31	28.49	0.82	11.56	20.6
PB02	7.14	6.89	7.85	51.90	19.29	17.42	7.80	41.44	1.06	12.17	33.7
PB03	7.72	7.49	8.71	51.02	20.50	17.84	16.19	50.50	1.23	12.84	30.1
RB01	7.39	7.32	7.05	30.78	25.81	19.19	10.20	23.57	0.92	13.40	47.3
RB02	7.50	7.38	9.79	37.81	26.71	20.37	14.19	40.14	1.10	14.36	66.9
RB03	7.76	7.58	11.24	43.76	30.10	18.77	16.63	50.50	1.21	15.19	79.7
P-SB	2.99	2.96	5.17	42.44	46.76	14.98	1.48	0.60	0.07	22.05	24.1
P-PB	4.47	4.30	2.45	42.30	8.74	15.07	2.44	1.83	0.11	27.42	>10,800
P-RB	3.02	2.91	1.62	23.48	15.86	3.79	2.19	0.38	0.06	24.36	23.5
$LSD_{0.05}$	0.04	0.03	0.13	2.67	7.64	2.06	0.67	3.32	0.13	1.89	3.4

(Tables 2 and 3). With increasing additions of chicken litter to the compost mix there was a significant increase in the WDPT (Table 3) although these values were substantially lower than the original waste bentonites (Table 2). In those treatments that did not undergo co-composting, the WDPT either declined from their original values in the case of the rice oil or remained the same in the case of the soybean and palm oil (Table 3).

The decline in the hydrophobicity of the waste rice oil bentonite after 84 days may in part be attributed to a rise in pile temperature observed in this treatment (Soda *et al*., 2005).

Changes in soil chemical attributes following the application of composted bentonite wastes to a degraded light textured soil.

Selected chemical properties of soils collected at the conclusion of the cropping phase are presented in Table 4. It is clearly evident that increasing rates of application of the co-composted waste oil bentonites resulted in a significant increase in soil pH (Table 4). The greatest increase in pH_{Ca} (a more meaningful measure of soil reactivity than pH_W as it negates the influence of soluble salt on pH) was observed in the RB03 treatment (pH 6.64) applied at 120 t ha^{-1} (Table 4). In addition, increasing the ratio of chicken litter in the original co-composted mix resulted in significantly greater increases in pH at any given application rate. Contrasting this, the application of the non-composted waste bentonite treatments (P-SB, P-PB and P-RB) had a mixed effect on the soil reactivity (Table 4). The waste soybean oil bentonite resulted in a significant decline in soil pH with increasing application rates, this being associated with the very acid (pH_{Ca} 2.98) nature of this material (Table 2). The waste rice bran oil bentonite had a variable effect on pH whilst the waste palm oil bentonite significantly increased pH, this again being a reflection of the overall pH of this material (Tables 3 and 4).

The electrical conductivity (EC) of the 1:5 extract ranged from 0.003 dS m^{-1} in the un-amended soil to 0.853 dS m^{-1} in the case of the non co-composted waste soybean oil bentonite (P-SB) at a rate of 120 t ha^{-1} (Table 4). The range in EC values do not exceed the threshold value associated with sensitivity to salinity in maize of 1.5-3.0 dS m^{-1} as published by Mass (1990). However, these relatively high values indicate a high level of soluble salts that are not associated with the soil exchange complex. A plot of ECEC ($\sum Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}$) versus CEC measured in an ammonium acetate buffered system clearly demonstrates the presence of a significant proportion of the measured cations being in a ‘soluble’ form (Figure 1). Intuitively, if all of the measured cations were held on the exchange complex, then a plot of ECEC versus CEC would cause the coordinates for each of the samples to fall very close to the 1:1 line. The results suggest that a significant proportion of the extracted cations are not associated with the exchange complex and are therefore subject to leaching loss. The fact that there is still a large amount of ‘soluble’ cations at the conclusion of the study may indicate either a lack of significant leaching events during the growth of the crop and/or the mineralization of root material after the harvesting of the final crop.

Measurement of CEC undertaken in a buffered system effectively allows an assessment of changes in exchange capacity that are not confounded by the generation of charge associated with pH. Increasing rates of treatment application resulted in significant increases in the amount of CEC generated with the greatest increase in CEC being observed with the application of non co-composted waste palm oil bentonite (P-PB) at a rate of 120 t ha^{-1} (Table 4). As one of the main reasons for applying these materials is to increase the CEC of these degraded soils, it is clearly evident from the results that this has been achieved. Furthermore, by developing CEC response functions for each of the materials evaluated, an estimate of the amount of material to be applied to achieve a predetermined target CEC can be made.

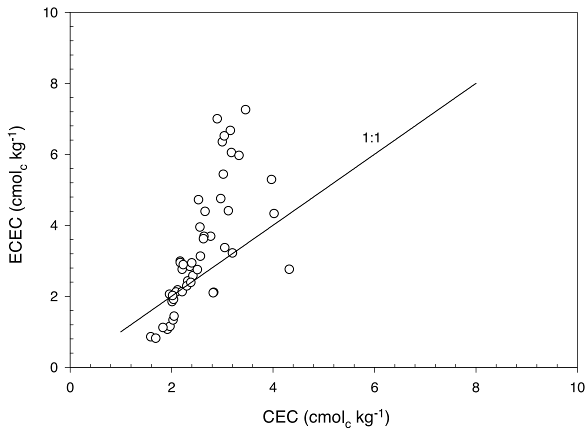

Figure 1. Relationship between measured CEC and the sum of exchange cations for soils treated with co-composted materials at the conclusion of two cropping cycles with maize

As expected, increasing additions of co-composted waste oil bentonites resulted in a significant increase in the organic carbon content of the soils (Table 4). The greatest increases were observed in

Table 4. Selective chemical properties of oils treated with co-composted and non co-composted waste oil bentonites at the conclusion of the study

Treatment	Rate of application (t ha^{-1})	pH_W	pH_{Ca}	EC (dS m^{-1})	CEC	Ca^{2+}	Mg^{2+}	K^+	OC (%)	WDPT end (sec)	WDPT start (sec)
					(cmol$_c$ kg^{-1})						
Control	0	5.13	4.02	0.003	1.59	0.51	0.14	0.04	0.39	0.16	0.16
SB01	15	5.56	4.89	0.070	2.12	1.26	0.38	0.03	0.44	0.18	0.19
SB01	30	6.36	5.74	0.127	2.17	1.84	0.63	0.04	0.46	0.19	0.80
SB01	60	6.81	6.19	0.214	2.77	2.82	0.82	0.07	0.57	0.24	0.20
SB01	120	6.91	6.40	0.431	3.02	4.36	1.43	0.39	0.70	0.26	25.00
SB02	15	6.26	5.46	0.064	1.96	1.33	0.41	0.04	0.41	0.19	0.20
SB02	30	6.75	6.07	0.106	2.17	2.14	0.65	0.04	0.51	0.19	0.20
SB02	60	7.02	6.40	0.197	2.56	3.10	1.05	0.17	0.59	0.21	0.21
SB02	120	7.10	6.59	0.376	3.00	4.76	1.68	0.61	0.68	0.29	0.26
SB03	15	6.32	5.52	0.064	2.09	1.40	0.30	0.04	0.44	0.19	0.20
SB03	30	6.79	6.16	0.106	2.36	2.04	0.50	0.06	0.48	0.19	0.21
SB03	60	7.17	6.45	0.186	3.12	3.30	0.93	0.21	0.56	0.19	0.22
SB03	120	7.15	6.57	0.367	3.16	4.97	1.43	0.67	0.70	0.34	0.23
PB01	15	6.49	5.59	0.045	2.01	1.29	0.36	0.04	0.39	0.19	0.23
PB01	30	6.94	6.08	0.065	2.32	1.84	0.58	0.05	0.46	0.19	0.24
PB01	60	7.13	6.38	0.099	3.05	2.72	0.99	0.09	0.51	0.20	0.25
PB01	120	7.17	6.46	0.175	3.97	3.81	1.48	0.33	0.68	1.47	0.28
PB02	15	6.63	5.75	0.048	2.04	1.28	0.37	0.04	0.38	0.20	0.23
PB02	30	7.03	6.15	0.069	2.42	2.01	0.57	0.05	0.46	0.20	0.26
PB02	60	7.21	6.38	0.126	2.64	3.01	0.87	0.18	0.39	0.18	0.27
PB02	120	7.26	6.52	0.230	3.18	4.57	1.69	0.66	0.69	1.76	0.30
PB03	15	6.62	5.85	0.049	2.21	1.40	0.49	0.05	0.44	0.19	0.29
PB03	30	7.15	6.30	0.074	2.57	2.06	0.72	0.07	0.47	0.18	0.28
PB03	60	7.29	6.49	0.129	2.97	3.12	1.08	0.18	0.52	0.18	0.35
PB03	120	7.39	6.57	0.227	3.46	4.26	1.77	0.72	0.67	0.47	0.35
$LSD_{0.05}$		0.14	0.09	0.033	0.48	0.29	0.16	0.04	0.09	9.64	7.18

Treatment	Rate of application (t ha^{-1})	pH_W	pH_{Ca}	EC (dS m^{-1})	CEC	Ca^{2+}	Mg^{2+}	K^+	OC (%)	WDPT end (sec)	WDPT start (sec)
					(cmol$_c$ kg^{-1})						
Control	0	5.13	4.02	0.003	1.59	0.51	0.14	0.04	0.39	0.16	0.16
RB01	15	6.48	5.11	0.062	2.21	1.93	0.49	0.05	0.43	0.19	0.22
RB01	30	6.90	5.98	0.081	2.51	1.74	0.64	0.05	0.46	0.49	0.25
RB01	60	9.99	6.27	0.128	2.63	2.41	0.82	0.07	0.44	0.39	0.24
RB01	120	6.99	6.45	0.266	3.33	4.07	1.24	0.31	0.67	0.30	0.27
RB02	15	6.40	5.45	0.060	2.02	1.35	0.45	0.05	0.42	0.18	0.25
RB02	30	6.77	6.09	0.095	2.40	2.08	0.64	0.05	0.42	0.23	0.26
RB02	60	7.15	6.47	0.156	2.66	3.02	0.90	0.17	0.53	0.30	0.27
RB02	120	7.31	6.58	0.280	3.04	4.11	1.34	0.51	0.65	0.22	0.30
RB03	15	6.55	5.66	0.061	2.30	1.57	0.46	0.05	0.43	0.19	0.30
RB03	30	7.03	6.25	0.083	2.23	2.02	0.60	0.06	0.46	0.21	0.27
RB03	60	7.29	6.51	0.148	2.53	3.25	0.95	0.22	0.55	0.27	0.30
RB03	120	7.42	6.64	0.270	2.90	4.31	1.54	0.57	0.70	0.19	0.42
P-SB	15	4.60	3.88	0.134	1.92	0.69	0.19	0.03	0.46	0.19	0.73
P-SB	30	4.26	3.78	0.245	1.97	1.00	0.29	0.03	0.57	0.19	1.00
P-SB	60	4.27	3.81	0.448	2.38	1.67	0.44	0.05	0.72	0.55	1.67
P-SB	120	3.82	3.53	0.853	4.02	3.16	0.81	0.14	1.08	17.73	3.00
P-PB	15	5.27	4.21	0.045	1.69	0.48	0.25	0.04	0.44	19.57	5.27
P-PB	30	5.24	4.32	0.068	2.03	0.81	0.38	0.06	0.56	74.50	154.02
P-PB	60	5.28	4.52	0.122	2.83	1.17	0.60	0.11	0.74	22.14	5,400
P-PB	120	5.01	4.51	0.286	4.32	1.61	0.71	0.15	1.18	4.17	6,300
P-RB	15	5.05	4.14	0.071	1.83	0.69	0.17	0.08	0.48	0.20	1.00
P-RB	30	4.91	4.17	0.129	2.05	0.96	0.23	0.04	0.58	0.73	3.30
P-RB	60	4.91	4.21	0.236	2.82	1.40	0.29	0.09	0.76	19.20	8.03
P-RB	120	4.40	3.99	0.520	3.20	2.40	0.41	0.15	1.26	20.20	10.37
$LSD_{0.05}$		0.14	0.09	0.033	0.48	0.29	0.16	0.04	0.09	9.64	7.18

the non co-composted waste oil bentonite treatments (P-SB, P-PB and P-RB). Increases in organic carbon would have contributed to the observed increases in CEC and would be of benefit to the overall quality of the soil.

Water penetration into those soils treated with the co-composted bentonites was rapid (Table 4). Clearly the co-composting process and time significantly reduced the hydrophobicity of these materials. As noted previously in the case of the non co-composted waste palm oil bentonite, the hydrophobic nature of the material remained unaltered (>10,800 sec) between the start and end of the composting phase (Tables 2 and 3). However, incorporation into the soil resulted in a significant decrease in water repellency indicating the potential role of inherent soil microbial populations in the breakdown of oils and fats (Table 4).

Changes in soil physical attributes

Total porosity

For all co-composted treatments at application rates of 15 and 30 t ha^{-1}, no significant increases in the total porosity (θp) were observed. In contrast, increases in θp were observed for the SB01, SB03, PB03, RB02, and RB03 co-composted waste oil bentonite treatments at application rates of 60 t ha^{-1} as compared with the respective 15 and 30 t ha^{-1} treatments. Further, all co-composted treatments of waste oil bentonite (SB, PB and RB) applied at 120 t ha^{-1} resulted in significant increases in θp as compared with the respective 15, 30 and 60 t ha^{-1} treatments (Figure 2). No increase in the total porosity was observed for the non-composted P-PB, P-SB, and P-RB waste oil bentonite treatments.

Soil moisture content at the permanent wilting point

For all co-composted and non co-composted waste oil bentonites, the soil moisture content at the permanent wilting point (θpwp) slightly but proportionally increased with increased application rates from 15 to 120 t ha^{-1} even though the observed increase in moisture content was <0.08 $m^3 m^{-3}$ (Figure 3).

Available water content

Figure 4 represents changes in the available water content for crop growth (θawc) associated with the application of the co-composted and non co-composted waste oil bentonite treatments. Available water content for crop growth for all treatments had a large deviation between samples ($LSD_{0.05}$ >0.026). However, increasing application rates of RB03 resulted in a proportional increase in θawc. For the co-composted RB01, and RB02 co-composted waste oil bentonite treatments θawc increased slightly with increasing application rate from 15 to 120 t ha^{-1}. Further, significant increases in θawc were observed between the 15 and 30 t ha^{-1} co-composted PB02 treatments.

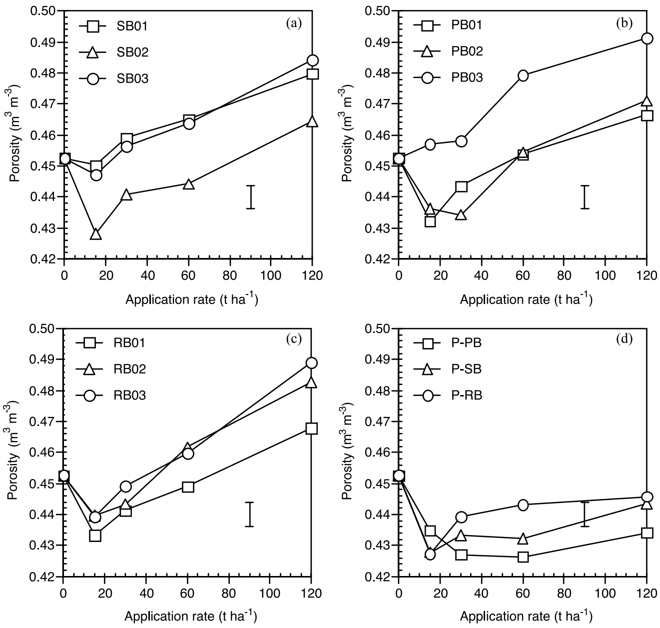

Figure 2. The effect of co-composted and non co-composted waste oil bentonites on the total porosity of soils. Vertical bars are the $LSD_{0.05}$ between treatment means

In addition, significant beneficial increases in θawc were observed when increasing the non co-composted P-PB application rate from 30 and 60 t ha^{-1}. However, no significant increase in θawc was detected when increasing the application rate of non co-composted P-PB to 120 t ha^{-1}.

Relationship between θpwp and nutrient holding capacity

The soil water retention at lower matric potentials (approximately <-100 kPa) predominantly depends on adsorptive forces between the soil solid surface components (including soil particles and organic matter) and the soil solution, hence it is significantly affected by the specific surface area of soils. The θpwp is fairly well correlated with the surface area of a soil and would represent, roughly, about 10 molecular layers of water if it were distributed uniformly over the solid surface of the soil (Hillel, 1998). This indicates that an increase in θpwp is associated with an increase in the specific surface area of the soil.

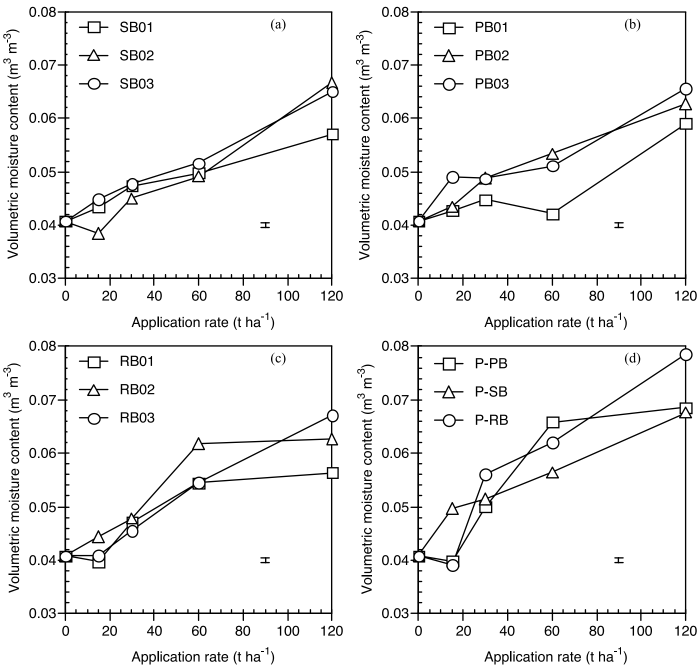

Figure 3. The effect of co-composted and non co-composted waste oil bentonites on soil moisture content at the permanent wilting point. Vertical bars are the $LSD_{0.05}$ between treatment means

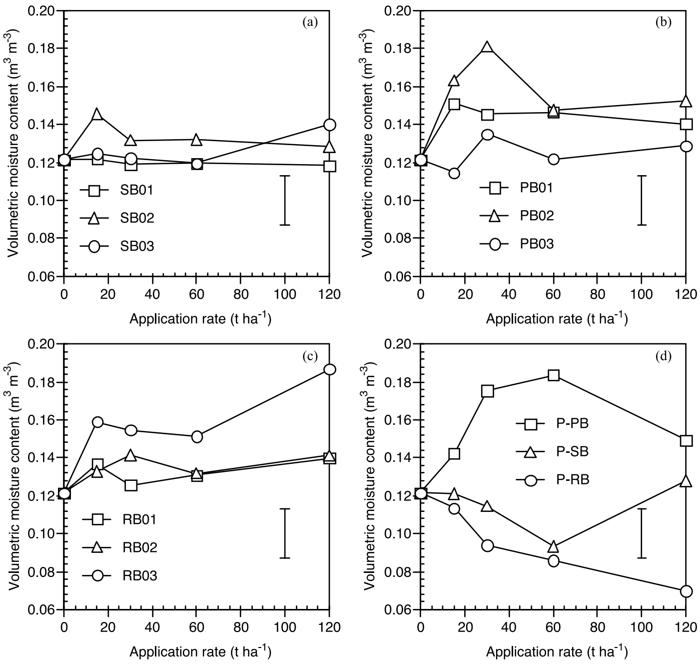

Figure 4. The effect of co-composted and non co-composted waste oil bentonites on the available soil moisture content for crop growth. Vertical bars are the $LSD_{0.05}$ between treatment means

As stated above, the observed θpwp of the degraded light textured sandy soil evaluated was significantly correlated with the co-composted and non co-composted waste oil bentonite treatments (Figure 4). It is suggested here that the inferred increases in specific surface area (as indicated by increased θpwp) is due to the applied bentonite and organic matter. In addition, the application of bentonite and organic matter in the co- and non co-composted treatments resulted in significant increases in CEC.

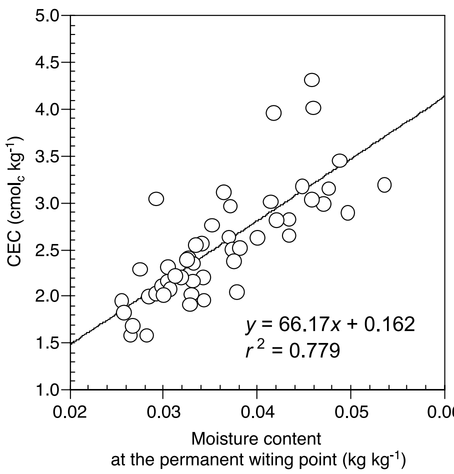

Figure 5. A relationship between gravimetric soil moisture content at the permanent wilting point (*x*) and cation exchangeable capacity (*y*) of the light textured sandy soils after application of different ratios of co-composted and non co-composted waste oil bentonites

Figure 5 illustrates the highly significant relationship between θpwp and CEC (R^2 = 0.779, P <0.01). Since negative surface charge is directly related to the specific surface area of clay minerals and organic matter (Jury *et al.*, 1991), the results of this study indicate that increases in CEC of the test soil through the incorporation of co- and non co-composted waste oil bentonites were due primarily to an increase in the specific surface area (and associated negative charges) as derived from the bentonite and organic matter. This has major positive implications with regard to the nutrient holding capacity of the test soil.

Conclusion

Through composting waste oil bentonites with readily available agricultural byproducts, the chemical and physical characteristics of these materials have been drastically improved. In addition, the composted materials have had beneficial effects on enhancing the chemical and physical properties of a degraded light textured sandy soil. The application of composted materials significantly increased the pH, and altered the characteristics of the soil through an increase in the soil organic matter, clay content and their nutrient supplying capacity. Further, they have had a positive impact on soil physical attributes resulting in an increase in total porosity and available water content. It is of note that composted materials are not fertilizers and hence there will be a requirement for the application of nutrients commensurate with crop requirements.

The process of co-composting these materials will reduce their potential negative impact on the environment through the neutralization of their acid reactivity and a decline in their hydrophobicity. Such processing, whereby locally available farm waste products (i.e. rice husk, chicken litter) can be utilized to produce an excellent soil amendment, may suit a small business model. Such a development would turn an environmental hazardous waste into a high quality soil amendment that would have a retail value.

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Short-term effects of agricultural practices on the soil structure and hydrodynamic in a deep tilled hardened sandy-silty volcanic–ash soil (*cangahua*) in Ecuador

Podwojewski, P.[1] *and J.L. Janeau*[2]

Keywords: volcanic ashsoils, Ecuador, erosion, rainfall simulation, infiltration, structure stability, soil fertility

Abstract

*In the Ecuadorian Cordillera, the hardened volcanic ashes (**cangahuas**) account for 15% of the cultivated area. The soil resulting from the fragmentation of these materials, generally by heavy machinery, shows an apparent stable millimetric structure. However, this new structure is highly susceptible to disintegration under rain, because it contains no organic matter and has a sandy-silt composition with very little mineralogical clay, and the material itself is readily eroded. In consequence we studied the evolution of soil aggregate stability in two factorial experiments during five cultivation cycles with two kinds of soil preparation and five fertilization treatments.*

*Rainfall simulation was implemented before and after three cycles of cultivation to asses the soils structure evolution and its erodibility. The cultivated plots had flat surfaces and the rainfall simulation tests were conducted after the harvest on bare surfaces. Surface soil crusting occurred rapidly within the cultivated plots when compared to the recent tilled **cangahua**. Runoff and soil loss were generally higher on plots with lower structural stability, generally with higher clay content.*

The aggregate stability was not influenced by either kind of soil preparation, nor by large additions of manure (80 t ha^{-1}) or green fertilizers (10 t ha^{-1}), nor by growing a perennial grass. The variation in the aggregate stability seemed to depend on the components inherited from the original volcanic material: in the plots with larger clay content, and with swelling clay minerals, the aggregates were less stable than those composed of isometric fine silt particles. In agreement with the structural stability measured in a laboratory, organic matter inputs increase the soil porosity but had no effect on the structural stability and resistance to crusting, and thus to runoff and to erosion. For these soils, no tillage and a permanent soil cover (pasture) would be the best agricultural option.

Introduction

This paper is a synthesis of different studies done in Ecuador (and also in Mexico) about rehabilitated hardened volcanic ashsoil. In several parts of highland tropical America there are beds of hard volcanic ash of late Pleistocene age at the surface or buried beneath a thin covering of loose ash. In Ecuador they are known as *cangahua*, and they occur mainly in the interandean valley at altitudes ranging from 2,200 to 3,000 m (Winckell and Zebrowski, 1992). Similar materials are referred to as *tepetates* in Mexico and *talpetates* in Nicaragua. They are increasingly being cultivated to feed growing populations, often with consequential erosion arising partly from the peculiarities of the material.

We studied the *cangahua* in the inter-Cordilliera valley of Ecuador (Figure 1), where attempts are being made to use the land for agriculture. The *cangahua* formation extends close to areas with a rural population density of 100 to over 150 inhabitants km^{-2} and a yearly demographic increase between 1.5 and 2%. Since the agrarian reforms of 1964 and 1974, small holders have extended their cultivation areas (De Noni *et al.*, 2001). Because of the presence of hardened *cangahua* surfaces at low altitudes the small holders expanded their cultivated areas towards loose deep Andisols located on higher altitudes, over 3,700 m and on slopes reaching 70 to 100%. Therefore, they invade and degrade the high altitude grassland ecosystem

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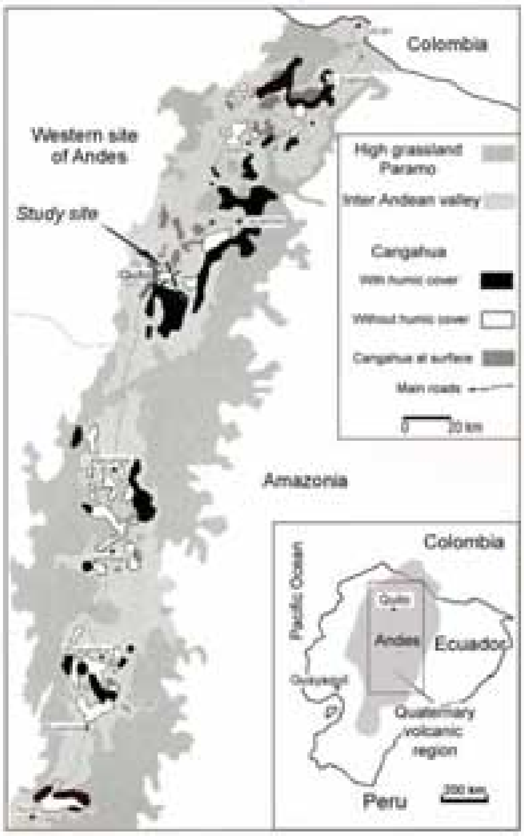


Figure 1. Study site area close to Quito City, Ecuador

(the *páramo*), which is considered as the water-tank of all the Andean population.

With fertilizer N at 80 to 120 kg ha^{-1} and P at 60kg ha^{-1}, maize can be produced on the *cangahua* at about 2tha^{-1} (Zebrowski, 1997). When fertilized with 800kgNha^{-1}, 100 kgPha^{-1} and 50 kgSha^{-1} Ray grass (*Lolium perenne*) can be produced at 25 t ha^{-1} year (Germain *et al*., 2000). Nevertheless, theses soils are still prone to erosion, and De Noni *et al*. (2001) recorded losses of 100 t ha^{-1}.

The aim of this study is to compare the evolution of soil structural stability in soils initially totally deficient in organic matter, after different complete cultivated cycles, on plots with (i) different soil preparation (production of coarse or fine fragments), (ii) different inputs of organic matter which is supposed to improve soil structural stability (Perfect and Kay, 1989; Haynes *et al.*, 1991; Tisdall and Oades, 1982) and, (iii) different fine root densities of low yields and high yields pasture plots with mycelium production, which is also considered as improving the soil structural stability (Reid and Goss, 1981; Gale *et al.,* 2000).

Material

The study site

The study area is located at the experimental farm of the Faculty of Agronomic Science of the Central University of Ecuador. It is situated near the city of Tumbaco, 20 km east of Quito near the Ilaló volcano, at an altitude of 2,465 m (Figure 1). This area is representative of the area where *cangahua* layers occur as earlier described by Winckell and Zebrowski (1992). The climate is equatorial mesothermic semi-humid. The annual average rainfall is 730 mm with two rainy seasons. The main season is from January to June and the minor one from October to November-December. The monthly average temperature is 15.7ºC with only minor annual variation. The relative air humidity is 75% and there are over 2,000 hrs of yearly insolation.

Before rehabilitation

The hard *cangahua* is covered locally by a layer of loose sandy ash (up to 50 cm thick) of Holocene age. The hard material appears at the surface when the most recent ash not indurate has eroded. The layers of *cangahua* in Ecuador are typically 50 cm but can be thicker, continuous, and with no structure. Like a soil horizon, they lie approximately parallel to the land surface. They consist of acidic volcanic ash with the composition of a weathered rhyolite or dacite. The material is hard but apparently weakly cemented, though the cementing agent has not been identified yet.

The unfragmented cangahua

When *cangahua* layers form the soil surface, they appear as made of tightly packed millimetric aggregates and thus as resulting from pedological processes. Weathering of isolated blocks of *cangahua* produces two types of fragments: (i) individual rounded fragments ranging from 2 to 10 mm in size that can be considered as weathered accretionary lapilli and, (ii) angular fragments of varying size, most ranging from 1 to 5 mm in size and including the lapilli. It seems that the deposition of the ash and lapilli was accompanied by heavy rains leading to the formation of a mud that cemented and hardened when it dried (Fischer and Schmincke, 1984). The *cangahua* material is porous but most pores are closed vesicles up to 200 µm in diameter. This structure does not readily transmit water, which therefore runs off when it rains heavily, leading to erosion.

The formation of a new material

To bring the land back into production, the hard layers are broken up by machines with teeth 60 cm deep. Thus large blocks are produced and then further fragmented by ploughing. The result is a material into which crops can be sown but that is almost totally lacking in organic matter (<0.1%) and deficient in nitrogen (N), phosphorus (P) and sulphur (S) for plant growth.

The *cangahua* has a neutral pH ranging between pH 6.5-7.5 in the presence of carbonate, and a high level of and well-balanced exchangeable cations (Table 1). However the organic matter content is very low and these formations have a very strong deficiency in N and P. The particle-size distribution that was measured randomly at three different depths before the experiment showed a rather homogenous composition in the whole plots with most particles in the fine sand and fine silt fraction (Table 2). The bulk density of this hard material is about 1.5 Tm $^{-3}$.

Table 1. Particle size distribution in three plots of the La Tola site

Sample	depth	Particle size distribution				
Plot	/cm	CS	FS	CSi /%	FSi	C
1-WFc	0-5	20.7	30.4	9.8	32.7	6.4
6-GREENf	5-15	23.7	27.4	5.4	34.2	9.3
9-NPKf	15-25	34.5	27.5	7.1	22.9	7.9

CS: coarse sand 2,000-200 µm; FS: fine sand 200-50 µm; CSi: coarse silt 50-20 µm; FSi: fine silt 20-2 µm; C: clay <2 µm

Table 2. Main chemical properties of the surface horizon (0-10 cm) at the La Tola site

Exchangeable cations					Organic matter			P	pH	
Ca^{2+}	Mg^{2+}	K^+	Na^+	CEC	C	N	C/N	P	in water	in KCl
/cmol (+) kg^{-1}					/g kg^{-1}			/mg kg^{-1}		
7.9	5.5	0.7	0.4	18.8	4.1	0.54	7.6	457	6.85	5.20

Methods

The rainfall simulation

Four rainfall simulation experiments were conducted over a 36 months period using a methodology adapted after Casenave and Valentin (1992). Three successive rainfall simulations (S1, S2 and S3) were conducted prior to the establishment of the agronomic treatments on small TEST plots, and the last rainfall simulation (S4) occurred after the third cropping cycle (Table 3) on larger cultivated plots. The rainfall simulator (Asseline and Valentin, 1978) generated artificial rains with controlled parameters (intensity, frequency, and duration) over 1 m^2 plots. Each rainfall simulation consisted of three successive runs. The second run occurred three hours after the end of the first run, and the third run 12 hours after the end of the first rain event. Each run lasted 60 minutes and comprised four continuous sub-runs of 15 minutes with intensities of 20, 40, 60 and 80 mm h^{-1}. Runoff water was collected at intervals depending on runoff rates. The turbidity (soil charge related to water volume) and the soil losses (C en gm^{-1}) were measured.

Before the agronomical trial, three replicates were performed for S1 in the centre of two plots 9 m^2 in surface area, manually tilled to a depth of 40 cm. Every plot was prepared to produce surfaces with contrasting average clod size, one plot where averaged clod size was about 5 cm (fine clods, F) and another plot where their averaged size ranged from 5 to 10 cm (coarse clods, C). The second rainfall simulation (S2) occurred one month after S1 on a bare soil surface that was exposed to natural rainfall events. The third rainfall simulation (S3) was conducted again one month after S2, immediately after a soil tillage to brake down the structural crust produced from the provider two simulations and natural rain.

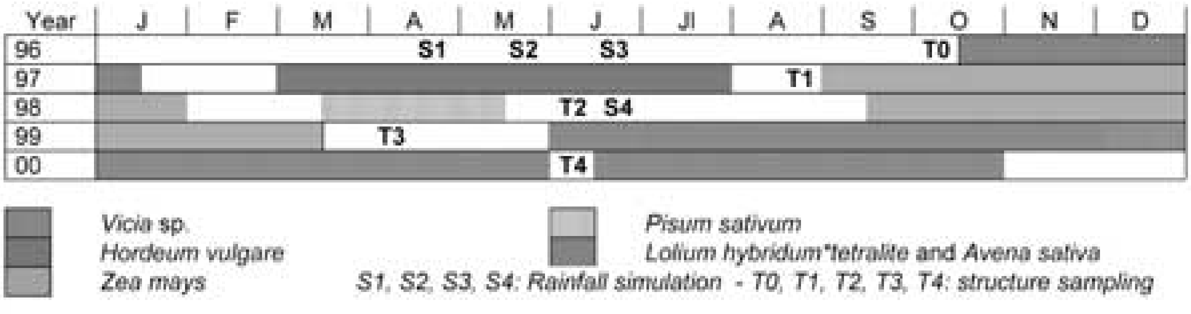
During the agronomic trial, the fourth rainfall simulation was implemented on five distinct terraces on 9 plots. Three replications were undertaken in each cultivated plots.

The agronomic trial

Five homogenous levels of *cangahua* with a step of 1 m high were chiselled to a depth of 60cm using a bulldozer and levelled into five flat terraces of 6×50 m^2. The rootable soil did not exceed 40 cm in depth. Each plot had a surface of approximately 100 m^2 (4.5×22 m^2). Initially, five plots were fragmented in coarse fragments (C), and fine fragments (F). Five fertilization strategies were studied on both preparations during the 5 cycles of cultivation (Table 3; Podwojewski and Germain, 2005):

- Incorporation of fresh cattle manure (OM plot) representing 40 tha $^{-1}$ of dry material before the first cultivation and a complement of 10 tha $^{-1}$ after every cultivation cycle representing a global amount over 80 t ha^{-1} after 5 years;
- Incorporation of green manure (GREEN plot), all the residues of previous cultivation being

Table 3. Calendar of rainfall simulation and cultivation



buried representing a total of 10 t ha^{-1} including 6 t ha^{-1} of *vicia* and 2 t ha^{-1} of *Pisum sativum* (pea), and chemical fertilizers as a complement;

- Initial mineral fertilization (NPK plot) with 300 kgha $^{-1}$ of N, 80 kgha $^{-1}$ of P with a complement of 50 kgha $^{-1}$ of N and 10 kgha $^{-1}$ of P after every cycle;
- Cultivation without any fertilizer (WF plot);
- Plots maintained bare and uncultivated BARE plots).

Samples were collected at different stages of cultivation as shown in Table 1. After 3 years cultivation, every plot was divided in 10 subplots for a cycle of perennial cultivation of *Lolium hybridum, v. tetralit* (ryegrass) or a cycle of *Avena sativa* (oat). Three fertilization strategies were applied on each subplot: L (low): 60 kg N, M (medium): 280 kg N, H (high): 960 kg N and 60 kg P. After four year's cultivation: the last sampling was made after nine cuts made every five weeks.

Analytical methods

The aggregate stability was measured with a methodology adapted from Kemper and Rosenau (1986). This size of 1 mm sieve used to discriminate macro and microaggregates is slightly different from the 250 µm usually adopted, because this size corresponds to the fine sand fraction, the most important granulometric class of the texture composition. Selective extractions of iron (Fe) were made with the citrate-dithionite-bicarbonate (CDB) method (Mehra and Jackson, 1960). The Fe concentration in the extract was measured using an ICP-AES spectrophotometer (IRD laboratory, Bondy, France). The grain-size distribution was determined on 10 g of soil after destruction of organic matter by H_20_2, after hexametaphosphate treatment and 30 minutes ultrasonic dispersion. The coarse silt (0.02-0.05 mm), fine silt (0.002-0.02 mm) and clay fraction (<0.002 mm) were determined with an X-Ray sedigraph (IRD laboratory, Bondy, France). The bulk density of hard *cangahua* fragments was determined by the paraffin method with five replicates.

Mineralogical determinations were made on two samples in the two western and eastern edges of the same terrace showing the most extreme behaviour. Mineralogical composition was determined by the clay fraction X-ray diffraction (XRD) with CuK-radiation. The shrinkage curves were made with a laser telemeter (Podwojewski and Germain, 2005).

Results and discussion

Runoff coefficient

In the undisturbed *cangahua*, the permeability is very low due to the small access to the pores. The runoff is close to 100% thus corresponding when present in the soil to a vertical discontinuity for water infiltration and consequently to a level lateral internal runoff. Another consequence is the great erodibility of the material above. Thus in its massive state, the permeability of *cangahua* is restricted due to small pore size resulting in a significant runoff and this predisposes the soils to significant erosion.

The values of the runoff coefficient (Kr) are presented in Table 4. In the test plots, during S1, the Kr values were <5% with a slight increase from the first to the third rain event. As suggested by Poesen and Ingelmo-Sanchez (1992), the presence of coarse elements favours the vertical circulation of water. However, during S2, Kr increased rapidly and regularly from the first to the third rain event. Kr increased from 12 to 16% on coarse preparation and from 24 to 32% on fine preparation (Table 4). During S3 after soil surface removal, Kr was low again but only for the first rain event.

For the cultivated plots (S4) and during the first rain event, the higher values of Kr occurred on plots located on the western part of the trial. For the second

Table 4. Runoff water coefficient (Kr in %)

Preparation	Kru (%)					
	Coarse			Fine		
	Rain 1	Rain 2	Rain 3	Rain 1	Rain 2	Rain 3
Simulation 1 – **TEST**	0.4	1.7	4.4	0.1	0.3	0.5
Simulation 2 – **TEST**	12.1	16.2	16.4	23.8	28.7	32.5
Simulation 3 – **TEST**	3.4	6.7	13.3	1.6	6.2	7.4
Simulation 4						
Plots – **OM**	49.5	76.0	82.7	41.1	73.0	79.9
Plots **GREEN**	32.7	54.7	74.4	38.7	76.2	83.4
Plots **WF**	38.5	61.8	76.4	37.6	62.3	69.5
Plots **NPK**	19.4	50.4	62.9	26.9	54.8	65.0
Plots **BARE**	21.8	61.0	72.2			

In gray: plots located in the western part of the trial with higher expansive clay content.

Table 5. Soil loss and structural stability

	Erosion				Unstable wet aggregates
	Rain 1	Rain 2	Rain 3	Total rains	UWA
	$g.m^{-2}$	$g.m^{-2}$	$g.m^{-2}$	$g.m^{-2}$	$g.100g^{-1}$
S1 coarse	± 0	± 0	± 0	± 0	
S1 fine	± 0	± 0	± 0	± 0	
S2 coarse	31.3	77.1	30.7	139.1	
S2 fine	26.8	61.7	45.1	133.6	
S3 coarse	46.2	37.0	26.7	109.9	
S3 fine	19.9	17.2	20.0	57.1	
OMc	88.4	98.4	106.5	293.4	39.5 ± 2.9
OMf	111.2	138.0	164.2	413.5	23.9 ± 5.9
GREENc	45.9	56.4	82.1	184.4	13.4 ± 3.2
GREENf	96.4	121.5	182.4	400.3	30.9 ± 6.3
WFc	124.0	144.4	184.7	453.0	23.7 ± 4.1
WFf	64.4	59.5	36.8	139.2	12.8 ± 0.6
NPKc	37.1	58.5	37.7	132.8	13.0 ± 6.7
NPKf	29.3	45.4	55.0	129.7	8.2 ± 1.4
BAREc	478.1	956.3	836.2	2,270.6	49.3 ± 14.7
BAREf					20.2 ± 4.5

rain event, an important increase in Kr is observed on all plots. For the third rain event, all plots showed a moderate increase in runoff. Total runoff had important values over 50%. Comparative to the first rain, the increase in Kr appeared to be the same, approximately 40%.

Soil loss

The soil detachment occurs generally when rainfall intensities exceed 40 mm h^{-1}. In the cultivated experiment, BARE and WFc plots soil loss occurred for intensity lower than 40 mm h^{-1} rainfall. Soil loss increased sharply between 60 and 80 mm h^{-1}. Soil detachment generally increases from the first to the third rain event (Table 5).

Prior to the implementation of agronomic treatments, soil loss was negligible after the first rainfall simulation (Table 5). For S2, the total soil loss for both the coarse and fine land preparation treatments was very similar (135 g m^{-2}). For S3, after the soil tillage, on the coarse plot the soil loss values were still high and decreased slowly from the first to the third rain event. For the fine preparation the soil loss was relatively constant and was half of that recorded during the second rain event.

In gray: plots located in the western part of the trial with higher expansive clay content.

For the far simulation (S4), on cultivated plots, for a total of 50 mm of rain in one hour during each rain, the soil loss varied from 30 to approximately 180 g m^{-2} except for the bare surface where soil loss was much higher than for the other plots (from 400 g m^{-2} to over 800 g m^{-2}). The highest rate of soil loss was observed on plots located to the west of the experiment.

The structure stability

There is a good relation between the rate of unstable aggregates and runoff or soil detachment as suggested by Barthès *et al.* (2000). The ANOVA made at T4 shows that soil preparation, and grass root and mucilage production had no significant effect on structural stability; only the sampling location on plots with different mineralogical properties had a high significant influence (Podwojewski and Germain, 2005).

After a 3 year period of cultivation (T3), the percentage of unstable wet aggregates increased significantly. All these plots with even numbers are located in the western part of the experiment. Plots with a dry matter production of 3 t ha^{-1} on the same terrace were not significantly different in structural stability from ones with micro plots with a dry matter production of more than 20 t ha^{-1}. The level of accumulated aboveground biomass of ryegrass did not influence the structural stability significantly in one-year rye grass cultivation.

The soil components

Structural stability and carbon content

The neoformation of a typical soil structure and its stability is generally linked to carbon content

(Tisdall and Oades, 1982), especially with root derived carbon (Gale *et al.*, 2000) and is the result of biological activity and organization of clay-organic matter stable bounds. In the case of *cangahua*, in early stages of an agricultural management, soil fragments have a structural stability independent of the presence of surface mycelium, density of roots and/or carbon contents.

For a positive effect on structural stability, the rate of organic matter should be higher than 2% in temperate climates. As there is no linear correlation between organic matter rate and structural stability (Perfect and Kay, 1989), the weak structural stability could be attributed to a weak concentration of organic matter, which was less than 3% even in plots with the highest rate of organic matter inputs. The values of C content are still low after inputs of over 80 t ha^{-1} of manure. The total lack of carbon in the *cangahua* formation could be attributed to rapid carbon mineralization. In similary soils in Mexico, after four months, more than a third of the input was mineralized (Etchevers *et al.*, 1997).

Structural stability and clay-content

After 3 years of cultivation, the particle-size distribution was different at the soil surface. Compared with the initial particle-size distribution in all plots, the coarse sand content decreased strongly and, conversely, the clay fraction and also the coarse silt fraction content increased. In the eastern part of the trial, plots were composed of homogenous material poor in clay, while the extreme western part showed an increase in clay content.

The X-Ray determinations of the oriented clay fraction showed no well-defined crystalline clays. However, a base line with an apparent higher intensity between 1 and 1.5 nm appears for samples with a larger content of clay-sized material. Nevertheless, this clear difference cannot be interpreted as a difference of clay type or clay crystallinity.

The lack of mineralogical clay restricts the constitution of bonds between clay and organic matter which form stable aggregates. But in the case of *cangahua* we observed that an increase in clay content corresponds to an increase in the rate of unstable aggregates and the aggregate stability may be related to iron oxides bounds (Figure 2). This unstable behaviour could be linked to the swelling-shrinkage properties. The clay-rich fragments present a shrinkage percentage between 5 and 8% after drying while the poor clay fragments had a shrinkage percentage of less

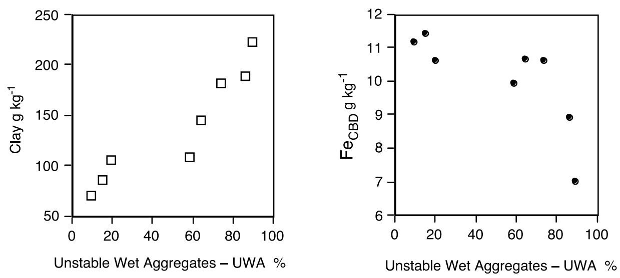


Figure 2. Relation between UWA and *cangahua* clay and Fe (cbd extract) contents.

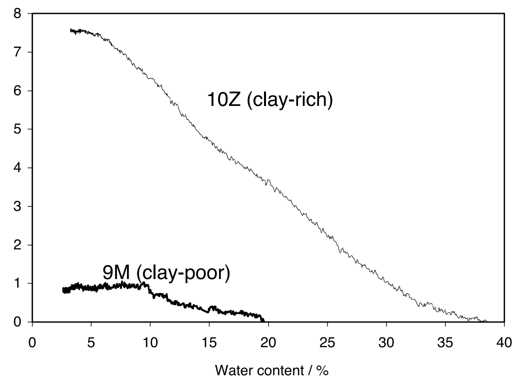


Figure 3. Shrinkage curves in function of water-content of clay poor (Plot 9M) and clay-rich (Plot 10Z) fragments

than 1% (Figure 3). This behaviour confirms the presence of swelling material, maybe proto-clays, which are much higher than the poor-clay samples and could be responsible for the scattering of the fragment components. In our case, iron oxides are probably part of the particles cohesion rather that amorphous silica. Therefore soil tillage could be partly responsible for high soil dispersion.

The *cangahua* can be considered as a rock in weathering process with higher expansive clay contents in the western part of the trial, especially in places were are localized the Bare plots. During this process, we observed a transition between the soil fragments to a soil structure. This transformation seems to be higher in the presence of strong biological activity in plots enriched with organic matter. Cemented fragments of hardened volcanic ashes have a stronger stability than the recent formed aggregates due to biological activity, which are therefore more prone to erosion than the previous soil fragments.

Geomorphologic and agronomic consequences

Coarse soil preparation and the conservation of hard fragments temporary limit the risk of runoff and erosion. However rapid infiltration can lead to the accumulation of water at the top of an impermeable untilled *cangahua* layer and therefore, generating landslides (Perrin *et al.*, 2000). Fine soil preparation increases the crusting of the topsoil. It could limit erosion by increasing runoff but only in the first steps of the erosion process. The concentrated runoff can lead rapidly to the formation of gullies first step to the removal of the hardened layers.

Due to rapid crusting and strong sensitivity to erosion, flat terraces are recommended. Because of the high cost of work, terraces of slow formation with a limited slope of 10 to 15% and protected downstream by a wall in a *cangahua* itself have been experimented with successfully and are now adopted in some agricultural communities (De Noni *et al*. 2001; Zebrowski *et al.*, 1997). These terraces by the time and a generalized sheet erosion.

In Mexico, where much work has been done on erodibility of *tepetates*, rainfall occurs once a year during a well-defined rainy season. In case of annual traditional crops like maize, the higher intensity corresponds to a period with maximum vegetation development so that the soil cover is at its maximum. However, in Ecuador, there are two distinct rainy seasons and very heavy rains can occur between two cultivation cycles so that bare soil could be exposed to erosion.

The potential production of Ray Gras could be estimated to 6 t ha^{-1} every 5 weeks. This potential production could be approach and Yields can reach over 5 t ha^{-1} after each cut, over 40 t ha^{-1} in irrigated condition with an initial N fertilization of 120 kg ha^{-1} and 80 kg ha^{-1} every 5 weeks, and 160 kg ha in P. Higher is the rate of N fertilization, higher will be the needs in P and after the 3rd cut, Ray grass shows deficiencies in K and S, which could be surprising in a volcanic environment. If K sulphate is introduced since the beginning of the trial, the high yields are constant after one year production (Germain *et al.*, 2000).

High inputs of organic matter are unlikely because of their high cost, limited availability, and their very fast mineralization. The best solution for agricultural development of the *cangahua* surface may be the planting of a perennial grass pasture. The fibrous root system of the grasses not only ramifies and opens up the soil but also encompasses individual crumbs in a net-like web to form crusts resistant to the slaking action of water (Tisdall and Oades, 1982; Kay, 1990; Reid and Goss, 1981). Any other cultivation must be made with minimum tillage.

Conclusion

In the early stages of *cangahua* removal, water infiltration is rather complete. But since one month of exposure to natural rains crusting limits runoff. Crusting occurs rapidly especially when the soil is left without soil cover and when it has fine fragments. After soil tillage, the runoff is only temporarily reduced, and increases regularly after each rain. After three cycles of cultivation, there is no major difference in behaviour between coarse and fine preparation. Crusting is very fast and limits the pre-pounding rain even in plots with higher porosity.

After four years of cultivation, soil preparation, organic matter inputs, root density and mucilage production had no effect on the aggregate structure stability. Initial structural stability of fragments is determined by their mineralogical composition: clay-rich material with shrink-swell properties is less stable than material containing low amounts of clay, with less shrink-swell properties and higher iron oxides contents. Their contrasting attributes are a result of progressive weathering and therefore, influence erosion processes.

Runoff and erosion develop after cultivation and are particularly important in plots with the highest rate of unstable aggregates with high expansive clay content. The introduction of organic matter probably generates a new pedological structure, but does not improve general structural stability, probably because it is present in insufficient amounts. However, organic matter fertilizers need more tillage and the new pedological structure is much weaker than the lithological fragments that form the initial structure.

To avoid any risks of erosion, soil preparation should be coarse to limit the effect of erosion in the early stages of plant development. These soils must be cultivated on flat areas, be protected by a perennial crop (pasture), which may produce an improvement in soil stability though its roots and slowly develop a new stable pedological structure different from the fragmented lithological structure. Volcanic ash soils could be deficient in S.

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Session 5

"The role of organic matter and biological activity"

Organic matter and biofunctioning in tropical sandy soils and implications for its management

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Keywords: soil microorganisms, soil fauna, crop management, soil carbon fractions

Abstract

Tropical sandy soils (or upper sandy horizons of tropical soils) have diverse physical and chemical constraints: poor structural stability (making soils sensitive to crusting, and compaction), poor nutrient holding capacity and low cation exchange capacity. In these soils, in which the clay content is low (3 to 15% by mass), organic matter is the main determinant of fertility, nutrient storage, aggregate stability, microbial and enzymatic activities. However, cultural practices or land uses aimed at increasing organic matter stocks have a minor impact if compared with the potential storage of organic matter in clayey soils. Nevertheless, this stock increase is possible in sandy soils and is mainly linked with the increase of the "vegetal debris" functional pool. Like organic matter, the abundance, activity, and diversity of soil biota are largely dependent upon land management. In these soils, biotic interactions such as termites-microorganisms or nematodes-microorganisms modify nutrient fluxes, N mineralization being higher in soil-feeding termite mounds or in the presence of bacterial feeding nematodes. Moreover, the management of organic residues represents a means to control the activity of soil microorganisms and the structure of nematode and other fauna populations. An adequate management of organic matter (through fallows, improved fallows, pastures, external organic inputs) through its consequences on soil biofunctioning, largely determines the agronomic (plant production) and environmental (carbon sequestration) potentials of sandy soils. In the present paper, we provide information on the biofunctioning in sandy soils, i.e., interactions existing between organic matter, biological activities (termites, earthworms, nematodes, microorganisms) and physical soil properties, in natural and cropped ecosystems. Data mainly originate from experiments and measurements from West (Senegal, Burkina Faso, Ivory Coast) and East (Kenya) Africa.

Introduction

Sandy soils are widely distributed in the tropics where they occupy most of arid and semi-arid areas. For instance, the total estimated extent of Arenosols is 900 million hectares, mainly in Western Australia, South America, South Africa, Sahel, and Arabia (WRB and FAO/Unesco soil map of the World). It is well known that these "problem soils" are characterized by a low soil organic carbon (SOC), a low cation exchange capacity (CEC), a high risk of nutrient leaching, a low structural stability, and a high sensitivity to erosion and to crusting. Both chemical fertility and physical stability are weak in these soils (Pieri, 1992; Sanchez & Logan, 1992). These characteristics are due to their sandy texture, the low reactivity of their clays, and to climatic conditions that often accompany tropical sandy soils. Due to their dominant mineralogy (generally: quartz, kaolinite, iron and aluminium oxides) and their sandy texture, the role of organic matter on the properties of these soils, on their potential of productivity and on the sustainability of agricultural systems is thus fundamental (Pieri, 1992; Feller et al., 1995b). The control of soil organic matter (SOM) on chemical (CEC, pH, some cations such as calcium and magnesium), and physical (porosity, structural stability) properties has often been demonstrated (Asadu et al., 1997). In sandy soils, it thus appears fundamental to manage all components that affect soil fertility: SOM, and soil biota. Biological processes are crucial to sustain the fertility of sandy soils as they control C and N fluxes (Menaut et al., 1985; Perry et al., 1989; Chotte et al., 1995; Lavelle,

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1997). Like in other pedoclimatic zones, the assessment of C, N and P in agrosystems on tropical sandy soils is a useful tool to define sustainable intensification plans necessary to respond to population increases and global change issues (Manlay et al., 2002a, b, c).

In this paper, we will successively analyse (i) the specificity of sandy soils with regard to their organic status, (ii) the agronomic determinants of their organic status, (iii) the agronomic determinants of their biological activities and, (iv) the relationships between SOM and biota with regard to agro-ecosystem management. The three latter parts are based on case studies essentially from West Africa.

Organic status of tropical sandy soils

Relationships between soil organic matter and soil properties

SOM controls many chemical, physical and biological properties that affect the capacity of a soil to produce food, fibres and fuel. It is the main source of ecosystem energy, and also the main source and a temporary sink of nutrients for plants in the agrosystems.

SOM plays a major role in soil fertility through different functions (Feller, 1995a):

- The storage of nutrients ("mineral supply" function). Some minerals like P, Ca, K, Mg are associated in a non-exchangeable form to SOM. They are released during OM decomposition and their dynamics is thus dependent on that of OM. In soils like sandy soils naturally poor in these elements, OM constitutes a interesting reserve for them.
- The increase in CEC ("exchange and sorption" function). This function is linked to the surface properties of soil organic and organo-mineral components: cation and anion exchange capacity, physical and chemical adsorption and desorption properties. These properties define the availability of some nutrients, cation equilibrium and the efficiency of fertilizers and xenobiotic molecules.
- The improvement of soil structural stability ("aggregation" function). Structural stability determines many soil physical and biological properties.
- The stimulation of faunal, microbial and enzymatic activities ("mineralization and immobilization" = "biological" function) that determines carbon C, nitrogen N and phosphorus P and sulphur S cycles. These elements follow successions of mineralization and microbial immobilization. This controls the fluxes of these elements in the soil-plant system (storage or losses) or between different soil compartments.

Relationships between soil organic carbon stocks and texture

Many studies in West Africa showed that SOM content in soil surface horizons is dependent on soil texture (Jones, 1973; Boissezon, 1973; Feller et al., 1991). Feller (1995a) and Feller & Beare (1997) proposed to link linearly SOC content with fine soil particles 0-20 µm, i.e., clay + fine silt (C + FS) (Figure 1).

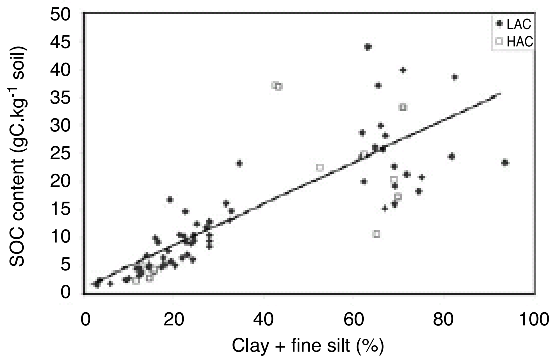

Figure 1. Relationships between soil organic content and clay + fine silt content in tropical 1:1 (low activity clay LAC) and 2:1 (high activity clay HAC) soils (adapted from Feller & Beare, 1997)

The relationship clearly indicates that the lower the clay + fine silt content, the lower the soil carbon content. Since this study, the same relationship has been observed in other tropical regions: in Senegal (Manlay et al., 2002b, c), in Martinique (West Indies) (Venkatapen et al., 2004). Tropical sandy soils are thus soils naturally poor in soil organic carbon.

Feller et al. (1991) showed that temperature was not a major determinant of SOC stocks differentiation in considered situations of West Africa (the effect of temperature is only expressed in altitude tropics with mean temperature below 18-20ºC). Feller et al. (1991) observed also only a weak effect of rainfall on SOC stocks with a slight increase in C stock in the most humid areas. Taking into account the effect of fine particles (C + FS) and rainfall R, the relationships between SOC content and these factors was:

SOC (gC.kg^{-1} soil) = 0.47 (C+FS) + 0.002 (R) – 1.74 Thus, tropical sandy soils are naturally poor in SOC. When analysing the contribution of Arenosols (main sandy soils) to the total SOC stocks in all World soils, it can be calculated that although Arenosols represent 4.4% (ca. 6 millions km^2) of total World soil area, these sandy soils contribute only to 0.6% (4.3 Pg C) of total SOC stock in the upper 30 cm (723 Pg C)[1].

Potential of carbon storage and sequestration in sandy soils

The potential of C storage can be assessed as the difference (ΔC) between SOC in native or perennial vegetation and SOC in annual crops. Feller et al. (1991, 2002) observed that ΔSOC are more important for clayey soils than for sandy soils (Figure 2).

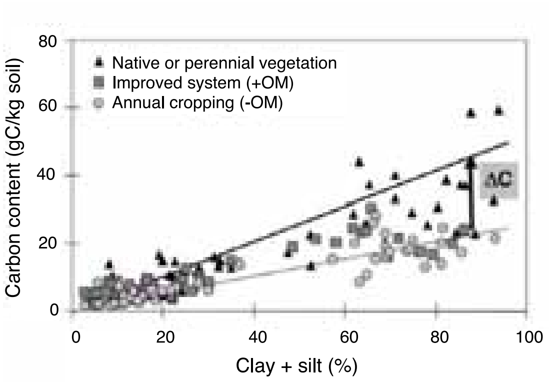

Figure 2. Effect of land use and soil texture on SOC content in different tropical soils (Feller, unpub. data)

Similar observations were made for other part of the tropics (Manlay et al., 2002c; Venkatapen et al., 2004). In sandy soils, SOC content in native or perennial vegetation, or in improved systems characterized by high organic inputs are not much higher than SOC content in annual crops. In West Africa, decreases in C content following the installation of crops represents 30 to 40% of non-cropped soils (Hien, 2004). Moreover, these variations appear more rapid for sandy soils (less than 5 years) than for clayey soils (5 to 10 years). As a consequence, sandy soils have a very low potential of carbon storage, compared to clayey soils. The role of tropical sandy soils in the mitigation of atmosphere greenhouse gaz (GHG) is thus very weak. Manlay et al. (2002c) hypothesized that the contribution of these soils to the global mitigation of GHG release does not necessarily require a local carbon sequestration. Settling people may be a means to limit deforestation and carbon release from more humid areas or more clayey soils. This can be achieved by a cropping intensification.

Organic compartments in tropical sandy soils

The morphologic observations at different scales (optical, electronic microscopy) of SOM associated with different particle size fractions in ferruginous and ferrallitic soils allowed Feller (1979) to gather SOM into 3 compartments:

- The fraction 20-2,000 µm is composed of plant debris at various stages of decomposition, associated with sand and coarse silt;
- The fraction 2-20 µm is made up of fungal and plant debris associated with fine silt and very stable organo-mineral aggregates;
- The fraction 0-2 µm consists of amorphous, colloidal OM, debris of plant and fungal walls associated with organo-mineral micro-aggregates.

Feller et al. (1991) and Feller (1995a) observed that these compartments vary with soil texture. In sandy to sandy-clayey soils of West Africa, the fractions 20-2,000 µm and 0-2 µm represent 30 and 36% of total soil carbon, respectively, while in clayey soils, they represent 17 and 58% of total soil carbon, respectively. Feller (1995a) studied the effect of soil texture on the variations in total SOC content and in organic compartment C content in soils: (i) in a succession deforestation-cropping, and (ii) in a succession cropping-fallowing.

In the former succession, the installation of crops after deforestation leads to decreases in SOC contents by 40%, 44%, and 55% in sandy, sandy-clayey, and clayey soils, respectively. Decreases in total C content are thus more important for clayey soils than for sandy soils. In the sandy soil, most of C is lost in the coarse organic fraction (20-2,000 µm) while in both other type of soils, total C loss is mainly due to losses in fine and medium-size fractions (0-2 and 2-20 µm) (Figure 3). For sandy soils, decrease in SOM is very rapid (3 years) for all fractions, even if the rate of decrease is lower for fine fractions than for coarse fractions.

Conversely, the installation of fallows after many years of cultivation leads to increase in SOC contents by 92%, 44%, and 36% in sandy, sandy-clayey, and clayey soils, respectively (Figure 4). In the sandy soil, most of C variation is linked to an increase in C of the coarse organic compartment (20-2,000 µm); in the sandy-clayey soil, the C content of the three organic compartments increase while in the clayey soil, total C increase was linked to increase both in coarse

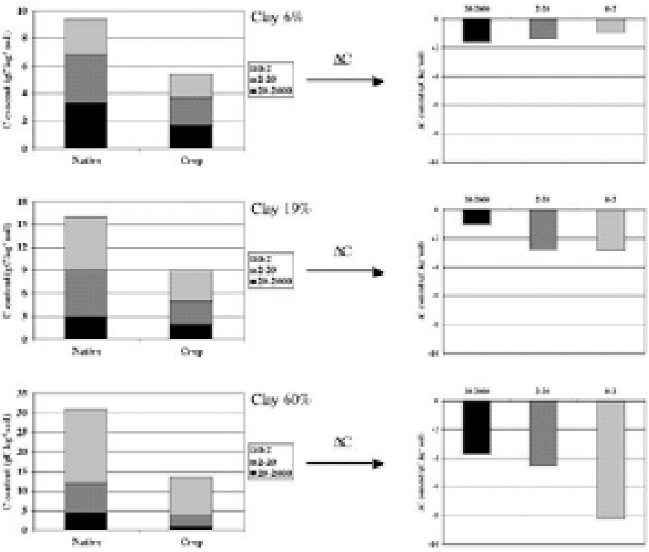

Figure 3. Effect of installation of crops after deforestation on SOC contents in soil and in three organic compartments. Variation in C content (ΔC) between native vegetation and crops (adapted from Feller, 1995a)

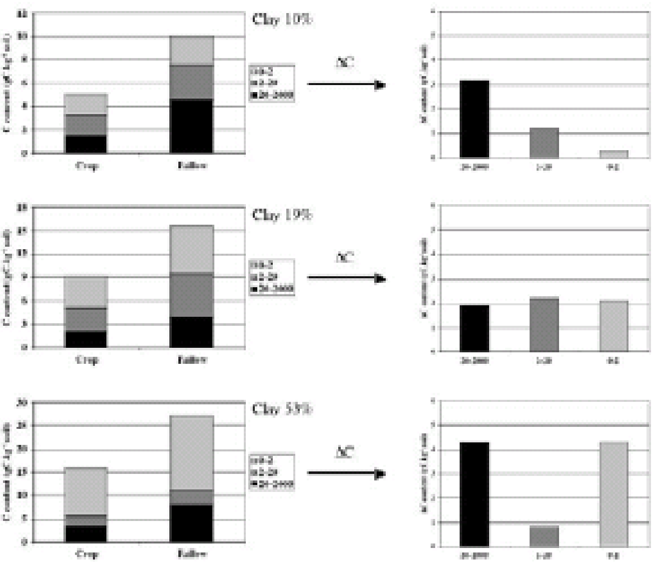

Figure 4. Effect of installation of fallows after cultivation on SOC contents in soil and in three organic compartments. Variation in C content (ΔC) between crops and fallows (adapted from Feller, 1995a)

and fine fractions. Low soil C content due to 10 years of cropping is rebuilt more rapidly (after 8 years of fallow) for 20-2,000 µm fraction than for the other fractions (15 years of fallow).

As a consequence, the renewal rate of C in organic compartments decreases from coarse to fine fractions. Mean residence time of the coarse fraction and in the medium + fine fractions in sandy soils has been estimated to as 12 and 30 years, respectively. When analysing the sandy soils only, the half time life was estimated to 8, 18 and 22 years for >50 µm, 2-50 µm and 0-2 µm fractions, respectively (Feller & Beare, 1997). This means that the coarse fraction (plant debris) in sandy soils plays a major role, in short- and medium-term SOM dynamics, on soil properties, and on soil-plant relationship.

In terms of agrosystem management, these results indicate that the restoration of SOM stock in sandy soils, which is linked to the dynamics of the coarse fraction, is possible in a medium-term (10 years). Conversely, SOM restoration in clayey soils is much longer and mostly concerns both fractions (Figure 5).

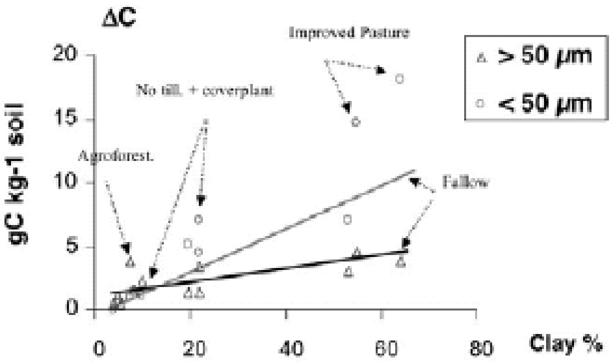

Figure 5. Variation in C content (ΔC) in two soil organic (fine and coarse) fractions as a function of soil texture in improved systems as compared with traditional systems (unpublished, adapted from Feller et at., 2002)

Functions of organic compartments

The three organic pools discussed above fulfil different functions in soils. As a whole, SOM is responsible for four main functions in soil: "mineral supply" function, "exchange and sorption" function, "aggregation" function, and "biological" function. The notion of functional compartment for SOM was discussed and quantified by Feller and co-authors (Feller 1995a; Feller et al., 2001). These authors demonstrated that in sandy tropical soils, the coarse organic compartment carries the biological function of the OM. This fraction plays an important energetic role as it represents more than 80% of easily decomposable C in sandy soils, but only 30% in clayey soils. On the other hand, medium (220 µm) and fine (0-2 µm) fractions are characterized in all soils by low C mineralization coefficients. Net N mineralization coefficients of coarse fractions are generally low especially when C/N ratio of the fraction is high. This coefficient increases from coarse to fine fractions; thus, in clayey soils, more than 85% of N mineralized comes from the fine fraction (0-2 µm) whereas in sandy soils, more than 50% of N mineralized comes from fractions larger than 20 µm. Studies in West Africa also showed that CEC increases with the decrease of organic fraction size. In these soils, C content, especially that of the fine fraction (0-2 µm) controls soil CEC (Guibert, 1999).

As a consequence, the way SOM improves soil properties depend on the compartments in which it is found (Feller et al., 2001). SOM in fine and medium fractions influences the capacity of a soil to store and exchange nutrients. In this respect, the application of a manure along with a N fertilizer is favourable for preferential storage of C in the fine fractions, thus showing the advantage of this practice in the stabilization of SOM (Hien, 2004). Conversely, SOM in coarse fraction has a rapid turnover and carries biological functions (mineralization of C, N, P in a short term). This fraction is specifically functional in soils with less than 10% clay (Feller, 1995a). Its function is biological: short-term mineralization of C, N and P, and storage ability for N or non-exchangeable calcium. The role of plant debris in the biogeochemical functioning of sandy soils appears fundamental. This is especially true for N, as in sandy soils, N initial reserve and storage potential are low and SOM turnover is rapid (Blondel, 1971a, b, c, d, e; Pieri, 1992; Ruiz et al., 1995). From an agronomic point of view, there is a need to favour agricultural practices that allow an important and constant restitution of plant or animal debris: composts, manures, successions of crops with strong root systems, short fallows, agroforestry, etc. (Ganry, 1991; Pieri, 1992; Feller, 1995a; Ganry et al., 2001; Manlay et al., 2002b, c).

Residue management, organic matter and organic compartments in sandy soils: case studies

It has often been demonstrated, for sandy soils of West Africa, that cropping systems that do not imply high levels of organic restitutions to the soil, either on a root form (fallows, pastures) or on organic amendments, lead to the decrease of plant productivity and/or to soil degradation (acidification, decrease in structural stability). This decrease is often linked to a decrease in SOC stocks (Feller et al., 1987; Pieri, 1992). The agricultural development of tropical sandy soils is often hindered by the fact that the decay of SOM is much more rapid than in clayey soils. This acceleration results not only from the low level of clay but also from the pattern of hydrometry throughout the year, both emphasizing the oxidation of SOM. The phenomenon is made all the more intense by the low soil protective colloids content.

The main question is: what is the relation between SOM and land productivity? Until the 1990s, the literature did not report a critical SOM content, assuming that the relation between SOM and productivity was more or less linear. Pieri (1992) studying Sudan-Sahel farming situations subjected to strong agro-environmental constraints showed that the strong relationship between the productivity of land and its organic richness were not rigorously linked. In Burkina Faso, Hien (2004) found a critical value of C in the soil, between 6 and 7 $gC.g^{-1}$ soil. The yields of sorghum decreased below 6 $gC.g^{-1}$ soil and stabilized above this value. Feller (1995a) established that the SOC threshold for the sustainability of agrosystems of Western Africa was 6.8 $gC.g^{-1}$ soil, this result being close to that of Hien (2004).

Here, we analyse the effect of different land uses on total SOM and distribution of C within the different organic fractions. Most of studies presented here come from West Africa (Senegal, Burkina Faso). Soils are sandy or sandy-clayey soils with sandy upper horizon; clay contents are always less than 15%.

Effect of annual crops and organic amendments

When natural vegetation is replaced with crops, one can observe a decrease in SOC stocks, and especially of C in the coarse fraction (>20 µm) (Feller et al., 1991). Manlay et al. (2002c) noticed that in crops (millet, maize, rice) in South Senegal (region of Sare Yorobana, soil with less than 10% clay), 90% of total C, 90% of total P and 95% of total N were found in the soil. As millet and maize received higher organic inputs and nutrients (manure, crop residues) than groundnut, their C and N contents were higher. In this region, the improvement of soil organic status under continuous crop can only be achieved in fields close to compounds where organic inputs are available.

Feller et al. (1987) and Feller (1995a) measured the effect of organic amendments on total C contents and SOC distribution in organic compartments, in a succession groundnut-millet in sandy soils of Senegal. In the first study (soil with 4% clay), C content was 2.0 $gC.kg^{-1}$ soil in the control and 2.4 $gC.kg^{-1}$ soil in the treatment with buried compost. All added carbon was found in the >50 µm fraction (Figure 6). In a second experiment (soil with 4% clay), C content in the control was 1.8 $g.kg^{-1}$ soil and it was 2.2 $g.kg^{-1}$ soil in the treatment with a straw mulch. In this case, all added C was found in the <50 µm fraction. In the third experiment (soil with 8% clay), the presence of a straw

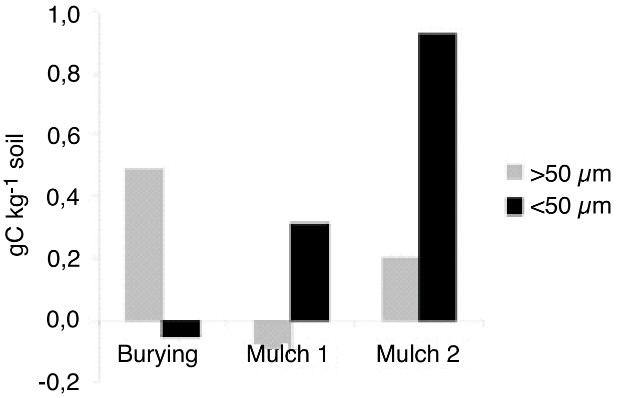

Figure 6. Variations in C content in two soil organic fractions between control and treatments with organic amendments in three experiments (see text for details) (unpublished, adapted from Feller et al., 2002)

mulch leads to an increase of C content (4.3 g.kg^{-1} soil) as compared to the control (3.1 g.kg^{-1} soil). C increase was mainly in <50 µm fraction and also in >50 µm fraction.

Organic transfers improve chemical properties in three ways: they are a net source of C and nutrients; they contribute to a gain in CEC and stimulate biological activity (Feller, 1995b; Asadu et al., 1997). Manlay et al. (2002c) observed also that organic practices in continuous crops had a more important effect on soil chemical status (P, Ca, K, CEC, S, pH) than fallowing.

Effect of cover crops

In Benin, the introduction of a cover crop (Mucuna pruriens var. utilis, Fabaceae) in maize crops, on a sandy soil (10% clay) lead to an increase in SOC content, and especially in C of the >50 µm organic fraction (Figure 7) (Azontonde et al., 1998; Bayer et al., 2001; Barthès et al., 2004). On the opposite, increase in SOC content is mostly linked to C increase in the <50 µm fraction in clayey soils.

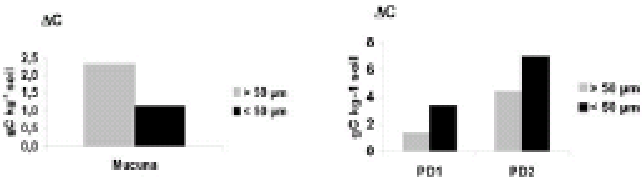

Figure 7. Variation in C content (ΔC) in two organic fractions in systems with cover crops, as compared with traditional systems without cover crops. Effect of *Mucuna pruriens* in sandy soils in Benin, and effect of no-tillage with cover crops in clayey soils in Brazil (two situations PD1 and PD2) (Azontonde et al., 1999; Bayer et al., 2001)

Effect of fallows and agroforestry

If the important decrease in SOC contents after deforestation in the tropics is well established (Maass, 1995), the potential of fallows to increase C contents has also been demonstrated (Manlay et al., 2002b). But the effect depends on soil texture, tree species, management, etc. (Szott et al., 1999). In sandy soils of Senegal, Manlay et al. (2000) measured an increase of SOC content with the age of fallows (4.7 gC.kg^{-1} soil in a 2-year old fallow, 9.0 gC.kg^{-1} soil in a 26-year old fallow). In the same time, calcium, magnesium and CEC increased with the age of fallows. With ageing fallows, coarse root biomass increases while herbaceous biomass decreases. Thus, in sandy soils, SOC increase with the age of the fallows is linked to an increase in tree root biomass and to more important litter inputs (Asadu et al., 1997; Floret, 1998). In most of agrosystems, especially those that are frequently burnt, as in West African Savannas, roots represent the main SOC source (Menaut et al., 1985; Manlay et al., 2000). In South Senegal, the effect of fallowing on soil organic status was only noticeable in the upper 20 cm of soils, but there was no effect on soil physical properties (Manlay et al., 2002a). The installation of fallows rapidly led to increases in soil C content (by 30% in one year); this was due to a rapid development of trees. Then, SOC content increase was not so rapid (Figure 8), maybe because of a poor protection of SOM against oxidation by biological activities in sandy soils; thus the protection of SOM against mineralization, erosion and leaching is not very efficient (Feller & Beare, 1997). In fact, mesh-bag experiment showed that 40 to 60% of woody roots disappeared after 6 months of incubation (Manlay et al., 2004). Fallowing mostly affected the >50 µm organic fraction whose contribution to total C doubled after crop abandonment. It also allowed a rapid restoration of N and available P contents (Friesen et al., 1997; Manlay et al., 2004).

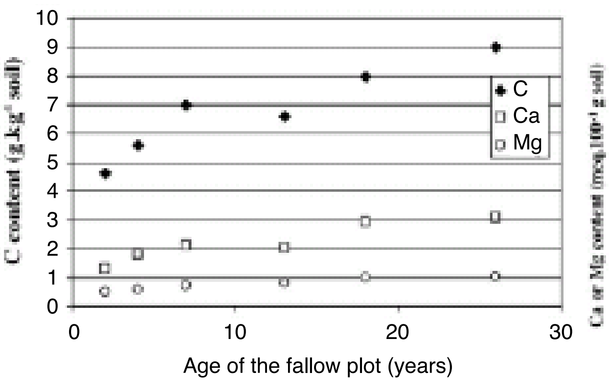

Figure 8. Effect of the age of fallows on C, Ca and Mg contents in South Senegal (Manlay et al., 2000)

In different sites of West Africa and West Indies, Feller (1995a) and Feller et al. (2001) obtained the same results as those obtained from South Senegal. Moreover, these authors demonstrated that in sandy soils, soil C increase observed in fallows (after crops) on sandy soils was mainly due to C increase in the >50 µm fraction, while in clayey soils, C increase in <50 µm fraction was mainly responsible for total soil C increase (Figure 9).

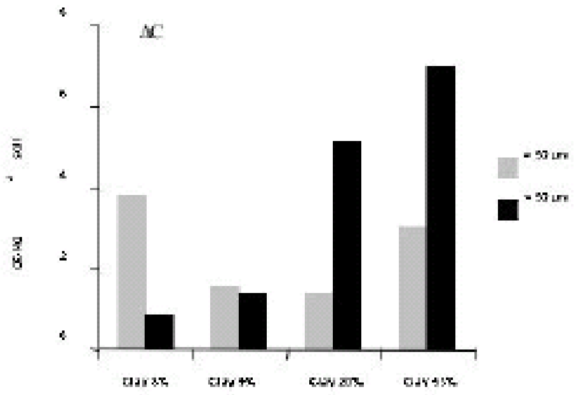

Figure 9. Variation in C content (ΔC) in two soil organic fractions in fallows, as compared with continuous crops, in soils with different clay contents (Feller, 1995a)

In Acacia plantations in Cameroon (soil with 5% clay), Harmand et al. (2000) measured after 4 years a SOC content increase as compared with continuous crops; this was mainly linked to an C increase in the >50 µm fraction. Agroforestry systems are often linked to a strong increase in the total SOC content of sandy soils (Figure 5).

As emphasized by Manlay et al. (2002c) C dynamics in fallows is a determining factor for following crops. A mineral fertilization without organic amendments leads to the mineralization of SOM and to a decrease in soil structure, pH and affects productivity (Pieri, 1992; Manlay et al., 2002c).

The biotic components in tropical sandy soils

As said above, SOM is the energetic source of soil biota and soil biota controls the dynamics of SOM, which is fundamental for the fertility and the properties of soils, and especially of sandy soils. Here we analyse some recent studies dealing with the relationships between land use, soil biota abundance and activity, SOM dynamics and plant productivity in sandy soils (West Africa).

Soil fauna

Soil fauna is known to influence soil chemical, physical and biological properties (Lavelle & Spain, 2001). Zoological groups more often studied with regard to plant productivity and soil properties are ecosystem engineers and nematodes. The former group gathers macroinvertebrates that modify soil physical organization through the production of biogenic structures, and modify the nature and availability of nutrients for other soil organisms (Jones et al., 1994; Lavelle, 1997). Main ecosystem engineers present in tropical sandy soils are termites and earthworms. Nematodes as they belong to different trophic categories affect soil microorganism communities (fungi and bacteria) and plants.

In sandy soils of the arid and semi-arid tropical areas, termites are generally the dominant group of soil macrofauna while earthworms are limited by low rainfall: below 800 mm of rainfall amount, earthworms become rare (Lavelle, 1983).

When present, the effect of earthworms on soil properties can be important. In the soil of the sub-humid savannas of Lamto, Ivory Coast (7% clay in the upper 20 cm of soil), communities are important (ca. 500 $kg.ha^{-1}$) and earthworms annually ingest up to 1,200 Mg $soil.ha^{-1}$ (Lavelle, 1978). As a consequence, the upper cm of soil is made up of earthworm casts that control physical and biological properties of soils (Blanchart, 1992; Martin & Marinissen, 1993; Blanchart et al., 1997). As showed in different field or laboratory experiments, earthworm activity tends to decrease C content of the coarse (>50 µm) organic fraction and to increase C content of the fine organic fraction in casts, as compared to non-ingested soil (Figure 10, adapted from Villenave et al., 1999). In these water-stable biogenic structures, SOM is physically protected against mineralization (Martin, 1991; Blanchart et al., 1993; Lavelle et al., 1998). The mutualistic interactions between earthworms and microorganisms, which start in earthworm gut and end in casts lead to a strong increase in microbial activities and a subsequent release of nutrients (N, P). The effect of earthworms on SOM dynamics is different according to the duration we consider: in the short term, earthworms stimulate microbial activity, decompose OM and release nutrients available for plants while in the long term, earthworms protect SOM against mineralization. Nevertheless, the presence of earthworms in cropped soil (with sandy upper horizons) does not seem to affect SOC stocks in a medium-term (Villenave et al., 1999).

Many studies have recently been dedicated to termite communities and activities in West Africa: effect on erosion and infiltration (Mando et al., 1996; Léonard et al., 2004; Valentin et al, 2004), on organic

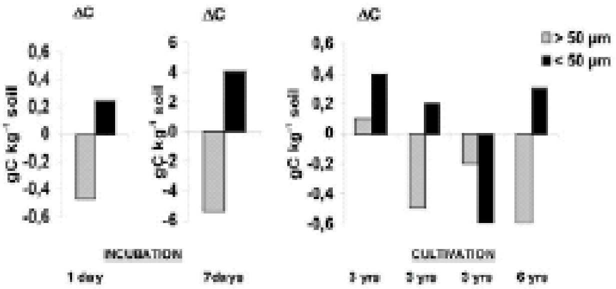

Figure 10. Variation in C content (ΔC) in two organic fractions in soils (clay content from 8 to 22%) with inoculated earthworms as compared with soils without earthworms. Data come from different laboratory (incubation) and field (cultivation) experiments. Duration of the experiments is indicated (adapted by Feller, 2002, from Villenave et al., 1999)

resource disappearance and nutrient release (Brown & Whitford, 2003; Rouland et al., 2003; Zaady et al., 2003; Ouédraogo et al., 2004), on soil microbial communities (Brauman, 2000; Fall et al., 2001, 2004; Ndiaye et al., 2003, 2004a; Jouquet et al., 2005), on nest properties (Fall et al., 2001; Mora et al., 2005). In a mesh-bag experiment in South Senegal, Manlay et al. (2004) measured a more rapid and important root disappearance in presence of fauna (mass loss 70% of initial root biomass after 12 months) than in absence of soil fauna (mass loss less than 50%). Termites and ants allowed the reallocation of OM and increased its availability for mineralization (in the presence of fauna, only a few fraction of C was stabilized in soil). In sandy soils, the important consumption of organic inputs by heterotrophic organisms is fundamental for the fertility of agrosystems.

Fallows (or agroforestry) allow the restoration of the biological control of ecosystem fertility (Manlay et al., 2002c). After crop abandonment, many studies show an increase of soil macrofauna (density, biomass, activity) (Fall, 1998; Manlay et al., 2000; Derouard, unpub. data). For instance, in South Senegal, the density of macrofauna was 3 times higher in a 10-year old fallow than in continuous crops (Fall, 1998). Some authors emphasize the importance of fallows in favouring ecosystem resilience and stability to climatic uncertainties, to poor nutrient status, and to poor physical stability thanks to the increase in soil diversity and density macrofauna and to root development (Menaut et al., 1985; Ewel, 1999; Manlay et al., 2002c).

The effect of termites on nematodes was studied in Senegal on a sandy soil and results showed that nematofauna structure in termite covers was comparable whatever the termite species, but it is different from that of the soil (0-10 cm). Many works show that plant parasitic nematode communities can be manipulated by managing vegetation, these nematodes being linked roots. Moreover, the pathogeny of nematodes depends on the structure of their community (Cadet & Spaull, 1998). For instance, it was demonstrated in Senegal that the presence of the species *Helicotylenchus dihystera* was associated with a reduction of the pathogeny of the whole nematode community because of the stimulation of root development (Villenave & Cadet, 2000). This species disappear with the establishment of crops after fallows; this may be due to the disappearance of woody roots. It thus seems necessary to preserve trees in agrosystems, and agroforestry could be a means to increase populations of *D. dihystera* and to reduce the impact of parasitic nematodes (Buresh & Tian, 1997).

Microorganisms

Microbial communities in soils are the actors of the decomposition of the organic matter. The complete decomposition of complex organic substrates such as organic residues relies on the succession of diverse microbial species characterized by different enzyme abilities (Swift et al., 1979; Zvyagintsev, 1994). In tropical sandy soils, very few investigations pointed out the importance of microbial community on decomposition processes.

Microbial status in fallows on tropical sandy soils

Organic and microbial status of soils (0-10 cm) under natural and improved fallows were studied in a Lixisol in two different field sites in Senegal (Sonkorong et Saré Yorobana) (Ndour et al., 1999; Ndour et al., 2001). At Sonkorong, soil organic matter and total microbial biomass were significantly higher in natural protected fallows than in non-protected ones and cultivated soils. No significant differences were recorded for non-protected situation, and cultivated soils. For managed situations, the duration of the fallow did not modify organic and microbial content of soils. Enzymes activities (ß-glucosidase, amylase, chitinase, xylanase) were investigated in these situations. Principal component analyses revealed a relationship between enzyme activities and the age (4, 11, and 21 year-old) and the management of fallows (fenced versus grazed), the vegetation (natural, *Acacia holocericea, Andropogon gayanus*). ß-glucosidase and amylase were significantly higher in the oldest natural fallows. The highest xylanase activity was recorded for the *Andropogon gayanus* improved fallows. This fallow showed also the highest chitinase, similar to that of the 21 year-old natural fenced fallow. Amongst the different management of the fallows, the introduction of Acacia holocericea depleted all the tested activities. In contrast comparisons between young and old fallows and crop plots at Saré Yorobana, did not show any significant differences. Coarser soil texture and higher frequency of land fires might explain these results.

Recent investigations on the impact fallow management on the diversity of the microbial community and the consequences of these modifications on soil organic decomposition function were carried out in a Lixisol (Senegal) (Sall et al., in press). Soil samples (010 cm) taken from a 21 year fallow and a plot that had been cultivated for 4 years after lying fallow for 17 years were incubated with or without the addition of *Faidherbia albida* litter under laboratory conditions (28ºC, 100% WHC) for 240 hours. Microbial diversity was assessed by molecular techniques (Denaturing Gel Gradient Electrophoresis) and in situ catabolic potential (ISCP) (Degens et al., 2000). In the non-amended soil, the activity of microorganisms was greater in the fallow soil, which had a greater microbial diversity than that in the cultivated soil. However, other soil properties (carbon and organic nitrogen content, total microbial biomass) may also explain this result. For the amended soil, only the first 8 hours of incubation showed a difference between the fallow and cultivated soil. During this period, the CO2 respiration in the fallow soil was higher than that recorded in the cultivated soil. This difference should be compared with the catabolic microbial diversity, which was higher in the fallow soil than in the cultivated soil. After this initial phase, the microbial community in the cultivated soil seemed to acquire similar functions to those in the fallow soil. These results show that the changes made to the microbial community by cultivation of a fallow over 4 years are not irreversible. The microbial community of this sandy soil very quickly recovers the same catabolic functions as those of the community in the fallow soil.

Effects of nematodes on microbial communities in tropical sandy soils

Nematodes can strongly affect microbial communities. In a microcosm experiment on a sandy soil (9.1%) from Senegal, the presence of bacterial feeding nematodes (Zeldia punctata or Acrobeloides nanus or Cephalobus pseudoparvus) led to a mean increase (+12%) in maize biomass compared to control soils and reduced concentrations of soil ammonium by the end of the experiment (50 days). Moreover bacterial feeding nematode activity led to a significant decrease in microbial biomass (-28%) and density of cultivable bacteria (-55%), however, nematodes stimulated bacterial activity (+18%) (Djigal et al., 2004).

Spatial distribution of biotic components

The distribution of organisms throughout the soil is controlled by the concentration in their substrates (Gray and Williams, 1971), soil water regime (Griffin, 1981), and soil structure (Elliott and Coleman, 1988; Hattori, 1988). Therefore any factors that modify these properties are likely to change the abundance and the activity of soil organisms.

Impact of termite biogenic structures on microbial abundance and diversity

In sub-sahelian sandy soils, termites are the only macrofauna actors during the dry season which last more than 7 months per year. Their activity translates mainly into the production of biogenic structures of various nature, size and constitution: mounds, soil sheeting, galleries and nest chambers. These soil translations are ecologically significant: in Senegal, 675 to 950 kg.ha^{-1} of soil are moved on the surface in the form of sheetings and galleries (Lepage, 1974). In Kenya, soil translation exceeds 1,000 kg.ha^{-1} (Kooyman & Onk, 1987). In the desert ecosystem of Chihuahua, about 2,600 kg.ha^{-1} are transformed annually into sheetings (Mackay & Whitford, 1988). These foraging structures, aside from their quantitative importance, present physicochemical, enzymatic and microbiological characteristics, which do not only differ from the control soil but also reflect the diversity of the organisms that produced them (Seugé et al., 1999; Fall et al., 2001; Sall et al., 2002; Mora et al., 2003). Thus, in this ecological context characterized by a relative stability of edaphic factors (temperature, humidity, soil structure), termites represent one of the main factor governing the activity and diversity of the microbial community.

An experiment realized in Senegal (soil with 1,013% clay) demonstrated that the impact of termites on soil properties depends on their biotic affiliation (soil feeding vs fungus growing) (Fall et al., 2001; Sall et al., 2002) and the type of structure, i.e., soil sheeting or nest, produced (Ndiaye et al., 2004a, b). Soil sheeting produced by the two main fungus growing termite species in Senegal (*Macrotermes subhyalanus* and *Odontotermes nilensis*) are characterized by an increased in organic C and mineral N, resulting in an increased in soil respiration whereas the microbial biomass was unchanged (Ndiaye et al., 2004a) and the enzymatic activities were weaker than in soil

(Brauman, 2002). Interestingly, these soil structures harbour a very different population of nematodes (Villenave and 2005, submitted) and fungi (Diouf et al., 2005), which demonstrates the role of termite as soil engineers. These properties did not depend on the quality of the organic substrate recover by the termite sheeting. Interestingly, these biogenic structures could be considered as a phenotypic characteristic of the species, as a multivariate analysis of the physi-cochemical, biochemical and microbiological of biogenic structures allows the separation of structures produced by different species of termites and earthworms (Seuge, PhD Thesis).

As underlined before, the termite nest of the soil-feeding termite has very different characteristics. Nests of Cubitermes niokoloensis with 5 times more C, 7 to 15 more N and 4 times more carbohydrates (Sall et al., 2002) could be seen as hot spots of organic matter and nutrients compared to the poor surrounding savannah soil. Moreover, the microbial community of these nests seems less diverse and heavily dominated by actinomycetes (Fall et al., 2004, Fall et al. submitted). Regarding N dynamics, the nests of soil-feeding termites present a decrease in potential denitrification and an inhibition of potential nitrification with the surrounding soil (Ndiaye et al., 2004). We could underline that the low or absence of the nitrification process seems a general feature of termite structures (sheeting and nest), showing a deep impact of termite on the global nitrogen cycle. Such modifications lead to important increases in NH4 and NO3 contents in biogenic structures (100 times more mineral N in nests of C. niokoloensis than in the soil). The absence of nitrification in termite nests despite high nitrate contents remains not completely understood. Brauman et al. (2002, 2003) hypothesised a termite or actinomycete origin (production of bactericide) or an inhibition by phenolic compounds presents in the nest.

In conclusion, termite mounds like earthworm constitute, in the context of the sandy tropical soil characterized by an intense mineralization rate, site of SOM preservations. The results reinforce the view of biogenic structures as earthworms cast and termite’s nest as true soil functional compartments like the rhizosphere.

Impact of soil structure

Soil is composed of an assemblage of solid particles and voids and represents the most complex habitat for organisms. Many authors have examined the effects of soil structure on the distribution and activities of the soil biota, including work on the distribution of soil microorganisms in particle-size fractions (Elliott, 1986; Gupta and Germida, 1988; Hattori, 1988; Kabir et al., 1994) and soil porosity (Killham et al., 1993). Much of the difficulty in studying the relationships between soil structure and soil microbial distribution and activity is based on our lack of knowledge of microorganims in undisturbed soil habitats. Therefore a gentle physical soil fractionation method based on a slaking procedure was developed and adapted for sandy soils (Chotte et al., 1993, 2002). This method has been used to describe the distribution of nematodes and microorganisms as part of a broader programme dealing with the impact of fallow shortening on soil fertility and biofunctioning.

Distribution of the nematode community within pores versus aggregates

Very few studies deal with the location in soil and activity of free living and plant parasitic nematodes. In the soil (14% clay) of Thyssé-Kaymor (Senegal), the repartition of nematodes in different soil fractions (aggregates >200 µm), inter-aggregates pores, fresh organic matter) vary according to their trophic behaviour (Figure 11) (Villenave, unpublished data).

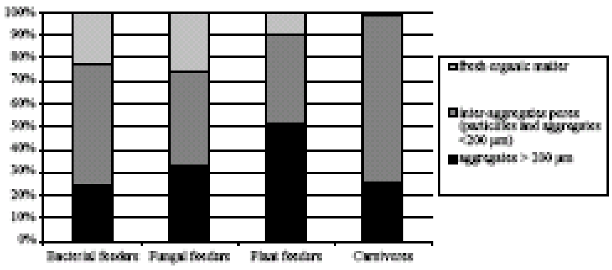

Figure 11. Distribution of the different feeding groups of soil nematodes between soil fractions (in % of the total nematode number in the soil sample)

Bacterial-feeding nematodes were essentially localized in inter-aggregate pores (>50%) and an important proportion of these nematodes was localized in fresh organic matter (24%). A relatively similar distribution was observed for fungal-feeding nematodes.

The other trophic groups presented slightly different distributions: plant-feeders had more than 50% of their total number in aggregates >200 µm. Predators were essentially localized in inter-aggregate pores. The density of bacterial-feeding nematodes was 17 times higher in the outer part of soil aggregates (e.g. in inter-aggregate pores and in fresh organic matter per g dry soil) than in the inner part.

In a sandy soil (17% clay) nematode activity (at a density of about 10 bacterivorous Cephalobidae per gram of dry soil during 21 days) led to modifications of the structure of the microbial community of the outer part of the soil (macroporosity) whereas changes were not significant at the scale of the total soil. Nematodes mainly and directly affected bacteria present in their influence area. In a clayey soil, the proportion of bacteria physically protected from nematodes is higher than in a sandy soil; so the influence of these organisms on the whole microbial community might be lower than in sandy soil.

Distribution of microbial community within soil aggregates

The distribution of the microbial community within soil aggregates has been investigated in different fallow situations in order to test the impact i) of soil structure on microbial abundance and diversity, and ii) of fallow management. Theses studies have been carried out in a Lixisol (Senegal) (Chotte & Jocteur-Monrozier, 1999; Chotte et al., 2002). These investigations indicated that long-term fallow (19 y) under Pennisetum was found to stimulate aggregation, while all clay particles were easily dispersed from the 3 y fallow soil. Hot spots of potential N2 fixation (Acetylene Reduction Activity, ARA) were observed in coarse soil fractions (>50 µm), suggesting that these microhabitats were favourable to active N2 fixers. In contrast, more than 70% of the N2 fixing microorganisms and 90% of the recovered Azospirillum were isolated from the dispersible clay fraction (0-2 µm). The reduction of the fallow period was responsible for the decrease of the amount of nitrogen potentially fixed by free-living bacteria. This was not due to the diminution of their abundance but to fact that environmental conditions favourable to their activity are not at their best in young fallow soil (lack of macro aggregates >2,000 µm). Diversity of Azospirillum species was assessed by hybridization with specific genetic probes on colonies within each fraction. This approach revealed the abundance of *A. irakense* in the 3 y fallow soil fractions only and a selective effect of fallow on *A. brasilense*/*A. amazonense* genomic species in the 19 y fallow soil. Similar works compared the distribution of cellulolytic bacteria. These bacteria, mostly represented by nonfilamentous cells, were mainly located within the organic residues (24% of the total number) and the silt-size aggregates (2-50 µm) (58%).

These studies clearly reveal that the changes of microbial communities as a result of modifications of land uses would have remain hidden if the investigation had been restricted to the non-fractionated soil. Current studies indicate that land management could have a deep impact of the functional diversity (denitrifier community) depending on the location in the different aggregate size fractions (Assigbetsé, personal com.). Further studies are needed to measure the consequence of the modifications in term of N20 fluxes, and the processes responsible for them.

Nitrogen mineralization in tropical sandy soils

In sandy soils, the evolution of mineral N during wet season can be divided into two main phases. The first phase is characterised by a significant net mineralization called nitrogen flush (on average 58 $kg.ha^{-1}$ on 1 m in Centre of Senegal); during this period (about 20 days) the net nitrification is also significant and it favours N losses by leaching originally largely of the acidification[4]. The second phase is characterised by a net mineralization and a very low to non-existent nitrifying activity (Blondel, 1971a, b, c). During this phase, the plant modifies the equilibrium by increasing mineralization when the mineral N contents of soil are low and promoting immobilization when these contents are high (Blondel, 1971d; Reydellet et al., 1997). The microbial biomass (BM-C) expressed as a percent of total soil organic C was higher than in temperate soil. The BM-C increased during rainy season. This might be a key factor in nitrogen flush at onset of rainy season in dry tropical areas, which is essential for installation of crop (Niane-Badiane et al., 1999).

Like for temperate agrosystems, plant N nutrition relies on soil organic stock, since most of N taken up by plants derives from N organic stock, even in fertilized plots (Niane-Badiane et al., 1999). Therefore, several studies have been targeted toward the manipulation of inorganic N fluxes through the management of organic resources at the field scale. The dynamics and the extent to which organic components decompose depend on soil characteristics and substrate quality. Quality of organic residues can be assessed by C to N ratio (Giller & Cadisch 1997), N content (Vigil & Kissel 1991), soluble-C content (Reinersten et al. 1984), lignin content (Berg 1986), lignin-to-N (Vigil & Kissel 1991), polyphenol-to-N (Palm and Sanchez 1991), and (polyphenol plus lignin)-to-N (Constantinides & Fownes 1994) ratios. Several studies have been carried out in semi-arid zones of West Africa (Senegal, Burkina Faso) to determine the impact of various litters on mineralization processes. Soil nitrogen mineralization patterns were investigated under field conditions in the presence of five leaf litters of different qualities, Faidherbia albida A. Chev., *Azadirachta indica* A. Juss., *Andropogon gayanus.*

Kunth., *Casuarina equisetifolia* forsk., and Eragrostis tremula Steud (Diallo et al., 2005). Any relationship could be drawn between litter quality (N content, cellulose, hemicellulose, lignin) and N mineralization during a mid-term field experimentation (12 months). In the presence of these litters, the concentration of inorganic N was higher than that in the control plot (without litter amendment). When comparing the inorganic N pattern in C. equisetifolia and F. albida amended soils, a higher inorganic N was measured in soil amended with C. equisetifolia despite the fact that F. albida had the lowest C to N ratio (21.4). The processes were then investigated during a 60 days laboratory incubation to compare the effect of Andropogon gayanus, Casuarina equisetifolia, Faidherbia albida on C and N dynamics in the presence or not of a source of inorganic N (Sall et al., 2003). The results indicated that during the first stage of incubation, CO2-C evolved was significantly correlated with the soluble C content of the litter. The pattern of soil inorganic N varied according to the litter quality. However, a similar immobilisation was obtained in soil amended with Andropogon gayanus and Casuarina equisetifolia, despite the fact that these materials have very different C:N ratios (51, and 35, respectively). The abundance of polyphenols in the Casuarina equisetifolia litter may explain this result. In fact, several studies have mentioned the negative effect of polyphenols on N mineralization processes (Palm and Sanchez 1991). The addition of inorganic N modified the patterns of CO2-C respiration and net N immobilization. The magnitude of these modifications varied according to the litter quality.

These studies indicated that the management of organic resources could be view as a means to modify N fluxes (and CO2) in sandy soils. However the definition of an accurate indicator to predict the decomposition of organic residues can not be based on a single parameter. It should take into account several litter characteristics (e.g. ratio of soluble C to phenol content, etc.). Moreover, the impact of the characteristics of the organic constituents on the gross CO2-C and inorganic N fluxes and on the diversity and function of soil microorganisms must be addressed.

Conclusion

Productivity of ecosystems characterized by sandy soils is generally low because of erratic rainfall pattern and soil texture; this results in a poor nutrient availability and unstable structure (Pieri, 1992). Studies on soil fertility, SOM dynamics and soil biofunctioning in sandy soils of West Africa, as presented above, emphasized the importance of coarse plant debris and soil biota in controlling most of physical, chemical and biological soil properties. The essential of the beneficial effect of organic management of soil fertility by fallows and manures is based on mineralization processes rather than on humification ones; this means that SOM content is a questionable indicator of the fertility of sandy soils and of the sustainability of agrosystems (Feller, 1995b). The response of biota to sandy soil constraints is a control of soil stability and porosity (perennial rooting systems, fauna, micro-organisms), a conservative management of inputs protected either in root biomass or in stable organic compounds (Menaut et al., 1985; Izac & Swift, 1994; Chotte et al., 1995; Giller et al., 1997). In sandy soils, biological mechanisms play a crucial role on processes driving plant nutrition. This has three implications:

- A particular attention should be given to SOM and biological processes. Studies confirm that in sandy soils, the coarse organic fraction (>50 µm) is the main relevant one (Feller et al., 2001).
- Soil biological components should be characterized and root component should be included in SOM total.
- Sandy soils should be seen as living and dynamic milieux.

As a consequence, SOC losses linked to biological activities (fauna and microorganisms) is the price to pay to maintain suitable soil organization and functioning (Perry et al., 1989; Manlay et al., 2002c).

As a consequence, cropping alternatives should take into account the traditional functions of fallows, i.e., biomass production and increase in biological diversity and activity (Feller et al., 1990; Pate, 1997; Manlay et al., 2000).

From a C sequestration point of view, although sandy soils have a poor potential of C storage, it seems possible to double C stocks in cropping systems through the integration of a tree component in culture and to use mineral fertilizers in order to stabilize SOM (Woomer et al., 1998). It seems also necessary to provide more important incomes to populations through intensified agrosystems; this would limit the need for other soils whose C storage potential is more important (more clayey soils, more humid zones). In West African savannas, as long term fallows are hard to achieve and as crop residues are often exported (fuel, building materials, cattle food), solutions could be rotations of crops with strong rooting systems, improved short-term fallows or agroforestry systems. Other practices such as hay-making, cover crops, slash-and-mulch, compost, no-till or integration of livestock could also be successful to increase or maintain C stocks and to make systems sustainable (Vierich & Stoop, 1990; Manlay et al., 2002c). Also, to increase SOC stocks, one can either increase C inputs or decrease SOM biodegradation processes. The first method consists in providing prehumified OM (composted manures), or to manage the quantity and quality of residues. The second method is to protect the soil with cover plants. The quality of SOM in an essential determinant of C storage (Feller & Ganry, 1982).

To limit fertility deterioration by acidification and allelopathy, appropriate cultural practices must be applied: varieties and agricultural profile (dense and deeply penetrating root system must be improved), crop rotation (monoculture is a poor practice; it neither improves the SOM balance nor sustains crop yield) and sowing date (early sowing date in semi-arid zone), and organic material applied (manure or compost, root residues possess the desirable quality).

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On-farm assessment of long term effects of organic matter management on soil characteristics of paddy fields threatened by salinity in Northeast Thailand

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Keywords: Organic matter management, paddy, fertilizer, farmer management

Abstract

In Southeast Asia, the long-term effects of organic matter management (OMM) on the soil's attributes have seldom been studied in on-farm situations. Most studies are carried out in experimental plots where, except for OMM, all practices are kept similar. Therefore, their results need to be validated in the various crop management, soil and climatic conditions prevailing in the region. This paper develops an on-farm approach to diagnose some impacts of farmers' OMM practiced during the last five years at least, in Northeastern Thailand. Surveys and field measurements were carried out on a network of 53 rainfed paddy fields belonging to 50 farmers. The network was designed to be representative of three OMM (straw burned; straw buried; and straw buried + animal manure) whose effects on soil characteristics can be more or less variable depending on the interactions between two rice establishment methods, (transplanting and broadcasting), various levels of N fertilizer (N<20 kg ha^{-1} and 20<N<100 kg ha^{-1}) and two topographic positions of the fields (170 m<altitude<190 m and 190 m<alt<210 m). Whatever the method of sowing, the level of N fertilization and the field's elevation, straw incorporation was not associated with higher soil organic carbon, pH, exchangeable cations, or with lower bulk density or electrical conductivity (EC) as compared with straw burning. Applications of animal manure were usually less than 1 t ha^{-1} and had no significant effect on these soil parameters. So far, there is little evidence that the various OMM currently practiced by farmers of this region will make any difference regarding the soil fertility evolution.

Keywords: Organic matter management (OMM); On-farm research; interactions; total C; salinity; sandy soils

Introduction

The possibility of rapidly forecasting long-term effects of cropping systems on soil fertility is one of the main concerns of sustainable agriculture (Hansen, 1996). In the rainfed paddy systems of Northeastern Thailand, this question is very important since many farmers, in order to reduce the cost of land preparation, burn the rice straw remaining on the fields after harvest. Conversely, others go to much trouble to incorporate it, or even to add animal compost, being convinced that these practices will improve the fertility and prevent salinization of the soil (Grunberger, and Hartmann, 2004). A decrease in organic matter content of soils in the longterm could be very harmful since many farmers of this region are too poor to invest in mineral fertilizers. Hence, they often rely on the indigenous soil N supply to satisfy most of the rice crop's demand (Olk et al., 2000; Powlson and Olk, 2000).

One of the difficulties of the assessment of these OMM in Northeast Thailand is the need to take into account the interactions of various cropping practices existing over the region (Olk et al., 2000; Powlson and Olk, 2000). Indeed, due to the higher yields associated with the transplanting method of establishing rice compared to direct seeding (Pandey et al., 2002), a higher input of carbon to soils via the residues can be expected. Therefore, effects of burning the straw on soil carbon evolution might be greater in fields where transplanting is practiced than in direct-seeded fields. Likewise, the use of inorganic fertilizer could interact with OMM effects, not only via the increase of residue inputs to soils but also through the rate of carbon mineralization (Whitbread et al., 2003, Shirato et al., 2005). As different fields elevation could be associated with varied water dynamics and salinity levels (Arunin,

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1984, Bolomey 2002, Grunberger and Hartmann, 2004), the effects of this factor on inputs of carbon as well as loss of carbon by erosion and mineralization could also be expected. Considering all these interactions, and the lack of a carbon turnover model validated for these tropical cropping systems (Parton and Stanford, 1989), the assessment of OMM over the region could be investigated using an on-farm approach rather than by a long term “in station” experiment. This on-farm approach, based on comparison of fertility criteria over a network of farmers’ fields, requires that the current cropping systems have been practiced for at least five years, so that differences in the soil fertility components can be attributed to differences in the current cropping systems (Hasewaga et al., 2005). With such a network of fields, derivation of the parameters of a generic model of organic matter evolution could be carried out. However, as many fields have to be explored, basic or summary models using few parameters could be more successful than complex models.

Few data are available on the long-term effects of the OMM practiced by the farmers in Northeast Thailand. Experimental data sets exist for the cassava system developed in the uplands of the region, but not for the paddy system (Shirato et al., 2005). Tangtrakarnpong and Vityakon (2002), regarding the paddy system as relatively homogenous in comparison with other land use types existing in the region (forests, cassava, sugarcane), showed that carbon pools (labile and stable) of the paddy system ranked second behind forest systems, as total soil organic matter decreased from 5.5 in the forest to 4.2 g kg^{-1} in the paddy system, and microbial biomass, which corresponds to the pools of higher turnover rate, decreased from 116 in the forest to 78 mg kg^{-1} in the paddy system. Whitbread et al. (2003) examined the effects of the removal or otherwise of straw, and of leaf litter application on soil carbon in experimental plots. However, because it was mainly focused on the testing of new organic matter management, this study did not consider the possible interactions of the various current cropping practices and topography of fields at the level of the region. Moreover, the burning of straw was not assessed. Other studies pointed out the possible positive effect of organic matter on soil pH, due to increase of Fe reduction in the flooded soils (Maegth, 2003; Quantin et al., submitted). In accordance with this hypothesis, Enet (2003), by comparing two fields annually receiving (or not) animal compost amendments, showed positive effects of organic matter application on soil pH, measured during the cropping period. It was however likely that this effect of organic matter could be a short term effect, not noticeable during the following dry period.

The purpose of this paper was to assess briefly, using surveys and observations over a network of farmers’ fields, long-term effects on soil carbon, nutrient content, soil pH, salinity and bulk density of various OMM strategies encountered in the paddy systems of Northeast Thailand. Comparison of annual inputs of carbon as crop residues and manure with the measured post-harvest carbon content of soils was used to formulate hypotheses for the carbon dynamics of these sandy soils threatened by salinity.

Materials and Methods

Study area

The study was carried out during the dry season of December to April 2005 in Khon Kaen Province (16ºN 102ºE) in the Northeast of Thailand. The study area was chosen as representative of the natural conditions of the region. The landscape is a gently undulating plateau containing the villages of Ban Daeng, Ban Non Bo, Ban Kraduang and Ban Non Khlong (Figure 1). The soils are classified according to the USDA Soil Taxonomy mostly as Paleaquults, and sometimes Paleustult in the central area (Craig and Pisone, 1988). They are sandy loams with a low clay fraction, mostly kaolinitic, and a low pH due to considerable leaching. Because of the presence of shallow, saline groundwater, some parts of the area can have an electrical conductivity of the saturated extract in the soil surface as high as 7 mS cm^{-1}. The mean annual rainfall in this region in the 1990s was around 1,000 mm, with 90% of this falling between May and the end of October. Daily mean temperatures vary from 20 to 28ºC during the year. Temperature and rainfall recorded at the experimental site of IRD at Ban Daeng during the 2004 cropping season are representative of the region’s annual mean (Figure 2).

A preliminary study in this region showed that the farmers mainly grow rice. The rice is transplanted once a year during the rainy season, with nothing grown in the dry season. The soil preparation, consist of two plowings to 15 cm depth using a powered cultivator. The rice is either transplanted as month-old seedlings or directly sown by broadcasting just before the second plow. Direct seeding is not associated with the adoption of zero tillage in this region, probably because herbicides are not used. It is likely that the main difference between soil preparation for direct seeding and transplanting is the soil moisture during the second plow. In case of transplanting, soil moisture

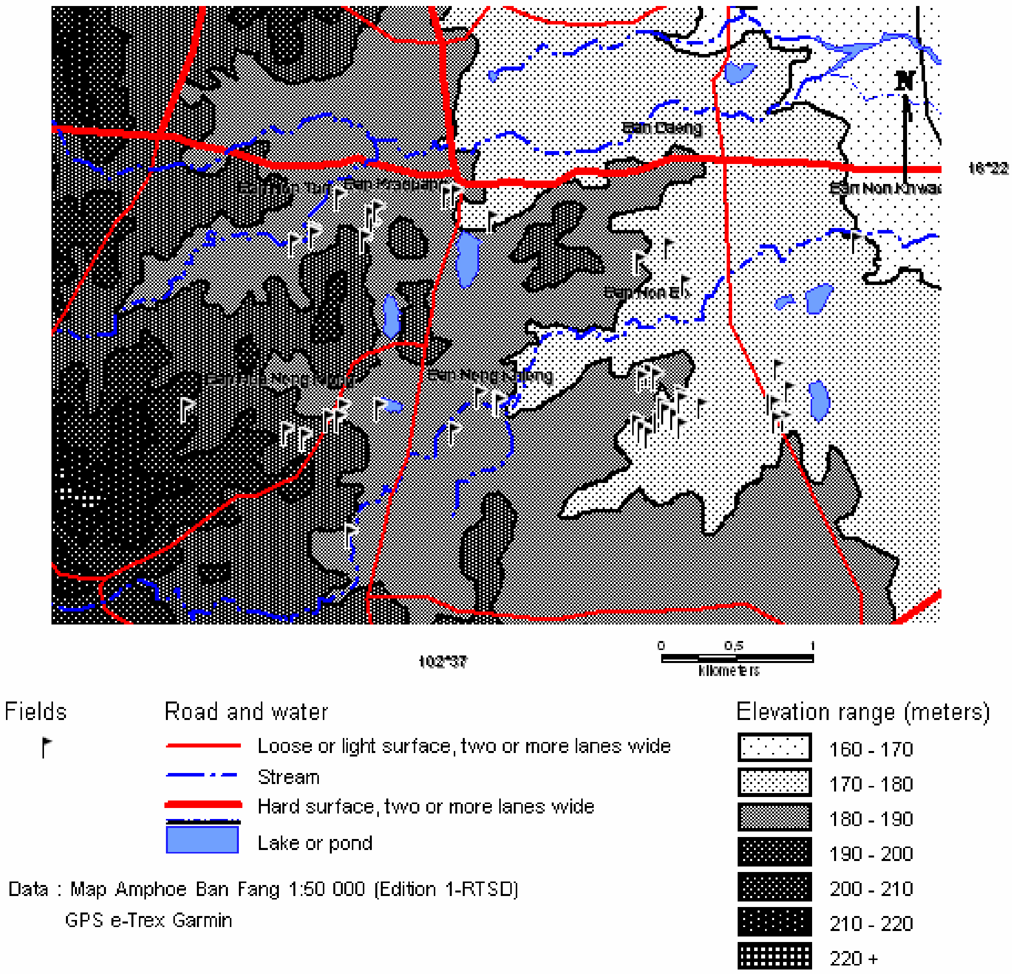

Figure 1. Map of the study area. Localisation of the paddy fields selected

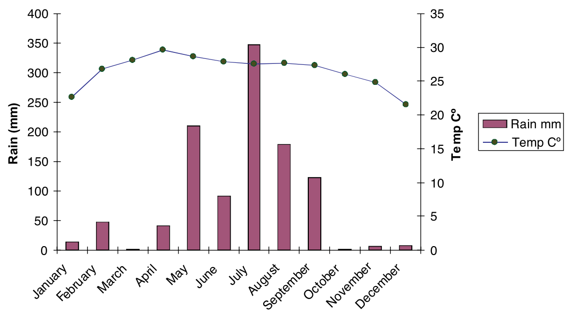

Figure 2. Monthly rainfall (bars) and average daily temperature (°) recorded in IRD site in Ban Daeng in 2004

should be very high so that the soil structure will look like a uniform mud after plowing. The most common rice variety (RD6) is glutinous, photoperiodic sensitive with a flowering period in mid-October and harvest in November. The sowing date depends on the rainfall and on the method of planting. Whereas transplanting has to be done into flooded soils, direct seeding can be done at the beginning of the rainy season when the rainfall is still light. Whatever the method of sowing, the rates of chemical fertilizers used are often less than 60, 25, 25 kg ha^{-1} of N P and K, respectively. Three main methods of organic matter management can be distinguished: 1) straw burning (SB), 2) straw incorporation (SI) or 3) straw incorporation and animal compost application (SI+C) before soil preparation. Application of animal compost is generally less than 1 t ha^{-1}.Potential yields in this area, estimated at 4 t ha^{-1} (Suzuki et al., 2003), are often not reached.

Surveys

A network of 53 plots, annually cropped with rice, were selected to represent the three main OMM methods, which were factorially combined with 2 topographic positions (lowlands, corresponding to altitudes from 170 m to 190 m, and uplands – altitudes between 191 m and 210 m), two methods of sowing (transplanting and direct seeding) and two fertilizer levels (low for applications of less than 20 kg N ha^{-1}, and high for applications from 20 to 60 kg N ha^{-1}). Applications of P and K are often combined with those of N. The structure of the network is presented

Table 1. Distribution of the fields according to organic matter management and altitude. Values in parenthesis indicate percentage of those fields using transplanting method for rice cropping

	Straw burned	Straw incorporated	Straw incorporated + animal compost
Lowland *(altitude <190 m)*	15 (60%)	14 (60%)	8 (66%)
Upland *(altitude = 190-210 m)*	6 (14%)	5 (37%)	5 (40%)
Total	**21**	**19**	**13**

in Table 1. Each plot corresponded to a set of practices stable over the last five years. The soil total N, C, cations content, pH and salinity level were considered in this study as output variables whose variations within the network could be explained by the various OMM methods interacting with various cropping practices. Within each plot, the following measurements and observations were made:

1) Soil analyses at the end of February (post-harvest period). At this time, the rice straw was still standing, as only the panicles were harvested by hand. No organic matter application or straw burning had yet been done. This period is probably the most appropriate to bring out long term effects of practices, as the short term effects of the crop management interventions are the least likely. Soil samples were made up of 5 cores collected from the 0-15 cm layer. Total organic carbon (C) was determined by the wet digestion method of Walkley and Black. Total N was determined by the Kjeldahl method. pH was determined in distilled water using 1:1 soil:solution ratio. Cation exchange capacity (CEC) was determined after a first exchange with 1M ammonium acetate at pH = 7, and a second exchange with 1 M NH_4Cl. Exchangeable (exch) Ca, Mg and K extracted with 1 M ammonium acetate at pH7 were determined by atomic absorption spectrophotometry and flame photometry. Available P was analysed using the Bray P nº2 method. Electrical conductivity (EC) was measured using a 1/5 soil water ratio.
2) Measurements of the amount of rice straw remaining on the fields after harvest (three replicates of 4 m^2).
3) Measurements of the amount of animal compost spread on the plots during the dry season, and records of farmers’ estimates of the amount spread during the last five years
4) Bulk density of the 0-15 cm ploughed soil layer (three replications using a 100 cm^3 cylinder).

Data Analysis

Effects of position of the field in the landscape, OMM, method of sowing and N fertilizer level on soil contents of C, exchangeable cations and on soil pH, EC and bulk density were analysed by four-way analysis of variance using the GLM procedure and type III sum of squares of SAS 9.1 (2003). Interactions between cropping practices were also analysed statistically. The Student-Newman-Keuls test was used to compare the average values of the recorded variables.

The mineralization rate of the organic matter (K2), which is supposed to be very variable according to soil and climatic conditions and cropping systems (Mary and Guerif, 1994; Olk et al., 2000), was deduced according to the basic equation of Jenny (1941), which considers the soil carbon content as homogenous as regards its decomposition rate:

$$C_1 = C_0\, e^{-K2t} + m\, c_r\, K1(1 - e^{-K2t}) / K2$$

Assuming the soil carbon content was at equilibrium:

$$K\,2 = m\, c_r\, K1 / C_1$$

where m is the amount of annual organic dry matter supplied (mainly as straw residues), c_r the carbon content of the residues, and K1 the iso-humic coefficient which generally varies according to the composition of the amendment (Mary and Guerif, 1994). C_0 is the soil C content in the first year of the OMM application. C_1 is the total C content given by the soil analysis at the end of February 2004. As it has to be expressed in t ha^{-1} rather than mass (kg kg^{-1}), the data recorded for soil bulk density are used. The annual C supplied by straw residue humification ($m^* c_r {}^*K1$) was calculated assuming values of 15% for water content. K1 of rice straw was fixed at 0.15 (Mary and Guerif, 1994), and carbon content of the humus at 50%. According to the observation that the most lignin rich parts of the residues are not affected by the burning, this practice was assumed to reduce the annual C input of straw by only 50%. A specific contribution of the rice roots to the total input of carbon to soils was ignored. Carbon supplied by the compost was considered as negligible, as the fresh weights of these amendments were less than 1 t ha^{-1}.

Results

Relationships between different soil criteria

The mean values and standard deviations of each of the studied variables and their mutual correlations are presented in Table 2. Carbon content was significantly positively correlated with soil CEC. As well as CEC, carbon content was significant correlated with exch. K, Ca, and Mg. Total C and N were highly correlated, with a C/N ratio of 11 that was quite stable among fields (not shown). No significant correlations between carbon content and pH, bulk density or EC were found. EC was significantly correlated with Na and Mg.

Changes in soil characteristics according to practices

Whereas altitude had a highly significant effect on soil exch. K and Na, EC and pH, OMM had no significant long-term effect on any of the measured variables. Significant effects of method of sowing appeared on available P and bulk density. Available P was lower in direct sowing as opposed to transplanting. Exch. K and bulk density were lower and soil pH higher in fertilized than in unfertilized fields (Table 3).

Calculation of K2 assuming organic matter equilibrium

The dry weight of the straw incorporated in the SI and SI + C fields varied from 2 to 7 t ha^{-1}. This variation is significantly associated with the method of sowing, but not to the elevation of the fields or to the use of fertilizer (not shown). The dry weight of residues in the direct-seeded fields was 0.70 t ha^{-1} less than in the transplanted ones. The mean value of K2 allowing equality between annual incoming carbon and mineralized carbon was 3% in the SI fields. The same value might not apply to the SB fields under the equilibrium hypothesis: if it is assumed that about 50% of the carbon of the straw is lost due to burning, the mean K2 value of these situations should not be more than 2% (Figure 3).

Discussion

This on-farm survey was conducted to compare long-term effects of the various OMM of paddy fields existing in a region. These OMM are developed on sandy soils with a very low carbon content of 0.5% on average (Table 2). The C/N ratio of 11 suggests that the organic matter mineralizes readily in all these situations. About 20% of the CEC is due to the humus. Exch. K and Ca were very low, consistent with the low CEC. EC values were, at the time of the study, mostly below the level considered to pose a salinity problem for rice production (Dobermann and Fairhurst, 2000); however, these EC are significantly correlated with the Na content of the soils, revealing that they are due to the upward movement of saline groundwater. Due to the effects of farmers’ practices, variations in soil bulk density and pH were not significantly related to EC levels.

This study revealed that the observed differences in OMM did not result in differences in the soil C content, nor in pH, EC, exch. cations or bulk density. This non-significant effect on total C is consistent with results of Whitbread et al. (2003) who

Table 2. Average values, standard deviations of measured variables and correlations between them. Bold values mean that the correlation is significant at the 0,05 probability level

	Mean	Root MSE	CEC CEC *(cmol kg^{-1})*	Total Carbon *(%)*	Exch K *(cmol kg^{-1})*	Exch Ca *(cmol kg^{-1})*	Exch Mg *(cmol kg^{-1})*	Exch Na *(cmol kg^{-1})*	EC *(µS/cm)*	pH H_2O	Bulk density *(kg dcm^3)*	P (Bray 2) *(mg P kg sol^{-1})*
CEC *(cmol kg^{-1})*	4.067	2.009	–	0.61	0.44	0.81	0.67	0.05	0.12	0.02	0.07	0.14
Total Carbon (%)	0.47	0.12		–	0.48	0.68	0.45	0.07	0.00	0.14	-0.20	0.05
Exch K *(cmol kg^{-1})*	0.092	0.091			–	0.40	0.29	0.01	0.12	0.04	0.16	0.10
Exch Ca *(cmol kg^{-1})*	1.522	1.535				–	0.87	0.06	0.16	0.21	0.11	0.06
Exch Mg *(cmol kg^{-1})*	0.343	0.326					–	0.31	0.32	0.14	0.06	0.01
Exch Na *(cmol kg^{-1})*	1.341	1.414						–	0.66	0.17	0.06	0.04
EC 1:5 *(µS/cm)*	290	278							–	0.04	0.00	0.19
pH H_2O	5.770	0.835								–	0.12	0.01
Bulk density *(kg dcm^3)*	1.557	0.065									–	0.07
P (Bray 2) *(mg P kg sol^{-1})*	7.930	10.515									–	

Table 3. Soil chemical properties of 52 rainfed paddy fields of Khon Kaen as affected by altitude, organic matter management, crop establishment method and N fertilizer level

Factor	n	Organic C (g 100 g^{-1})	K (cmol kg^{-1})	Ca (cmol kg^{-1})	Mg (cmol kg^{-1})	Na (cmol kg^{-1})	Bray-2 P (mg kg^{-1})	pH	EC 1:5 (µs/cm)	Bulk density (kg dcm^{3})
Elevation										
Lowland (<190 m)	37	0.46	0.10 **a**	1.59	0.38	1.69 **a**	9.76	5.59 **b**	374 **a**	1.57
Upland (<=190 m)	16	0.48	0.06 **b**	1.36	0.25	0.53 **b**	3.68	6.18 **a**	96 **b**	1.53
Organic management										
Straw burned	21	0.46	0.09	1.77	0.41	1.36	7.43	5.82	283	1.56
Straw incorporated	19	0.49	0.10	1.47	0.32	1.66	8.79	5.90	364	1.55
Straw incorporated + OM	13	0.44	0.06	1.19	0.26	0.84	7.25	5.48	194	1.56
Crop establishment method										
Transplanting	31	0.49	0.09	1.67	1.37	1.59	10.71**a**	5.70	379	1.55 **b**
Direct seeding	22	0.44	0.08	1.31	1.29	0.98	4.01**b**	5.86	165	1.57 **a**
N fertilizer level										
Low (<20 kg ha^{-1})	26	0.47	0.10 **a**	1.49	0.31	0.98	7.83	5.66**b**	212	1.58 **a**
High (<=20 kg ha^{-1})	27	0.46	0.08 **b**	1.55	0.37	1.68	8.02	5.87**a**	365	1.53 **b**
Mean square										
Elevation	1[a]	0.00	0.03*	0.13	0.08	7.70*	294.53	6.59**	397,222 *	0.00
Organic management	2[a]	0.01	0.00	1.39	0.09	1.29	20.29	0.51	36,801	0.00
Establishment method	1[a]	0.09	0.00	1.39	0.04	0.65	403.9*	0.04	209,736	0.01*
N fertilizer	1[a]	0.00	0.03*	0.05	0.00	0.03	103.0	3.04*	63	0.03**

Asterisks (*, **, ***) mean significant at the 0.05, 0.01 and 0.001 probability level respectively. Numerals with different letters are significantly different at the 0.05 probability level using the Student-Newman-Keuls Test of SAS.

[a] Degrees of freedom (d.f).

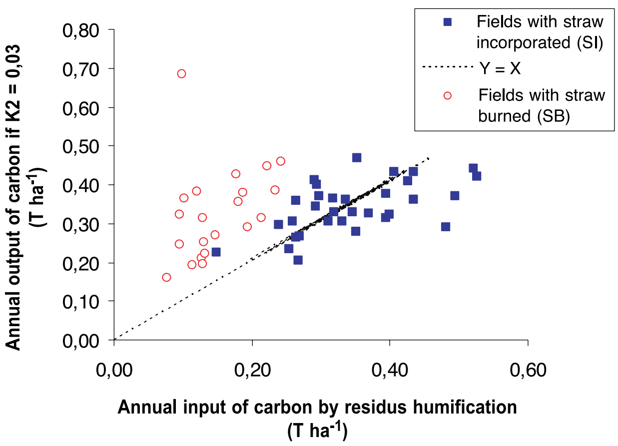

Figure 3. Values of annual output of carbon assuming mineralization rate of K2 = 3% for total soil C content

compared the removal and non-removal of rice straw during a six-year experiment. Unless the rice straw was returned in combination with the application of at least 50-14-14 kg N-P-K ha^{-1}, they did not find any significant difference in total C of soils among the treatments. Non-significant effects of the various OMM on exch. K and available P are in accord with the fact that most of the K and P contained in the fresh straw is still present in the ash. The non-significant effect of OMM on soil pH agrees the non-significant effect of OMM on the soil carbon content and the soil redox status, as the process of increasing pH found by Quantin et al., (submitted) and Maeght, (2003), was related to the increase of soil carbon content and the reducing conditions of flooded soils.

Comparison of the carbon inputs with the calculated outputs using the basic equation of Jenny (1941) at equilibrium (Figure 3), suggested that the non-significant effect of burning straw is due to a very low mineralization rate (K2) of the organic matter remaining in the soil after burning. Hence, the quality of this organic matter could be different from that of fields where the straw is incorporated every year. The average K2 of 3% is deduced for these situations, whereas the highest values mentioned in the literature for sandy soils in temperate zones reach 2% (Boiffin et al., 1986). Using the Jenny equation, this K2 value refers to the total organic matter content of the soils, with no distinction between more or less recalcitrant, or old or fresh organic materials. Therefore, it is certainly much lower than the mineralization rate that would be expected in such a tropical area for the incoming residues only (Shirato et al., 2005). It’s clear that it would have been more accurate to distinguish two different pools in the total C amount: labile carbon, and less quickly mineralized carbon. The pool of labile carbon could be approached either by the microbial biomass (Alvarez et al., 1998), or following Blair et al.

(1995), by the KMnO4 extractable C fraction. Although Jenny’s very basic model of carbon turnover is not the appropriate tool to accurately predict the qualitative evolution of organic status of soils, it had for this study the advantage of referring to an easily measurable carbon pool and to allow preliminary comparisons between different cropping practices.

The variation in exch. Na, EC and pH over the network of farmers’ fields were mainly related to the position of the fields in the landscape. The higher values recorded for these variables in the lower lands were due to the proximity of the saline water table. The non-significant effect of topographic position on soil C content could mean that carbon movement by erosion is negligible. The effect of the method of sowing on available P (Table 3) could be due to a higher uptake of P by the recently harvested rice in the direct seeding method, whereas with transplanting most of the P would be fixed by the ferrous iron concentrated in the submerged soils during the cropping period. The lower soil bulk density in transplanted fields with fertilizer application could be due to the higher root volume developed by the recently harvested rice, or perhaps to a higher level of labile carbon in these soils. The lower exch. K in fertilized plots (Table 3) suggests that greater uptake of the initial soil K was possible by the rice crop. The higher pH recorded in fields receiving the higher fertilizer should be confirmed as acidification effect of urea application is more often observed.

Conclusion

Using a survey approach over a network of fields, it has been possible, within a short time, to examine some long-term effects of practices developed in paddy fields of Northeastern Thailand. More detailed data are in many cases still needed to draw definite conclusions. Future research should include assessment of labile carbon, as a more sensitive and early indicator of a change in the organic status of soils. Input of carbon by the roots, and leaching by drainage should be assessed for more accurate estimation of carbon budgets. Loss of carbon by the light burning practiced by the farmers should be measured. Estimation of nutrient uptake and root density of the rice with the various practices would allow our hypothesis to be used to explain variation in P and K availability and bulk density over the network. Besides the effects of farmers’ practices on the soil chemical and physical attributes, changes in incidence of weeds, diseases and insects on the rice crop should be studied. The present preliminary results call into question farmers’ assertions about the decrease in the extent of saline patches in their fields over time due to straw incorporation. Although the practice of burning straw should be avoided owing to air pollution, as regards soil fertility it does not seem to differ from the incorporation of straw. Therefore, positive short-term effects of straw incorporation on rice grain yield need to be large enough to persuade the farmer to accept its higher cost compared with burning.

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Nitrogen mineralization capacity of coastal sandy soils of the Thua Thien Hue Province, Central Vietnam

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Keywords: sandy soils, Central Vietnam, nitrogen mineralization, cropping pattern

Abstract

Coastal sandy soils of Thua Thien Hue Province in Central Vietnam represent an important soil order that increasingly contributes to regional economic growth. However these soils have generally low productivity because of chemical and physical constraints associated with low pH values and coarse texture; sand contents exceeding 70%, are common for those soils. Obviously, organic matter management represents a key factor for crop productivity improvement on these soils. However, before considering the possible contributions of various organic amendments, it is important to evaluate the actual contribution of the initial soil organic matter, through its N-mineralization, considered as a prime source of N for plants. Therefore, 14 soil samples (0-20 cm) representing different cropping patterns on coastal sandy soils were collected before the spring season to determine their N-mineralization capacity. After air drying and grinding to pass 2 mm sieve, the samples were incubated under waterlogged conditions for 7, 14, 28, and 42 days; in addition, these soil samples were analysed for chemical and physical characteristics. Because of significant differences between major physical and chemical characteristics, the soils were grouped in two classes: soils under rice cultivation and soils with other crops. The rice soils had, on average, lower sand content, higher clay content, higher organic carbon content, higher cation exchange capacity and lower pH_{water}*. The release of* NH_4^+ *was, on average, higher in rice soils, but no statistically significant differences were found between the two groups of soils. Fitting the results with a first order kinetic equation led to the calculation of potentially mineralizable nitrogen. As expected, the values were much smaller than the total soil-N content, which indicates different soil-N pools. The N-pool identified in this study can be considered as very labile N which might be available to crops within few weeks. Therefore, the total N-content of soils cannot be considered as a reliable indicator of short term N-availability, though some limited correlation was observed between these characteristics.*

Introduction

Careful management of soil nitrogen (soil-N) is crucial for plant production and environmental reasons. In ecological/traditional farming systems, N deficiency is often seen in early spring, partially due to low soil temperatures which limit microbial activity, and thus mineral-N production through N-mineralization. In a variety of ecosystems, rates of N-mineralization and the total soil-N are indicators of soil fertility (Nadelhoffer *et al*., 1983; Pastor *et al.*, 1984; Vitousek and Matson, 1985). However, a large nitrification rate can reflect potential N losses, either through leaching, leading to groundwater pollution, or through gaseous emission, contributing to greenhouse effect (Likens *et al*., 1969; Vitousek and Melillo, 1979; Krause, 1982; Vitousek and Matson, 1985). One strategy to meet crop N demand in these farming systems is to maximize the stabilization of organic-N inputs to soils, and thereby, build up a soil organic matter pool, rich in organic-N. In such systems, N-mineralization from this organic pool determines the amount of available N for crops.

In conventional/modern farming systems, mineral-N fertilizers are applied in spring to meet crop N demand. However, even if mineral N-fertilizer is applied, N-mineralization from soil organic matter remains an important source for crop N-uptake. As pointed out by Macdonald *et al.* (1989), the leaching risk is mainly due to nitrate derived from soil organic matter mineralization after harvest, rather than from unused fertilizer-N applied in spring. Consequently, predicting N-mineralization from soil organic matter is important, both in ecological and in conventional

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farming systems, to meet crop N demand and to reduce nitrate leaching during autumn and winter.

In coarse sandy soils (<5% clay), mineral-N is generally low (<10 kg N ha^{-1}) with very small variations between sites (Østergaard *et al.*, 1985). Correlation between mineral-N in spring and nitrogen uptake in aerial plant parts is low, indicating that mineral-N provides little information about the mineralization potential of sandy soils.

Environmental impact of excessive fertilizer use has increased the demand for valid and accurate methods leading to optimum nitrogen supply to agricultural crops. Due to added and native soil organic matter, complex turnover processes, this optimum N-fertilizer supply, aiming to maximize profits and minimize nitrate leaching risks, represents a great challenge, both for scientists and for farmers. However, before considering the possible contribution of organic amendments, it is important to evaluate the actual contribution of the native soil organic matter, through its N-mineralization considered as a prime source of N for plant. Therefore, a study was carried out to estimate the N-mineralization capacity of coastal sandy soils in Thua Thien Hue Province, with different cropping patterns. In this province, the crop-lands cover some 84,000 ha with 66,000 ha on sandy soils.

Materials and methods

Study area, soils sampling and characterization

The research was conducted in 4 communes of the coastal area of Thua Thien Hue Province: Phong Hoa, Quang Loi, Vinh Xuan, and Vinh Phu. The sandy soils used in this study were selected from a previous survey including 300 cultivated plots. The selection aimed at gathering a collection of samples representing the main differences of soil characteristics and cropping patterns encountered in the general survey. The total number of soil samples was fixed by laboratory constraints.

Fourteen composite soil samples were collected from the top horizon (0-20 cm) of cultivated plots before spring season. The samples references as well as the land uses are presented in Table 1. The cropping patterns include the following annual rotations: two rice crops, one rice crop, one rice crop followed by another crop (cassava, peanuts, sweet potatoes) referred as cash crop, one or two cash crops. All the soil samples were air dried and ground to pass 2 mm sieve. They were analysed by standard techniques for particle size distribution (pipette method), pH in water and in 1 M KCl (1:5 soil-solution ratio), electrical conductivity (EC, 1:5 soil-water ratio), organic carbon

Table 1. Characteristics of the 14 soils used in this study. The reference codes denote the origin of the samples: PH-Phong Hoa. QL-Quang Loi. VX-Vinh Xuan. and VP-Vinh Phu. Last line of table: statistical test for significant differences between rice soils and other soils

Ref.	Annual cropping pattern	sand %	silt %	clay %	pH_{H2O}	pH_{KCl}	EC $\mu S.cm^{-1}$	OC %	N %	CEC $cmolc.kg^{-1}$
Rice soils										
VX1	Rice-cash crop	90.7	5.0	4.3	5.22	4.49	13.2	1.56	0.078	4.25
VX2	1 rice crop	83.8	8.9	7.3	4.68	4.36	179.2	1.22	0.078	3.11
VP4	1 rice crop	74.6	20.3	5.2	5.36	4.61	18.0	0.82	0.045	1.35
VP6	Rice-cash crop	91.2	5.8	3.0	5.25	4.57	10.4	1.59	0.056	2.45
QL8	2 rice crops	70.8	26.6	2.6	5.72	4.82	4.5	1.81	0.050	3.52
QL9	2 rice crops	75.4	23.2	1.4	5.57	4.64	19.2	1.87	0.053	3.52
QL10	2 rice crops	70.3	27.7	1.5	5.84	4.75	9.1	1.69	0.047	3.56
	mean	**79.5**	**16.8**	**3.6**	**5.38**	**4.61**	**36.2**	**1.51**	**0.058**	**3.11**
	SD	9.0	9.9	2.2	0.39	0.15	63.3	0.37	0.014	0.95
Soils with cash crops only										
VX3	1 cash crop	92.1	5.4	2.5	5.67	4.53	7.7	0.89	0.050	1.51
VP5	1 cash crop	94.7	5.3	0.1	6.10	4.68	2.7	0.59	0.022	1.42
QL7	1 cash crop	84.0	12.8	3.2	5.48	4.34	5.0	1.47	0.067	1.68
QL11	1 cash crop	83.8	15.2	1.5	5.51	4.30	5.0	1.05	0.039	2.05
QL12	1 cash crop	85.4	9.3	2.3	6.15	4.54	6.6	1.19	0.059	1.28
PH13	2 cash crops	83.1	16.4	0.6	6.09	4.72	3.4	1.56	0.050	1.62
PH14	1 cash crop	97.0	2.2	0.9	5.99	4.61	1.9	0.52	0.011	1.20
	mean	**88.6**	**9.5**	**1.6**	**5.86**	**4.53**	**4.6**	**1.04**	**0.043**	**1.54**
	SD	5.8	5.5	1.1	0.29	0.16	2.1	0.40	0.020	0.29
	p	**<0.05***	**NS**	**<0.05***	**<0.05***	**NS**	**NS**	**<0.05***	**NS**	**<0.01****

content (OC, Walkley and Black method), total nitrogen content (Kjeldahl method), cation exchange capacity (CEC, leaching with 1 M NH_4-acetate pH 7, desorption with 1 M KCl, and measurement of NH_4^+ by distillation).

Incubation experiments

The air-dried soils were incubated in waterlogged conditions at optimum temperature for biological activity following a technique recommended for characterizing the mineralization capacity of soil organic matter (e.g. Waring and Bremner, 1964; Keeney, 1982; Bundy and Meisinger,1994; Drinkwater et al, 1996). From each soil sample, subsamples of 5 g were transferred to screw caped test tubes, 16 mm in diameter, and 12.5 mL of deionized water were added. Closed tightly to prevent air exchange, the tubes, 3 for each sample, were then stored at constant temperature (37°C), and incubated for periods of 7, 14, 28, and 42 days. Another subsample of each soil (5 g) was used for extraction of the initial NH_4^+-N content by 2 M KCl, based on a method described by Bundy and Meisinger (1994). The same procedure of extraction was applied to the incubated samples at the end of incubation times. All incubation and extraction procedures were followed by three blanks treated exactly the same way. The NH_4^+-N concentration was determined using a micro-Kjeldahl distillation method.

Results and discussion

Soils characteristics

Selected characteristics of the 14 soils are presented in Table 1. The soils were grouped in two classes according to two main different cropping patterns: soils with at least one rice season, and soils without rice cultivation, i.e. with cash crops only. Indeed, significant differences were found between these two groups for the following major physical and chemical properties: sand and clay content, pH_{H20}, organic carbon, and CEC.

Rice soils were on average less sandy and contain more clay than the other soils. This might be due to the fact that farmers empirically chose these soils for rice cultivation because they were less permeable than the others. Organic carbon (OC), though being generally low, was higher in rice soils, which may result from their higher clay content which stabilizes humus compounds and from smaller mineralization rate in waterlogged conditions, i.e. higher humus content at steady state. The CEC values were low for all soils because of low clay and organic matter content; good correlation was observed between CEC and OC with the following equation: CEC (cmolc.kg^{-1}) = 0.05 + 1.78 OC (%); this means that the CEC of soil organic matter was some 178 cmolc.kg^{-1} OC, which stresses on the need of maintaining a high soil OC pool by careful management of organic matter in farming systems, more especially in soils with naturally low clay content. The soil pH (measured in water suspension) varied from 4.7 to 6.1, and rice soils appeared on average more acid than the others. This can result, among other reasons, from oxidation reactions when waterlogged soils are re-aerated or dried after sampling.

N-mineralization

The N-mineralization data, expressed as NH_4^+-N extracted from soils after each period of incubation, are presented in Figure 1. For all soils, NH_4^+ increased regularly from 0 to 42 days, and though starting from similar values at initial time, the rate of

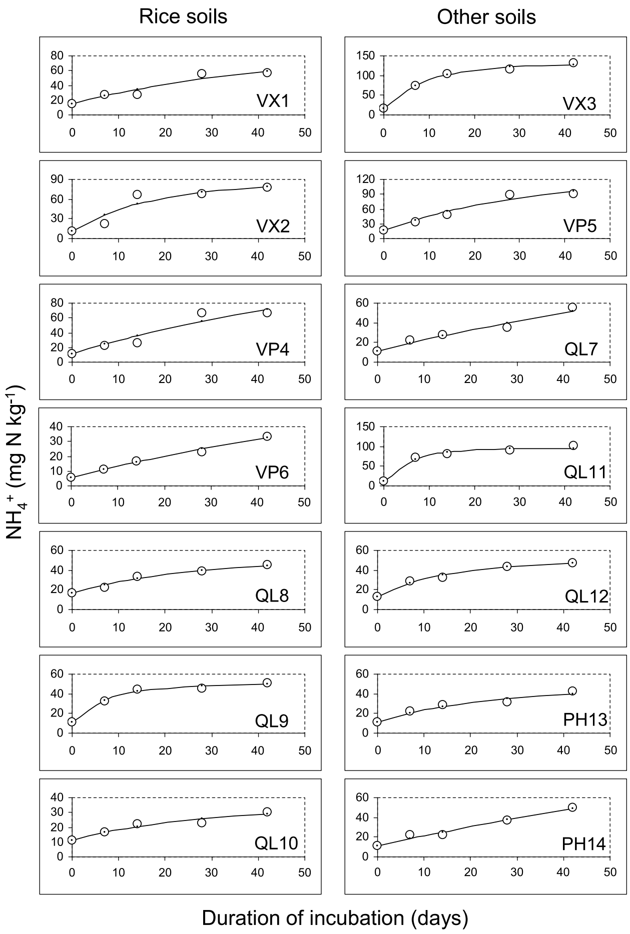

Figure 1. NH_4^+-N extracted from soils as a function of incubation time. Left: rice soils; right: other soils. Open circles: experimental values; lines: non linear regression according to first order kinetic equation for N-mineralization

N-mineralization was, on average, higher in rice soils than in the others. However, the differences between the two groups of soils were not statistically significant at the 0.05 probability level.

The shape of NH_4^+ release *vs* time curves have a typical curvilinear shape, which indicates a decreasing mineralization rate with increasing time. It can be attempted to fit such type of curves with a first order kinetic equation for N-mineralization. If N_{soil} is the soil-N pool which is susceptible to be released by mineralization at the time scale of our experiments (often called potentially mineralizable nitrogen), the variation of N_{soil} with time, t, is given by:

$$\frac{dN_{soil}}{dt} = -k\, N_{soil}$$

By integrating from time 0 to t

$$N_{soil,\,t} = N_{soil,\,0}\, e^{-k\,t}$$

If we consider that the amount of NH_4^+ released from time 0 to t is equal to the decrease of N_{soil}, then the balance equation is:

$$[NH_4^+]_t - [NH_4^+]_0 = N_{soil,\,0} - N_{soil,\,t}$$

$$[NH_4^+]_t - [NH_4^+]_0 = N_{soil,\,0}\,(1 - e^{-k\,t})$$

$N_{soil,\,0}$ and k can be calculated by non linear regression of experimental values of extracted NH_4^+ *vs* time (Figure 1). The values of $N_{soil,\,0}$ calculated from our data were in the range 22 to 132 mg $N.kg^{-1}$. The mean values of the regression parameters for the two groups of soils were: $N_{soil,\,0}$ = 63 and 50 mg $N.kg^{-1}$, and k = 0.06 and 0.04 d^{-1} for the rice soils and the other soils respectively, but these difference are not significant at the 0.05 probability level. As expected, the $N_{soil,\,0}$ values were much smaller than the total N content of soils presented in Table 1, i.e. 580 and 430 mg $N.kg^{-1}$ for the two groups of soils respectively. Indeed, the N-pool revealed after some weeks of incubation can be qualified as labile organic-N and represents only a small fraction of total N. According to different authors (e.g. Dommergues and Mangenot, 1970; Wander *et al.*, 1994), at least two other N-pools may be distinguished in soils, one pool of stable but still labile organic-N, and one pool of more stable organic-N which is involved in humification processes and only released at long term scale.

One question at the start of this study was to know whether short term N-mineralization might be related to any of the soil characteristics reported in Table 1. Correlations were calculated between these properties and NH_4^+ release at any given time. The best, though limited, correlation was found with total N content. These correlations are shown in Figure 2 with their respective r^2 values.

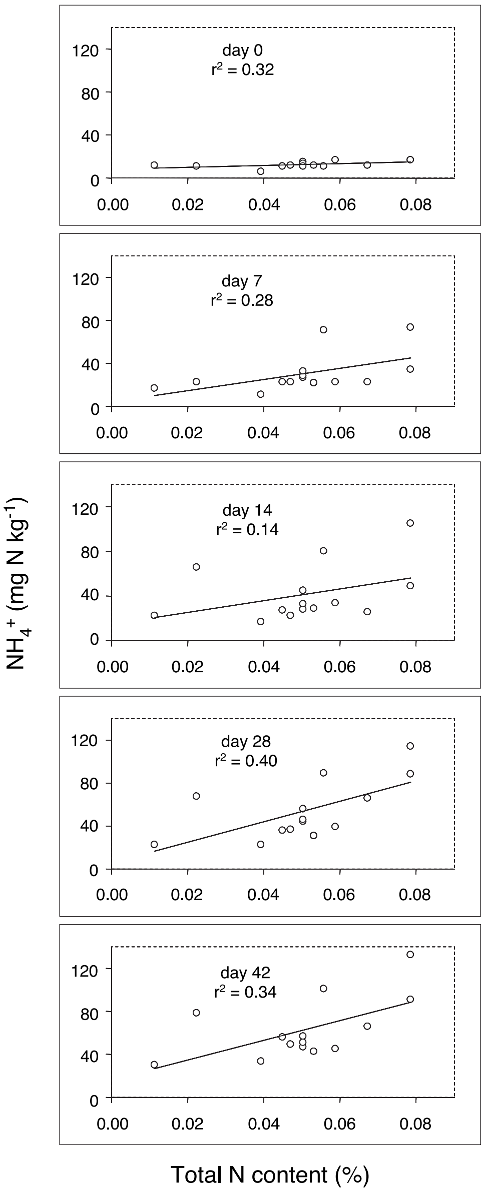

Figure 2. NH_4^+-N extracted from soils at different times of incubation as a function of total initial N content in the 14 soils

Figure 3 presents the best correlations which were found between potentially mineralizable nitrogen, $N_{soil,\,0}$, and soil characteristics (total N, C/N, pH_{water}, and clay content). Combining two soil characteristics in multiple regression analysis resulted in r^2 = 0.27 for $N_{soil,\,0}$ *vs* C&N, r^2 = 0.33 for $N_{soil,\,0}$ *vs* Clay&N, and r^2 = 0.34 for $N_{soil,\,0}$ *vs* Clay & pH. These r^2 values are not definitely greater than what was obtained with simple regressions, indicating autocorrelation between variables.

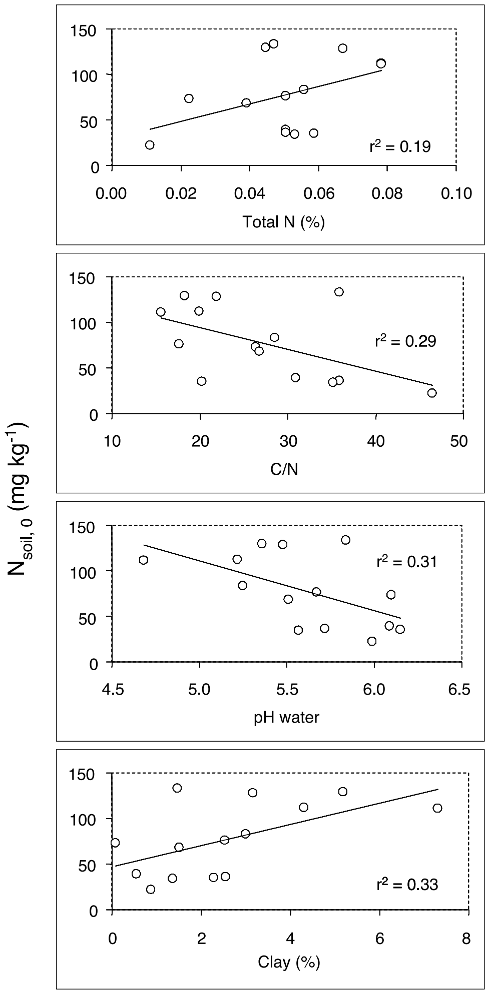

Figure 3. Correlations between potentially mineralizable nitrogen according to first order kinetic model, $N_{soil,\,0}$, and soils characteristics

Conclusion

Through a short period of experimental observations, the sandy soils of the coastal area of Central Vietnam have been investigated for their N-fertility potential, generated by various soil characteristics and cropping patterns. The experimental approach focused on the initial soil organic matter contribution to the production of mineral-N, considered as a prime source of available N for plants.

Based on significant differences between major physical and chemical properties, two groups of soils were distinguished: soils with rice cultivation and soils with cash crops only. Mineralizable-N was usually higher for rice soils which had higher mean OC content, but the differences between the two groups of soils were not statistically different. More samples might be necessary to ascertain such conclusion.

According to a first order kinetic equation, the soil N-pool participating in short term N-mineralization was much smaller than the total N content, which supports the general view of different soil N-pools with different potential availability to plants. Consequently, even if some correlation was observed between NH_4^+ release and total N content, this routine characteristic of soils cannot be considered as a reliable indicator of N-availability for crops cultivated in the coastal sandy area of Central Vietnam. This justifies further study to better assessment of native fertility of these soils and proper techniques for optimum management of organic matter in local farming systems. To that purpose, long term mineralization experiments, according for example to the leaching-incubation method proposed by Stanford and Smith (1972), are also necessary.

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Effects of salinity-tolerance cyanobacterium *Nostoc* sp. on soil characteristics and plant growth

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Keywords: cyanobacterium Nostoc, soil salinity reclamation, tolerance to salinity

Abstract

Soil degradation is a serious problem due to global population increase, with desert areas expanding at 6 millions ha per year. Terrestrial cyanobacterium ***Nostoc,*** *a blue-green algae, forms a mat on soil surface and is dry- and heat-resistant.* ***Nostoc*** *is known as a pioneer organism, which can photosynthesize, fix atmospheric nitrogen, and secrete polysaccharides. Therefore the inoculation of* ***Nostoc*** *may have potentiality to reclaim degraded soil ecosystem, for example salt-affected sandy soil or alkaline soil. In order to explore the potential of* ***Nostoc*** *to be utilized for countermeasures to soil desertification, we examine salinity-tolerance of* ***Nostoc*** *which is found in temperate and tropical regions including Khon Kaen, Thailand. We also investigate the physicochemical soil properties suitable for cyanobacterial growth, effect of* ***Nostoc*** *on soil chemical and biological properties and plant growth both in a laboratory and an outdoor experiment.*

Salinity-tolerance of ***Nostoc*** *isolated from Khon Kaen soil was comparable or better than isolates from temperate region.* ***Nostoc*** *produced largest amounts of polysaccharides without saline condition, which may play important role in salinity-tolerance. Application of* ***Nostoc*** *increased soluble C and N soil content. In the outdoor experiment,* ***Nostoc*** *created a crust structure on the soil surface, reduced soil temperature fluctuations and delayed soil surface evaporation. These results indicate that the application of* ***Nostoc*** *to the soil surface presents a potential for organic matter production and could be a tool to reclaim degraded soil ecosystem.*

Introduction

Soil degradation is a serious problem in the context of global population increase, with desert areas expanding at the rate of 6 millions ha per year. Terrestrial cyanobacterium *Nostoc* is resistant to heat and dryness, and forms a mat on the soil surface. *Nostoc* is known as a pioneer organism that can photosynthesize, fix atmospheric nitrogen, and secrete polysaccharides. Polysaccharides contribute to soil structure, increase soil C and N, and promote plant growth. Through these characteristics, *Nostoc* has a potential to be used to reclaim degraded soil, for example salinized or alkalinized soil in semi-arid or arid areas. Carbon and nitrogen fixation by cyanobacteria in arid or boreal soil ecosystems is significant (Zaddy 1997; Okitsu et al. 2003). In the semi-arid regions of Southwest United States, primary production in soil crusts, mainly made of cyanobacteria, reached 6 to 23 kg C ha^{-1} yr^{-1} (Eldridge and Greene 1994), and the cyanobacterial mat prevented soil erosion, especially under dry conditions (Johansen 1993). Under such conditions soil salinity is often an issue, thus the use of salt-tolerant cyanobacteria may be an option.

Application of cyanobacteria mixed with gypsum and sulfur changed the soil pH from alkaline to neutral, reduced exchangeable Na and EC, and led to the development of soil aggregates in India (Kaushik and Mutri 1981; Kaushik 1989, Subhashini and Kaushik 1984). However these results were obtained with an application of a mixture of cyanobacteria together with a chemical. The quantitative evaluation of single species of cyanobacteria had not been conducted yet.

In our study, we evaluated the potential of single species of cyanobacteria *Nostoc* to prevent soil degradation. We investigated the effects of *Nostoc* application on the biochemical properties of the soil and on plant growth in outdoor and laboratory experiments.

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Materials and methods

Three types of experiments were carried out. In the first and second the *Nostoc* species under study was isolated from the Chiba Prefecture Warm Horticulture Research Institute in Tateyama, Japan. This type of cyanobacteria is common on the soil surface, especially after rain. In the third type of experiment, four species of *Nostoc* were studied: the isolate from Tateyama, a strain from a dried-up paddy field in Ban Kham Pia, Khon Kaen, a strain from Morioka, Northern Japan, and the Himeji strain (HK strain), Western Japan.

Experiment 1: Effects of *Nostoc* application on soil characteristics.

1-1 Outdoor experiment

In this experiment, *Nostoc* was applied to the surface of soils in 30 l plastic containers (length: 41 cm, width: 31 cm) at the rate of 0.02 g cm^{-2}. *Nostoc* contained 340-430 mg C, 36-52 mg N and 46-50 mg polysaccharides g^{-1} dry matter.

The soil used was a Brown Forest soil taken from the Chiba Prefecture Warm Horticulture Research Institute. Its main biochemical properties were: total C and N: 14.4 and 1.38 g kg^{-1}, respectively, pH (H_2O): 6.1, EC: 9.6 mS m^{-1}, and CEC: 28.4 cmol (+) kg^{-1}. The soil depth was 15 cm, and about 5 cm of gravel was added at the bottom. The sensors of an auto-thermo recorder (T&D, Ondotori TR-71) were installed at a depth of 1 cm to record soil temperature (Figure 1). Ceramic soil suction meters (Fujiwara Seisakusho, SPAD PF-33, sensing range pF 1.3 to 3.9) were also installed at 6 and 12 cm depth to record soil water potential. *Nostoc* was cultivated in outdoor plastic containers for 90 days from June 1 to September 1, 2002, without irrigation. *Nostoc* un-amended containers were set up as a control. Both treatments and control were replicated three times.

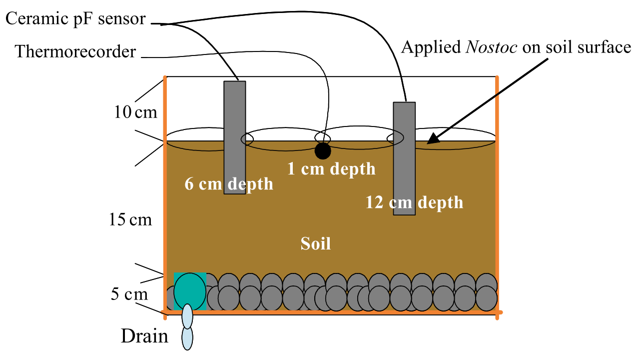


Figure 1. Set up of the outdoor experiment

After 90 days of cultivation, soil samples were taken for analysis at depths of 0-2.5, 2.5-5.0, 5.0-7.5 cm. Soluble soil organic C and N content were determined after extraction with 0.5 M K_2SO_4 solution (soil: solution 1:5 w/v) using a TOC meter (Shimadzu, TOC 5000) for C and the persulphate oxidation-hydrazine reduction method (Sakamoto et al. 1999) for N. Soil pH was measured using a soil:water or 1 M KCl ratio of 1:2.5 (w/w). Electrical conductivity (EC) was measured using a soil:water ratio of 1:5 (w/w). The number of soil microorganisms (fungi and bacteria) was measured by the dilution plate method (Soil Microbial Society, 1992). The cation exchange capacity (CEC) of the soil was measured by the Schorenberger's method and exchangeable cations (Na, Mg, K, Ca, Mn) were measured in a 1.0 M ammonium acetate extract by ICP (Shimadzu, ICPS-1000IV) (Muramoto et al. 1992).

1-2 Growth chamber experiment

In this experiment *Nostoc* was applied at the rate of 1.0 g dry matter on the surface of 160 g of autoclaved Brown Forest soil or river sandy soil in 500 ml pots (diameter: 7.5 cm; height: 8.0 cm) either as dried ground powder or fresh minced mass after homogenisation. *Nostoc* un-amended pots were set up as a control. *Nostoc* was grown for 30 days at 30°C inside a growth chamber with a 16 h light (80 µmol m^{-2} s^{-1}) and 8 h darkness cycle using irrigation to maintain moist conditions. Both treatments and control were replicated three times. At the end of the cultivation, the soil samples were analyzed for soluble organic C and N, CEC and exchangeable cations with the methods indicated in experiment 1-1.

Experiment 2: Effects of *Nostoc* application on plant growth.

2-1 Sandy soil

In this experiment, *Nostoc* (0.4 g dry matter) was applied on the soil surface or mixed with the autoclaved river sandy soil (100 g) placed in plastic seedling trays (5 cm × 5 cm × 5 cm). Weeping love grass (*Eragrostis curvula*) seeds (0.5 g) were planted and the trays were incubated in a growth chamber at 25°C for 30 days under similar illumination cycle and irrigation as in experiment 1-2. For comparison with *Nostoc* application, two more treatments, autoclaved river sandy soil that received only chemical fertilizer or not (control), were setup. Chemical fertilizer (N:P:K 8:8:8) was applied at a rate equivalent to 200 kg N ha^{-1} (designated as fertilizer amended control). The soil not amended with *Nostoc* or fertilizer was called fertilizer un-amended control. Five replicates were prepared for each treatment. The above-ground dry biomass was measured at the end of the experiment.

2-2 Filter paper cultures

Seeds of weeping love grass were placed on pairs of filter paper (Advantec) in sterile plastic dishes and let to germinate for 3 days in a growth chamber at the same temperature and illumination conditions as in experiment 1-2. Evenly seedlings were selected and further grown for 7 days with or without *Nostoc* application of 2 g (fresh weight, equivalent to 20 mg as dry weight) in N-free Knop's culture solution (Namiki, 1990). Sodium chloride solution (0.1 or 0.2 M) or distilled water was then added to the Knop's culture solution as treatments. Four replications, each with 6 seeds, were prepared for the individual treatments. Plant growth was evaluated by measuring the height of the shoot at the end of the experiment.

2-3 Brown Forest soil

Sixty-five grams of the Brown Forest soil (the same soil as in experiment 1-1) were placed in plastic Petri dishes, and autoclaved after they were amended with a quantity of Na_2CO_3 equivalent to 15 cmol kg^{-1} dry soil. The pH and EC of the Na_2CO_3-amended soil were 10.0 and 0.8 dS m^{-1}, while those of the Na_2CO_3-un-amended soil were 6.6 and 0.07 dS m^{-1}, respectively. The Na_2CO_3-amended soil was then divided into four parts and further treated as follows: (i) no fertilizer amendment (referred to as salt-amended [-] fertilizer), (ii) amendment with a chemical fertilizer (N:P:K 8:8:8) at a rate equivalent to 200 kg N ha^{-1} (referred to as salt-amended[+]fertilizer), (iii) *Nostoc* (3 g fresh weight) amendment mixed with the soil (referred to as salt-amended[+]*Nos* mixed) and (iv) *Nostoc* (3 g fresh weight) amendment applied on the soil surface (referred to as salt-amended[+]*Nos* surface). Half of the Na_2CO_3-un-amended soil samples were also further amended with a chemical fertilizer at the same rate as for the Na_2CO_3-amended soils (referred to as salt un-amended[+]fertilizer), the other half did not receive any fertilizer (referred to as salt un-amended[-]fertilizer). Seeds of weeping love grass (0.05 g) were planted in each Petri dish and grown in a growth chamber for 7 days at the same temperature and illumination conditions as in experiment 1-2. Three replications were prepared for each treatment. Plant growth was evaluated by measuring the height of the shoot and the fresh weight of the above-ground biomass at the end of experiment.

Experiment 3: Comparison of growth and salt-tolerance between isolates from Khon Kaen, Thailand and from Japan

The growth of four strains of *Nostoc* was compared after a stay of 168-192 h in a growth chamber. Salinity tolerance was also examined by growing the strains for 72 h in a 0.1-0.6 M NaCl media. Total polysaccharide production was also compared after a 72 h incubation in BG 11 media and filtrated (0.47 μm) then determined by the phenol sulphate method.

Results and discussion

Effect of Nostoc on soil characteristics

When *Nostoc* was applied on the surface of soils in plastic containers kept outdoor and cultivated for 90 days in experiment 1-1, soil moisture and temperature were more steady when compared with the un-amended soils. After heavy rain, the amount of drained water was the same in the *Nostoc* amended and un-amended treatments. Without rainfall or irrigation, soil pF in the topsoil remained low, indicating moist conditions, for a longer period in the soil where *Nostoc* had been applied compared with *Nostoc* un-amended soils (Figure 2). In addition, the pF in the deeper soil layers remained unchanged for about one week in the *Nostoc* treatment whilst it started to rise after four days [RP3] in the *Nostoc* un-amended soils. The maximum daily soil temperature with *Nostoc* application was about 4 to 6°C lower than without *Nostoc* application (Figure 3). Thus *Nostoc* application to the soil surface led to a decrease in the maximum soil temperature and the retention of soil moisture under the dry conditions of mid summer. These two effects can be attributed to the crust mat of *Nostoc* developed on the soil surface. Crust mat development resulted in a reduced evaporation from the soil surface, and therefore helped retain the water, as indicated by the low water potential (pF), for longer period than without *Nostoc* application. The crust mat also reduced the incident solar radiation on the soil surface, and this led to the observed

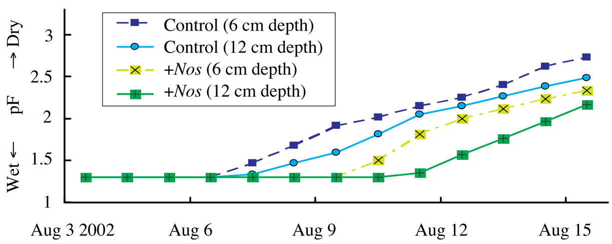


Figure 2. Effect of *Nostoc* application on soil water potential

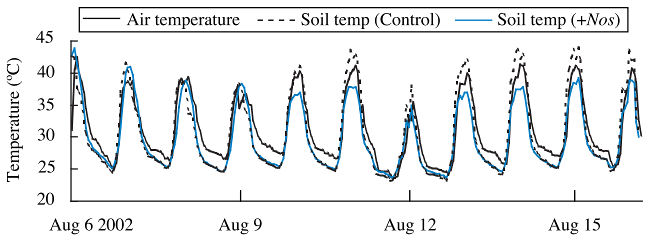


Figure 3. Effect of *Nostoc* application on soil temperature (1 cm depth)

decrease in maximum soil temperature. The decreased maximum soil temperature and the retention of soil moisture by *Nostoc* may influence other soil biological and chemical properties. Indeed soil moisture is an important factor in determining the quantity and activity of soil biota. Soil borne organisms, including microorganisms, are very active at soil moisture content of about 60% of the field capacity, but their activity becomes restricted at a lower moisture content. The optimum soil temperature for soil organisms is between 20-30°C. Some soil organisms may endure up to 35°C, but they become severely restricted above 40°C.

Soluble organic C and N contents at soil surface (0 to 2.5 cm) increased significantly (p <0.01; t-test) with *Nostoc* application after 90 days of cultivation (Table 1). *Nostoc* application also significantly increased the amount of soluble N at depths from 2.5 to 5.0 cm. The increase in soluble C and N was attributed to the secretion of polysaccharides from *Nostoc*. Polysaccharides are known to contribute to the structural stability of the soil, to increase soil C and N, and to promote plant growth (Foth 1990). Some organic compounds were applied when *Nostoc* was inoculated, but this initial amount of polysaccharides was much less than the quantity observed after 90 days of cultivation.

There were no significant effects of *Nostoc* application on the other soil chemical and biological characteristics such as soil pH, electrical conductivity, number of fungi and bacteria, CEC and exchangeable cations (Table 1). However, significant differences in some of these soil properties between the different soil depths were observed. For example, the electrical conductivity, the amount of soluble N and the number of microorganisms decreased with depth in both *Nostoc* amended and un-amended soils. Interestingly, while the amount of soluble C increased with depth in the control, it decreased with *Nostoc* application. The soil used in this experiment was neutral, and rather rich in soil organic matter, as indicated by its biochemical properties listed under experiment 1-1. The effects of *Nostoc* application on the soil chemical and biological properties might have been limited in such an unfertile soil.

In experiment 1-2, when *Nostoc* was applied on the surface of pots of Brown Forest and sandy soils either in the dry ground or freshly minced forms, soluble organic C and N were significantly increased, even in a period shorter (30 days) than in the outdoor experiment (90 days) (Table 2). Like in experiment 1-1, the biochemical properties were not modified by *Nostoc* application. The similarities in the effects of dry or fresh minced *Nostoc* on soluble C and N may be due to the fact that the photosynthetic and nitrogen fixing activities of the dried *Nostoc* can recover within a few hours after re-wetting to become comparable to fresh samples (Apte and Thomas 1997). From this

Table 1. Effect of *Nostoc* application on soil properties

Soil depth (cm)	Treatment	pH		EC (mS/m)	Number of microorganisms (CFU/kg.d.s.)	
		H_2O	KCl		Fungi	Bacteria
0~2.5	Cont	6.11 ± 0.4	4.53 ± 0.03	43.4 ± 15.4	(5.7 ± 1.8) × 10^4	(2.9 ± 1.3) × 10^6
	+*Nos*	5.95 ± 0.1	4.66 ± 0.1	41.9 ± 10.8	(4.3 ± 1.2) × 10^4	(3.7 ± 1.0) × 10^6
2.5~5.0	Cont	6.18 ± 0.1	4.18 ± 0.1	12.1 ± 2.65	(2.4 ± 0.6) × 10^4	(2.2 ± 0.5) × 10^6
	+*Nos*	6.10 ± 0.1	4.33 ± 0.02	16.9 ± 1.71	(2.0 ± 0.5) × 10^4	(1.8 ± 0.6) × 10^6

Soil depth (cm)	Treatment	Soluble C (mg/kg d.s.)	Soluble N (mg/kg d.s.)	CEC (cmol/kg d.s.)	Exchange cation (cmol/kg d.s.) Na	Mg	K	Ca	Mn
0~2.5	Cont	177 ± 34	12.1 ± 1	25.1 ± 1	0.78	3.65	1.24	7.44	0.03
	+*Nos*	242 ± 14*	26.3 ± 4**	28.6 ± 3	0.76	3.66	1.14	7.25	0.06
2.5~5.0	Cont	232 ± 64	7.7 ± 1	26.7 ± 2	1.18	4.25	1.12	8.14	0.07
	+*Nos*	197 ± 27	16.6 ± 1	30.6 ± 5	1.22	4.00	1.17	7.79	0.06
5.0~7.5	Cont	230 ± 74	7.6 ± 1	30.6 ± 3	0.99	3.74	1.16	7.82	0.07
	+*Nos*	160 ± 18	12.7 ± 4	29.8 ± 2	1.03	3.54	1.18	7.25	0.04

* and **: Significantly different from control at p <0.05 and p <0.01, respectively (t – text). (n = 3)

Table 2. Effect of *Nostoc* application on soil properties

Soil type	Treatment	Soluble C (mg/kg d.s.)	Soluble N (mg/kg d.s.)	CEC (cmol/kg d.s.)	Exchange cation (cmol/kg d.s.) Na	Mg	K	Ca	Mn
River sand	Cont	13 ± 2	N.D.	2.0 ± 0.1	0.46	N.D.	0.90	0.92	0.02
	+*Nos* (dry)	*48 ± 10	*18 ± 3	2.2 ± 0.1	0.52	N.D.	0.87	1.05	0.02
	+*Nos* (wet)	*47 ± 11	*15 ± 3	2.0 ± 0.1	0.40	N.D.	0.77	1.00	0.03
Brown forest soil	Cont	151 ± 11	15.2 ± 2	20.8 ± 2.0	0.62	2.29	2.13	7.59	0.34
	+*Nos* (dry)	*209 ± 10	*25.0 ± 2	18.6 ± 2.1	0.65	2.63	2.35	8.29	0.57
	+*Nos* (wet)	*227 ± 33	*31.5 ± 3	18.6 ± 0.9	0.66	2.32	1.53	7.63	0.22

*: Significant difference at p <0.01 (t – test) n = 3

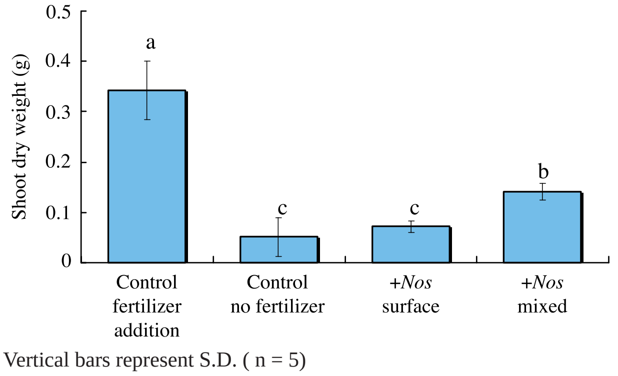
observation, it can be anticipated that it is possible to use dry *Nostoc* instead of fresh material.

Nitrogen fixation is an important N source in marginal soils like sandy or coastal saline soils. In salt-affected areas in India, application of cyanobacteria combined with gypsum or sulphur changed the soil pH from alkaline to neutral, reduced exchangeable Na and EC, and led to the development of soil aggregates in the long term (Kaushik and Mutri 1981; Kaushik 1989, Subhashini and Kaushik 1984). It is necessary, therefore, to conduct long-term experiments to see all the effects of *Nostoc* application.

Effect of *Nostoc* on plant growth

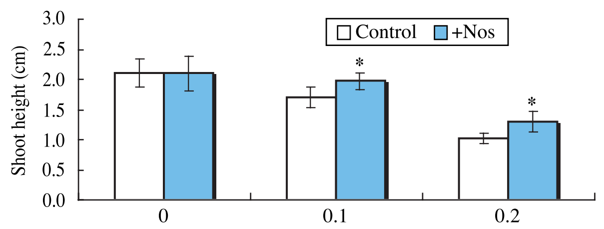
In experiment 2-1, when *Nostoc* was applied either on the surface or mixed homogeneously with the soil, and the soils were sown to weeping love grass, the mixing *of Nostoc* enhanced plant growth, compared with *Nostoc* un-amended soils, even though the best plant growth was obtained with fertilizer application (Figure 4). The plant growth in the control (no fertilizer application) and surface-applied *Nostoc* were similar, and these were significantly lower than the plant growth obtained with the mixing of *Nostoc* with the soil. Due to the absence of light in the topsoil, *Nostoc* mixed with the soil did not grow, but was probably mineralized by heterotrophic soil microorganisms. This mineralization provided probably plant-available nutrients, especially N, that was taken up by plants to improve their growth. This growth was better than in the samples where *Nostoc* was applied to the surface. The soil microbial biomass may have also immobilized part of the C and N mineralized from the *Nostoc* cells, and a great portion of this C and N may have ended up being incorporated into the soil organic matter.

When the seedlings of weeping love grass were transplanted in a N-free growth medium with or without addition of NaCl in experiment 2-2, plant growth was significantly decreased with NaCl addition (Figure 5). However, at the NaCl concentration of 0.1 and 0.2 M, the growth of the seedlings in *Nostoc* amended dishes was significantly higher than that in the control. In experiment 2-3, the addition of Na_2CO_3 also reduced plant growth by decreasing both the shoot height and fresh weight, but this decrease was mitigated by the application of *Nostoc*, especially when it was applied at the soil surface (Figure 6). The results presented in the last two figures (5 and 6) indicate that *Nostoc* can partly compensate the negative effects of salts on plant growth in sandy or saline soils. There has been no report so far to describe such an effect of cyanobacteria on the growth of higher plants, so further study is important.



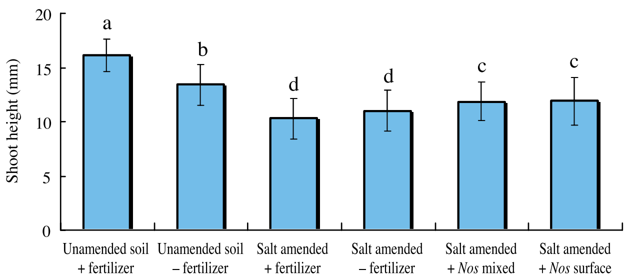
Vertical bars represent S.D. (n = 5)
Bars with the same letter are not different (Fisher’s LSP: p <0.05)

Figure 4. Effect of *Nostoc* application on plant growth in a sandy soil



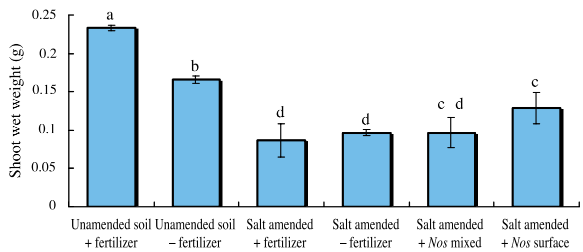
Vertical bars represent S.D. (n = 24)
*: Significant difference at p <0.01 (t – test)

Figure 5. Effect of *Nostoc* application on plant growth under sodium stress in growth medium



Vertical bars represent S.D. (i) shoot height (n = 60), (ii) wet weight (n = 3)
Bars with the same letter are not different (Fisher’s LSD: p <0.05)

Figure 6. Effect of *Nostoc* application on plants shoot height (i) and wet weight (ii) in soils



Vertical bars represent S.D. (n = 3)
Bars with the same letters are not different (Fisher’s LSD: p <0.05)

Figure 7. Effects of *Nostoc* application on plants shoot wet weight in soils

Comparison of growth and salt-tolerance between tropical and temperate isolates

Growth was faster in the Khon Kaen isolate when compare to temperate (Japanese) isolates, except HK which had most rapid growth (Figure 8). The salinity tolerance of *Nostoc* isolated from Khon Kaen was comparable to other isolates (Figure 9). *Nostoc* isolated from Khon Kaen produced the largest amount of polysaccharides followed by HK, Tateyama and Morioka (Figure 10). HK and Khon Kaen *Nostoc* isolates produced substantial amounts of polysaccharides in saline condition, which may have interesting implications to remediate saline soils.

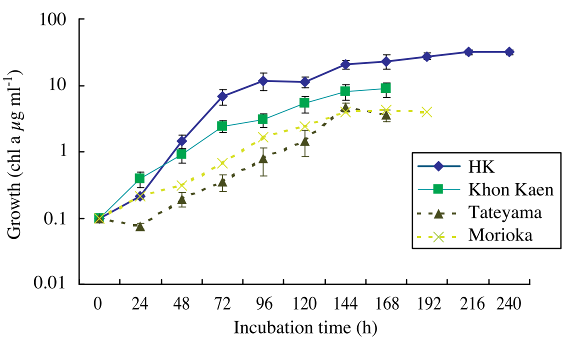


Figure 8. Growth rate of *Nostoc* isolates from Khon Kaen and from Japan

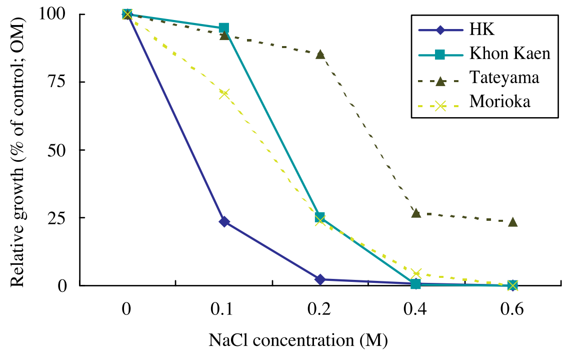


Figure 9. Salinity tolerance of *Nostoc* isolates from Khon Kaen and from Japan

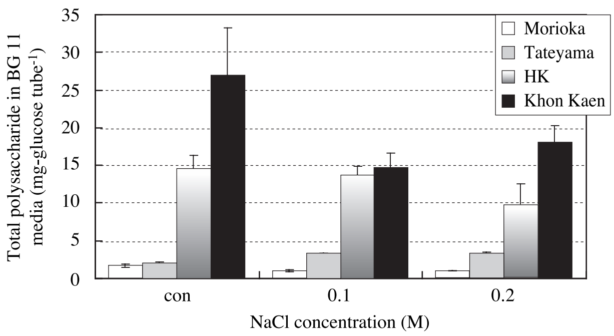


Figure 10. Total polysaccharide production of *Nostoc* in saline conditions

Conclusion

Nostoc has some potential to help re-vegetate arid, saline or alkaline soils. The Khon Kaen isolate may be an option for some tropical sandy soils. Indeed, the Khon Kaen isolate produced the largest amounts of polysaccharides and exhibited an average tolerance to salinity. However, further studies are needed before *Nostoc* can be introduced to farmers. In particular, long-term field experiments are needed to ascertain medium-to long-term effects.

Acknowledgment

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Dry matter production and digestibility of *Centrosema pubescens* and *Pueraria phaseoloides* with rock phosphate fertilization and mycorrhizae inoculation in Latosolic soil

Lukiwati, D.R. [1]

Keywords: *Centrosema pubescens, Pueraria phaseoloides*, rock phosphate, mycorrhizae

Abstract

Centrosema pubescens *(centro) and* ***Pueraria phaseoloides*** *(puero) are important forage legumes as protein and mineral sources for ruminant livestock in the tropics. However, most of the land that is used for forage production is characterized by a low phosphorus content. As the high cost of superphosphate is a major limiting factor, a combination of rock phosphate (RP) fertilization and vesicular-arbuscular mycorrhizae (VAM) inoculation maybe a promising approach to increasing available P. A field experiment was conducted on a latosolic soil (low pH and low available Bray II extractable P) to evaluate the effects of RP fertilization and VAM inoculation and their interaction on dry matter (DM) production and* ***in vitro*** *dry matter digestibility. A completely randomized block design with 3 replicates was used. The main experiment consisted therein the combination of three factors as follows 1) legume species (centro, puero), 2) VAM inoculation (with, and without VAM inoculation), and 3) rock phosphate fertilization (0, 44, 87, 131, and 175 kg P ha^{-1}). The period of defoliation was used as sub factor (defoliation I, II, and III). Results showed that DM production and DM digestibility of puero was higher compared to centro after defoliation. Dry matter digestibility of VAM inoculated puero was higher compared to uninoculated one. Rock phosphate fertilization increased DM production of VAM inoculated legume. Dry matter production was not significantly different with or without VAM inoculation. When inoculated, rock phosphate fertilization increased DM production. Success of VAM inoculation in the field is affected by the effectiveness of indigenous-VAM fungi or is dependent upon VAM inoculum potential.*

Introduction

Centro (*Centrosema pubescens*) and puero (*Pueraria phaseoloides*) are important forage legumes as protein and mineral sources for ruminant livestock in the tropics. Centro and puero have also been used as cover crops in forest plantations or in agroforestry systems. However, most land used for forage production in Indonesia is characterized by a low phosphorus (P) content and a low soil pH (latosolic soil). The application of P fertilizer during the periods of active growth increases forage legumes production and quality (Coates *et al*.,1990).

Superphosphate (SP) fertilizer has been widely used to improve agricultural production. However, its high cost makes the use of rock phosphate (RP) attractive. Rock phosphate is a slow release source of phosphorus, thus the inoculation with vesicular-arbuscular mycorrhizae (VAM) fungus is a promising technique to increase P bio-availability. According to Jones (1990), the response obtained to applications of P fertilizers is a function of many factors i.e. the initial availability of soil P, the form of fertilizer applied, and the presence or absence of effective mycorrhizae in the soil.

Most research on VAM inoculation has been done on forest-trees and agricultural crops, but rarely on forage crops. The VAM fungus of *Glomus mosseae*, for instance, is the most common species associated with agricultural crops or forests (Chen *et al*., 1998). Centro and puero are suitable host plants for VAM fungi culture (Lukiwati & Supriyanto, 1995). Two species of VAM (*Glomus fasciculatum*, *Entrophosphora columbiana*) proved to increase dry matter production and nutrient uptake of *Pueraria phaseoloides* similarly (Lukiwati & Simanungkalit, 2004). The results showed that SP can be replaced by RP when combined with VAM fungi inoculation (Lukiwati & Simanungkalit, 2001). Success of VAM inoculation in the field affected by effectiveness of indigenous-VAM fungi or depending upon VAM inoculum potential (Mitiku-

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Habte & Fox, 1993). The symbiosis between VAM fungi and legumes has been less studied in unsterilized soils than in sterilized soils. The objective of this work was to investigate under field conditions the effect of RP fertilization, VAM (*Glomus* sp) inoculation, and their combination on dry matter production and digestibility of centro and puero in a latosolic soil low in available P.

Materials and Methods

A completely randomized field experiment with three blocks was conducted for 7 months on an acid (pH (H_2O) 5.1 to 5.3) latosolic soil low in available P (Bray II extractable between 4.0 and 5.7 g/kg^{-1}). The experiment was conducted on 4×5 m plots.

The design consisted in three factors as follows 1) legume species (centro, puero), 2) VAM inoculation (with, and without VAM inoculation), and 3) five levels of rock phosphate fertilization (0, 44, 87, 131, and 175 kg P ha^{-1}). The periods of defoliation were used as sub factors. The defoliation of the plants was done three times. Standard fertilizers, i.e. 50 kg N ha^{-1} as urea and 83 kg K ha^{-1} as KCl, were applied to each plot. Legume seed of centro and puero were dibbled into small holes made with a wooden stick at the rate of two seeds per hole, spaced 100×50 cm. Each plot was inoculated with 100 gram of VAM inoculum/hole at sowing. The inoculum of VAM contained approximately 820 spores/100 gram. The parameters measured were dry matter (DM) production at the three times of defoliation, and in vitro DM digestibility on the second and third defoliation only, because of the limited biomass at the time of the first defoliation.

The first defoliation was conducted three months after sowing and subsequent defoliations were conducted every two months. The plants were cut close to the soil surface to determine dry matter production. Dry matter production of each replicate was calculated from 1 m^2 subplots. To measure DM production the defoliated forage legumes was chopped, subsampled, and oven-dried to constant weight at 70ºC for 48 hours. The samples of the second and the third defoliation were finely ground and analysed to determine in vitro digestibility by the Terry and Tilley method (1963).

The analysis of variance on DM production and DM digestibility was done using the general linear model procedure of SAS. The significant differences among the treatments were tested using Duncan's Multiple Range Test (DMRT).

Results and Discussion

Results

The effect of RP fertilization was not significant on the DM production of uninoculated legume (Table 1). Rock phosphate fertilization increased DM production on inoculated legume. The DM production of inoculated legume was not significantly higher than of the uninoculated one, at the same level of RP except on the unfertilized treatment.

Table 1. Dry matter production (kg ha^{-1}) of forage legumes with rock phosphate fertilization and mycorrhiza inoculation

P levels (kg P ha^{-1})	Uninoculated	Inoculated
0	92.2 ab	67.0 c*
44	92.7 ab	80.7 bc
87	90.1 ab	88.4 ab
131	88.7 ab	93.9 ab
175	97.4 ab	106.8 a

* Means followed by the same letters are not significantly different at DMRT 5%

Dry matter production of centro and puero increased after the first and after the second defoliation (Table 2). Dry matter production was higher for puero than for centro at the second period of defoliation (120.8 kg ha^{-1} against 90.6 kg ha^{-1}).

For the same level of RP, dry matter production of the second and third defoliation was significantly higher compared to the first defoliation. Dry matter production of the third defoliation was significantly higher compared to the second defoliation for 0, 131, and 175 kg P ha^{-1}. RP fertilization did not significantly increase DM production at the first defoliation. However, RP fertilization increased DM production on the second and the third defoliation (Table 2).

Table 2. Dry matter production (kg ha^{-1}) of forage legumes on three periods of defoliation

Treatment	Period of defoliation		
	I	II	III
Species of legume:			
Puero	40.7 c	120.8 a	121.1 a*
Centro	50.3 c	90.6 b	115.1 a
P levels (kg ha^{-1}):			
0	39.6 e	89.5 d	109.8 bc
44	47.9 e	110.3 bc	102.0 c
87	45.9 e	111.6 bc	110.4 bc
131	48.0 e	99.1 cd	126.7 ab
175	46.3 e	118.2 bc	141.9 a

* Means followed by the same letters are not significantly different at DMRT 5%

Dry matter digestibility of puero was significantly higher compared to centro, with or without VAM inoculation on the second and third defoliation (Table 3). Dry matter digestibility of centro and puero inoculated with VAM was not significantly different compared to uninoculated one on the second defoliation. However, DM digestibility of centro was significantly lower compared to uninoculated one on the third defoliation. Contrasting this, DM digestibility of puero inoculated by VAM was significantly higher compared to uninoculated one on the same defoliation.

Table 3. Dry matter digestibility (%) of forage legumes on the second and third period of defoliation with mycorrhiza inoculation

Species of legume	Uninoculated		Inoculated	
	Period of defoliation			
	II	III	II	III
Puero	47.3 cd	49.4 b	46.1 cd	50.8 a*
Centro	43.4 e	47.3 c	43.5 e	45.3 d

* Means followed by the same letters are not significantly different at DMRT 5%

Discussion

Dry matter production of VAM inoculated legumes was increased by rock phosphate fertilizer. However, both VAM inoculated and uninoculated legumes gave a similar DM production at the same level of rock phosphate (Table 1). Previous field experiments have shown that the response to VAM inoculation in the field greatly varies, and sometimes inoculation did not increase the production (Lin and Hao, 1991). This is because most of agricultural soils already contain indigenous populations of VAM fungi. Mycorrhizal inoculation would be successful in the field only if the native population was low and low effectiveness of indigenous-VAM fungi or depending upon VAM inoculum potential (Mitiku-Habte and Fox, 1993). Field experiment was carried out on the unsterilized soils. A year before, cassava had been harvested from the field, and since then the field was underfallow. Cassava is a VAM-obligate type. Cassava rhizosphere could increase the effectiveness of indigenous-VAM fungi (Potty, 1988). Spore isolation in the beginning of the field experiment showed that, there was an indigenous population of VAM fungi with a density up to 496 spores/100 g. During an experiment aiming at isolating spores from the soil, some spores infected by pathogen fungi were found. These pathogens could have decreased the effectiveness of VAM inoculum. Mycorrhizal spores could have been infected by pathogen fungi during the storage of the soil inoculum (Bagyaraj, 1988).

Rock phosphate fertilization did not significantly increase DM production of forage legumes at the first defoliation (Table 2). That was because the plants were still at the initial growth, while rock phosphate belongs to the group of slow release source of phosphorus (Jones, 1990).

The DM production of puero was higher compared to centro after first and second defoliation (Table 2). Performance of plant growth and root geometry (number of roots and distribution in the soil) of each plant species are different, as well as their response to the treatments (Kerridge and Ratcliff, 1982). Dry matter production stimulated after the first and the second defoliation promoted new stolon growth. Defoliation promoted vegetative regrowth of legume as shown in the DM production. At the earliest period, the growth of puero was slower compared to centro, therefore, DM production of puero was lower compared to centro. However, the regrowth of puero was faster than centro, therefore, the DM production of puero was higher than centro after each defoliation which in turn decreased the copper (Cu) content of puero (data not showed). This is so because of Cu as co-factor phenoloxidase enzyme which influenced the lignification process (Dell *et al*, 1995). Increase in phenoloxidase activity tend to increase the lignification process. As a result, in vitro DM digestibility of centro was lower than puero on the second and the third defoliation with or without VAM inoculation (Table 3).

Conclusion

Dry matter production on the second defoliation and DM digestibility of puero was higher than centro. Rock phosphate fertilization could increased the DM production of VAM inoculated legumes. Success of VAM inoculation in fields is affected by the effectiveness of indigenous-VAM fungi or depending upon VAM inoculum potential.

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Short-term dynamics of soil organic matter and microbial biomass after simulated rainfall on tropical sandy soils

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Keywords: Soil organic matter, microbial biomass, microbial activity, soil organic matter management

Abstract

Simulated-rainfall experiments were conducted during the dry season on sandy soils under two different farming systems in terms of the amounts of residue input to soils – that is, a sugarcane field in Northeast Thailand (SJ) and a millet field in Niger (SD). The main objective of the experiment was to evaluate the possible effects of rapid wetting/drying on soil microbial activity and the rate of soil organic matter (SOM) decomposition on tropical sandy soils in the two systems under field conditions. Three treatments were imposed: (1) C plot, receiving no water; (2) W plot, treated with 10 mm of rainfall water; and (3) G plot, sprayed with glucose as a substrate, together with the 10 mm of rainfall treatment. The CO_2 efflux rate and microbial biomass (MB) were measured at the field for about 2 weeks. After the rainfall treatment, a rapid CO_2 flush was observed in the SJ-W, SJ-G and SD-G plots during the initial 4 days. At the same time, the MB increased rapidly in these plots and resulted in a higher CO_2 efflux. In the SJ-G plot, the cumulative CO_2 efflux was twice that of the SD-G plot due to a higher growth rate of MB in the former. In contrast, this simultaneous increase of MB and CO_2 efflux rate was not observed in the SD-W plot or in the C plots. Therefore, the effects of rapid wetting/drying on SOM dynamics were considered to depend both on the dynamics of MB and on the microbial activity in tropical sandy soils. In particular, the multiplication of MB largely contributed to a prolonged CO_2 flush. The increase in CO_2 flush after the addition of substrates and/or water was more pronounced in the SJ plots, which had been receiving higher amounts of residue input in recent years. To conclude, it is necessary to take account of such historical factors of land management to appropriately simulate SOM dynamics in tropical sandy soils.

Introduction

It is necessary both to understand the dynamics of the soil organic matter (SOM) from an environmental perspective (for example, whether soils are possible sinks or sources of atmospheric CO_2), and also from an agricultural perspective, as it is widely recognized that SOM is closely related to soil fertility. Microbial biomass (MB), which is defined as the living microbial component of the soil, is the primary agent of the soil ecosystem that is responsible for the decomposition of SOM, nutrient cycling and energy flow (Wardle, 1992). Above all, many studies have been carried out to evaluate the effects of drying/rewetting on the decomposition of SOM and microbial dynamics due to its importance in the overall dynamics of SOM and atmospheric CO_2 (Kieft *et al*., 1987; Van Gestel *et al*., 1993a, b; Pulleman and Tietema, 1999; Franzluebbers *et al*., 2000; Fierer and Schimel, 2002; Fierer and Schimel, 2003; Wu and Brooks, 2005; Mihka *et al*., 2005). However, most of these experiments were conducted under laboratory conditions in which soil moisture contents were mostly fixed at high values after rewetting, although soils actually redry rapidly after rewetting under field conditions. There are few reports studying the effect of the dry-wet cycle on SOM and/or soil microbes under field conditions (Murphy *et al*., 1998; McNeil *et al*., 1998). To evaluate the actual dry-rewetting effect, responses and sensitivity of soil microbes to dry-rewetting changes should be investigated in more detail under field conditions. In addition, there is little information in arid/semi-arid ecosystems (Schwinning *et al*., 2004; Saetre and Stark, 2005), as most studies were carried out in temperate regions. Austin *et al*. (2004) report that pulsed-water events have a key role in a number of below-ground processes in arid/semi-arid ecosystems, and that changes in the nature of pulsed events due to human impact may be more important than larger-scale changes in total rainfall or

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average temperature in affecting biogeochemical cycling in water-limited ecosystems. As our understanding of the MB in tropical climates remains poor, it is important to identify whether general trends generated for mostly temperate ecosystems can also apply to tropical ecosystems (Wardle, 1992).

In tropical sandy soil, it is expected that the short-term dynamics of SOM and MB are crucial in the overall dynamics of SOM, because sandy soils are inherently poor in SOM retention and high temperature usually accelerates rapid SOM decomposition. It is possible, therefore, that the effect of drying/rewetting on tropical sandy soil is different from the results obtained in temperate ecosystems. In this study, simulated rainfall experiments were conducted in Thailand and Niger. Both soils are classified as tropical sandy soil. In Thailand, relatively high amounts of crop residues (sugarcane), composed of leaf and root biomass (1.1 and 1.0 Mg C ha^{-1} y^{-1}, respectively), were incorporated into the soils at harvest, in addition to a considerable amount of litter-fall occurring during the cropping period and, according to Funakawa *et al.* (2005), approximately 4 Mg C ha^{-1} y^{-1} of SOM was annually decomposed. On the other hand, most of the crop residues were removed from the cropland after harvest either by humans or by cattle, so that only below-ground crop residues were incorporated into the soil in Niger. The Niger plots had been left fallow for more than 10 years and were converted to millet field 2 years ago. Annual SOM decomposition rates were about 1.0 Mg C ha^{-1} y^{-1} (Shinjo 2005; data not shown). Therefore, the dynamics of SOM are very different in the two regions.

The objectives of this study were (1) to evaluate the possible effects of rapid wetting/drying on the dynamics of soil microbes and the rate of SOM decomposition on tropical sandy soils by applying simulated-rainfall experiments under field conditions on the two tropical sandy soils, and (2) to compare the effect of different farming systems on the short term dynamics of SOM and microbial biomass. The influence of the residue management was also analysed in relation to microbial responses to water/substrate additions.

Materials and methods

Description of the study sites

The experiments were conducted on two tropical sandy soils at the end of dry season; the soils had different farming systems. One was Sam Jan Village near Khon Kaen City, Thailand (SJ) and the other was ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) Sahelian Center (ISC) near Niamey City, Niger (SD). The soils of SJ and SD are classified into Typic Ustipsamments and Psammentic Paleustalfs, respectively, according to Soil Taxonomy (Soil Survey Staff, 2003). The soil properties of SJ and SD were, respectively: pH determined in water, 6.0 and 5.2; soil texture, sand with 90.7 and 95.1%; and organic C, 1.2 and 1.5 g kg^{-1}, and total N contents, 0.1 and 0.1 g kg^{-1}. Mean annual precipitation and average temperature in SJ and SD were 1,189 and 560 mm, and 27.1 and 29.1°C, respectively.

Experimental design

The experiments were carried out at the end of the dry season (13-28 March 2004 in SJ and 26 May – 8 June 2004 in SD, respectively). We installed each of the three experimental plots (C, W and G plots) in the cropping field of SJ and SD (Figure 1-a). Each cropping field was bared and there were just plant residues.

1) The C plots (SJ-C and SD-C) were left without simulated rainfall as a control.
2) The W plots (SJ-W and SD-W) were treated with 10 mm of simulated rainfall at the start of the experiments.
3) The G plots (SJ-G and SD-G) were sprayed with a glucose solution (at a rate of 75 g C m^{-2}) as a substrate, together with the 10 mm of rainfall treatment. The G plots were designed to compare the possible activities of soil microbes with the effect of substrate addition at each site.

Each plot was further divided into subplots A and B (Figure 1-b) to measure the CO_2 efflux rate and MB, respectively, after removing visible plant residues from the soil surface.

The rainfall treatment was then applied, and it took 0.5 h for the irrigation procedure; following this, the start time of the experiment was set to 07:00 h to observe the effect of the drastic evaporation in the initial stage of the experiment. The W and G plots were left dry after the simulated rainfall.

Monitoring of air and soil temperature and moisture content

The air and soil temperature at a depth of 5 cm and the volumetric soil moisture content in the surface 0-15 cm were continuously monitored at the C and W

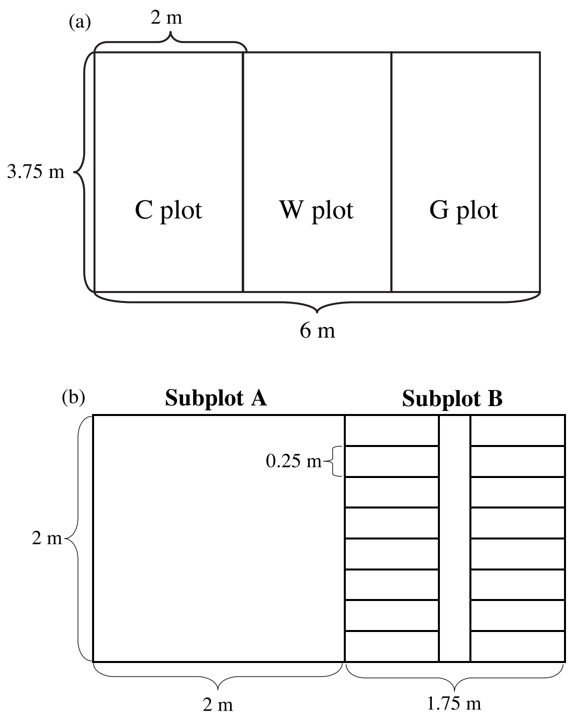

Figure 1. Design of experimental plots (a), and plot description (b)

plots using a data logger system (107 thermistor probe for soil temperature and CS616 for soil volumetric moisture connected to CR10X data logger; Campbell Scientific, Inc., Logan, USA).

Measurement of CO_2 efflux rate from soil surface

The CO_2 efflux rate from the soil surface was measured using a closed-chamber system in the subplot A in triplicate. For each measurement, a polyvinyl chloride (PVC) cylinder (13 cm in diameter × 15 cm height) was inserted into the soil to a depth of 5 cm immediately after the simulated rainfall. For each measurement, after the top of the cylinder was covered tightly with a plastic sheet and left for 40 min, a 50-mL gas sample was collected using a syringe, and then kept in a 30-mL glass vial until measurement, which was previously evacuated. At the same site, an air sample was collected to determine a baseline atmospheric CO_2 concentration. The concentration of CO_2 was measured using an infrared CO_2 controller (ZFP9AA11; Fuji Electric, Tokyo, Japan) and the increase in CO_2 concentration during the 40 min relative to the control sample was assigned as the CO_2 efflux from the soil surface. Sample collection was carried out at 4, 6.5, 9, 12, 14.5, 26, 32, 38, 50,5, 56, 61,5, 75,5, 86,5, 99.5, 346.5 and 363.5 h in the SJ plots, and 3.5, 5.5, 8, 11, 14, 26, 32, 37.5, 50, 55, 60.5, 99, 122, 317 and 320 h in the SD plots after the simulated rainfall in triplicate.

Measurement of MB and its activity

The microbial biomass was measured in the subplot B every 4-6 h using an applied substrate-induced respiration (SIR) method (Anderson and Domsch 1978; Lin and Brooks 1999), as follows:

1) As the SIR is strongly influenced by soil water content, a sufficient amount of water was added to the surface soil prior to each measurement to adjust water content to above 50% of the field-holding capacity. The amount of water added was determined based on the amount of evaporation expected. After the upper 5-cm layer of soil was well mixed, water was sprayed onto soil surface.
2) Glucose solution was sprinkled onto the soils using a syringe at a rate of 60 g C m^{-2}. Then, the upper soil was mixed uniformly.
3) After 30 min, a cylinder (the same one as for the CO_2 measurement described above) was placed into the soil to a depth of 5 cm, and then the top was covered tightly with a plastic sheet.
4) After 1 h, a 50-mL gas sample was collected using a syringe, and then kept in a 30-mL glass vial, which was previously evacuated. The concentration of CO_2 was measured using the infrared CO_2 controller (ZFP9AA11; Fuji Electric).
5) At the same time, an air sample was also collected to determine the atmospheric CO_2 concentration.

SIR method is commonly used for laboratory experiment, but we applied the method for field experiments, in order to evaluate the short term dynamics (4-6 h) of microbial biomass.

Sample collection was carried out at 5.5, 9.5, 15, 26.5, 38.5, 51, 62, 100, 124, 346.5 and 364 h in the SJ plots, and 3.5, 8, 13, 25.5, 36.5, 49.5, 59.5, 98.5, 121.5 and 316 h in the SD plots after the simulated rainfall in triplicate.

To calculate the microbial biomass based on the SIR measured, we used the following equation (Anderson and Domsch, 1978):

$$B = (40.04R + 0.37)/1000 \quad (1)$$

where B is the microbial biomass C (g) and R is the soil respiration rate (mL h^{-1}). Since this equation is established on temperate soils and on laboratory condition, we tentatively used this equation for comparison.

It is widely recognized that temperature is one of the controlling factors for soil CO_2 efflux. To eliminate the effect of temperature fluctuations over a day, we corrected the soil respiration rate based on the Q_{10} relationship, where the Q_{10} factor is the ratio of respiration rates observed at temperatures differing by 10ºC (Fang and Moncrieff, 2001):

$$Q_{10} = (R_2/R_1)^{(10/(T2-T1))} \qquad (2)$$

where R_2 and R_1 are the respiration rates observed at temperatures T_2 and T_1, respectively. There are many reports on the relationship between temperature and CO_2 efflux from both a short-term and long-term perspective (Fang and Moncrieff, 2001; Parkin and Kaspar, 2003). We used Q_{10} values of 2.2 and 1.7 for SJ and SD, respectively, which was preliminary calculated by our laboratory incubations. Using these parameters, we converted the respiration rate measured (R_1) to that expected at 22ºC (R_2) using MB determined by SIR.

It has been suggested that microbial activity reflects the effect of environmental conditions (Anderson and Joergensen, 1997; Mamilov and Dilly, 2002), and that the activity can be measured through the efficiency of substrate utilization (Dilly and Munch, 1998). In this study, we evaluated the contribution of microbial activity to the decomposition of SOM after drying/rewetting, using the following equation:

$$\text{Microbial activity} = CO_2 \text{ efflux rate/microbial biomass C} \qquad (3)$$

In this equation, both the CO_2 efflux rate and the microbial biomass C were expressed on an area basis (g m^{-2} h^{-1} and g m^{-2}, respectively). The CO_2 efflux rate was corrected to 22ºC based on the Q_{10} relationship, as in SIR methods, in order to eliminate the effect of temperature fluctuation over a day.

Results

Fluctuation of air and soil temperature and soil moisture during the experiments

The air temperature at the SJ and SD plots fluctuated from 21ºC and 23ºC to 40ºC and 39ºC, respectively. Similarly the soil temperature at the SJ and SD plots fluctuated from 23ºC and 29ºC to 46ºC and 49ºC, respectively (Figure 2).

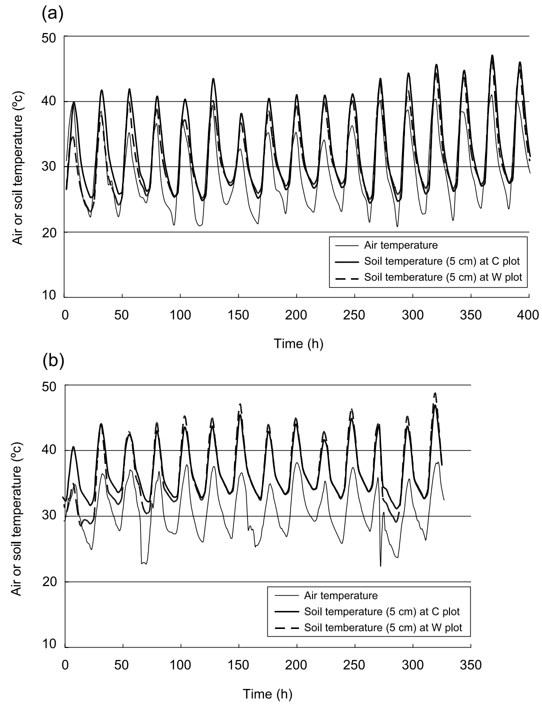

Figure 2. Fluctuation of air and soil (5 cm) temperature at the SJ plot (a) and the SD plot (b)

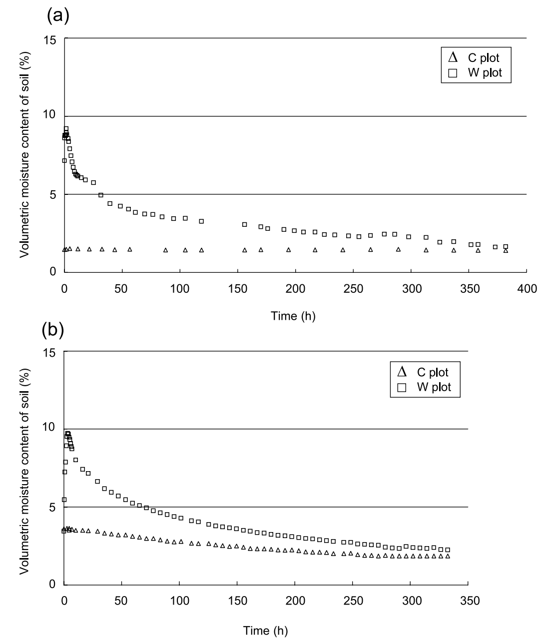

Figure 3. Fluctuation of volumetric moisture contents of soil (0-15 cm) (%) at the SJ plot (a) and the SD plot (b)

The daily temperature fluctuation was therefore substantial. On the other hand, before the experiment the soil was very dry – that is, the volumetric moisture content (VMC) in the SJ and SD plots was 1.5 and 3.5%, respectively, which is equivalent to -4.3 and -1.9 MPa, respectively. The simulated rainfall increased VMC in the SJ and SD plots up to 9.2 and 9.7%, respectively, which is equivalent to -7.7 and -3.5 kPa, respectively. Thereafter, the surface soil started to dry and VMC decreased continuously (Figure 3). Water loss through evaporation was high, especially in the daytime compared with the night-time. VMC in the SJ and SD plots decreased to 5.7 and 7.0% after 1 day, 3.7 and 3.9% after 3 days, and 2.0 and 2.9% after 2 weeks, respectively. The final VMC in the SJ and SD plots was equivalent to -3.8 and -2.2 MPa, respectively.

CO_2 efflux from the soil surface

The soil surface CO_2 efflux, which was mostly due to microbial respiration in our experiments, was small in the C plot compared with the W and G plots. After the simulated rainfall, the CO_2 efflux rate in the SJ-W, SJ-G and SD-G plots increased immediately, whereas that in the SJ-C, SD-C and SD-W plots did not change appreciably (Figure 4). In the SJ-W, SJ-G and SD-G plots, the CO_2 efflux rate continued to increase up to 6 h, and finally reached 2.6, 8.0 and 2.8 times higher than that of the control plots, respectively. After the peak of CO_2 efflux, it gradually decreased with fluctuation for fluctuated temperature. After correction of CO_2 data by soil temperature, however, there is no fluctuation of the CO_2 efflux (data not shown). The CO_2 efflux rate in the SJ-G plot was still 1.4 times higher than in the SJ-C plot at the end of the experiment, whereas CO_2 effluxes of the SJ-W and SD-G plots were almost equal to that of the control plots after 100 and 122 h, respectively.

The cumulative CO_2 efflux for the SJ-C, SJ-W, SJ-G, SD-C, SD-W and SD-G plots reached 4.25, 7.43, 13.68, 2.46, 2.68 and 7.16 g C m^{-2}, respectively, up to the 13th day of the experiment. The difference in the cumulative CO_2 efflux between each treated plot and the control plots was 3.18, 9.43, 0.22 and 4.70 g C m^{-2} in the SJ-W, SJ-G, SD-W and SD-G plots, respectively. These differences were primarily contributed to by the CO_2 flush in the initial 100 h.

Microbial biomass and activity

In the SJ-W, SJ-G and SD-G plots, MB was increased rapidly after the simulated rainfall (Figure 5). MB of the SJ-W plot was increased up to 10 h and then stabilized without decreasing in spite of rapid drying. After 100 h, it started to decrease to the level of the

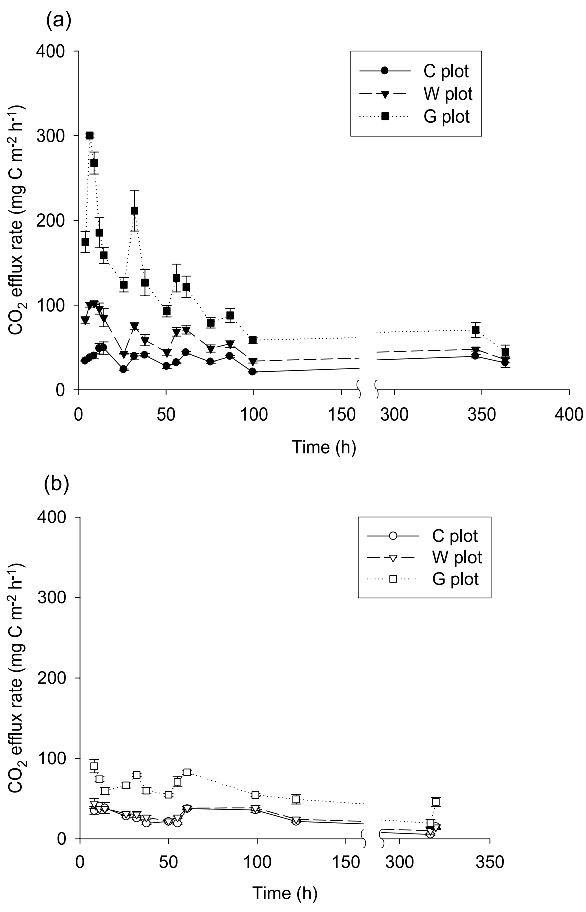

Figure 4. Fluctuation of CO_2 efflux rates at the SJ plot (a) and the SD plot (b) Bar indicates standard deviation

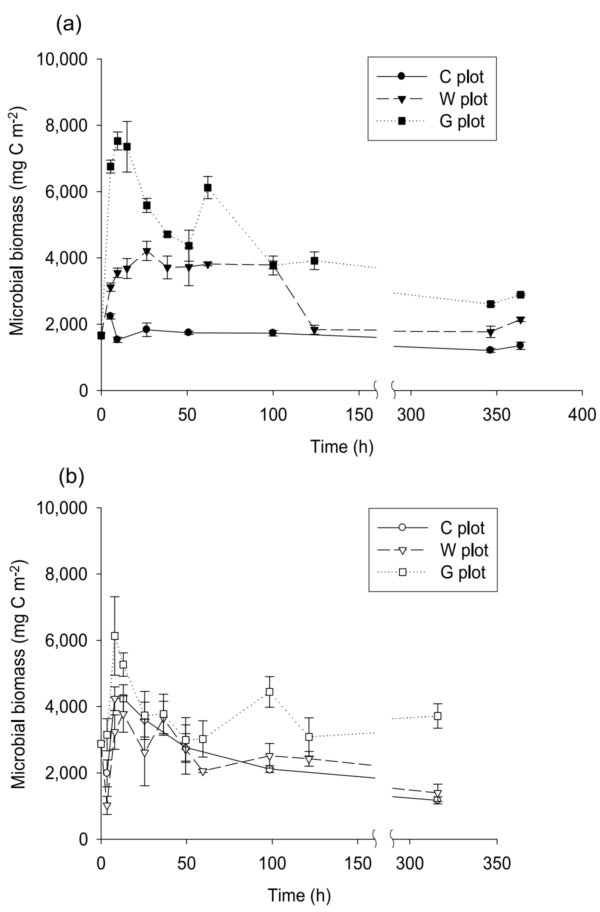

Figure 5. Fluctuation of microbial biomass at the SJ plot (a) and the SD plot (b) Bar indicates standard deviation

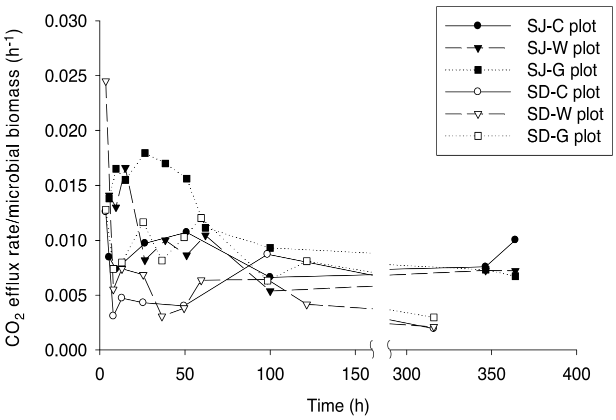

Figure 6. Fluctuation of microbial activity (CO_2 efflux rate per microbial biomass)

SJ-C plot. The MB of the SD-W plot fluctuated similarly to that of the SD-C plot, keeping a low level throughout the experiment. The MB of the SJ-G and SD-G plots was 5 and 1.5 times, respectively, higher than that of the control plots after 10 h and then gradually decreased with drying, but was twice that of the control plot by the end of the experiment (Figure 5).

Generally, the microbial activity reached the highest a few hours after the simulated rainfall and then decreased with water depletion (Figure 6). The duration of high microbial activity of the G plots was longer than that of the W plots.

Discussion

CO_2 flush and multiplication of soil microbes

The simulated-rainfall treatment significantly increased the MB and the microbial activity in the SJ-W, SJ-G and SD-G plots, resulting in large differences in the cumulative CO_2 efflux compared with the C plots. Many studies reported that the CO_2 flush after drying/rewetting could be caused by the increase of microbial activity and finished within a few days (Cui and Caldwell, 1997; Franzluebbers *et al.*, 2000; Fierer and Schimel, 2003). Mihka *et al.* (2005) also reported that the flush of CO_2 was mainly related to microbial activity and microbial turnover (or microbial origin), and it finished in a day under laboratory conditions. In these studies, a rapid multiplication of MB after the drying/rewetting was not postulated. In our field experiments, however, not only microbial activity but also MB was rapidly increased in the SJ-W, SJ-G and SD-G plots after the rainfall treatment and the CO_2 flush lasted for 4 days, which were longer than the studies cited above. It is possible to assume that the longer CO_2 flush in our experiment was caused mainly by the multiplication (and subsequent stabilization) of MB, in addition to the increased microbial activity, although its reasons are still unclear as there are few reports on the effect of drying/rewetting on tropical sandy soils (Murphy *et al.*, 1998).

Response of soil microbes to rewetting under different cropping systems in terms of residue management

The MB in the SD-W plot did not increase appreciably, unlike that in the SJ-W plot. This is one of the reasons why the CO_2 efflux rate in the SD-W plot did not increase significantly after water addition. As smaller amounts of visible plant residues were observed in the SD plots than in the SJ plots, readily decomposable SOM may also be less in the former in spite of similar total carbon contents in the soils. Such differences in the amount of available substrates, which were primarily caused by residue management in the respective farming systems, may have resulted in the differences in the response of soil microbes at the W plots in the present study. The cumulative CO_2 efflux in the SJ-G plot after simultaneous addition of water and glucose reached twice that of the SD-G plot and the difference was mainly caused by the CO_2 efflux rates in the initial 100 h. To demonstrate the multiplication of MB at the W and G plots, the ratios of MB of the W or G plot to the comparable C plots were plotted in Figure 7. It is clearly shown that the multiplication of MB in the SJ-G plot was significantly larger than the SD-G plot. There were small differences in environmental conditions between plots – that is, the much carbon substrate, the soil temperature and moisture contents condition, and soil texture. Therefore, the large differences observed for cumulative CO_2 efflux between the SJ-G and SD-G plots might be caused by the responses of soil microbial communities to substrate addition – namely, some species could increase rapidly using substrates added in the SJ plots, unlike in the case of SD. It might be one of the possible explanations for this; namely, each farming system in

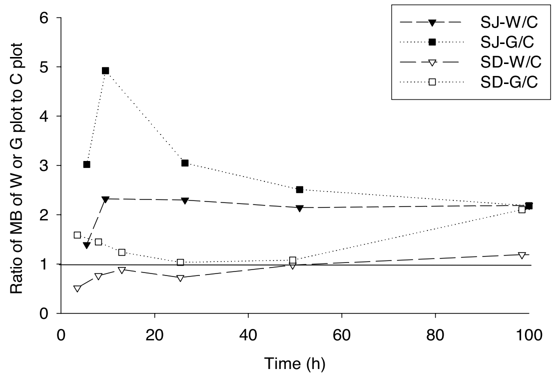

Figure 7. The ratio of microbial biomass of the W or G plot to the comparable C plot

SJ and SD makes different amounts of crop residues, which were put into the soil, resulting in different decomposition dynamics. Another factor, which affects the microbial communities, still remains, for examples, climate and soil.

Generally, sandy soils cannot retain SOM in soils compared with clay soils, as sandy soils are more aerated and SOM is scarcely protected from decomposition by being bound in clay-humus complexes or sequestered inside soil aggregates (Brady and Weil, 2002). Actually, most plant residues in SJ and SD would be decomposed within 1 or 2 years because of high temperature, so that there were few visible plant residues after 2 years from the last addition of plant residue in the SD plots (Funakawa and Shinjo 2005, data not shown). In addition, the turnover rates of MB and SOM in sandy soils and/or tropical regions are higher than in clay soils and/or temperate regions (Gregorich *et al*., 1991; Sakamoto and Hodono, 2000; Wardle, 1992). Therefore, it is possible to assume that the change of microbial composition is induced by rapid depletion of SOM (within 1 or 2 years) in the tropical sandy soils. We therefore suggest that in tropical sandy soils the farming histories strongly affect the decomposition dynamics of SOM through inducing different microbial responses, such as rapid multiplication on rainfall events. In general, established models for simulating SOM dynamics – for example, the Century model (Parton *et al*., 1987) and the Roth-C model (Jenkinson *et al*., 1991) – do not take into account the direct influence of the farming history on the composition of the soil microbial community. Further studies are needed to elucidate the influence of land-use histories, such as past-residue incorporation, on the response of soil microbes under fluctuating environments on tropical sandy soils.

Conclusion

The effects of rapid wetting/drying on SOM dynamics lasted for a limited number of days and depended on both the dynamics of the MB and the microbial activity in the tropical sandy soils. The multiplication of MB largely contributed to the initial CO_2 flush.

The acceleration of the CO_2 flush after addition of substrates and/or water was more pronounced in the SJ plots, which had been receiving higher amounts of residue input in recent years. Hence, it is necessary to take account of such historical factors of land management to appropriately simulate SOM dynamics in tropical sandy soils.

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Eucalypt litter quality and sandy soils: addressing two cumulative effects on topsoil organic-matter and soil faunal activity in African plantations

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Keywords: phenolics, soluble organic matter, soil organic matter fractionation, eucalypt, acacia

Abstract

A constraint in many sandy soils is their low organic matter content. Originating mainly from litterfall in forests, soil organic matter (SOM), besides its importance for soil fertility, is the feeding resource for soil fauna, essential for soil functioning. Because eucalypt are known for their low quality litter, their influence on SOM and soil fauna on sandy soils was investigated in comparison with a loamy-clay soil (Senegal) and a clay soil (Congo) and with tree species with contrasting litter quality. For this purpose particle size fractionations at the soil-litter interface were performed, and invertebrate density was assessed with the TSBF method. Eucalypt litter has a low N content and a high phenolic content. Both soil texture and tree species controlled SOM at the soil-litter interface, and low amounts of SOM were observed in the fine particulate fraction and the organo-mineral fraction under eucalyptus on sandy soils. High phenolic content in the litter might decrease particulate SOM. Tree species and soil texture influenced earthworm density, whereas termite and ant densities were mainly dependent on soil structure. The other litter-dwelling invertebrates were mainly dependent on tree species. Eucalypts and sandy soils present together some adverse effects on soil fertility, through both organic matter and biological activity. More extensive sampling in clay soils and experimental studies on the chemical influence of litters are required for a better understanding of soil structure-SOM-soil invertebrate relationships. However silvicultural practices which are able to increase organic matter in eucalypt plantations on sandy soils are essential for their sustainability. Logging residue management are currently being studied by UR2PI (Unit de Recherché usr la Productivity Des Plantations Commercials) who also tests the input of organic matter from non-eucalypt vegetation by inter-planting acacias with eucalyptus.

Introduction

Eucalypts are extensively grown in the tropics, either as farmer forestry or as industrial plantations mainly for paper pulp production. In Africa, many eucalypt plantations are grown on sandy soils, usually nutrient poor, which however are able to support tree growth. Eucalypt plantations were tried in the semi-arid Senegal in the years 1970-80s, on sandy soil and on loamy sand soil. In the Congo, commercial plantations are grown since 1978 near Pointe Noire, covering now more than 40,000 ha on sandy soils, under a wet climate, and a few experimental plantations are also grown on clay soils.

The main constraint of African sandy soils is their low soil organic matter (SOM) content and its decrease with cultivation (Feller et al. 1991, Walker and Desanker 2004). However SOM provides exchange sites, which contribute to nutrient conservation. Besides its importance for soil fertility and structure, SOM is the primary feeding resource for most soil living organisms and especially soil invertebrates, which in turn are essential for soil functioning (Lavelle and Spain 2001). So for sustainability of fast growing tree plantations, it is of significant importance to manage sandy soils in order to increase SOM.

In a forest environment, SOM originates mainly from litterfall and litter decomposition. It is well known that the litter quality of eucalypts is low (Woods 1974). Eucalypt leaf litter contains large amounts of phenolics (Bernhard-Reversat et al. 2001) which are antibiotic and anti-feeding agent for invertebrate and vertebrate fauna (Waterman and Mole 1994; Harborne 1997). Eucalypt litter quality leads to low biological activity and results in a low litter decomposition rate in eucalypt plantations.

Whether this low decomposition rate results in SOM accumulation in the topsoil is not clearly

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understood. The observation of particulate SOM fractions at the soil litter interface could bring some useful information. SOM fraction distribution was shown to be dependent on soil texture and on vegetation (Feller et al. 1991). The aim of the present paper is to study the effect of eucalypts and soil texture on organic matter incorporation to soil, and on macro-invertebrate density which is known to be dependant on vegetation (Lavelle and Spain 2001). Planted tree species of contrasting litter quality were compared to eucalypts.

Sites and methods

The climate of the Senegalese sites is semi-arid with nine dry months, and the study was carried out over several-years that included periods of lower rainfall than the average. One site was on a loamy sand soil (mean annual rainfall 500 mm) and the other on a sandy soil (mean annual rainfall 800 mm), both being tropical ferrugineous soils. The clay content of the topsoil is 5 and 15% respectively. In both situation the native vegetation was a dry forest dominated by *Acacia seyal*. The study was conducted in experimental plantations where several tree species were grown, and *Azadiracta indica* is compared here to *Eucalyptus camaldulensis* (Table 1). Eucalypts were finally shown not to be suitable for the climatic region. *A. indica* was previously extensively planted in villages, on roadsides, and in small farmer plantations.

In the Congo, large commercial plantations are grown around Pointe Noire on a ferralic arenosols

Table 1. Vegetation of the studied sites and number of samples for soil fractionation of SOM

Country Soil	Veget	Species	nb	Age
Senegal sandy	native	*Acacia seyal*	7	
	planted	*Eucalyptus camaldulensis*	11	8-10
		Azadirachta indica	6	9
Senegal sandy-clayey	native	*Acacia seyal*	6	
	planted	*Eucalyptus camaldulensis*	5	6-7
		Azadirachta indica	2	12
Congo sandy	native	savanna	9	
	planted	*Eucalyptus PF1*	65	6-16
		Eucalyptus HS2	38	7-11
		Acacia mangium	6	6-10
		Acacia auriculiformis	3	10
Congo clayey	native	savanna	3	
	planted	*Eucalyptus PF1*	3	12
		Eucalyptus HS2	3	7
		Acacia mangium	3	8
		Acacia auriculiformis	3	8

(sandy soil), and in experimental plantations in the Niari valley on a ferralic clay soil. The clay content of topsoil is 5 and 50% respectively. Both sites have a seasonal equatorial climate (mean annual rainfall 1,250 mm) with four dry months, although atmospheric humidity remains high throughout the year. *Eucalypts* were hybrid clones resulting from the 1950-70s forestry research, *Eucalyptus* PF1 and *Eucalyptus* 12 ABL x *saligna*, here called HS2 (Delwaulle and Laplace 1988). Australian *Acacia mangium* and *Acacia auriculiformis* (Table 1) were established experimentally and are not usually planted in Congo. The Congolese eucalypt plantations area was large and comprised many plots among which many samples were collected. Only a few plots were available for the clay soil situations where the sampling was less extensive.

Litter analyses were carried out on freshly fallen leaves from various sites, and the results were averaged regardless to the soil texture, which had little influence compared to species. Litter samples were air dried before being ground at 1.5 mm. Chemical analysis methods were previously described (Bernhard-Reversat 1998). Soil sampling for particle size fractionation was made in the 0 to 1-2 cm layer. The particle size fractionation of organic matter was adapted from Feller (1979), by sieving under water and floating. Carbon analysis was performed on each fraction. In the present paper, the data of the SOM fractions were collected in order to give three fractions, a coarse particulate fraction from 0.5 to 4 mm (Senegal) or 0.5 to 2 mm (Congo), a fine particulate fraction from 0.05 mm to 0.5 mm, and the remaining organo-mineral fraction less than 0.05 mm. In Senegal samples, the coarse particulate fraction under *A. seyal* included part of the small leaflets before their decomposition. It was observed in the Congolese plantations that soil organic matter content increased with the age of plantations, regardless to logging, and the planted plots older than 12 years old were not taken into account in order to have comparable age ranges in all planted species. Carbon was analysed with a Carmhograph® (Senegalese soils) or with the Ahn method (Congolese soils). Soil C mineralisation was measured in some experiments by CO_2 release during *in vitro* incubations of humid soil at 30ºC, by the NaOH method (Bernhard-Reversat 1993).

Soil invertebrate density was estimated in the Congolese plantations, through the TSBF method (Tropical Soil Biology and Fertility Program, Anderson and Ingram, 1993) in ten soil monoliths per studied plot. On clay soils, only one plot was investigated for each species, and the results should be checked with further studies.

Comparisons were made with the non-parametric tests of Kruskal-Wallis and Mann-Whitney, with the software Statview®.

Results and discussion

Litter quality

Annual litterfall from *Eucalyptus* accounted for 2.9 to 3 $t.ha^{-1}$ in the Senegalese plantations and approximately 5 to 7 $t.ha^{-1}$ in the Congolese plantations (Bernhard-Reversat 1993, Laclau *et al.*, 2003). Australian *Acacia* litterfall ranged from 9 to 10 t ha^{-1}, whereas *A. seyal* litterfall was only 1.4 to 1.9 t ha^{-1}. Freshly fallen leaves of eucalypt species, compared to acacia species or other species had a low N content and had a high water-soluble organic matter and phenolic content (Table 2). However *A. seyal* seems to be an exception among leguminous plants, with also a very high phenolic content, also observed in green leaves (Breman and Kessler). Water-soluble compounds in eucalypts ranged from 20 to 40% of litter dry weight. Soluble organic matter included a great amount of water-soluble phenolics which ranged from 9 to 15% of litter dry weight. The total water soluble and methanol soluble phenolics reached 15 to 20% of litter dry weight in eucalytpt leaf litter compared to 2 to 5% in the other species studied but *A. seyal*.

Table 2. Chemical composition of fresh leaf litter from various tree species, in mg g^{-1} of litter dry weight, with standard error in brackets. Solu OM: soluble organic matter, Solu phen: soluble phenolics, N.s. phen: non-soluble phenolics, Lign: lignin

Tree	*Solu OM*	*Solu phen*	*N.s. phen*	*N*	*Lign.*
Acacia seyal	240	178	151	8.0	64
Acacia mangium	98 (7)	38 (11)	81 (9)	7.8 (0.24)	315 (17)
Acacia auriculiformis	163 (23)	39 (4)	78 (10)	9.0	283 (27)
Azadirachta indica	134	12	8	17.0	256
Eucalyptus camaldulensis	48 (22)	68 (7)	28 (8)	8.1 (0.8)	103 (12)
Eucalyptus PF1	177 (5)	88 (4)	69 (4)	5.9 (0.2)	164 (3)
Eucalyptus HS2	113	120	44	6.5	166

Soil organic matter at the soil-litter interface

Organic matter at the soil-litter interface represents the first stage of litter incorporation into the soil. The SOM particle size distribution was significantly dependent on soil texture, as previously observed by Feller *et al.*, (1991). The particulate organic fractions of SOM accounted for an average of 83% of total SOM in sandy soils, 75% in loamy sand soils, and 53% in the clay soils. Only the SOM in the organo-mineral fraction was significantly higher in the loamy sand soil than in the sandy soils. Unlike this, both fine particulate and organo-mineral fractions were significantly higher in the clay soil than in sandy soils (Figure 1). The adsorption of soluble organic compounds on the clay fraction and the formation of complexes with clay might be involved. In a laboratory experiment with Senegalese soils, 15% of added soluble C from *E. camaldulensis* litter was mineralized within 6 days in the sandy soil, and 4% in the loamy sand soil, showing the protection of the organic matter by clay.

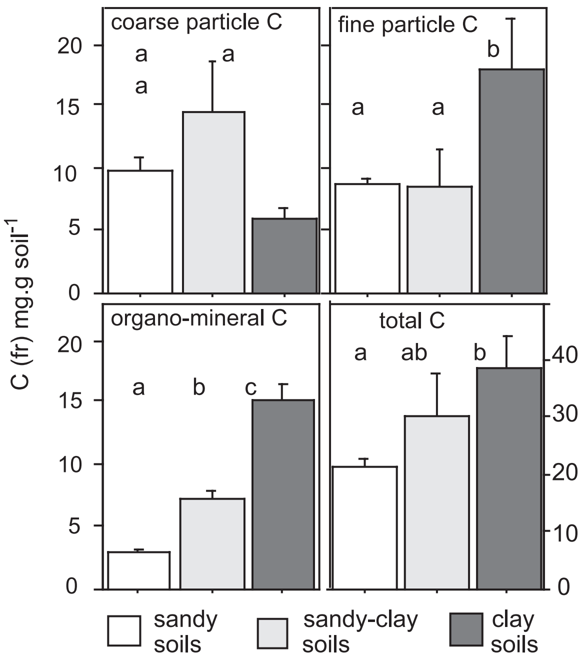

Figure 1. Carbon in the SOM particle size fractions of the 0-2 cm layer of soil, in mg g^{-1} of soil, according to soil texture, in Senegalese and Congolese tree plantations

SOM particle size distribution was also dependent on tree species. The eucalypt effect resulted in a lower amount of all SOM fractions, compared to the other tree species in the Senegalese sites (Figure 2). In the Congolese sandy soils, the fine particulate SOM fraction was lower under both eucalypt hybrids, whereas only *E.* HS2 showed this trend in the clay soil (Figure 3). Consequently, SOM accumulation was low in eucalypt plantation compared to other tree species, (comprising some species which are not presented here, as *Prosopis juliflora, Acacia laeta*, and except

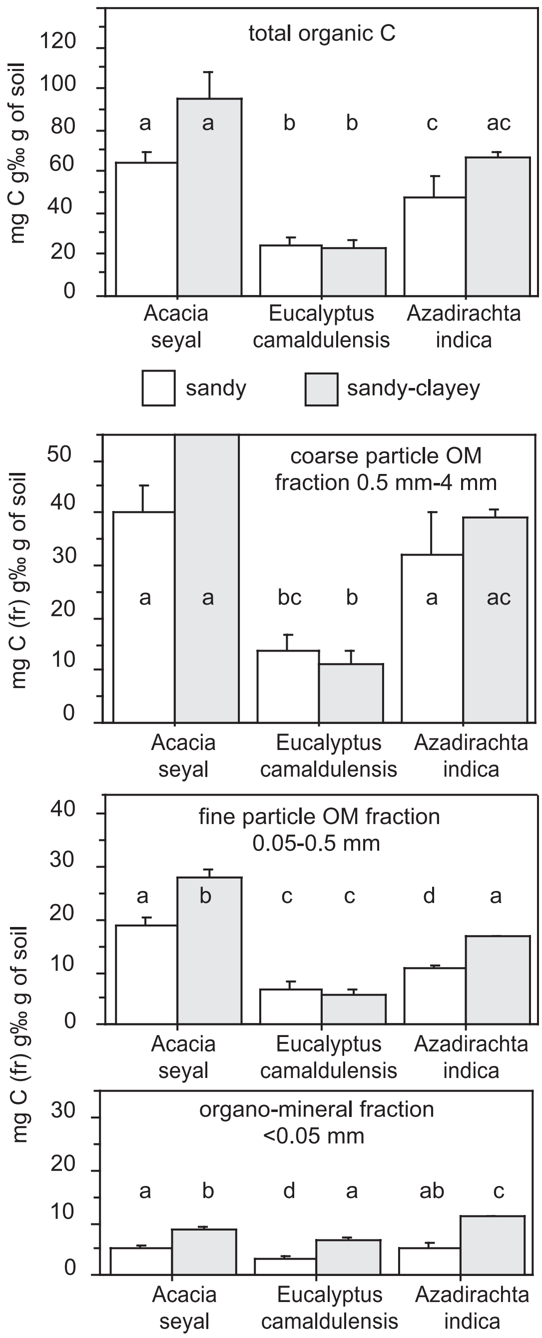

Figure 2. Carbon in the SOM particle size fractions of the 0-2 cm layer of soil, in mg g^{-1} of soil, in tree plantations and native vegetation in Senegal

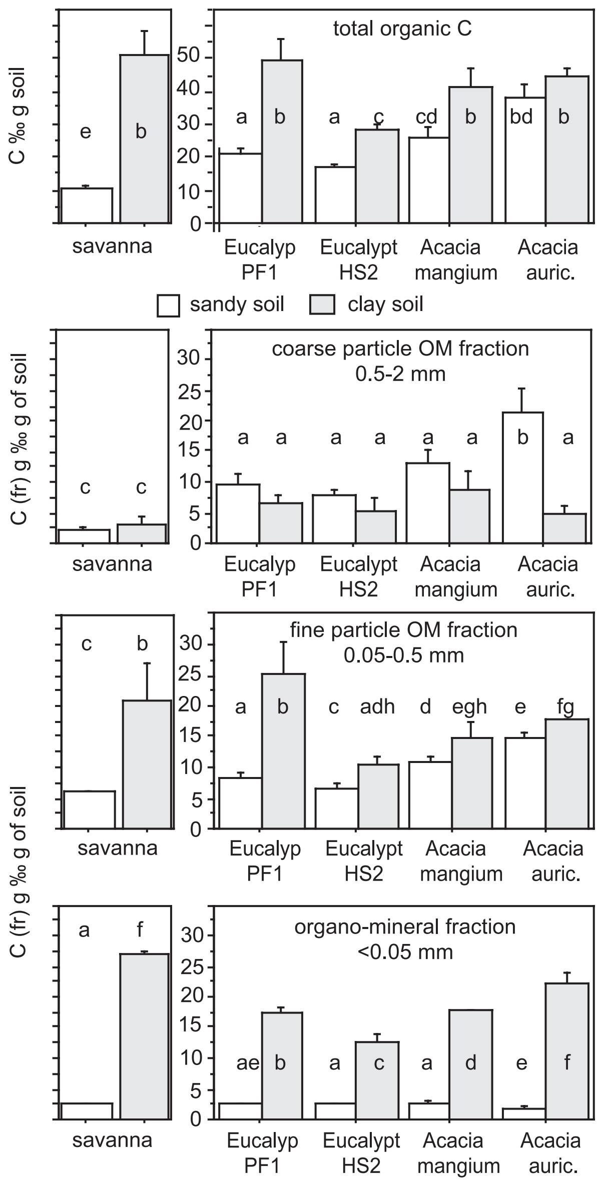

Figure 3. Carbon in the SOM particle size fractions of the 0-2 cm layer of soil, in mg g^{-1} of soil, in tree plantations and native vegetation in Congo

Pinus caribaea). This may be associated with litter quality. The lower accumulation of particulate SOM fraction under eucalypts might be related to the high non-phenolic soluble organic matter of eucalypt litter, as suggested by its significant relationship with the amount of fine particulate SOM in the species studied (Figure 4). The effect of phenolics on SOM is difficult to asses. Phenolics are known to exert an adverse effect on decomposition (Coûteaux *et al*., 1995) and thus might enhance organic matter accumulation at the soil-litter interface. Phenolics also prevent SOM accumulation (Inderjit and Mallik 1997) through the formation of soluble metal-organic complexes (Bernhard-Reversat 1999; Jansen *et al*., 2004). In the present study, the negative effect of soluble phenolics on SOM accumulation was obvious on all the component sizes of the particulate organic matter fractions (coarse and fine, Figure 3). No relationships were observed between litter quality and organo-mineral C fraction, the amount of which was highly related to soil texture.

Soil macro-invertebrates

The positive effect of soil invertebrates on soil fertility is now recognized (Lavelle and Spain 2001).

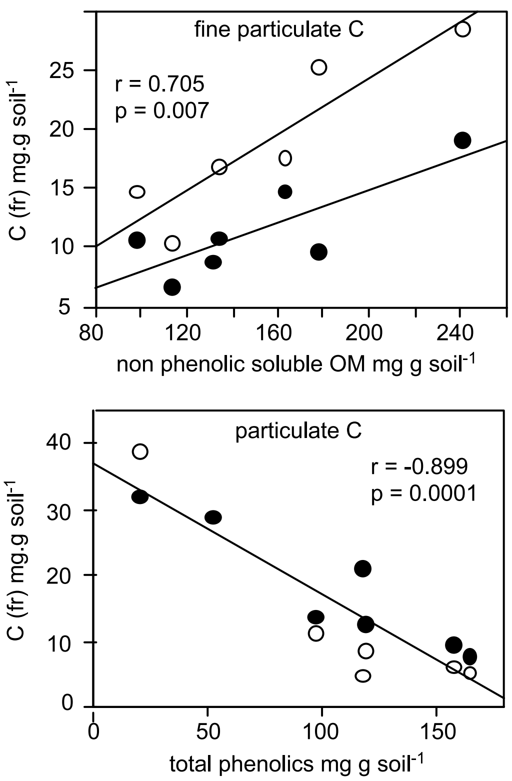

Figure 4. Relationships between the particulate organic matter of the 0-2 cm layer of soil and the litter quality of the corresponding vegetation, in Senegal and Congo. Data on *A. seyal* forests were removed from the total particulate C, because the coarse fraction contained a part of litterfall

Acacia and eucalypt plantations were compared on the Congolese soils (Mboukou *et al*., 1998). The density of earthworms was higher on clay soil than on sandy soil in eucalypt plantations, unlike what was observed in *A. mangium* plantations, where earthworms were more numerous in sandy soil (Figure 5). It appeared that soil texture effect was added to eucalypt litter effect to keep earthworm density at a low level, although Lavelle and Spain (2001) reported the influence of vegetation having a significant influence. Termite and ant density was higher in sandy soil under the two tree species. According to Jones (1989), soil texture influences termites, and Meyer *et al.*, (2000) reported the preference of some termite taxa for sandy soils. The other litter-dwelling taxa, taken together as "litter group", were much more numerous under *A. mangium*, which has a higher quality litter, than under eucalypts, but the density was not influenced by the soil texture. Although the low number of species for which we recorded invertebrate density and SOM fraction data, (four) did not allow a statistical evaluation, relationships between particulate SOM amount and termite density (r = -0.984) and earthworm density (r = 0.931) could be expected significant with more data.

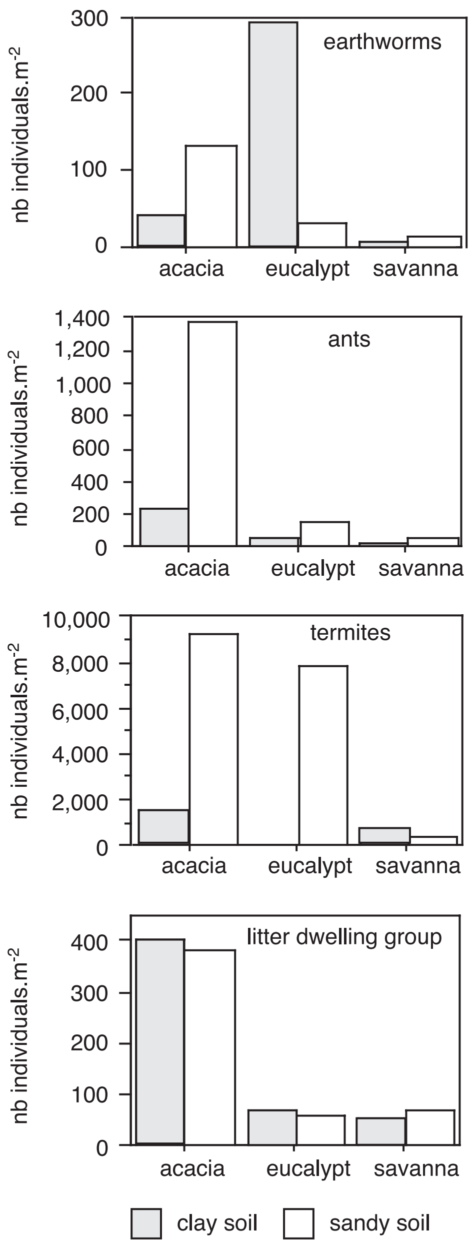

Figure 5. Density, in number of individuals per m², of some invertebrate taxa in Congolese *E.* PF1 and *A. mangium* plantations

The negative effect of soluble phenolics on termites was suggested in previous researches on Congolese sandy soils, when eucalypt litterfall leaves were considered (Mboukou-Kimbatsa and Bernhard-Reversat 2001). A weak negative effect of the insoluble phenolics from the forest floor litter on earthworms ($p = 0.06$) and soil-feeding termites ($p = 0.05$) was also suggested in another study with 27-28 TSBF samples containing the taxon from 50 samples. The depressive effect of eucalypt plantations on soil invertebrates was reported previously (Zou 1993; Maity and Joy 1999), but its relationship with sandy soil texture should be assessed with more extensive studies.

Conclusions

Eucalypts and sandy soils present together some adverse effects on soil fertility, through both organic matter and biological activity. However more extensive sampling on clay soils and experimental studies on the role of litter chemistry should provide a better understanding of these relationships. Nevertheless, silvicultural practices that may increase SOM are essential to the sustainability of eucalypt plantations on sandy soils. The management of logging residues is currently adopted in Congolese commercial plantations in order to increase organic matter and nutrient conservation, and research in this area is being conducted (Nzila *et al.*, 2004). Input of organic matter from non-eucalypt vegetation would also help increase SOM and invertebrate density. This is practiced by UR2PI (Unité de Recherche sur la Productivité des Plantations Commerciales) in studies on inter-planting leguminous trees with eucalypt, in order to improve soil nitrogen in Congolese plantations, but also expected to change litter quality and soil biology.

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Effect of fallowing on carbon sequestration in a humid tropical sandy soil (Mangodara, Burkina Faso)

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Keywords: fallow, carbon, nitrogen, mineralization, soil particles

Abstract

Although many studies focused on the effect of fallow on soil fertility, the process of soil organic matter recovery following cessation of cultivation remains little understood. This paper examines the relationships between the fallow duration and organic matter pools and their mineralization activities. The effect of fallowing on the dynamics of soil organic matter was studied through the chemical and biological characterization of whole soils and their organo-mineral particles. Soil samples were collected under fallows of different duration (5, 10 and 30 years) in the Mangodara area (Burkina Faso, West Africa), and analysed for their organic C and total N contents, and soil respiration.

The length of fallow did not influence organic C, total nitrogen contents, and CO_2 *production of the whole soils. Fallow only affected the 20-2,000 µm fractions, in which C content significantly increased with the duration of fallow: 24, 32 and 37% higher for the 5, 10 and 30 year-old fallows, respectively. The contribution of coarse fractions to C mineralization was 2 times less in the old (10 and 30 years) than in the young fallow, suggesting that the quantity of easily mineralizable compounds associated with coarse fraction decreases with the age of fallow.*

These results clearly indicate that in sandy soil, soil organic storage is mainly controlled by soil particles larger than 20 µm, but its depletion occurs through fine organo-mineral particles, particularly under old fallows.

1. Introduction

When soil is brought into cultivation there is a progressive decline of organic matter content, and soil becomes quickly infertile (Piéri 1992). Therefore, particularly in Sudanian cropping systems, soil is left uncropped for several years (fallow) to improve soil fertility. The effect of fallow on soil rehabilitation processes, particularly on soil organic matter recovery has been extensively studied and benefits (Somé 1996; Manlay et al., 2002), as well as no significant changes (N’Dour et al. 2000) have been reported. The process of soil organic matter recovery following cessation of cultivation remains little understood, probably because it depends on physical, chemical and biological processes which are influenced by local environmental conditions.

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Soil organic matter is made of a physically and chemically heterogeneous mixture of organic compounds at different stages of decomposition. Study of the relationship between the physical environment of soil microorganisms and their activity is useful for a better understanding of the dynamics of soil organic matter (Christensen 1992). Indeed microbial mineralization activities depend on soil organic matter quantity and quality, and may change in response to management practices. Although many studies focused on the effect of fallow on soil fertility, the simultaneous C and N net mineralization of soil fractions under this agricultural management has never been studied. This paper examines the relationships: (i) between the fallow duration (5, 10 and 30 years) and organic matter pools of soil size fractions and (ii) between these organic pools and their mineralization activities.

2. Materials and methods

2.1 Site characteristics and soil sampling

Soil samples were collected in the Mangodara area (9º54′N 4º25′W, Burkina Faso, West Africa). The average temperature is 27°C and annual rainfall averages 1,100 mm yr^{-1}. The rainfall is characterized by high intensity and short duration (May to September). Soils are classified as tropical ferruginous soils (FAO-UNESCO 1990?: Acrisols). The vegetation is a typical open savannah dominated by *Isorberlinia doka* and Andropogonea.

Samples were collected in June 2001 from the 0-40 cm depth under three fallow sites from which cultivation had been excluded for 5, 10 or 30 years. In each of the nine sampling areas, ten samples were randomly collected, air-dried, thoroughly mixed, and gently sieved (<2 mm) to disrupt the macro-aggregates. The fraction >2,000 µm was discarded.

2.2 Determination of soil texture and isolation of organo-mineral particles

Soil texture was determined after the destruction of organic matter by H_2O_2, dispersion in hexametaphosphate, and shaking for 16 hours, according to Balesdent et al. (1991). The organo-mineral particles of the soil were also separated as above, but without using H_2O_2, and hexametaphosphate; only shaking soil samples in water (20 g: 200 ml, ratio soil:water). The resulting 6 fractions were dried at 40ºC: 250 to 2,000 µm (coarse sand), 100 to 250 µm (fine sand), 100 to 50 µm (very fine sand), 20 to 50 µm (coarse silt), 2 to 20 µm (fine silt), and 0.05 to 2 µm (clay). The silt and the sand fractions were gathered; the following three fractions were thus obtained: 0.05 to 2 µm (clay), 20 to 50 µm (silt), and 50 to 2,000 µm (sand).

2.3 Analysis

Organic C and total N were determined using an automatic CHN analyser (NA 1500 Series 2, Fisons). The results were expressed as µg C g^{-1} soil, and µg N g^{-1} soil. Soil respiration was determined by placing 15 g soil in 130 ml closed flasks at 80% of their water holding capacity and incubated in the dark at 28ºC (±0.5ºC) for up to 3 days. The contribution of each size fraction to the total microbial activity in soil was assessed according to the method of Nacro et al. (1996), by comparing the activity of the whole soil to the activity of soils without a soil fraction (soil without coarse sand; soil without fine sand; etc.). Each incomplete soil was prepared by combining 5 fractions in the same proportions as in whole soil. The omitted fraction was replaced by chemical-free sand (particles >20 µm). Soil prepared by combining the 6 fractions was used as reference soil. The CO_2 concentration (µg C-CO_2 g^{-1} dry soil) of each sample was measured on a gas chromatograph (Auto Analyser apparatus, Chrompack CP-2002 P Micro GC) after 1 and 3 days. Gas samples were automatically taken from the flasks with a 250 ml gas-tight syringe.

2.4 Statistical analysis

Analyses were replicated four times for organic C and total N, and three times for soil respiration. Data were subjected to an analysis of variance using SAS (Statistical Analysis System, SAS Institute Inc. 1990). Means that differed significantly were separated using the Scheffe's test-; all tests were performed at the 95% level of probability.

3. Results

3.1 C and total N distribution

Organic C content of the whole soil increased slightly from the younger (3,005 µg C g^{-1} soil) to the older (3,400 µg C g^{-1} soil) fallow (Table 1). A reverse trend was observed for total N (Table 1): the lowest level was observed in the 30 year-old fallow (197 µg N g^{-1} soil), and the highest in the 5 year-old fallow (246 µg N g^{-1} soil). However, the effect of the lenght of fallow on organic C nor total N contents was not significnat. On the other hand, the C:N ratios of whole soils significantly increase with the fallows' age (Table 1).

The C and N contents of the fractions are shown in Table 1. Most of soil organic matter (69 to 75% of total C) was found in the silt fractions (-2,248 to 2,264 µg C g^{-1} soil) and this content was not significantly modified with the age of fallow. The lowest C content was found in the clay fractions and it decreased significantly with the fallow duration. The C content of the sandy fraction increased significantly with the fallow age. Regarding total N content, only the clay fractions were significantly affected by the fallow age. The C:N ratios of the sand fractions were 2 to 8 times higher than in the silt and clay fractions (Table 1), showing the recent origin of organic matter associated with the sand fractions.

3.2 Soil respiration

The CO_2 evolved by whole soils, and the contribution of each fraction are shown in Table 2. The potential contribution of a size class to C mineralization was calculated by subtracting the quantity of C-CO_2 produced by the incomplete soil lacking this class from the quantity of C-CO_2 produced by the completely recombined soil. The CO_2 production of the whole soils was low (11 µg g^{-1} dry soil) and not influenced by the fallow age. The

Table 1. Particles size distribution (percent of dry soil), and its relationship to organic carbon (μg C g^{-1} soil), total nitrogen (μg N g^{-1} soil) content, and C:N ratios of soils after fallows of 5, 10 and 30 years duration

	Age of fallows (years)		
	5	10	30
Texture			
0-2 μm	4.87 ± 0.69^a	4.19 ± 0.59^a	4.61 ± 0.39^a
2-50 μm	9.58 ± 1.03^a	14.7 ± 0.65^b	10.6 ± 0.88^a
50-2,000 μm	84.4 ± 1.12^a	80.4 ± 0.95^b	84.3 ± 0.76^a
Sum	98.9	99.3	99.5
C content (μg g^{-1} soil)			
0-2 μm	83.6 ± 4.73^a	62.2 ± 1.44^b	43.2 ± 0.98c
2-50 μm	2,264 ± 79.6^a	2,248 ± 315.3^a	2,249 ± 105.7^a
50-2,000 μm	529 ± 2,358^a	772 ± 29.1^b	1,024 ± 153.0^c
Sum	2,876 ± 77.7^a	3,082 ± 309.9^a	3,316 ± 103.5^a
Unfractionated soil	3,005 ± 217.7^a	3,089 ± 318.3^a	3,400 ± 106.9^a
N content (μg g^{-1} soil)			
0-2 μm	19.3 ± 3.48^a	12.0 ± 2.30^b	8.29 ± 1.84^b
2-50 μm	183 ± 20.4^a	180 ± 13.5^a	156 ± 6.8^a
50-2,000 μm	21.1 ± 0.62^a	22.4 ± 0.75^a	26.1 ± 3.48^a
Sum	223 ± 24.3^a	214 ± 14.3^a	191 ± 7.85^a
Unfractionated soil	246 ± 40.0^a	210 ± 16.9^a	197 ± 16.5^a
C:N ratios			
0-2 μm	4 ± 1^a	5 ± 1^a	5 ± 1^a
2-50 μm	12 ± 1^a	13 ± 3^a	14 ± 0^a
50-2,000 μm	25 ± 2^a	35 ± 2^b	39 ± 5^b
Unfractionated soil	12 ± 1^a	14 ± 3$^{a, b}$	17 ± 1^b

Means in a row with the same letter are not significantly different ($\alpha = 0.05$; *t*-test), (n = 36)

CO_2 production of soil fractions varied from 0.30 to 8.78 μg C g^{-1} soil (Table 2). As observed for the C content, only the soil respiration of silt fractions was not affected by the fallow age, whereas that of clay increased after 30 years of fallow. On the other hand, soil respiration of sand fraction decreased with the fallow age (Table 2).

Table 2. Calculated net contributions of separate size classes to C mineralization (μg C-CO_2 g^{-1} soil), and ratio of carbon mineralized to initial organic C (% kc) after 3 days of incubation

	Age of fallows (years)		
	5	10	30
CO_2 (μg g^{-1} soil)			
0-2 μm	0.30 ± 0.08^a	0.31 ± 0.06^a	1.63 ± 0.29^b
2-50 μm	8.03 ± 0.96^a	8.78 ± 1.27^a	7.76 ± 1.37^a
50-2,000 μm	5.22 ± 0.43^a	2.57 ± 0.29^b	2.80 ± 0.36^b
Sum	13.6 ± 1.39^a	11.7 ± 1.06^a	12.2 ± 1.97^a
Recombined soil	11.4 ± 2.12^a	10.6 ± 2.59^a	11.0 ± 2.31^a
kc (%)			
0-2 μm	0.45 ± 0.09^a	0.49 ± 0.10^a	3.77 ± 0.60^b
2-50 μm	0.53 ± 0.09^a	0.31 ± 0.07^b	0.26 ± 0.04^b
50-2,000 μm	1.09 ± 0.09^a	0.31 ± 0.05^b	0.29 ± 0.03^b
Recombined soil	0.38 ± 0.07^a	0.35 ± 0.11^b	0.32 ± 0.06^b

Means in a row with the same letter are not significantly different ($\alpha = 0.05$; *t*-test), (n = 27)

4. Discussions

Usually soil C content increases significantly during an extended fallow period (Somé 1996; Manlay et al., 2002). This was not observed here, probably because the C input to soil was reduced by fire in the dry season and grazing all year long, or because C "produced" was mostly added to the standing biomass rather than to the soil component (Pieri, 1992; Manlay et al. 2002). It could also be due to the nature of the soil, the crop history, and the land management. Feller et al. (1993) have shown that the effect of fallow on C content is particularly important on soils that are clayey. Soils studied here are very sandy (81 to 85%) with a low clay content (4 to 5%).

The C content of sand fractions increased significantly with the fallow age, indicating that dead plant matter enters gradually the soil organic matter pool: the greater the fallow age, the more organic matter enters the soil through the sand fractions. This clearly indicates the influence of the sand fractions on total organic C variation in sandy soils. However, the contribution of sand fractions to soil organic C was low (10 to 31%) probably because of intense microbial activities leading to high accumulation of by-products in the fine fractions especially in the silt.

Just as fallow age had no effect on soil organic C content, the CO_2 released from whole soils, and the C mineralization coefficients (Dommergues 1960) were also unchanged (Table 2). Since plant diversity and composition change considerably with time in fallow systems, an opposite result was expected. Probably in the short term, the overall soil respiration depends on the proportion of ready available C rather than on plant diversity and composition.

By contrast with its effects on organic C distribution, the contribution of sand fractions to C mineralization decreased with fallow age (from 38% to 28 and 23% respectively for the 10 and 30 year-old fallows). A reverse trend was observed for the silt (59 to 75%) and clay fractions (3 to 13%). This indicates that the quality of organic compounds associated with mineral fractions changed with time during the fallow (Ashman et al., 2003). In the same way, the C mineralization coefficient values (Table 2) showed that 0.3 to 1% of organic C associated with the sand fractions was mineralized, against 0.3 to 4% for the silt and clay fractions. The highest values were observed for the clay fractions from the 10 and 30 year-old fallow; hence, we can hypothesize that in the young fallow (5 year-old), C mineralization activity mainly depends on the availability of C associated with the sand fraction. But later, the C mineralization activity will be determined by the quality of organic compounds and microbial activity associated with the clay fraction. Such activity can lead to losses of soil organic matter, mitigating the effect of fallow on carbon sequestration in sandy soils. Further investigations are needed to understand that process.

5. Conclusion

While fallowing is generally expected to increase soil organic matter, long-term fallow (up to 30 years) did not significantly affected the soil organic C content of a sandy tropical soil. However, the C content of sand fractions was significantly affected by the age of fallow, suggesting that in sandy soil, soil organic matter storage is mainly controlled by soil particle larger than 50 µm. But when considering soil microbial activity, most of the CO_2 was potentially produced by the particles smaller than 50 µm, particularly in old fallows. Therefore, if soil organic matter increases through plant residues entering the soil, its depletion occurs through fine organo-mineral particles. This paradox can be explained by the fact that most heterotrophic soil micro-organisms (Kandeler et al. 1999) and most of easily metabolisable compounds were associated with the fine particles. It seems that soil microbial activity is controlled by the coarse fractions in the young fallow, and by the fine fractions in the old fallow. Fallow is an efficient tool for improving soil fertility, but in line with the findings of Manlay et al. (2002), our results show that long fallows are potentially constrained in their accumulation of soil organic matter content on sandy soils.

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Soil organic matter loss and fertility degradation under different agricultural land uses in sandy soils of Northeast Thailand and the use of organic materials of different qualities as a possible restoration measure

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Keywords: agricultural land uses, heavy fraction, humic substance, light fraction, microbial biomass, nitrogen mineralization, qualities of organic residues, soil organic matter pools

Abstract

Conversion of natural forest to agricultural land use has significantly contributed to lowering of the soil organic matter (SOM) content in sandy soils of Northeast Thailand. The first part of the paper presents the findings of a comparative study of contents of SOM pools (labile, i.e. microbial biomass, and particulate organic matter; and stable, i.e. humic substance) and related soil aggregate formation, in forest covered plots (original natural state with tree component) and cultivated fields (monocrop of cassava and sugarcane, and rice paddy) in a study site representative of the northeast from the viewpoints of terrain (i.e. undulating), soils (sandy), and land use. Monocultural agriculture brings about degradation of all SOM pools and associated soil aggregation as compared to the forest system because of decreased organic inputs and more frequent soil disturbance in the agricultural systems. The second part deals with restoration of SOM and fertility (nitrogen) in degraded soils. Results of some studies show that SOM build-up can be achieved through continuous recycling of organic residues produced within the system. Low quality organic residues make the largest contribution to SOM build-up as seen in whole SOM and SOM pools, including particulate organic matter and humic substance. To restore N fertility, however, high quality organic residues, i.e. those with low C/N ratios, lignin, and polyphenols, are also needed. However, employing a mixture of high and low quality residues can manipulate the time of N release to suit crop demand. In addition, selection of appropriate organic residues for N sources will have to take into account environmental factors, notably soil moisture regimes, that are different in upland field crops and lowland paddy subsystems of the northeast farming systems.

Introduction

Soil organic matter (SOM) can be used as an indicator of land degradation arising from agricultural land use. Different pools of SOM, notably labile and stable pools, as well as total SOM can give different kinds of useful information regarding soil fertility as well as soil degradation. Total SOM or total carbon (measured conventionally by wet or dry combustion) is not sensitive to impact of various ecological and management factors compared to the labile pool of SOM, i.e. microbial biomass and light fraction of particulate SOM.

Although SOM in sandy soils of Northeast Thailand is intrinsically low, the conversion of natural forest to agricultural land use that occurred in this region in the course of the past hundred years has resulted in significant further lowering of the SOM content. Some of the factors bringing about lowering of SOM in an agro-ecosystem as compared to the natural forest ecosystem include decreased amount of OM recycling, frequent and heavy soil disturbance and reduced biodiversity. To restore the SOM, input of organic materials is required with an emphasis on different qualities of organic materials to ensure the improvement of different pools of SOM.

The objectives of this paper are to review and synthesize results of several past studies in Northeast Thailand on (1) assessment of degradation of sandy soils under agricultural land use compared with original forest land use employing different pools of SOM as a soil degradation indicator, and (2) the use of organic materials of different qualities to restore SOM and fertility (nitrogen) in degraded soils.

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Degradation of SOM and soil quality of sandy soils under agricultural land use

Soils of the undulating terrain of Northeast Thailand generally have coarse texture and low organic matter leading to their inherent low fertility. Different systems of land use and soil management have brought about soil degradation manifested by the decline in SOM and fertility. Vityakon (1991) compared the soil organic carbon (SOC) content of topsoils of Warin sandy loam (Oxic Paleustult) in three adjacent plots under forest, 10-year continuous cassava, and paddy rice. The SOC in the agricultural land was reduced by 40% (from 10.2 g kg^{-1} under forest to 6.1 and 5.5 g kg^{-1} under cassava and paddy rice, respectively). Saenjan et al. (1993) found that Korat sandy loam soil (Oxic Paleustult) under continuous pasture for 10 years had SOC content of 6.3 g kg^{-1} which was reduced to 5.1 g kg^{-1} after it was changed to an upland cash crop, kenaf, for 2 consecutive crops. Gibson (1988) found that in Korat sandy loam soil, organic C was lost at an average rate of 0.24 g $kg^{-1}yr^{-1}$ under continuous cassava (3 g kg^{-1} soil organic C) as compared to the original organic C of 5.6 g kg^{-1} of the virgin soil. Vityakon et al. (2000) found that without addition of organic residues, ongoing SOM oxidation reduced organic C at the rate of 855 kg C ha^{-1} yr^{-1} (or 0.39 g $kg^{-1}yr^{-1}$ @ 1.45 Mg kg^{-1} soil bulk density) in a sandy upland soil of the northeast. These studies showed that SOM in these sandy soils tends to decrease after the original low disturbance land use is replaced with one involving more serious soil disturbance.

A recent study (Tangtrakarnpong and Vityakon, 2002; Tangtrakarnpong, 2002) compared different pools of SOM (labile and stable as well as total C) under forest and agricultural land use plots situated adjacent to each other along a gentle slope (with forest on the topslope) in typical undulating terrain of the northeast. The soils at the study site were typical sandy soils (Oxic Paleustults). The agricultural land uses included upland field crops of cassava and sugarcane and lowland paddy rice. All pools of SOM studied, i.e. total C, total N, soil litter, particulate organic matter,

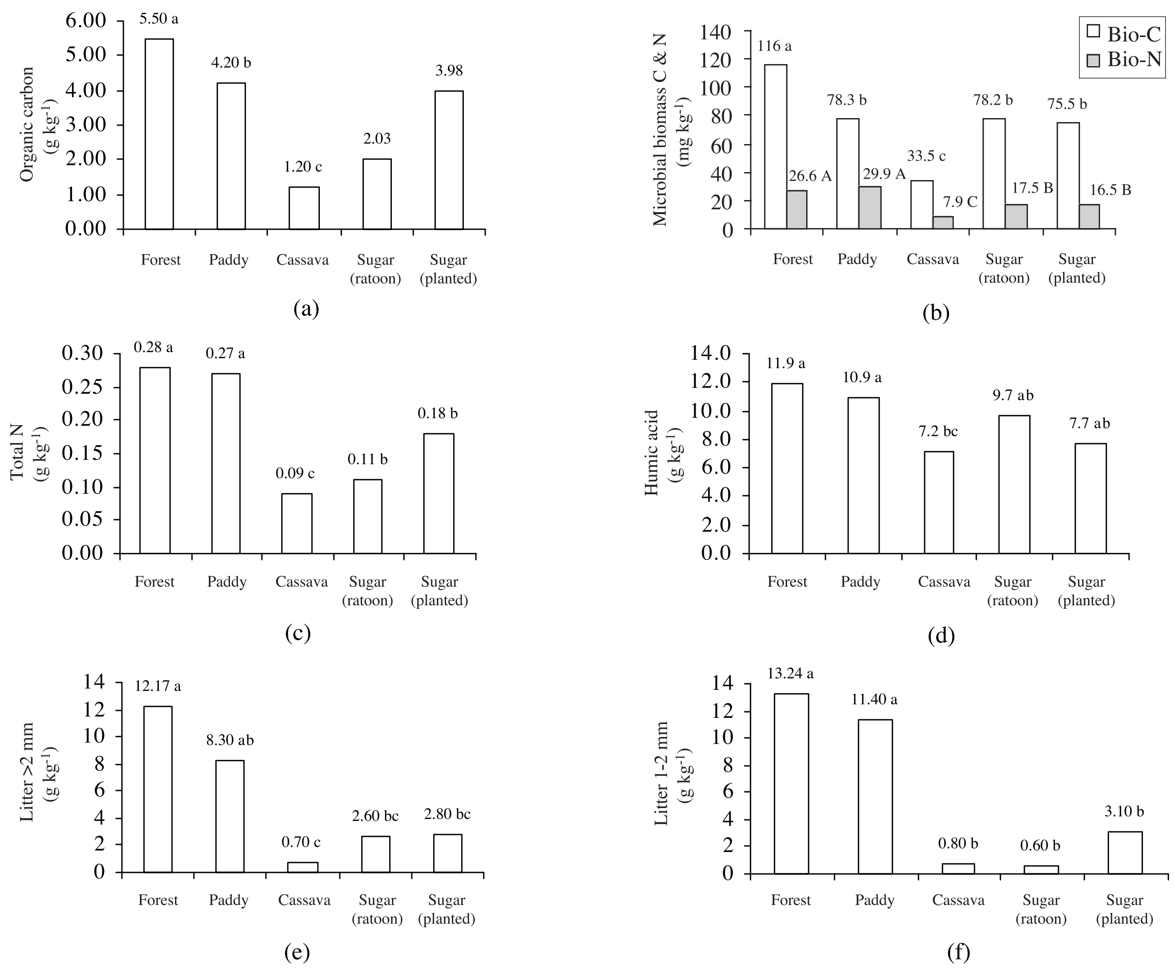


Figure 1. Contents of organic carbon (a); microbial biomass carbon and nitrogen (b); total N (c); humic acid (d); soil litter (>2 mm) (e); and soil litter (1-2 mm) (f) of soils (0-15 cm depth) under different land-use systems. *Means with similar letters are not significantly different at 95% level of probability (LSD)*. (Tangtrakarnpong and Vityakon, 2002)

Table 1. Carbon of particulate organic matter, i.e. litter (size >2 mm and 1-2 mm), light and heavy fractions and humic acid in sandy soils (0-15 cm depth) under different land-use systems

Land-use systems	Litter C[1] >2 mm (g kg^{-1})	Litter C[1] 1-2 mm (g kg^{-1})	LF-C[1, 2] (0.053-1 mm) (g kg^{-1})	HF-C[1, 2] (0.053-1 mm) (g kg^{-1})	Humic acid-C[1] (g kg^{-1})
Forest	1.13 a	0.40 b	0.31 b	1.97 a	2.93 a
Paddy	1.17 a	1.07 a	0.26 b	1.66 b	2.39 b
Cassava	0.15 b	0.17 b	0.06 c	0.44 c	1.25 d
Sugarcane (ratoon)	0.78 a	0.14 b	0.22 b	0.67 c	1.82 c
Sugarcane (planted)	0.85 a	0.64 b	0.47 a	1.63 b	1.51 cd

[1] *Means in the same column followed by similar letter are not significantly different at 5% level of probability (LSD).*
[2] LF = SOM fraction lighter than 1.3 g cm^{-3}
HF = SOM fraction heavier than 1.3 g cm^{-3}
Sources: adapted from Tangtrakarnpong (2002); Tangtrakarnpong and Vityakon (2002)

microbial biomass, and humic substance, were found to be lower in the upland cultivated fields than in the lowland paddy and the forest. SOM pools under forest land use were in most cases higher than those under agricultural land uses (Figure 1 a-f; Table 1).

Factors contributing to high SOM in forest land include high inputs of organic residues and a low degree of soil disturbance. Dry dipterocarp forest at the study site produced 4.4 t ha^{-1} of litter fall during the dry season (Dec 2000 – Aug 2001). Soil disturbance in the forest is wild fires occurring during the dry seasons, i.e. February and March. On the other hand, upland fields planted with cassava received a much lower residue input, i.e. 1.3 t ha^{-1} in a cropping season, and suffered much more frequent and severe soil disturbance by various cultural practices including ploughing and weeding. In addition, a large part of the biomass produced by the crop was removed through harvest of the roots and removal of the leaves and stems from the field. Cultivation of sugarcane, however, did not lead to as low SOM pools as cassava. This was because sugarcane cultivation produces more organic residues than cassava. Leaf litter fall input in planted and ratoon crops were relatively high, i.e. 4.1 and 6.5 t ha^{-1}, respectively. In addition, extensive roots and stumps remained in the soil after harvesting. Overall, planted sugarcane produced higher SOM than the ratoon plot counterpart. In fact, it produced higher LF-C than and comparable HF-C fractions to the forest and paddy rice (Table 1), reflecting the high quantities of organic amendments that were received by this plot. As for paddy rice, it produced the highest SOM (with exception of LF and HF) among all the agricultural land uses due to high organic return from stubble which was incorporated back into the soil. In addition, the plots were located in a lowland area that received deposits of organic materials eroded from the uplands, especially in the rainy season. Furthermore, the paddy soil is slightly more clayey than the upland soils.

Soil structure was also degraded once forest land use was changed to agricultural land use. This same study (Tangtrakarnpong, 2002) showed that aggregate size and stability was lower in cultivated land use as compared to the forest (Figure 2). In addition, significant positive correlations were found between aggregate size and stability with the quantities

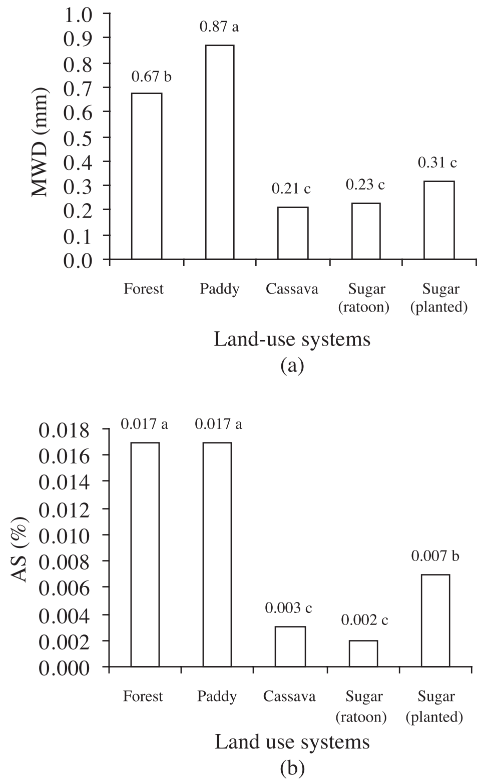
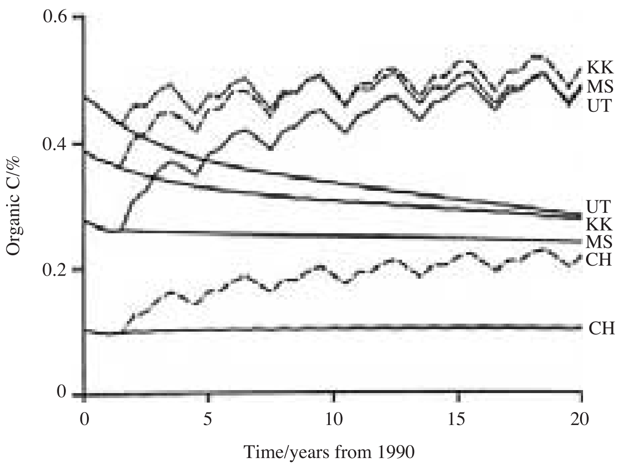


Figure 2. Mean weight diameter (a) and water stability of aggregates of soils (0-15 cm depth) under different land-use systems. *Means with similar letters are not significantly different at 95% level of probability (LSD).* (Tangtrakarnpong, 2002)

Table 2. Correlation coefficients of mean weight diameter (MWD) and aggregate stability in water with total C and quantity of humic acid under forest and agricultural (upland crops and paddy fields) land use systems

Soil parameters	Statistical parameter	Correlations with MWD[1]	Correlations with water stable aggregates[1]
Total C (g kg^{-1})	r	0.73	0.73
	|p|	(0.00)	(0.00)
Humic acid (g kg^{-1})	r	0.74	0.64
	|p|	(0.00)	(0.00)

[1] n = 54
r = correlation coefficients
|p| = probability
Source: Tangtrakarnpong (2002)



KK = Khon Kaen experimental site; MS = Mahasarakham site; UT = Udonthani site; and CH = Chaiyapoom site.

Figure 3. Model-predicted changes in the contents of soil organic carbon under continuous cassava (solid lines) and ley-aerable (2-year ley + 1-year cassava) rotation (dashed lines) in the soils. (Wu et al., 1998)

of total C and humic acids (Table 2). Humic substances as well as partially humified particulate SOM play important roles in cementing soil particles into stable aggregates (Piccolo, 1996).

Restoration of soil organic matter in sandy soils employing organic residues of different qualities

Soil organic matter build-up

Applying continuous inputs of organic residues and minimization of soil disturbances are measures that have been shown to restore SOM in sandy soils in the Northeast. Input of organic residues can be done *in situ* through adoption of agricultural systems that provide organic input continuously. Such systems, that produce significant quantity of litter, both aboveground and belowground, to compensate for the harvestable parts taken out of the systems, include pasture, agroforestry systems with tree components that provide leaf and root litter, and rotational cropping systems incorporating green manure crops. The inputs of organic materials can also be brought in from outside the system, such as application of composts, animal manure and some organic industrial by-products. A 3-year field experiments-based modeling study in Northeast Thailand comparing continuous cassava (3-year cassava) with ley-arable (2-year ley + 1-year cassava) systems showed continuous decline at decelerating rates of organic C in continuous cassava during a 20 year period. On the other hand, a trend of organic C build-up was found under ley-arable farming system where 1-year cassava was alternated with 2-year ley pasture (Figure 3) (Wu et al., 1998). A long-term (10 year) SOM experiment on an upland sandy soil belonging to the Korat series (Oxic Paleustults) which is widespread in Northeast Thailand, where plant residues of different qualities are applied once a year, has shown accumulation of total C. In addition, it showed that frequent soil disturbance (the soil was ploughed every 2 months) lowered the total C below that of the soil deprived of additional organic materials (Figure 4) (P. Vityakon, unpublished data). These results serve to show that SOM build-up in sandy soils in the northeast is possible under a system where continuous input of organic materials is provided and soil disturbance is minimized.

The quality of organic residues applied is an important driving factor in the build-up of SOM in sandy soils. The quality of organic materials is determined by their chemical as well as physical

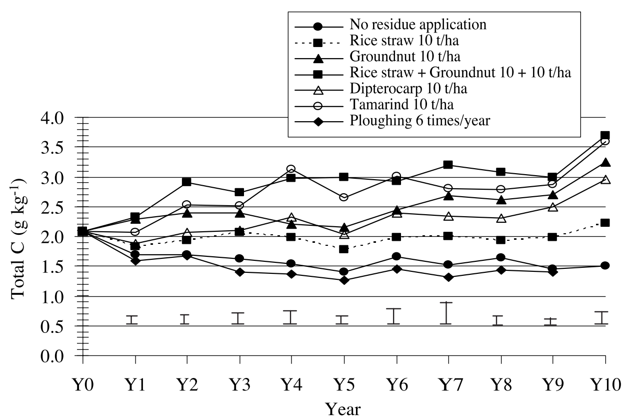


Figure 4. Ten-year changes in soil organic carbon (0-15 cm soil depth) as influenced by organic residues of different quality and soil disturbance in a sandy soil. ***Vertical bars represent SED.*** **(P. Vityakon, unpublished data)**

characteristics that influence decomposition and nutrient transformation of the residues. Although chemical characteristics, notably residue contents of carbon, nitrogen, carbon to nitrogen ratio, lignin and polyphenols, have been more widely investigated than physical characteristics, i.e. size, toughness, cutin concentration etc., some investigations have produced a firm body of knowledge as to the influence of some physical properties of residues on their decomposition in soils (Heal et al., 1997).

It has been hypothesized that residues resistant to decomposition, i.e. those that contain large amount of recalcitrant C compounds, such as lignin and polyphenols, and possess high C/N ratios in general, can bring about greater SOM accumulation relative to easily decomposable residues, i.e. those with a low amount of recalcitrant C compounds and (usually) low C/N ratios. However, a still-in-progress long-term study of SOM accumulation in the northeast that compared various locally available organic residues of different qualities has found a more complex situation. The results showed that after the first cycle of one-year period of incorporation of these residues, the highest C build-up (total C in <1 mm particle size) of 33% of initial C applied was found in high quality residues, i.e. groundnut stover, whereas low quality residues, i.e. dipterocarp leaf litter, produced a C build-up of only 10% (Vityakon et al., 2000). The probable explanation for this unexpected outcome was that a large proportion of C derived from dipterocarp leaf litter remained in particulate form of >1 mm in size which was not included in total C (<1 mm) analysis. In addition, soil C build-up exhibited significant correlation with two indicators of the chemical quality of the residue, i.e. a positive correlation with %N ($r = 0.66^*$) and a negative correlation with C/N ratios ($r = -0.62^*$). The fact that the total C values were obtained from soil of particle size <1 mm reflects that the C accumulation taken into account was in those fractions only. The parallel results at the end of the second year of the experiment were similar to the first year. However, when the quantity of particulate organic matter larger than 2 mm size in the second year was analyzed, it exhibited a significant positive correlation with C ($r = 0.66^*$), lignin ($r = 0.68^{**}$), and polyphenols ($r = 0.67^*$) contents (Vityakon, 2004). These latter results showed that low quality organic materials lead to accumulation of particulate macro organic matter and appear to support the original hypothesis.

Considering the effects of different quality plant residues on accumulation of the stable form of SOM, i.e. humic substance, an analysis of the results of an earlier study on decomposition of various types of leaf litter and associated humus formation (Adulprasertsuk et al., 1993) was conducted. It found that the leaf litter rate of decomposition (k) and their respective lignin contents (Table 3) was closely associated, i.e. negative correlation coefficients (r) of -0.84 was found. In addition, k was positively correlated with E_4/E_6 ratios of humic acid ($r = 0.71$). The E_4/E_6 ratios indicate the degree of development of humic acid, i.e. lower ratios indicate high degree of humic acid development (more condense aromatic structure). These results showed that the types of leaf litter that resist decomposition (possess high k and lignin) tend to bring about more developed humic acid than those that are more rapidly decomposed and have lower content of lignin.

Table 3. The E_4/E_6 ratios of humic acid in soils affected by litter from various trees of different quality as shown by their lignin and decomposition rates (k)

Tree name	k (day^{-1})	Lignin ($g\ kg^{-1}$)	E_4/E_6 ratios of humic acid
Dipterocarpus tuberculatus	0.0014	220	4.76
Irvingia malayana	0.0044	96	5.20
Samanea saman	0.0028	164	5.82
Shorea obtusa	0.0021	160	4.58
Tamarindus indica	0.0054	130	6.10
Xylia xylocarpa	0.0020	210	5.23

Source: adapted from Adulprasertsuk et al. (1993)

Nitrogen transformation

Nitrogen mineralization and availability of mineral N in soils receiving organic amendments is an indicator of the effectiveness of the applied organic materials in restoring degraded soils. The chemical composition of organic materials (residue quality) has an important bearing on their decomposition and N mineralization. Studies on various green manure species have shown that N, lignin and polyphenols are the three most important limiting factors for N mineralization under aerobic conditions (Palm and Sanchez, 1991; Oglesby and Fownes, 1992; Constantinides and Fownes, 1994; Handayanto et al., 1994). A study in Northeast Thailand compared pattern of N mineralization of various on-farm available organic residues including groundnut stover, rice straw, and leaf litter from common farm trees, i.e. tamarind (*Tamarindus indica*) and dipterocarp (*Dipterocarpus tuberculatus*). It was shown that under upland aerobic conditions groundnut stover exhibited peak mineral N release 4 weeks after residue incorporation while the mixture of groundnut stover and rice straw delayed peak mineral N by 4 weeks (Figure 5). These results

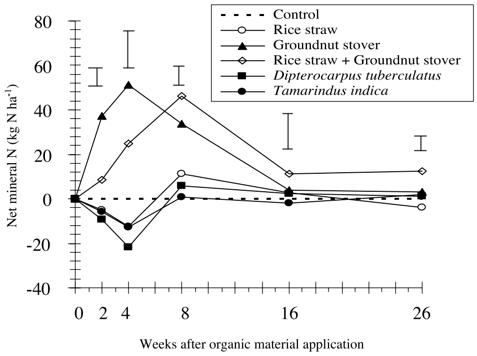


Figure 5. Net quantity of mineral nitrogen produced by different organic residues under upland conditions. *Vertical bars represent SED.* (Vityakon et al., 2000)

demonstrate that by mixing high C/N ratio residues (i.e. rice straw) with low C/N ratio residues (i.e. groundnut stover), we can manipulate the temporal pattern of N release to better suit the needs of the crop plants. This is the core idea of the ‘synchrony’ concept (Myers et al., 1997). On the other hand, rice straw and dipterocarp and tamarind leaves had an initial immobilization phase and did not contribute significantly to the mineral N pool even after the immobilization phase was over. The difference in N mineralization patterns among these residues is attributable to their chemical composition. Groundnut stover, which has high N and low C/N ratio, lignin and polyphenol contents, is considered to be a high quality residue, whereas rice straw and dipterocarp and tamarind leaves which have low N and/or high lignin and/or polyphenol contents (Table 4) are considered low quality residues. The influence of residue chemical compositions on N release is confirmed by the significant positive correlations between N release and N content of the residues, while negative correlations are found between N release and C/N ratio and polyphenol content of the residues during the first 4 weeks period after residues were incorporated (Table 5).

Nitrogen transformation processes (mineralization-immobilization of N in organic residues) are mediated by microorganisms. Parallel studies of patterns of microbial biomass N after residue incorporation (Figure 6) threw light on the resulting observed N mineralization-immobilization patterns especially that of groundnut stover + rice straw mixture which exhibited delayed N released compared with groundnut stover alone. It was found that microbial biomass N in the mixed treatment was the highest among various residues studied. This was the combined result of the large amount of available C (from both groundnut stover and rice straw) as well as the immobilization of N readily available from groundnut stover. This combined effect resulted in the delayed N mineralization observed as shown in Figure 5.

Agricultural land use in Northeast Thailand farming system is determined by its undulating terrain.

Table 4. Chemical quality characteristics of plant residues

Residues	C (%)	N (%)	C/N	L[1] (%)	L/N	Pp[2] (%)	Pp/N	(L + Pp)/N
Rice straw	39	0.49	79	3.6	7.4	1.48	3.02	10.4
Groundnut	39	1.73	23	9.9	5.7	1.57	0.91	6.6
Dipterocarp	42	0.68	62	24.9	36.6	4.98	7.32	43.9
Tamarind	42	1.23	31	16.9	13.7	4.61	3.75	17.5

[1] Lignin
[2] Polyphenal
Source: Vityakon et al. (2000)

Table 5. Correlation coefficients relating amounts of soil mineral N (NH_4^+ + NO_3^- -N) to chemical characteristics of plant residues under upland (n = 12) conditions

Period	Parameters[1]	%C	%N	C/N	%L	L/N	%Pp	Pp/N	(L - Pp)/N
Week 0-2	r	0.52	0.79	-0.62	-0.33	-0.51	-0.57	-0.72	-0.55
	|p|	(0.090)	(0.002)	(0.031)	(0.292)	(0.087)	(0.052)	(0.008)	(0.063)
Week 2-4	r	-0.38	0.58	-0.47	-0.29	-0.43	-0.43	-0.57	-0.46
	|p|	(0.219)	(0.047)	(0.126)	(0.367)	(0.158)	(0.165)	(0.054)	(0.134)

[1] r = correlation coefficient
|p| = probability value
Source: Vityakon et al. (2000)

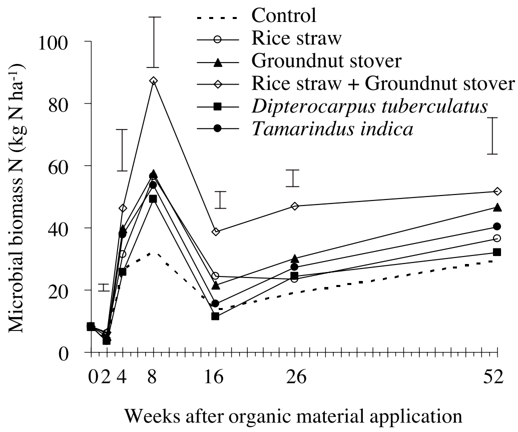


Figure 6. Dynamics of microbial biomass nitrogen as affected by different organic residues under upland conditions. ***Vertical bars represent SED.*** **(Vityakon et al., 2000)**

This results in two major subsystems: upland fields for production of cash crops, principally cassava and sugarcane; and lowland paddy rice fields. The use of appropriate organic residues as N sources to improve soil fertility of the two subsystems is dictated by their differing soil water regimes. The upland subsystem is virtually continuously aerobic while the lowland subsystem is periodically submerged. It has been shown that N mineralization in anaerobic conditions is higher and faster than in aerobic conditions. A pot study (Vityakon and Dangthaisong, 2005) comparing the performance of various kinds of leaf litter (both leguminous and non-leguminous) from trees found in the northeast farming systems under submerged and aerobic conditions in sandy soils found that there was higher net N mineralization and lower immobilization under submerged than aerobic conditions. In addition, N mineralization was more rapid in submerged (first peak mineralization within 2-4 weeks) than aerobic conditions (Figure 7, 8 a, b). The higher and more rapid N mineralization in submerged than aerobic conditions is partly because the microflora in flooded soils (with a higher proportion of bacteria) have a lower N requirement stemming from their lower synthetic efficiency compared with the aerobic population (with more fungi and actinomycetes) (Broadbent, 1979; Ono, 1989 as cited by Vityakon and Dangthaisong, 2005). In addition, leaching and/or dilution of polyphenols may also lower efficiency of the compounds in binding proteins and consequently inhibit N release under submerged conditions.

Based on chemical compositions alone, Palm et al. (2001) have classified organic residues into 4 types to guide the selection of residues that provide optimal N inputs for soil fertility management. The classification employs a minimum set of quality indicators, i.e. N, lignin and polyphenol content of organic materials (Figure 9). Vityakon and Dangthaisong (2005) have shown that this classification system may have limited applicability in a farming system that has both upland crops and paddy rice subsystems, such as is commonly found in Northeast Thailand, because organic residues (leaf litter from some trees) exhibited different N mineralization-immobilization patterns under submerged and aerobic conditions. For examples, under submerged conditions, leaf litter of *Samanea saman* and *Xylia xylocarpa* exhibited net N

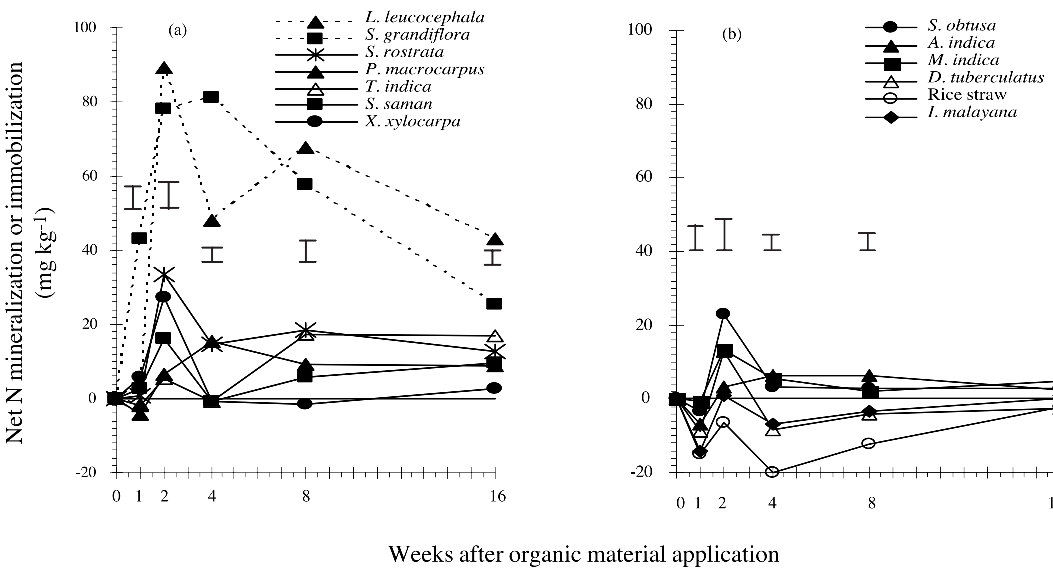


Figure 7. Net quantity of mineral nitrogen present in submerged soil of Northeast Thailand at various times after amendment with different organic residues: (a) legume residues, (b) non-legume residues. ***Vertical bars represent SED.*** **(Vityakon and Dangthaisong, 2005)**

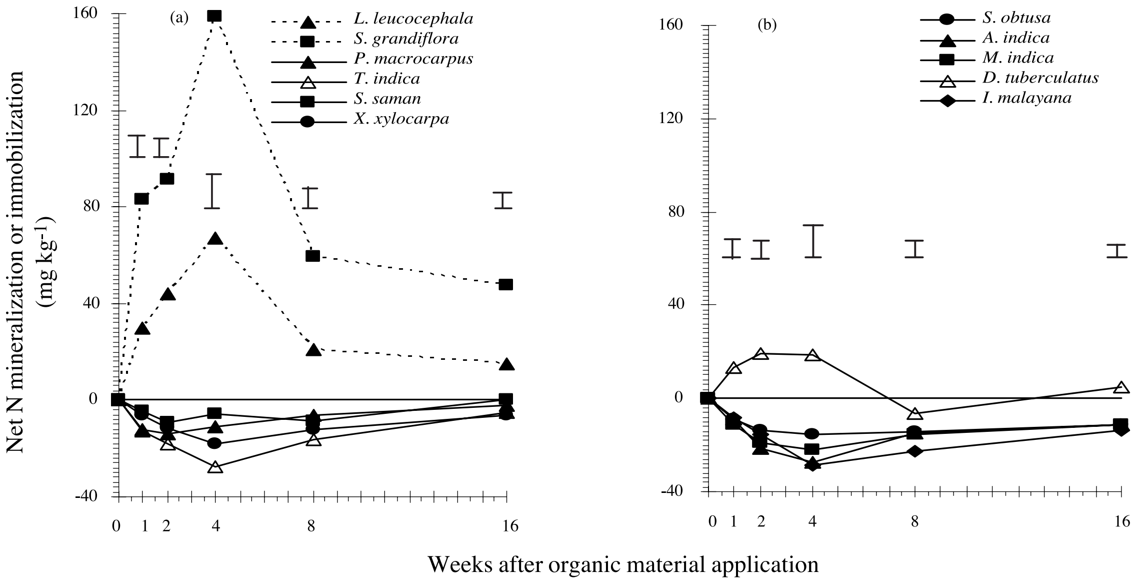


Figure 8. Net quantity of mineral nitrogen present in aerobic soil of Northeast Thailand at various times after amendment with different organic residues: (a) legume residues, (b) non-legume residues. *Vertical bars represent SED.* (Vityakon and Dangthaisong, 2005)

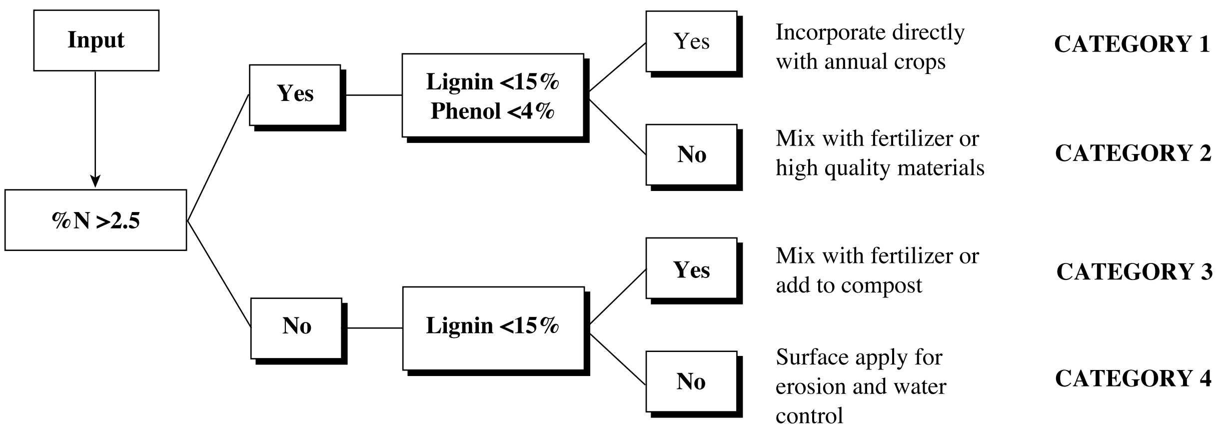


Figure 9. Criteria for selecting organic residues as nitrogen sources for soil fertility management as proposed by Palm et al. (2001)

mineralization peak during the early phase (week 2) of decomposition followed by slight net N immobilization during the intermediate phase which preceded low net N mineralization in the final period (Figure 7a). However, under aerobic conditions they exhibited net N immobilization throughout the 16-week period after incorporation into the soil (Figure 8a). This has further shown that they should be managed differently under submerged and aerobic conditions. In submerged conditions, they showed some early low N release (Figure 7a) and, hence can be used as an immediate N source to supplement other higher release N sources. However, in aerobic conditions they did not release N during at least the 16-week study period (Figures 8a), therefore they may have to be managed in the way suggested for the lower categories of the classification of Palm et al. (2001), i.e. to be mixed with mineral fertilizers or high-quality organic materials to delay N release, or to be composted before soil application, or to be used as surface mulch for erosion and water control.

Conclusions

In comparison to natural forest, soil degradation has occurred in sandy soils under agricultural land uses in Northeast Thailand as indicated by declines in the various pools of organic matter. The degradation is due to reduced input or recycling of organic materials and higher disturbance of soil due to soil management practices. In upland fields, the degradation of SOM pools was more severe under cassava than sugarcane because sugarcane returns more organic residues to the soil than cassava. Paddy rice cultivation does not bring about significant SOM degradation because the paddy fields usually possess less sandy soil (higher clay content than upland fields), receive organic deposits eroded from upper lying land in undulating terrain, and recycle crop residues in the roots and stubble of the rice plants.

SOM levels in cultivated sandy soils can be built up by increasing organic inputs into the system in two ways. Firstly, by generating increased quantities of organic residues within the system itself, such as under pasture, rotation with green manure crops, or having trees that produce litter of desirable quality. It can also be achieved by bringing organic inputs from off-farm sources, such as industrial by-products, animal manure etc. Quality of organic residues also influence different pools of SOM. While high quality residues bring about short-term nutrient release, low quality (slowly decomposed) residues tend to enhance the stable pool (humic substance) of SOM. Another measure is to minimize soil disturbance, such as ploughing, since ploughing has been shown to reduce SOM content.

Restoration of soil fertility, notably nutrient N, can be achieved through the use of organic residues of different qualities. The high quality residues can release N within a short term, which can be useful when the crop requirement is immediate, otherwise the mineral N produced can be wasted. Mixing high and low quality organic residues at appropriate ratios can bring about the ability to manipulate the time of N release to coincide with crop demand. This is the basis of the ‘synchrony’ concept. Low quality residues are also useful as N sources when mixed with high quality residues or chemical fertilizers. N release of low-quality residues can be enhanced if applied in submerged conditions, i.e. in paddy rice conditions. Therefore, different kinds of organic residues are appropriate as N sources under submerged and aerobic conditions. In classifying organic residues for appropriate use as N sources, one needs to take into account environmental conditions affecting N mineralization, in addition to residue chemical compositions. In addition to non-harvestable organic residues, tree litter is another organic residue available in farming systems of Northeast Thailand that can potentially enhance SOM build-up and N fertility of the sandy soils.

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Session 6

“The management of these agro-ecosystems”

The management of the agro-ecosystems associated with sandy soils

Bell, R.W. *[1] and V. Seng [2]*

Keywords: agro-ecosystems; erosion, leaching, nutrient cycles, water balance, sandy texture

Abstract

Sandy soils are prevalent in tropical environments especially where felsic volcanic, or siliceous sedimentary rocks and their erosional products are found. Whereas some of these soils are only sandy in the surface layers, others are sandy throughout the root zone. In terms of the agro-ecosystems developed on sandy soils, the prime limiting factors and the main concerns for sustainability, vary according to their position in the landscape (steeplands, uplands and lowlands) and agro-ecological zoning. Sandy soils occur in arid, semi-arid and humid rainfall zones of the tropics and from coastal lowlands to high altitudes. Sloping sandy soils tend to be used for conservation reserves, forestry (including plantations) and for shifting cultivation, and may also serve as important water catchments. Sandy uplands and lowlands are used for a range of cropping systems including rice-based systems. Plantation crops and forestry are also prevalent. The continuously or seasonally waterlogged lowlands are largely developed for irrigated and rainfed rice cultivation. Tropical sandy soils have a wide range of limiting factors for agricultural use, these include nutrient deficiencies, acidity, water stress and poor physical attributes. The environments in which they occur are prone to degradation risks from nutrient decline, erosion, leaching, salinity, and acidification. Development of sustainable agro-ecosystems in these sandy terrains should be based on optimisation of key ecosystems processes: closing nutrient cycles, restoring hydrological balance; enhancing biodiversity and strengthening resilience of these processes to perturbations. A range of opportunities exist to achieve sustainability of sandy landscapes through plantation forestry, agroforestry, clay and other mineral soil amendments, maintenance of soil organic matter, balanced fertilisation, strategic irrigation, and breeding species for adaption to the constraints present. Management of agro-ecosystems associated with sandy soils will be explored with respect to agricultural productivity and sustainability, and the supply of ecosystem services.

Introduction

Sandy soils as defined in the World Reference Base (FAO-ISRAC-ISSS, 1998) contain <18% clay and >65% sand in the first metre of the solum. Generally, the main Reference Group for sandy soils is the Arenosol (FAO-ISRAC-ISSS, 1998). The nearest Soil Taxonomy equivalent is the Psamment sub-order (Van Wambeke, 1992). However, amongst tropical soils, sandy textures in the surface layers are more prevalent than sandy textures throughout the profile, and the shallow sandy soils may share similar attributes and constraints as deeper sandy soils for shallow rooted crops such as padi rice. Hence, in areas where lowland rice is prevalent it may be important to broaden the scope of sandy soils beyond the Arenosols to include those Reference Groups with members that are sandy in the surface layers: Regosols, Leptosols and Fluvisols.

Tropical sandy soils are prevalent in landscapes where felsic volcanic, or siliceous sedimentary rocks and their erosional products are found. They are also prevalent in desert regions, and as beach deposits and dunal features in coastal zones. The lower Mekong River Basin in Southeast Asia has an extensive area of sandy soils (Mekong River Commission, 2002). Other major provinces for sandy soils in tropical environments include: the Sahel zone of West Africa, the Kalahari basin (covering two-thirds of Botswana and Angola), and Northern Australia. However, smaller but still significant areas of sandy soils occur in most tropical regions including parts of central Vietnam, Pakistan, Saudi Arabia, Iran, and Brazil (FAO, 2005).

In terms of the agro-ecosystems developed on sandy soils, the prime limiting factors and the

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main concerns for sustainability, vary according to topography, *viz*, steepland (>12% slope), uplands and lowlands; sub-divided further by agro-ecological zoning. Sandy soils occur in arid, semi-arid and humid rainfall zones of the tropics and from coastal lowlands to high altitudes. For the purposes of this paper, we will exclude sandy soils in desert regions due to their low potential for land use except where irrigation water is available.

Sandy soils in steeplands tend to be used for conservation reserves, forestry (including plantations) and for shifting cultivation, and may also serve as important water catchments. Sandy uplands comprise all those soils that are neither seasonally waterlogged nor steep. They are used for a range of field cropping systems depending on the agro-ecological zoning and elevation. Plantation crops and forestry are also prevalent. Sandy soils in the continuously or seasonally waterlogged lowlands are largely developed for irrigated and rainfed rice cultivation especially in Asia. While sandy soils are not highly suitable for rice cultivation, because rice is the major subsistence crop in Southeast Asia, sandy soils commonly are used for this purpose. Rice is also common in West Africa. Because of the shallow rooting zone of padi rice which is restricted to 0-20 cm, the surface texture has a more dominating influence on lowland rice than in upland cropping. Hence it is common to refer to soils in lowlands as sandy if they have sandy surface textures regardless of the subsoil texture. Indeed, White *et al.* (1997) in their Cambodian Agronomic Soil Classification system (CASC), developed for rice soils, restricted their consideration of soil properties to the 0-50 cm depth. The continuously or seasonally waterlogged lowlands are also important fisheries habitats, for aquaculture and for flood control.

The environments in which tropical sandy soils occur are prone to degradation risks from nutrient decline, erosion, leaching, salinity, and acidification. Management of agro-ecosystems for sustainable production on these landscapes will need to find technologies to overcome these constraints for economic viability of the enterprises. Development of sustainable agro-ecosystems in these sandy terrains should be based on optimisation of key ecosystems processes: closing nutrient cycles, restoring hydrological balance; enhancing biodiversity and strengthening resilience of these processes to perturbations. A range of opportunities that exist to achieve sustainability of agro-ecosystems in sandy landscapes will be outlined.

Development of sustainable agro-ecosystems in sandy terrains

Sustainable agro-ecosystems need to simultaneously satisfy three sets of criteria: economic viability; ecological processes; and social acceptability (Lefroy et al., 1992). This represents an advance on earlier thinking that focussed on economic viability of agro-ecosystems. It also recognises that focussing only on ecological processes will not be sufficient for sustainable agro-ecosystems since economic viability continues to drive many key decisions by farmers, and society increasingly is expressing a voice about the practice of agriculture in terms of the quality of food it delivers to markets and the off-site impacts of agriculture.

Economic viability of agriculture

Tropical sandy soils have a wide range of limiting factors for agricultural use: these include nutrient deficiencies, acidity, low water storage and poor physical attributes. Limiting factors may have a major bearing on the economic viability of agriculture on sandy soils. For example, a large province of sandy soils in Western Australia was deficient in the micronutrients, Zn, Cu and Mo (Bell *et al.*, 2004). Until the discovery of these deficiencies and practical means of correcting them, it was not economically viable to use these sandy soils for agriculture.

Low nutrient levels are common on sandy soils, and crops grown on these soils commonly express multiple nutrient disorders which limit productivity of crops (e.g. Northeast Thailand, Bell *et al.*, 1990). While fertiliser can correct these disorders, it is often difficult to achieve the optimal mix of nutrients and other soil amendments to make it economic (e.g. Ragland and Boonpukdee, 1987). Failure to diagnose all the limiting nutrients in a soil will lead to ineffective use of fertilizer and poor responses to those fertilizers that were applied. The widespread use of N alone often provides poor returns from fertilizer investment since on sandy soils deficiencies of P, S, K and/or micronutrients also commonly limit crop production.

In part the difficulty of fertilizing crops when there are multiple deficiencies is lack of availability of appropriate fertilizer products. In Thailand, for example, there are a large range of fertilizer products available, but limited understanding by farmers of the types most suited for particular soils and crops (Bell *et al.*, 1990). A range of NPK formulations are commonly available in the Thai market but they vary in S content (Chunyanuwat *et al*., 1993). Since S deficiency is quite common in Northeast Thailand, NPK formulations with different S content may give quite different responses in crops (Bell *et al*., 1990). Similarly, NPK formulations in Thailand vary in B content which would affect responses since large areas of sandy soils in Northeast Thailand are low in B (Bell *et al*., 1990). Market supply of micronutrient fertilizers varies nationally and locally and in many places such fertilizers are not readily available, e.g. Bangladesh (C. Johansen, pers. comm.). Finally, according to Ragland and Boonpukdee (1987) responses to fertilizers alone on sandy soils in Northeast Thailand are poor without addition of organic matter.

The high percolation rates of the deep sands are a major limiting factor for rainfed agriculture. Drought is the most important consequence for crops. However, leaching of N and other nutrients may also limit productivity of these soils even when water is not limiting. For example, the deep sandy Prey Khmer soil in Cambodia has lower potential productivity for rice even with fertilizer application than the other major sandy lowland soil (Prateah Lang), which has a higher clay content in the subsoil (White *et al*., 1997).

Acidity is common on sandy soils. Where lowland rice is the main crop, flooding alleviates acidity (Kirk, 2004). However, for rainfed crops, acidity may give rise to a range of fertility constraints including Al and Mn toxicities and deficiencies of nutrients (Dierolf *et al*., 2001). Poor N fixation in legumes is often a consequence of soil acidity due to the low tolerance of Rhizobia to acidity, and to low levels of plant available Mo.

Salinity is a common constraint on sandy soils wherever irrigation is used in semi-arid environments. In sandy coastal zones, salinity is associated with seawater intrusion (White *et al*., 1997). Less well recognised is dryland salinity, which arises from perturbation of the hydrological balance in rainfed environments. It is a major problem in Northeast Thailand where a large percent of soils are sandy: currently dryland salinity affects about 12% of the lowland soils but is predicted to spread to cover up to 30% (Yuvaniyama, 2001).

Optimisation of key ecosystems processes

In undisturbed ecosystems, key processes such as the cycling of nutrients, hydrological balance, energy capture and flow, biodiversity, and resilience maintain ecosystem function. Disturbance of ecosystems for agriculture alters each of these processes. It has been argued that sustainable agro-ecosystems could be developed by mimicking the operation of the key ecosystem processes (Lefroy and Stirzaker, 1999). Hence a way forward for sustainable agriculture in sandy terrains is to understand key ecosystem processes that operated in pre-existing ecosystems and to model agriculture on those processes. However, there are practical limits to the application of this approach. Firstly, there are as yet inadequate studies of ecosystem function in tropical sandy terrains. Secondly, where harvested products are exported from the location from which they were produced, the nutrient cycle is interrupted and nutrient supply needs to be maintained through inorganic and/or organic inputs.

Closing nutrient cycles

In undisturbed ecosystems, the cycling of nutrients through the biomass and soil compartments ensures that leakage of the store of nutrients is negligible (Grierson and Adams, 1999). Small amounts leave the ecosystem but may be offset by accretion in rainfall, by nitrogen fixation etc. However, most agricultural systems allow significant nutrient losses through harvested product removal, leaching, gaseous losses, and erosion. While these losses may be offset by fertilizer use or the return of crop residues to the field, the losses of nutrients still represent inefficiency in nutrient use and may have off-site consequences. Sandy soils in Northeast Thailand, for example, have lost considerable nutrient capital since the clearing of dipterocarp forests (Noble et al., 2000) and changed nutrient cycles and hydrology have made these soils prone to acidification. Nutrient budgets calculated for farm land in Northeast Thailand show large net losses at the field scale and at regional scale (Lefroy and Konboon, 1998).

Restoring hydrological balance

Water balance considers the partitioning of rainfall to evaporation, transpiration, runoff, deep drainage and to the change in soil water storage. In sandy terrain, the runoff component may be low especially in the pre-existing ecosystems. Change of land use to agriculture would normally alter hydrological balance by changing runoff, transpiration and deep drainage components (Lefroy and Stirzaker, 1999). Northeast Thailand is a relevant case study demonstrating the consequences of hydrological change in a sandy terrain. The development of dryland salinity appears to be related to a change in the landscape water balance following clearing of the forest for agriculture (Williamson *et al*., 1989). Rapid clearing in Northeast Thailand occurred in the 1960's (Ruaysoongnern and Suphanchaimart, 2001). Prior to that, the salt stored in the halite strata of the near-surface sedimentary formation was not mobilised because the vegetation used most of the rainfall allowing little deep drainage to groundwater. However, under rice-based and upland cropping, significant deep drainage to the groundwater occurs annually and this has caused watertables to rise regionally over time. When groundwater reaches the soil surface or within 2 m of the surface, discharge of salt occurs annually at the soil surface. The gentle relief of the Northeast Thailand and the widespread shallow halite-bearing sediments place large areas of Northeast Thailand at risk of dryland salinity.

As the development of salinity in sandy soils of Northeast Thailand is essentially a water balance problem (Williamson *et al*., 1989), its long term solution will come from changes in land use that decrease deep drainage to regional groundwater. Given the current prevalence of lowland rice cultivation, this will prove a challenge in the short term. Tree planting or revegetation with perennial vegetation across a significant portion of the landscape may be needed to restore water balance, but the minimum amount needed to be effective is not known. Currently upland areas are mostly targeted for tree planting. More extensive agroforestry planting in lowlands may also be needed to help restore the water balance.

However, wherever large areas are seasonally flooded, deep drainage will continue. Lowland rice is uniquely dependent on surface hydrology and the duration of standing water in relation to crop growth stages (Fukai *et al*., 2000). Marked alteration of the hydrology of sandy terrain inevitably occurs with its cultivation. High deep drainage rates are a common problem in the sandy lowland rice soils of Cambodia (White *et al*., 1997), Laos and Northeast Thailand (Fukai *et al*., 1995). Deep drainage rates varied from 1 to 6 mm d^{-1} on sandy soils (Fukai *et al*., 1995). Model simulations for Ubon in Northeast Thailand show about a 50% increase in rice yield if the deep drainage rate of a sandy soil (6.3 mm d^{-1}) under puddled conditions could be reduced to 1.4-1.8 mm d^{-1} (Fukai *et al*., 2000).

Fields in the high or upper terraces of the sandy lowlands lose large amounts of water, particularly after heavy rainfall, through surface runoff and subsurface lateral water movement, while those in the lower terraces may intercept the flows from the upper paddies (Fukai *et al*., 2000). Moreover, location of on-farm drains, and road embankments and drains under roads can markedly affect where the runoff is directed. Lateral redistribution of water results in water availability and rice growth duration varying by 30 days or more, within quite small areas. Fukai and colleagues have used simulation models to estimate the sensitivity of rice yield to the effect of variation in one parameter while all others are held constant. In sandy terrain at Ubon in Northeast Thailand, the influence of run-on to the lower terrace diminished as the deep percolation rate was reduced from 6 to 1 mm d^{-1}. With 1 mm d^{-1}, there was almost no water stress throughout the growth period and hence the effect of water movement was small, whereas, with 4-6 mm d^{-1}, rice experienced periods with standing water interspersed with periods of water stress. In this case, simulated grain yield was strongly influenced by variation in lateral water movement.

Enhancing biodiversity

Agricultural ecosystems generally involve a decrease in biodiversity relative to the prior native ecosystems that existed. This is particularly the case where monocultures of cereals or plantation crops dominate the landscape. Biodiversity in these monoculture-dominated agro-ecosystems is usually greatest around villages and home gardens, and in the remnants of the prior ecosystems especially in less favoured agricultural environments such as riparian zones along rivers, streams and wetlands. Enhancing biodiversity within the agricultural system can be achieved through agroforestry, intercropping and crop diversification. *In situ* conservation of wild relatives of crop species has an important role in conserving genes that may be useful in future breeding programmes (Rerkasem, 2004). Flora in greatest need of conservation is in the sandy uplands due to their widespread use for agriculture. Conservation in the steeplands is often compromised by short rotation shifting cultivation, but there are cases in Southeast Asia of the compatible use of steeplands for agriculture and the conservation of biodiversity (Rerkasem, 2004).

Opportunities to improve sustainability of sandy landscapes

Sandy soils represent an ongoing challenge for water and nutrient management at landscape and field scales. Productivity on these soils tends to be low, even when recommended agronomic practices are followed. However, there are a number of promising avenues for sustainable development of agro-ecosystems dominated by sandy soils.

Maintenance of soil organic matter

Sandy soils generally have lower organic matter levels than heavier textured soils given similar rainfall, temperature, land use and tillage. Clay levels on deep sandy soils may be too low to protect organic matter from oxidation (Baldock and Nelson, 2000). Reducing tillage may help maintain organic matter levels. Perennial crops will also tend to maintain higher organic matter levels. However, there are practical limits to the levels of organic matter that are achievable on sandy soils (Shirato *et al*., 2005). Research with the aim of boosting organic matter levels in sandy soils often fails to recognise this limit and as a result there has been much wasted investment on organic matter management. Organic matter levels can be enhanced in sandy soils through minimum tillage, zero burning and retaining crop residues. Slowly decomposing litter appears to build organic matter levels over a period of several years on sandy soil in Ubon, Northeast Thailand (Naklang *et al*., 1999).

Clay and other mineral soil amendments

Possibly the most effective long term investment in improving productivity and sustainable use of sandy soils would be to increase their clay content. Application of clay to sandy soils has been suggested as a semi-permanent treatment to enhance water and nutrient retention in Northeast Thailand (Noble *et al*., 2004). Enhanced clay content would allow soils to accumulate increased organic matter levels, and hence retain more water and nutrients and buffer soils against significant change in chemical properties. However, this strategy is limited by the availability of clays, the cost of transporting the required amounts of clay and by a still rudimentary knowledge about potential benefits. Initial research on the sandy soils of Northeast Thailand suggests very strong responses in growth can be achieved by clay amelioration. Further work is ongoing to demonstrate the benefits of this technology. Northeast Thailand has numerous deposits of high activity clay in lacustrine sediments, S. Ruaysoongnern (pers. Comm.). The relevance of this technology for other parts of the region, particularly for the Prey Khmer (Arenosols) and Prateah Lang (Acrisols) soils of Cambodia (White et al., 1997; Bell and Seng, 2004) warrants further investigation.

Balanced fertilization

Sandy soils commonly suffer from multiple nutrient deficiencies. These problems can be compounded by Al toxicity. For this reason, the concentration of research on N or NP fertilizer use that has yielded significant benefits for farmers on loam and clay soils often gives disappointing results on sandy soils. Our research on farmers’ fertilizer use on sandy soils in Southern Cambodia suggest that they over-used N and under-used P, K and hardly used S (Ieng *et al*., 2002). Even a focus on NPK fertilizer use may lead to ineffective fertilizer programmes since S and micronutrient deficiencies such as B, Zn, Cu and Mo are common. Bell *et al*. (1990) reported extensive areas of multiple deficiencies on sandy soils of Northeast Thailand yet as discussed above S contents of fertilizers vary and relatively little use of B fertilizer has occurred despite there being solid evidence of crop yield responses to this element. The challenge for achieving balanced crop nutrition in sandy terrain is to provide simple advice and tailored fertiliser advice and products so that it can be efficiently delivered to large numbers of small farmers. Nutrient budgets may be a useful strategy for guiding farmers to consider the important issues for balanced nutrition and sustainable crop production. However, it needs to be supported by a parallel business development approach that seeks to supply fertilizers of the right type in the markets where they are needed, at an affordable price.

Plantation crops, forestry and agroforestry

Where the pre-existing ecosystems were forests or woodlands, a sustainable agro-ecosystem probably needs to incorporate a similar vegetation structure, as plantation crops, plantation forestry, or agroforestry. The soil cover provided by perennial vegetation minimises erosion and nutrient leaching, while the decrease in cultivation intensity and frequency helps maintain soil organic matter levels and soil structure. Ecosystems benefit from restoration of water balance, closed nutrient cycling, and enhanced biodiversity. Agroforestry may provide similar benefits to plantations (Young, 1997).

Breeding species for adaption to the constraints

Where a soil constraint is widespread and difficult to overcome by conventional agronomy, there is a strong case for breeding for tolerance to the stress. In sandy soils, this would commonly mean breeding for drought tolerance first, followed by tolerance of mineral disorders, including soil acidity.

Management of agro-ecosystems associated with sandy soils

Ecosystems provide a range of services that tend to be undervalued, and those existing on sandy terrains are no exception. Changed water balance which is the consequence of land use for agriculture in most cases, gives rise to land degradation that has on-site and off-site effects. Sandy soils in river basins deliver water that is used for a variety of purposes downstream. Changed water flow patterns and changed water quality may harm downstream wetlands and riparian zones on which the livelihoods of communities depend. Changed water flow patterns may give rise to downstream flooding events that impact on major settlements and cities. Excess nutrients or sediment from sandy terrains may cause harm to fisheries and fisheries breeding places. Hence there is a need to develop institutional arrangements that pursue integrated river basin management outcomes that recognise the connection between upstream and downstream users and achieve equity between their respective costs and benefits (Kam *et al*., 2001). Such institutional arrangements need to incorporate the range of stakeholders that have an interest in the structure and function of river basin management, including government natural resources management agencies representing both production and conservation, private sector business, educational institutions and civil society groups.

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Long-term topsoil changes under pearl millet production in the Sahel

Anneke de Rouw[1]

Keywords: Sandy soils, pearl millet, fallows, organic matter, manures

Abstract

In the Sahel, cultivated soils are commonly described as low fertility and acid sands. The fertility maintenance for pearl millet cultivation, the dominant source of food, relies either on fallowing or on manure application. The restoration of fertility under fallow is linked with increases in soil organic matter. A second amendment is dust that is wind blown from the Sahara, and for this, the tree and shrub-covered fallow land constitutes a considerable clay + silt trap. This study investigates the impacts on soils and yields resulting from the gradual shortening of fallow periods and the increasing use of manure to replace the fallow. Observations were conducted on farm (9 fields under a fallow system, and 5 fields under a manure system) over four years. Soil organic matter (0-20 cm) declined from 3.69 g kg^{-1} under long fallow management (>15 years) to 2.31 g/kg under short fallows (3-5 years), while the clay + silt fraction reduced from 107 g kg^{-1} under long fallows to 57 g kg^{-1} soils under short fallows. On manured fields (>10 years), soil organic matter (OM) stabilized at 2.97 g kg^{-1} soil. Short periods of fallow with no inputs resulted in topsoils that were very poor in N (long fallows 183 mg N kg^{-1}, short fallows 117 mg N kg^{-1}) with very low CEC (long fallows 1.04 cmol$_c$ kg^{-1}, short fallows 0.71 cmol$_c$ kg^{-1}).

Fallow managed fields had a pronounced micro relief (8-9 cm) related to trees and shrubs on steep-sided crusted micro hills generating runoff. In manured fields, the micro relief was mainly composed of aeolian micro dunes favouring infiltration due to the trapping of sand by dung, herbs and millet stubble. Grain production was approximately 400 kg ha^{-1} in long fallow fields and manured fields alike, but only 200 kg ha^{-1} under short fallows. With time, cultivated soils lose part of their clay-silt content from the topsoil through wind erosion which is enhanced by manual cultivation. Loss of fine particles results in less surface crusting and gradually, the entire field surface becomes highly permeable and eventually results in sandy skeletal soils that are entirely unproductive without constant inputs of manure. Farmers state that this transformation takes approximately 40 years. Losses of fine earth can only be achieved by the trapping of dust during long term fallowing. Manuring allows prolonged cultivation while it stabilises soil O.M. but it does not stop the loss of fine earth by wind erosion.

Introduction

In the African Sahel, between the 400 and 700 isohyets, people subsist on pearl millet, the only profitable crop. Agriculture and husbandry are often linked in this semi-arid region. However, both crops and livestock productions suffer from a combination of low soil fertility and scarce and unpredictable rains. Most soils in the Sahel are derived from acidic or aeolian parent materials which are poor in clay and nutrients, especially N and P (Bationo & Mokwunye, 1991). Almost all nutrients are found in the soil organic matter, a fraction that is also very low. The decline in nutrient status during cultivation is an inevitable consequence of clearing and is reinforced by the effects of cultivation (Ahn, 1970 p. 244; Feller & Beare, 1997). The ongoing physical land degradation in the Sahelian zone of West Africa, sealing, crusting, hardsetting of soils and the long-term reduction in amount of diversity of the natural vegetation, is enhanced by population growth and a marked drier climate since the 1970s (Sivakumar, 1992; Valentin, 1995).

Cultivation clears the soil and leaves the soil surface almost bare. Due to the heavy rains, the soil undergoes serious structural deterioration. The impacts of the drops separate the fine soil particles and the organic matter from the sand, and the soil pores get clogged. This makes the sandy soils of the Sahel very liable to surface crusting (Ambouta et al., 1996). Soil surface crusting reduces the infiltration rate, and thus triggers runoff and erosion. It constitutes a serious

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constraint for cultivation in dry areas (Casenave & Valentin, 1992). However, wind erosion is probably a greater constraint. Land clearing reduces the soil protection provided by the standing vegetation and the litter (Bielders et al., 2000). Moreover, any soil tillage breaks the surface crusts, and the detached material can be easily carried away by the wind during the storms (Valentin, 1995). The protection of the soil surface is improved by the presence of stable aggregates at the soil surface, which obviously resist better to the impact of the raindrops (Feller et al., 1989). It is also improved by any object, crop residue, dung or vegetation fragment lying on the soil, as they absorb the energy of the rains (Collinet & Valentin, 1985) and trap wind-blown particles during the storms (De Rouw & Rajot, 2004b).

Dust trapping is particularly important in the Sahel. In contrast with the local soils, which tend to be acid and highly weathered, the dust from the Sahara exhibits appreciable quantities of water-soluble and exchangeable cations (Hermann, 1996). About 25% of the dust-load consists of clay, silt and organic matter, the rest being very fine sand (Möberg et al., 1991). Though dust constitutes an important long-term factor of nutrient renewal for these soils, and though dust is supposed to help maintain soil fertility, the actual quantities involved are difficult to assess. Estimations of annual dust input in Southwest Niger varies widely, depending on method and scale: 0.9 t ha^{-1} (Buerkert & Hiernaux, 1998), 6.8 t ha^{-1} (Chappell et al., 1998), and 1.9 t ha^{-1} (Herrmann et al., 1994). When open buckets are used to measure dust deposition, only the airborne material that falls down vertically like rain is trapped. However, dust accumulates on vertical obstacles, thus tree- and shrub-covered fallows that constitute a considerable dust-trap. An appropriate method to determine the complementary dust input due to tree and shrub trapping would be to wash the dust from the vegetation and to estimate the leaf area. Though the sedimentation of dust is evident and the chief processes of soil restoration and soil losses is well documented, there is a need to investigate how pearl millet cultivation respond to this.

Most farmers in the Sahel are too poor to use external inputs (Powell et al., 1996). Subsequently, the long-term success of pearl millet cultivation depends on the recycling of nutrients in the topsoil. In practice this means either by manuring or fallowing. Model-based farm studies integrating livestock, pasture and cropland components suggest that the continuous cultivation of soils in the Sahel can be achieved by manure application, even if low quantities are applied (Harris, 1999; Abdoulaye & Lowenberg-de Boer, 2000; Buerkert & Hiernaux, 1998; Bielders et al., 2002). Minimum dung inputs observed in farmers’ fields are 1.3 t ha^{-1} every two or three years (Powell & Williams, 1993) and 1.1 t ha^{-1} $year^{-1}$ (De Rouw & Rajot, 2004a). No such farm studies are available for fallowing. This study focuses on the changes in top soil due to long-term cultivation of soils and aims to relate well-known processes of soil restoration and degradation to farming practices.

Materials and Methods

Study area

The study area is located 60km east of Niamey , Niger, near the village of Banizoumbou (13º31′N, 2º39′E). The village territory, approximately 80 km², was exploited by 84 farms with an average number of 10 persons per farm. Part of the best land had been cultivated for about 150 years in alternation with periods of bush fallow. By 1990 this type of cultivation has spread over 70% of the village territory, the remaining 30% being marginal land or unfit for cultivation yet suitable for pasture (Loireau, 1998). In 1978, cultivation with regular manure application started and this practice was used at the time of the study over about 10-15% of the annually cropped area. Only 15% of the farms had more than 10 domestic animals (zebus, goats and sheep), the others had less or no livestock. However, exchange contracts were often made between farmers and nomadic herders about the manuring of fields. In the dry season, animals are left free at night in the field to let the dung and urine fall on the soil surface and decompose in situ. In the day-time these herds move to permanent pasture or fallow land. This labour-extensive practice is widespread in the Sahel (Landais & Lhoste, 1993; De Rouw & Rajot, 2004a).

The climate is hot and dry most of the year. The mean annual rainfall is 550 mm, the rains falling between June and September. The four years of experiments (1993-1996) were near average as far as total rainfall was concerned (total rainfall: 461, 642, 509 and 523 mm) but the distribution of the rain events varied largely between years and sites.

Crop production was entirely rainfed. Pearl millet was cultivated on every field, the fields being usually very large (minimum and maximum area of individual fields 4 and 30 ha, respectively). The crop was sown in hills and generally two weeding rounds were required. Weeding was performed using the “hilaire”, a shallow cultivating hoe that not only cuts the roots of the weeds but, more importantly, breaks the superficial crusts to allow the rains to infiltrate. All tillage operations (cultivation, clearing, sowing, thinning, weeding) were entirely made by hand and no chemical fertilizers were applied. Thick aeolian sand deposits, up to 9 m thick, were the preferred areas for cultivation, provided the slopes were less than 4%. These deposits were uniformly sandy, from 91% sand, 6% silt and 3% clay in the topsoil upper slope to 90% sand, 6% silt and 4% clay downslope. The organic matter content in the topsoil was very low, but slightly higher downslope (0.27%) than upslope (0.23%) (D'Herbès & Valentin, 1997). These cultivated soils are classified as Psammentic or Cambic Arenosols (FAO).

Sites and cropping systems

A survey among 60 farms gave four cropping systems depending on the farmers' access to arable land and manure.

Fallow system – long cycles. Farmers with land but no access to manure cultivate the same field for about 10 years then let it lie fallow for more than 15 years (four fields).

Manure system – new fields. Farmers with land and access to manure open up new fields and apply small quantities of manure each year thus cultivating the same site for over 15 years (four fields).

Fallow system – short cycles. Farmers with little land and no access to manure cultivate the same plot for short periods, 4-6 years, after which a fallow period is necessary of 3-5 years (four fields).

Manure system – old fields. Farmers with little land but access to manure recuperate impoverished land that they make productive by annual manure application (three fields).

It should be kept in mind that all fields are under the pressure of population increase, resulting in two long-term trends: (1) The gradual shortening of the fallow period, i.e. fields of the Fallow system – long cycle will progressively pass into the group Fallow system – short cycle. (2) Manure replacing the fallow, i.e. some fields of the Fallow system will evolve into field of the Manure system.

Plot size and other observations

Pearl millet stands can be extremely variable over short distances. Part of this variability is organized along the slope (Rockström & de Rouw, 1997). In order to capture this variability, the plots were arranged in transects of 100 m*5 m running down the slope. However, some variability appeared at random in the fields. This was mainly due to contrasting soil surface features ranging from highly permeable micro dunes to almost impermeable crusts. The size of the plots was adjusted to the scale of these heterogeneities (5*5 m).

Some transects were studied for four years (3 fields), others for two years (9 fields), and some for only one year (3 fields). The general description of each field (n = 15) included the area, the slope and the history of the site, with an estimate of the family's access to manure, workforce and land. Annual records for each field (n = 33) included the daily rainfall and the cropping practices. Annual records of each plot (n = 1,320) included: (1) in the first week after sowing: cover by dung and crusts (typology after Valentin & Bresson, 1992), maximum height and origin of micro relief (between 5 and 50 cm), and the meso relief (over 50 cm, mainly gullies); (2) at harvest: number of woody plants, grain yield and total aboveground biomass of the crop. Fresh biomass was weight in the field and a sample was taken and ovendried (24H 70ºC) for dry weight determination.

Soil sampling and analysis

Topsoil (0-20 cm) samples were taken at harvest. As the analysis of every plot each year was too costly, two compromises were made: (1) as transects ran down the slope and the soil texture was known to slightly increase downslope, samples of two adjacent plots were mixed, up to a maximum of four plots in case they looked homogeneous; (2) When the soil conditions were different in adjacent plots (*e.g.* a gully or sand fan) the soil samples were analysed separately. As a result, the number of soil samples analysed per field varied between a minimum of 10 in transects with a relatively uniform soil surface, to a maximum of 14 in transects with heterogeneous soil surface. In order to get a representative set of data, both the mean and the standard deviation of each variable were weighed by the number of plots mixed in the soil sample.

Soil analyses included pH-water, total carbon, particle size distribution (<2 µm, 2-20 µm >20 µm), N-tot, P-Bray and P-tot. The cations Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} were determined using the ammonium acetate method, H^{+} and Al^{3+} were determined using 1 M KCl. The effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable bases and exchangeable acidity. Zebu dung was collected from the soil surface in May 1994, where it had dried in situ. Preliminary analysis of the data.

Data gathered over three or four years from the same transect were analysed to determine whether they showed a trend with time. None of the soil variables demonstrated such a trend. For example, the organic matter content did not decline as the number of years of cultivation increased from the third to the sixth year. Instead, all the data from a given field tended to remain clustered. The variables “height of micro relief”, “proportion of permeable surface”, “number of woody plants ha^{-1}”, “grain yield” and “crop residue” were also unrelated to the year of cultivation. Hence, a single data set per field was enough. In order to facilitate the comparison among fields of the fallow system, the data analysed were those of the third year of cultivation after clearing. For the manured fields, the data were those of the last available year.

Results

Analysis of topsoil

In farming systems with no chemical fertilizers applied, organic matter and clay are determinant for the cation exchange capacity of the soil and therefore the key elements to appreciate the nutrient status of the soil. Organic matter and clay + silt contents were very low in all samples (Figure 1). These values are typical of the Sahelian sandy soils cultivated with pearl millet. In fields where fertility maintenance relies exclusively on fallowing, the topsoils of long fallow fields were different from those of short fallow fields by their higher clay + silt content, and to a lesser degree by their slightly higher organic matter content. Fields where manure was applied were split in two groups, the “old” fields being sandier than the “new” fields.

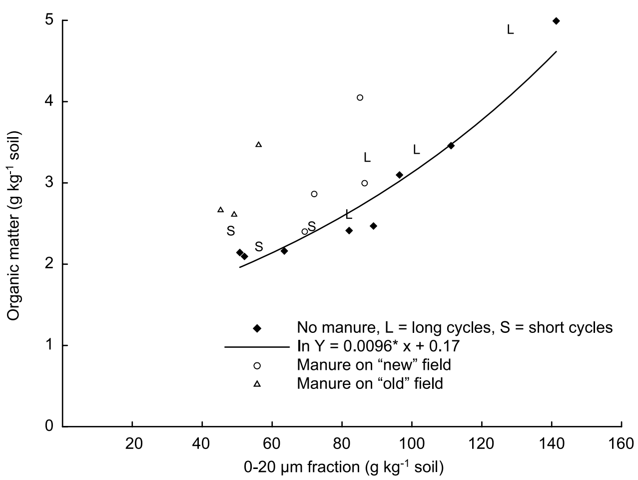

Figure 1. Organic matter content and soil particles <20 µm content of topsoil (0-20 cm) of pearl millet fields, fertility management by long or short-term fallowing, with or without manure input, Banizoumbou, Niger

Soil organic matter was not different in the two groups, probably because the quantities of manure applied yearly were equally low across all the fields.

The well-known relationship between organic matter and clay + silt contents is usually interpreted as an indication of land degradation, because uncultivated soils exhibit the highest values, over cultivated soils the lowest and normally managed soils intermediate values. The difference with the literature is that the values observed in the study area were much lower. Data from fields after long and short fallow periods were located on a continuum because transitions from long to short fallow cycles occur. The reduction of fallow periods and the accumulation of rotations resulted in a gradual decline in soil organic matter from 3.7 g kg^{-1} under long fallow management to 2.3 gkg $^{-1}$ under short fallow, while the clay + silt content decreased from 107 g kg^{-1} under long fallows to 57 gkg $^{-1}$ soils under short fallows. Thus, the solid line in Figure 1 describes the loss in soil particles <20 µm and in soil organic matter as cultivation becomes more frequent.

In fields where manure is applied, the most frequently cultivated sites were also the poorest in soil particles <20 µm, but the organic matter content was not different. Thus manure application seems to make up for some of the organic matter reduction enforced by cultivation, but manure application cannot prevent the topsoil from becoming sandier with frequent cultivation.

Table 1 shows the chemical analyses of the soil samples and zebu dung, the principal input. These results confirm the overall very low fertility of millet fields. Rotation of short fallow and cultivation without manure application resulted in the poorest topsoils in N, P and exchangeable cations.

Micro relief and soil surface

In the absence of tillage other than the breaking of the surface crusts, the micro relief is always natural. The micro relief can be microdunes (favouring infiltration) or crusted micro heights and lows (generating runoff). Both kinds of micro relief were found in every millet field, but the repartition between infiltrating and impermeable micro relief was strongly correlated with cropping practices (Table 2).

In manured fields, the micro relief was mainly made of microdunes formed around any obstacle littering the soil surface. Their maximum height (up to 8 cm) depended on the degree these obstacles could trap aeolian sand. In fields of the fallow system, the

Table 1. Analytical data from topsoil (0-20 cm) of pearl millet fields, Banizoumbou, Niger, according to cropping system

Cropping system	pH-H_2O	pH - KCl	0-20 µm g kg^{-1}	O.M.	N-tot	P-tot	P-Bray	Exchangeable cations $cmol_{(+)}$ kg^{-1}						Cation exchange capacity
								K	Ca	Mg	Na	H	AI	
Fallow system – long cycles 10 yrs cult/>15 yrs fallow	5.0	4.0	107	3.7	183	49	2.5	0.06	0.51	0.17	0.04	0.10	0.16	1.04
Fallow system – short cycles 4-6 yrs cult/3-5 yrs fallow	5.2	4.2	57	2.3	117	33	2.0	0.04	0.31	0.13	0.02	0.08	0.15	0.71
Manure system – "new" field	5.4	4.4	77	2.8	153	40	1.9	0.11	0.43	0.19	0.03	0.05	0.06	0.78
Manure system – "old" field	5.5	4.4	54	3.0	156	40	3.0	0.09	0.40	0.18	0.02	0.07	0.08	0.83
Significance														
P< 0.1 = ***; 0.5<P<0.1 = **	**	***	***	ns	ns	**	ns	***	ns	ns	ns	**	**	ns
Dung [1]	7.4 [2]			470	1,400	174		18.7	51.5	15.0	1.23	0.00	0.00	86

[1] Zebu dung, collected from the soil surface in may 1994 where it had dried in situ

[2] 1 part dung to 4 parts of water

Table 2. Mean maximum micro relief and soil surface characteristics according to cropping system, Banizoumbou Niger. Observations in 25 m^2 plots, 5-15 days after the sowing of pearl millet

Cropping System	Micro Relief (cm)	% Related to						
		Crusted areas (generating runoff)			Sandy areas (favouring infiltration)			
		Tree or shrub	Other	Total surface	Millet stumps	Dung	Other	Total surface
Fallow system – long cycles 10 yrs cult/>15 yrs fallow	8.8	51	13	64%	16	1	19	36%
Fallow system – short cycles 4-6 yrs cult/3-5 yrs fallow	7.6	54	4	58%	17	0	25	42%
Manure system – "new" field	4.4	7	8	15%	60	16	9	85%
Manure system – "old" field	5.7	36	1	37%	33	21	9	63%

micro relief was mostly related to trees and shrubs. The micro mounts were highest in fields cleared after a long fallow period because trees and shrubs were oldest. Each individual or cluster of trees and shrubs stood on its own steep-sided pedestal, often over 15 cm high. Fallow-managed fields carried an average of 700 (long cycles) and 480 (short cycles) woody plants ha^{-1}. Manured "new" fields had an average densities of 340 woody plantsha $^{-1}$ but manured "old" fields carried only 80 plantsha $^{-1}$. Being relicts of the fallow vegetation, these plants managed to grow over successive cultivation periods, but woody plants tend to disappear with frequent cultivation. They also disappear gradually from manured fields, possibly because of heavy grazing.

Generally, the higher the micro relief, the more the soil is protected against erosion because with increased surface roughness, the water stays longer on the soil surface and thus can infiltrate. This seems to account for the sand dunes, the more and the higher these sand masses were, the less signs of water erosion were observed. The opposite seems to be true for the micro mounts formed by woody plants. In contrast with the gentle slopes of the aeolian sand deposits, these slopes were steep and impermeable. Instead of favouring infiltration, they accelerated the circulation of water over the soil surface. Field cultivated after long fallow periods had the highest micro relief and the largest amount of crusted surface, also showed evidence of much superficial water movement: gullies, sand fans, depositional crusts and eroded areas were frequent. By contrast, in fields where microdunes were highest and occupied most of the cropped surface, i.e. in manured fields, these indications of water erosion were scarce.

Pearl millet production

Sowing requires little effort in terms of time and sowing seed, compared to weeding and thinning. At the onset of the rains, as much land as possible is planted and later preferential choices are made as to in what part of the field crop care will continue. Most often, where crop establishment is bad, cultivation will stop. However, the transects were weeded and harvested even when the plots were regarded as hopeless by the farmers.

Table 3. Pearl millet production according to cropping system, Banizoumbou Niger. With indication of the proportion of the field abandoned after sowing because of expected low yield

Cropping system	All planted land[1]	Planted, weeded and harvested land [2]			Part of the field abandoned[2]
	Grain yield kg ha^{-1}	Grain yield kg ha^{-1}	Total biomass t ha^{-1}	Crop residu t ha^{-1}	
Fallow system – long cycles 10 yrs cult/>15 yrs fallow	301	385	1.7	1.1	25%
Fallow system – short cycles 4-6 yrs cult/3-5 yrs fallow	122	195	0.9	0.6	47%
Manure system – “new” field	339	371	1.9	1.4	10%
Manure system – “old” field	399	399	2.5	1.8	0%

[1] Cultivation continued in the experimental plots
[2] Farmers’ practice

Fields of the fallow system had large parts of abandoned land, compared to manured fields where almost the entire planted area contributed to grain yield (Table 3). In long fallow fields, unproductive areas were associated with gullies, coarse sand deposits (sand fans) and large tracts of erosion crusts. In short fallow fields, the abandoned areas were patches of extremely sandy soil, too poor to sustain production. In fields of the manure system, 90% to 100% of the sown land contributed to grain yield because gullies, sand fans were largely absent and because patches of extremely poor sand were fertilized with dung. Considering the grain production under farmer’s management, that is the yield from that part of the field where cultivation continued after sowing, then grain yields were slightly under 400 kgha $^{-1}$ in all cropping systems, except for the short fallow fields without manure input where grain yields did not exceed 200 kgha $^{-1}$ (Table 3).

Discussion and conclusion

In the Sahel ecosystem, the soil particles <20 µm of the topsoil constitute a capital on which the long-term success of pearl millet cultivation depends. This study demonstrates that this capital can be lost, because, with time, cultivated soils loose part of their clay and silt fraction from the topsoil. Though the loss of fine particles results in less surface crusting and visible products of water erosion like gullies and sand fans, and though most of the soil surface can be sown to pearl millet, the final result is the development of extremely skeletal soils. This loss constitutes a real threat to pearl millet cultivation as can be seen by the very low yield obtained in the plots that have been cultivated for a long time in alternation with short fallow periods.

Long-term processes

During fallowing, the woody vegetation is allowed to grow. Part of the vegetation that dies at the end of the rainy season is worked by the macro soil fauna and buried into the soil, thus increasing the soil organic matter content and forming more stable aggregates (Feller et al., 1989). Airborne particles accumulate on obstacles like shrubs and trees. Some of this material gets incorporated into the soil via stemflow beneath the shrubs or trees, and some is washed down to lower parts of the land (Ambouta et al., 1996). With land clearing and the cutting of the vegetation, not only the input of biomass stops but also the dust-trap disappears. While mineralization rates have gone up because of increased exposure, reduced organic matter means loss of soil structure and subsequently less stable aggregates. Repeated weeding further disrupts the aggregates and clay + silt particles are subject to erosion (Valentin, 1995; Pieri, 1989; Feller & Beare, 1997). Particles <20 µm are liberated when unstable aggregates are disrupted by raindrop impacts, they clog the pores and form crusts. Cover by crusts is highest in fields cultivated after a long period of fallow because the building material of crusts is relatively abundant, secondly during cultivation the reduction of organic matter from the topsoil is probably more rapid than the loss of fine earth. On the other hand, high organic matter content increases the structural stability of soils, preventing them from disintegrating. This makes newly cleared fields that are manured less prone to crusting. Despite the still considerable clay + silt fraction of the topsoil, the decomposed dung mixed with soil by organisms ameliorates its structure so aggregates become less sensitive to disintegration. A second argument is that the soil surface of manured fields is littered with dung, thus dung protects the soil against aggressive rains. The farmers in Banizoumbou are aware that the issue of crusting, typical of long fallow fields can be greatly reduced by the application of manure. The best option is to start applying manure even before clearing, in the last year of fallowing. In the history of land use in Banizoumbou, this was a general practice when opening new land for cultivation (Loireau, 1998) but this option is now only open to the few well-off farmers.

Rajot (2001), by studying a field and an adjacent fallow during the same storm event, demonstrated that vegetated sites accumulated dust whereas cultivated fields lost dust. Wind erosion from fallowed land was always very limited, but it could be very large from the millet fields. He assessed that the mass budget of wind erosion (erosion versus deposition) at the scale of a village territory was positive in Banizoumbou, about 150 kgha $^{-1}$year $^{-1}$ and calculated that a further clearing for cultivation of only 6% of presently vegetated land would lead to a budget of zero (Rajot, 2001). Both the above-mentioned studies and our data show that the dominant process driving the fallow system is wind erosion. The loss of fine particles is enhanced by manual cultivation and the subsequent loss of fertility can only be restored by the trapping of dust during a long-term fallowing. Manure can only partly replace the fallow as a means of sustaining fertility. Dung application can supply the necessary nutrients to provide an average of 400 kg of grain yield/ha^{-1}. Under the current forms of manuring, visible traces of runoff and water erosion disappear and the soil organic matter content stabilises at a low level. However, the clay + silt content of the topsoil keeps declining with time.

Time span

How much time is needed to reach such losses of clay, silt and organic matter and to change a relatively productive skeletal soil, into an unproductive soil without the constant application of manure? As this is a long-term process, no direct measurements are available.

Ga-koudi, department of Maradi, Central Niger has similar climate and soils but the pressure on arable land is much higher than in Banizoumbou (Micheau, 1994; Wango, 1995; Dosso et al., 1996). Two types of soils are cultivated with pearl millet, one called Jigawa, a very sandy soil (typical value 55 gkg $^{-1}$ of <20 μm) and the other Hako, a less sandy soil (typical value 81 gkg $^{-1}$ of <20 μm). Local farmers reported that the Jigawa soils, located close to the village, were formally Hako, and they estimated that the transformation took about 40 years of cultivation (Dosso et al., 1996). They further ascertained that the reverse was possible under long term fallowing. Hako soils are regularly returned to fallow for short periods and seldom manured. They produce an average grain yields of 250 kgha $^{-1}$, similar to those obtained in Banizoumbou under short cycles. All the manure is applied on the Jigawa soils, where the average yields reach about 300 kgha $^{-1}$ (Dosso et al., 1996). In Ga-koudi, the practice of long-term fallowing has disappeared. Most of pearl millet production depends entirely nowadays on the yearly application of manure. However, dung is becoming increasingly scarce because fallow land, formerly used as pasture, has been cleared for cultivation.

A second estimate comes from Banizoumbou farmers. Farmers crop long season pearl millet land races called Somno (120-130 days) exclusively in long fallow fields because they consider that Somno requires a heavier soil, and they plant the short season Heinkirey land races (90-100 days) in the other fields. Farmers observe that after cropping the same field for a certain period (generally over 40 years) they must shift from long- to short-season cultivars because the topsoil becomes sandier.

The use of long-season varieties has become less and less frequent with time. The growing popularity of short-season land races should be attributed to the spread of very sandy topsoils and this is due to the gradual loss of the clay + silt fraction by wind erosion from cultivated soils, losses that are no longer compensated by long-term fallowing.

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Subsurface leaky pipe irrigation with vertical option as a suitable irrigation method for light soils

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Keywords: leaky pipe irrigation, moisture pattern, deep percolation

Abstract

Problems associated with areas around sandy soil hills are significant as soils picked up by wind result in soil erosion, desertification, human health problems and finally migration of farmer and people from these areas. These issues are important in desert management. For many years mechanical, chemical, physico – chemical and biological methods have been used to stablilize running sands in many countries. By undertaking these methods that are costly sands are often stablilized but with little economic benefit. In order to control soil loss from these areas the preservation of plant coverage through agriculture is a method that is often viewed as highly desirable. However, a problem associated with these soils is their high level of infiltration and deep percolation when common irrigation methods are used. However, small scale irrigation methods such as drip and porous pipe irrigation methods may produce better results as they provide water to the root system at a minimum level and at an adeqaute rate thereby minimizing deep percolation. In this way the subsurface leaky pipe irrigation method with vertical option was used at Albaji sand hills which are located in 28 kilometer of Ahvaz – Andimeshk road, Khuzestan Province in Iran in October 2003. To monitor the soil moisture pattern, five pieces of leaky pipe sections, 22 mm in diameter and lengths of 30, 45 and 60 cmwere installed on a polyethelene pipe with a 32 mm diameter and with 1.5 m distance between each piece of leaky pipe. Three heads of pressure were applied: 2, 4 and 6 m of water. The moisture patterns were observed along the pipe on a cross sectional basis and vertical and horizontal expansion of the wettting front were recorded. The moisture content at 10 points within the wetting pattern were measured with time. The results indicate that this system is suitable for light textured soils since it controls deep percolation with time and requires minimum pressure to operate.

Introduction

There are many areas around the world which are associated with sandy soils. Because these areas are often associated with arid or semi-arid climatology, crop coverage as a means for preventing soil erosion is minimal and sandis blown away by wind erosion. Therefore, agricultural lands around these areas are affected by desertification.

About 300,000 ha of sandy lands exist in Khuzestan Province in Iran and are surrounded by the Karkheh and Karoon Rivers. Because of the existence of a high rate of infiltration for sand in these areas, irrigation water is easily lost by deep percolation. Fortunately, salinity is not major in these sandy soil because of the high level of infiltration but a suitable method for irrigation is needed to manage these soils. A successful irrigation method will develop crop coverage which results in the prevention of wind erosion, development of an agricultural economy, and improved health and social affairs. It seems that the porous pipe irrigation technique is one of the best methods applicable to sandy hills, because it discharges a low level of water allowing slowirrigation. Porous pipe works like a clay pot which was used in Central Iran, Pakistan, India and Egypt centuries ago. Porous pipe can be used at the soil surface or subsurface. This pipe is called by other names such as ‘Leaky Pipe’ (in USA) and ‘Proflex’, ‘Ecopore’ and ‘Tuporex’ in France. The porous pipe irrigation method is currently used in USA, Europe, Australia, China, Japan and other countries and many researchers such as Fok and Willardson (1971), Tollefson et al. (1985), Yoder and Mote (1995), Teeluck and Sutton (1998), Camp et al. (1998), Khorramian et al. (2001) and Akhoondali (1998, 2003) have evaluated different aspects of this

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irrigation method. However, these researchers have used this system with a common condition of horizontal installation of the porous pipe irrigation system.

Fok and Willardson (1971) presented a method for analysis and design of a subsurface irrigation system that uses field data, system capacity, depth and distance between pipes and irrigation frequency.

Tollefson et al. (1985) reported a pipe life up to 10 years and successful commercial installations.

Yoder and Mote (1995) evaluated discharging of unused porous pipes. In this study each piece of porous pipe was 0.3 m long and the manufacturing coefficient of variation was calculated for discharges at 14, 34.5, 69 and 138 Kpa pressure. The results showed that variation in discharge along the pipe was substantial for pipes of different series.

Teeluck and Sutton (1998) compared discharge uniformity of pieces of 6 m length under 10 and 20 Kpa of pressure head with filtered water and nonfiltered water. Results showed that for the two types water, discharge decreased with time but, nonfiltered water discharge constantly. Manufacturing coefficient of variation with filtering water was from 20% to 35% and these values were increased with time.

In a review, Camp (1998) reported that lateral drip depths ranged from 0.02 to 0.7 m, depending upon both soil and crop type.

To assess moisture movement in a light-textured soil, Akhoondali (2003) used horizontal porous pipe of 40 cm length at a soil depth of 30 cm and applied pressure heads of 4, 6, 8 and 10 meter of water for time periods ranging from 30-300 min.

The results showed that:

1) Vertical water movement for time periods of 30-300 min and 10 meter pressure was 10 cm. Therefore, the depth of setting these pipes in light-textured soil shouldn’t be more than 10 cm.
2) Increasing pressure head caused increased discharge.
3) Volumetric soil moisture ranged from 25% to 40% for 4 and 6 meter of water pressure, and was equal to field capacity. At 8 meter of water pressure, volumetric soil water was a little more than field capacity, and at 10 meter of water pressure, soil was saturated.

Khorramian et al. (2001), for evaluation of hydraulic characteristics of porous pipes, tested 6 meter lengths of these pipes under pressure ranging from 20 to 100 Kpa. The emission rate was compared and evaluated for three treatments including unused dry porous pipe, unused soaked porous pipe and used porous pipe.

The results indicated that: emission rate was approximately a linear function of pressure; emission rate of unused soaked pipe was always lower than unused dry pipe at constant pressure; and the emission rate in used porous pipe was very low.

As cited above, a lot of research has been done for horizontal setting porous pipe and evaluation of porous pipe characteristics hydraulic was done but, in Iran two research of vertical setting pipe were reported.

Akhoodali (1998) studied moisture movement pattern with vertically installed porous pipe in glass boxes on three types soil; light, medium and heavy textured. For this study three lengths of pipe (30, 45 and 60 cm) of 13 mm diameter were used under 2 m of water pressure and 1, 2, 3, 5, 7, 9, 14, 24, 34, 49, 64, 79, 94, 109, 124, 139, 154, 169, 184 min of time.

Results showed that:

1) At this pressure the wetting pattern was cylindrical.
2) The radius of the wetted cylinder was a power function of time.
3) Vertical moisture depth under the end of the pipe in medium and heavy soil was equal to the pipe length, and in light soil, equal to double the length of pipe.
4) The average moisture content in the three types of soil was equal to field capacity and this is a good soil moisture status for plants.
5) A set of empirical equations was obtained for observed soil moisture patterns which were produced with time.

Characteristics of studied site

Sandy hills in Khoozestan Province are located between eastern longitude of 47º40' to 49º20' and 31º5' and northern latitude 32º20'. These hills are developed from northwest to southeast and are comprising 3,500 ha and representing 5.4% of the total land area of Khoozestan and 29.5% of the agricultural lands of the province.

Table 1. The soil texture of Albaji hills

Particle type	Coarse sand	Medium sand	Fine sand	Very fine sand	Silt	Clay
Particle diameter (mm)	0.5-1	0.25-0.5	0.25-0.1	0.05-0.1	0.002-0.05	<0.002
Percent	0	28	65.5	1.5	2	2.5
Texture			Sand			

This field study was done in October 2003 at the natural resources station, at Albaji located between 31º20'N 48º40'E and 20 m above sea level.

The physical characteristics of the soil

The field texture of the soil is fine sand, and its particle size analysis is presented in Table 1.

Materials and methods

For this test, porous pipe (HD2216) was used. Three lengths of pipe (30, 45 and 60 cm) were provided, and one end was blocked.

For uniformity in each test, unused, dry pipes were used. In this test vertical installation was used for several reasons:

1) Roots could aggregate along the length of the pipe
2) It was reasoned that moisture patterns along the length of the pipe would be similar to a root system distribution.
3) In regions like the experimental region, roots are needed to reduce wind erosion by holding the soil together. In the vertical option with controlled time and pressure roots can be encouraged to grow at any depth that is wanted because roots will grow to the moisture.
4) In vertical application, salt moves from the discharge point and out of profile and this prevents accumulation of salt around the root system. According to research, the horizontal option causes salt accumulation in the 10-15 cm layer of surface soil, depending on physical and chemical characteristics of water and soil.
5) If irrigation frequency is not suitable, then there is a possibility that roots will grow into the pipe and cause obstruction. However, in the vertical option, even if one of the leaky pipe sections is obstructed, water can still move along the head pipe and in other leaky pipe sections.

The experiment was done over five times (10, 30, 60, 180 and 300 min) with pressure heads of 2, 4 and 6 meters of water and three lengths of pipe (30, 45 and 60 cm). So, 45 units were involved. In this study, five pieces of leaky pipe of 22 mm diameter were installed on a polyethylene pipe 32 mm diameter and 1.5 m distance between each section of leaky pipe. The polyethylene pipe was linked to a Robine pump that pumped the required water from the source water to the system. The required pressure head was regulated by a control value and a gauge (Figure 1). Wetting patterns were observed along the pipes on a cross section and vertical and horizontal expansion recorded with time. In addition to vertical and horizontal records of soil moisture movement, a set of soil samples were taken from 10 points to measure soil

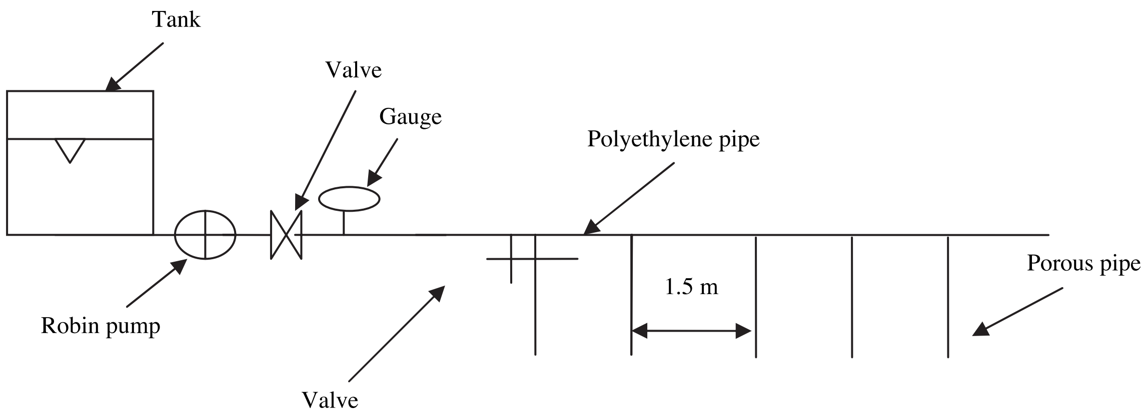

Figure 1. Schematic of system

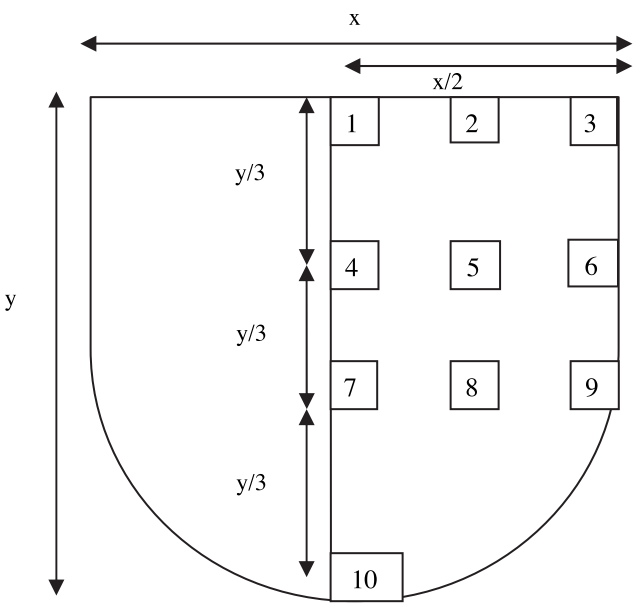

Figure 2. Schematic of moisture profile and the sample points

moisture. These points were selected randomly on one side of the pipe. In this paper, the data are presented for the 300 min time period.

Results

1. Vertical expansion frompipes of 30, 45 and 60 cm length

Table 2 and Figure 3 show that in porous pipe of 30 cm length for 2, 4 and 6 meter water pressure, vertical expansions were 45, 50 and 60 cm, for units of 45 cm length, 60, 65 and 85 cm vertical expansion, and for units of 60 cm length, 78, 85 and 110 cm vertical expansion.

Maximum vertical expansion occurred at 6 meter water pressure, and at this pressure, vertical expansion from the end of the pipe was equal to the length pipe. In other words, at 6 meter water pressure, the total vertical expansion was equal to approximately double the pipe's length.

2. Horizontal expansion from pipes of 30, 45 and 60 cm length

Table 2 and Figure 3 show that the range of horizontal expansion in pipes of 30 cm length with 2 meter of water pressure was from 5 to 12 cm, with 4 meter of water pressure from 5-15 cm and at 6 meter of water pressure from 12 to 38 cm. For pipes of 45 cm length with 2 meter of water pressure, horizontal expansion ranged from 6 to 12 cm, at 4 meter of pressure from from 6 to 16 cm and at 6 meter of water pressure from 13 to 48 cm. For pipes of length 60 cm[2] meter of water pressure, horizontal expansion was from 4 to 13 cm, for 4 meter water pressure from 5 to 16 cm, and for 6 meter of water pressure, from 20 to 60 cm. These data show that horizontal expansion was changed a little by changing the length of the pipe. However, with variation in pressure, horizontal expansion changed much more, particularly from 4 to 6 meter of water pressure. This pipe was designed for 6 and 8 meter water pressure.

3. Moisture diagram

Table 3 and Figures 4-12 show that soil moisture decreases at the front of the wetting pattern because of the decreasing matrix potential gradient from pipe to wetting front. Along the pipe the amount of moisture increased because of increasing gravity

Table 2. Vertical and horizontal expansion (cm) in porous pipe after 300 min

Length of pipe (cm)																										
30									45									60								
Pressure (meter of water)																										
2			4			6			2			4			6			2			4			6		
x_1	y	x_2	x_1	y	x_2	x_1	y	x_2	x_1	y	x_2	x_1	y	x_2	x_1	y	x_2	x_1	y	x_2	x_1	y	x_2	x_1	y	x_2
6	0	6	6	0	6	19	0	18	6	0	6	7	0	8	19	0	19	6	0	6	7	0	7	18	0	16
6	15	6	7	15	8	19	15	19	6	15	6	8	15	8	23	15	24	6	15	7	8	15	8	21	15	22
5	30	5	5	30	6	15	30	15	5	30	5	7	30	6	24	30	24	6	30	6	7	30	8	26	30	26
2	45	3	4	45	4	11	45	12	5	45	5	6	45	5	19	45	18	5	45	5	6	45	6	29	45	28
			2	50	3	7	60	5	3	60	3	5	60	4	17	60	16	4	60	4	5	60	5	30	60	30
												3	65	3	12	75	11	2	78	2	4	75	4	25	75	26
															6	85	7				3	85	2	20	90	20
																								15	105	16
																								10	110	10

Table 3. Gravimetric moisture content at 10 points in the wetted profile around porous pipe after 300 min

Number of point	Length of pipe (cm)								
	30			45			60		
	Pressure (meter of water)								
	2	4	6	2	4	6	2	4	6
1	14.7	14.9	16.3	15.2	15.8	17.1	15.4	16.0	17.5
2	14.5	14.6	15.0	15.0	15.5	16.8	15.2	15.8	17.0
3	14.1	14.2	14.8	14.9	15.3	16.5	15.0	15.5	16.7
4	14.9	15.1	16.5	15.4	16.0	17.4	15.6	16.2	17.7
5	14.8	14.8	15.4	15.1	15.6	17.1	15.3	16.0	17.4
6	14.4	14.5	15.0	15.0	15.5	16.9	15.2	15.6	17.0
7	15.0	15.3	16.7	15.6	16.2	17.7	15.7	16.4	17.9
8	15.1	15.0	15.5	15.4	15.9	17.3	15.4	16.1	17.7
9	14.7	14.7	15.2	15.3	15.7	17.0	15.2	15.8	17.3
10	15.5	15.5	15.6	15.5	16.0	17.6	15.5	15.9	17.8

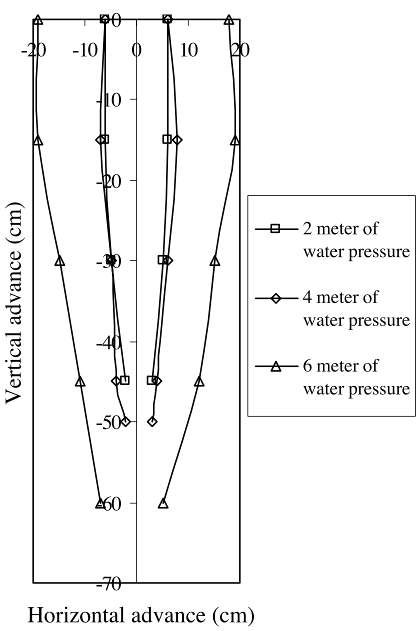

Chart 1. Advance moisture in porous pipe with 30 (cm) length after 300 (min)

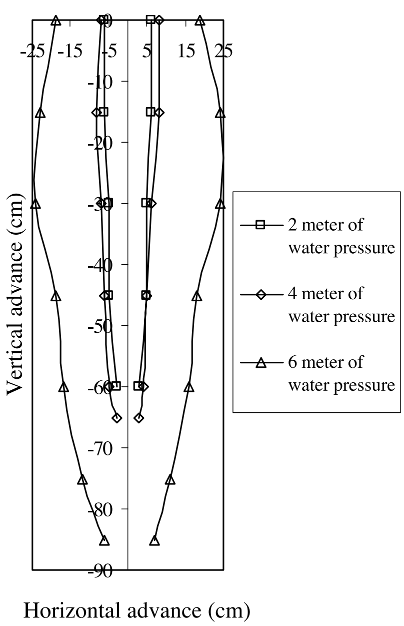

Chart 2. Advance moisture in porous pipe with 45 (cm) length after 300 (min)

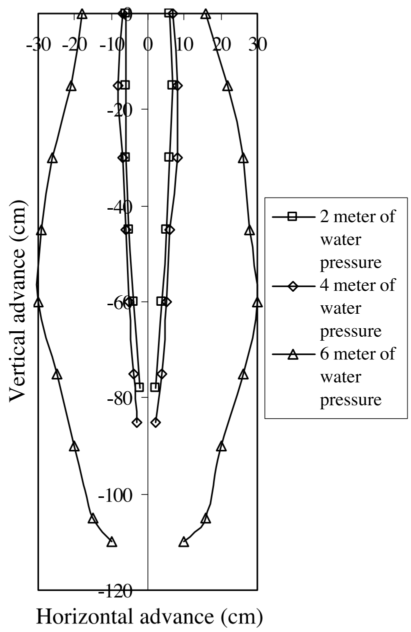

Chart 3. Advance moisture in porous pipe with 60 (cm) length after 300 (min)

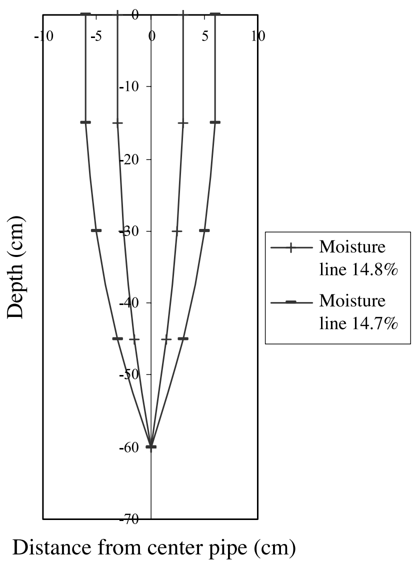

Chart 4. Iso moisture in 30 (cm) length of porous pipe, 2 meter pressure

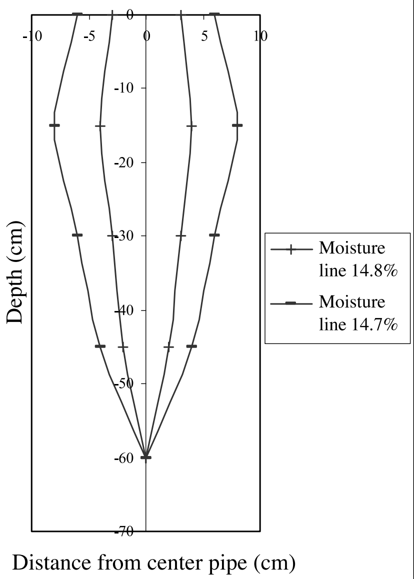

Chart 5. Iso moisture in 30 (cm) length of porous pipe, 4 meter pressure

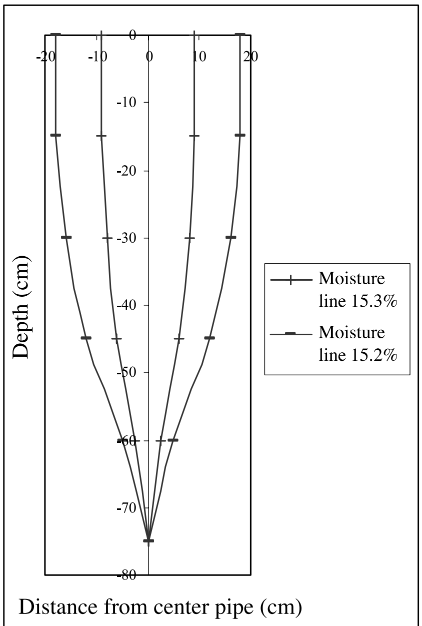

Chart 6. Iso moisture in 30 (cm) length of porous pipe, 6 meter pressure

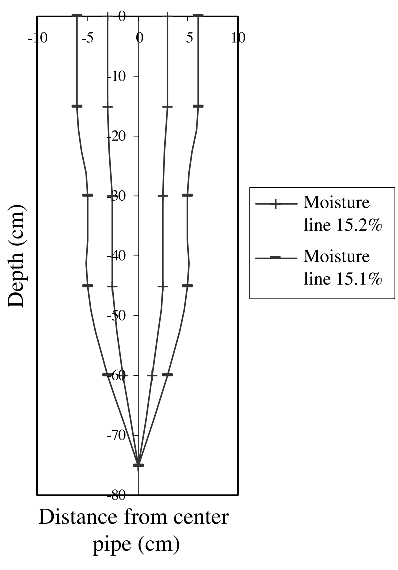

Chart 7. Iso moisture in 45 (cm) length of porous pipe, 2 meter pressure

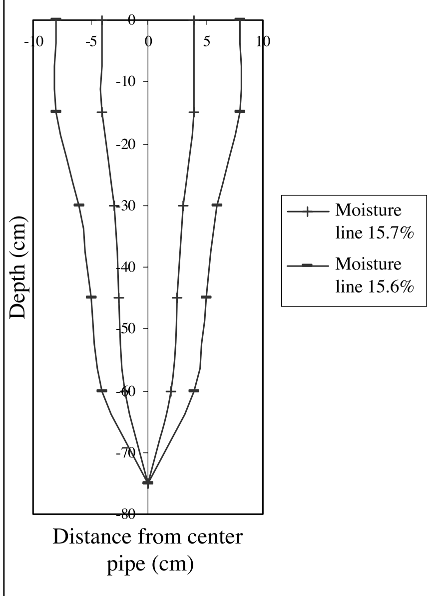

Chart 8. Iso moisture in 45 (cm) length of porous pipe, 4 meter pressure

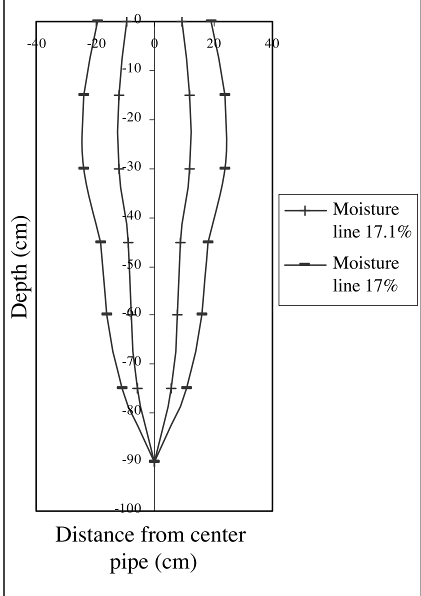

Chart 9. Iso moisture in 45 (cm) length of porous pipe, 6 meter pressure

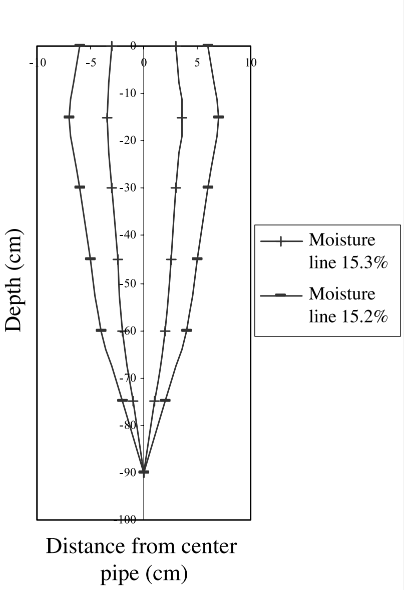

Chart 10. Iso moisture in 60 (cm) length of porous pipe, 2 meter pressure

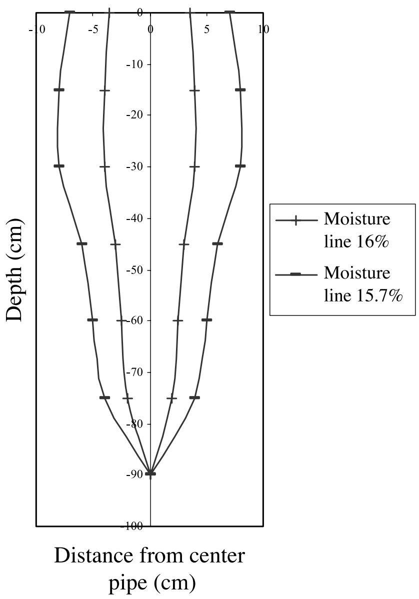

Chart 11. Iso moisture in 60 (cm) length of porous pipe, 4 meter pressure

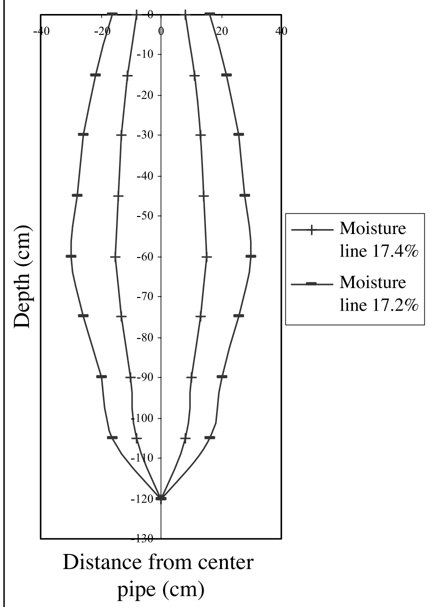

Chart 12. Iso moisture in 60 (cm) length of porous pipe, 6 meter pressure

force and with increasing pressure, the amount of moisture increased because of increasing discharge.

Conclusion

1) By changing the length of pipe, pressure and time, the designer can choose a suitable moisture pattern for plant age, root system and available pressure, and can control deep percolation.
2) At 2 and 4 meters of water pressure, the moisture pattern is suitable for saplings and with increase in the age of plant, a large number of pipe sections or a high level of pressure would be appropriate because in sandy soil areas roots should go deep to keep plant standing against the wind.
3) The patterns showed that the maximum horizontal development was with 6 meter of water pressure and in half and quarter of pipe length. According to the adsprition low of water (10%, 20%, 30% and 40%), 6 meter of pressure is suitable pressure in this experiment.
4) Soil moisture content was calculated to be a little more than field capacity, and this is the best moisture for plant growth.
5) In this system obstruction of one unit doesn't cause obstruction of the whole of pipe.
6) Because of the texture of the soil used in this experiment, Increasing time doesn't cause horizontal expansion but vertical expanded.

Aknowledgement

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The optimal size of farm ponds in N.E. Thailand with respect to farming style and multiple uses of water and under various biophysical and socio-economic conditions

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Keywords: farmer support, farm modeling, multiple uses, farming style, simulation, optimization

Abstract

Water is a limiting factor on farms in Northeast Thailand because of weather and soils. Variable rainfall leads to high risks in cultivation. Catching and storing rainwater and subsequent use for irrigation reduces risk and increases farm productivity. A practical question posed by farmer organizations is ‘what is the optimal size of a farm pond?’ In trials, optimum values of around 12% of the farm area have been reported. For individual farms, however, this fraction may be much different due to features of farm soils, landscape and local climate, economic factors (prices of produce and multiple productive uses of water) and the preferred farming style (i.e. the farming household minimizes inter-annual risks, maximizes income, is innovative in trying the latest techniques, or has farming as a secondary source of income).

To consider a wide range of variables and choices in a systematic and transferable manner, we developed the farm simulation model BoNam-FS (Farm Simulation). It was used to simulate sets of scenario’s (farming styles, soil types, weather patterns, innovations) to determine farm performance over a range of farm pond sizes. Benefits of innovations, such as pond sealing and alternative irrigation methods, can be quantified. The results can be analysed with the spreadsheet BoNam-SA (Scenario Analysis) and summarized in graphs.

Results have been presented to farmer organizations to show the options for water management and how to pick a scenario that suits best a specific situation. BoNam-SA is available for further analyses, such as by farm advisors. BoNam-FS is available for in depth analysis of farm water balances in existing or new scenario’s. For detailed explorations, specific data from the farm-in-case are needed.

Introduction

Deforestation and unbalanced farming systems have brought much land and water degradation in N.E. Thailand since the 1960’s, particularly by nutrient mining (Bridges et al., 2001). Several farmer organizations (FOs) emerged in N.E. Thailand in the 1980’s (Chamrusphant, 2001), either spontaneously or promoted by NGO’s (Chutikul, 2001, Bepler, 2002). Since the early and mid 1990’s some FOs promoted the adjustment of farming practices to reverse degradation (Ruaysoongnern and Suphanchaimart, 2001). This often included construction of a farm pond and crop diversification. Investments for pond construction are often arranged through revolving funds, managed by the farmers groups, and entail loans that are repayable within 12 months (Bepler, 2002, Ruaysoongnern and Penning de Vries, 2005). In addition to empowering many individuals and setting common action agenda’s, these organizations gained a strong political influence in the government. Significant funds are now available to speed up the expansion of the number of farm ponds. Government spending will be increased further for 2005-2007 as a regional drought in 2004/2005 has given “water” an even higher priority. The Land Development Department (LDD) advises the government on implementation of the pond development scheme. The new Thai constitution strongly promotes participation of the people in the “conservation, maintenance and use of natural resources” (Hungspreug, 2001), and LDD and FOs search how to make this effective and to design realistic loan schemes for individuals.

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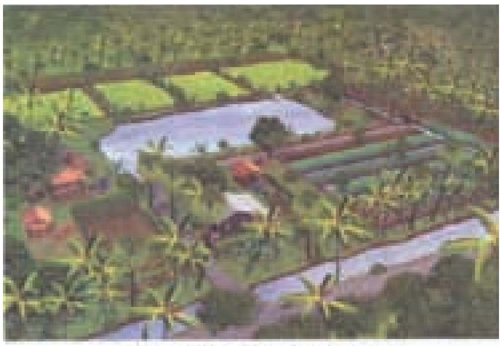
Goto and Koike (1997) report that modern farmers near Khon Kaen often cultivate 2-3 ha of land, divided into 2-3 plots and worked with 4-7 persons. On average, 50% of the area is in rice and 10-15% in vegetables. The authors also report that there are usually 1-2 rice crops per year yielding 2.7-3.7 t ha^{-1} cleaned rice of which only 10% is consumed domestically. Vegetables, 4-5 crops per year, include beans, cabbage and onions, are generally sold to middle men and yield 50-100 k Baht ha^{-1} yr^{-1}. Pond water is used to irrigate vegetables, flowering plants and fruit trees. Some farmers produce and sell fish as well. Farmers may also grow some trees for convenience wood (e.g. teak, Eucalyptus) for sale when cash is needed. An analysis of modern farming systems and a comparison with non-improved systems has been carried out by Tipraqsa (2005). Cassava, a common crop in N.E. Thailand, is never irrigated and therefore not considered in this study.

The New Theory for agricultural development by His Majesty King Bhumibol of Thailand (LDD, 2005) underlies the thinking of FOs with respect to farm and livelihood development. It promotes integrated farming to achieve household food security, self-reliance and a reasonable income from agricultural products from a farm with ample biodiversity and a sustainable farming system. Farm ponds are crucial in the New Theory (Figure 1).



A Thai Farm in the New Theory of His Majesty the King of Thailand

The water balance on farms is complex. Farm ponds receive water from rain and runoff from the fields and uncultivated surfaces. A high groundwater table may add to filling, but drainage from ponds is more common, particularly on sandy soils. Some farms pump groundwater for domestic and productive uses, but as a salt layer underlies the groundwater in some areas there is a threat that saline water is extracted (Srisuk et al., 2001). Roof water harvesting for domestic water is common (Bepler, 2002); water supply through pipes by water providers is uncommon.

The optimal size of a pond relative to the size of the farm is important but difficult to establish. It is important because the water surface itself is not productive. It is difficult to establish because it depends on many factors: the crops grown (type and area), on the prices they can fetch on the market, the local weather and soil types, and other factors. Also farmer objectives affect the optimum ratio. The track record of new farms is still short (Tipraqsa, 2005), so that farmers have not yet sufficient experiences to be used as a guideline. Experimentally, LDD found 12% to be an optimum (Khao Hin Sorn, 1999). In the New Theory, a pond as large as 30% of the farm surface is proposed. It would allow full irrigation of all crops year round, but could require water supplies from major reservoirs outside the farm. Irrigation only where and when really needed can reduce the water demand significantly and allows smaller and cheaper ponds. Realizing this complexity and local specificity, FOs asked scientists for help and formulated three pertinent questions (Box 1).

Box 1. Three questions to scientists formulated at a meeting of farmer networks in N.E. Thailand, Kalasin, 20 January 2004; text in parenthesis by the authors.

- *(What are the) Land: water resource ratios for best productivity in different ecosystems (at farm scale)?*
- *(How is the) Water management for water use efficiency for each crop, both monocrops and integrated farming system?*
- *(What are the) Water productivity potentials in different ecosystems for productivity gap analysis of each farm?*

The method: simulation modelling and scenario analysis

When experience provides no guideline to determine the optimum water/land ratio on farms, trials can be carried out. Such trials should last at least 5-10 years and occur across N.E. Thailand due to the variability of the weather and differences in soils. They are therefore slow to provide conclusions and expensive. The LDD experiment station in Khao Hin Sorn carries out trials in one rainfall zone. An alternative approach, potentially much faster, with a wider range of answers, and cheaper, is through simulation modelling. Optimally, the modelling approach goes together with field research and calibration.

In a dynamic simulation model the way how crops, soils and ponds ‘respond’ to management and weather is calculated for short time intervals (here: one week). Calculations are repeated over periods of 1-10 years. Indicators of ‘farm performance’ are derived from the computed results. With little effort, the simulations can be repeated for many scenarios of farm management to explore the options available to the farmer. Characteristics of weather, soil, landscape, and other factors are kept as close as to the conditions of the end user as feasible. Management is characterized by planting dates and target yields, irrigation methods and mulching. From the values of the indicators in the different scenarios, the farmer can select the outcome that fits his/her farm best.

This way of identifying the optimum farm pond size makes full use of scientific knowledge and of local insights. The modelling approach supports non-specialist with applicable scientific knowledge. Croke et al. (2005) give examples from Australia of the impact of modelling support to local persons and organizations and of the improved water and land management.

Several models have been published that address optimization on farms. These include SWB (Annandale et al., 1999), Tradeoff Analysis Model (Antle and Stoorvogel, 2000), Dam Ea$y (Lisson et al., 2003), Planwat (Van Heerden, 2004) and TechnoGIN-3 (Wolf et al., 2004). But they do not provide all features required to answer the request of the FO (Box 1), particularly not with respect to multiples uses of water, farming styles and weather variability.

The model ‘BoNam’ for Thai farms

Outline. We developed the simulation model BoNam-FS (bon am is Thai for ‘pond’, Farm Simulation) to support farmers across N.E. Thailand to determine the optimum relative pond size for the conditions of any particular farm and for the preferred farming style of its farm manager. The model is built in the language SIMILE (Muetzelfeldt and Massheder, 2003); its outputs can be analysed with MS Excel. Running the model and comparing results for different scenario’s is user friendly. This paper presents briefly our approach in modelling to support FOs and some results obtained with BoNam version 3-09. A copy can be obtained from the first author. The data used to characterize the farms and locations in this paper are from actual observations and from measurements reported in literature. The data, however, may not be representative for a particularly farming situation because we want to demonstrate possible uses in contrasting environments and did not attempt to identify parameters from specific cases.

The actual simulation model consists of 15 modules: one for the water balance of each of five farm plots, one for each of the three productive activities (vegetables, rice and fish), one for inputs with respect to strategic decisions on farm layout and one for operational decisions in management, one for time management, two for weather and price data, and two to track simulated farm performance (water balance, income, etc.) and annual totals. A full description of the model is in preparation (Penning de Vries, 2006). (It is technically straight forward to add modules for other water demanding activities such as for sugarcane, fruit trees, feed crops and livestock. However, the number of farm management options for the users grow too large to be helpful, certainly in the early stages of support in decision-making with the model. Hence we opted at first for a small set of contrasting uses of water in BoNam. Further feedback from farmers may indicate that another selection of activities, or indeed a larger range of water use activities, is required). SIMILE provides transparency of the model and easy inspection and modifications. Several checks and double accounting in the model assure consistency in modelling processes and reduce errors. Because the farming season begins in July and may extend well into the next year with a second rice crop, we compute the annual totals from July onwards. To deal with uncertainty, a normal simulation run consists of 9 consecutive years. This allows the user to take into account carry over effects between seasons and to calculate realistic annual averages and estimate uncertainty.

The first question about an optimum ratio between land and water (Box 1) can be answered by repeating simulations for a range of pond sizes and varying the size of the irrigated plot. The first approach is needed when a farm pond is (re-) designed, the second when optimizing multiple uses of water from a fixed size pond. In this short paper, we deal with variable sizes.

Farm layout: the default farm surface area is 1 hectare; other values can be specified. It consists of five sections: (i) the farmhouse, yard and the unplanted area surrounding the pond, (ii) the pond, (iii) the rice field, (iv) a plot with vegetables and (v) a park with trees (Figure 2). Only the vegetable crop is irrigated, if possible, not the transplanted rice. Recognizing the importance of rice production for the household, any increase in pond area is at the expense of the vegetable

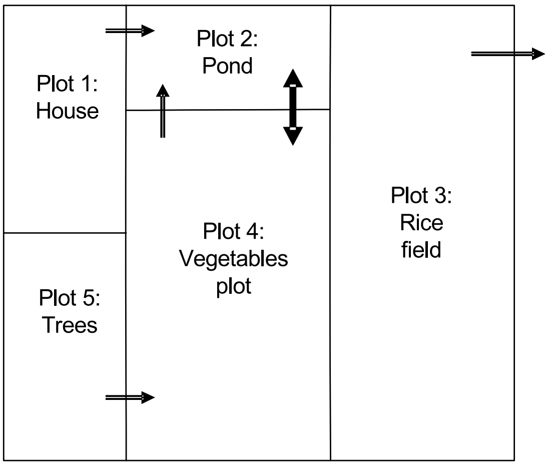


Figure 2. Approximate layout of the five plots on a farm. Single arrows show the direction of flow of runoff water. The double arrow suggests that this border between the vegetables plot and the pond can be moved between simulation reruns

plot. The water balance connects the plots, if there is excess water on the plots, it runs into the reservoir; if there is too much for it to contain, it runs off from the farm. Runon from nearby roads or field can be important. The dynamics of groundwater is insufficiently known to be simulated.

Management. Management of the entire farm is considered rather than that of individual plots. Management is characterized by choice of planting dates and target yields of crops planted, irrigation levels, use of the soil amendments (e.g. bentonite) or mulch, and presence of fish. There are different styles of managing a farm enterprise, and these lead to different results. About 20 parameter values and settings in BoNam are affected by 'style'. E.g., if a farmer goes for a relaxed style of farming, this will be reflected in selected crops and target yield levels, etc. We distinguish four styles:

- Style A ('conservative'): the solid, slightly conservative farmer who makes sure that his family has always adequate rice and who prefers stability over high income. Fraction of farm in rice cultivation: 0.4. Vegetables 2-3 crops per year. Low levels of inputs.
- Style B ('income'): the farmer who seeks maximum benefit and does not mind to borrow some money to purchase rice in an unusually dry season. Mostly commercial production input intensive: irrigation, fertilizer, labour. Year round production with 3-4 crops. Fraction farm in rice cropping: 0.25.
- Style C ('scientist'): the curious, enterprising farmer who tries out new methods for water distribution, new crops, etc. Fraction farm in rice: 0.25. This style is characterized by the most efficient ways of doing things.
- Style D ('with other jobs'): the farmer has off-farm income and farm activities demand little work and monitoring. No fish production. Fraction rice on farm: 0.5.

Performance. Simulated results of the farm are expressed in four indicators: annual farm income, number of weeks per year that the pond is dry, quantity of water that runs of the farm, and the volume of water used in irrigation. While it is straight forward to add other indicators to the model (e.g. the length of the drought period in the rainy season), expressing farm performance in these four dimensions provides already a large amount of output. We consider that these four indicators give much insight into options for farm management but adaptations can easily be made if needed.

Input data. We use weekly data of evapotranspiration and temperature (averaged over nine years) and rainfall data (from the Mekong River Commission) for the individual years for Korat (1995-2004, in SW corner of N.E. Thailand), Khon Kaen (1987-1996, in the centre), Ubon Ratchatani (1961-1969, S.E.) as well as for Nong Khai (1961-1969, N.E.). The average annual rainfall at these sites increases from 1345 via 1522 and 1,673 to 1,984 mm. The pattern of cumulative values of the highest and lowest rainfall sites are shown in Figure 3. The duration of the rainy period at these locations is about equal, the growing season longer in Nong Khai. The potential evapotranspiration (ET_0) in Khon Kaen is 1971 mm yr^{-1} (RID, 1994). Assuming that this value is a fair approximation for all of N.E. Thailand, it shows that the risk of drought is significant in all locations particularly at the beginning and end of the growing season, particularly in the southeast. We do not address the question whether the climate of N.E. Thailand is slowly getting drier and the rainy season occurring later, but the eventual consequences of such changes could be explored through modelling.

Data from the soil map of Thailand could not be used for these simulations since the scale is too small. We characterized the rice soil on the farm as 'clayey' and the soil on the vegetables plot as 'loamy' (Penning de Vries et al., 1989). Simulations apply for conditions without runon from outside the farm and water supply by providers. Drainage from the pond is set at a small fraction of its contents per week (0.5%). Soil fertility

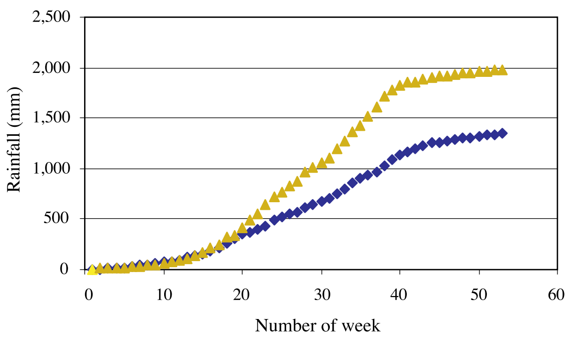


Figure 3. Cumulative average weekly values of precipitation for Korat and Nong Khai, representing the driest and wettest locations in N.E. Thailand, respectively

is addressed implicitly in crop growth. The landscape of the farm is characterized by runoff patterns between the plots. For this paper, we did not pursue simulation of farms with sandy soils as their rate of drainage is high and building a pond not economically attractive. Moreover, even within a sandy area, heavier soils are present on parts of many farms.

Crop simulated have characteristics of 'lowland rice' and of 'bean crops' in their development and growth parameters (Penning de Vries et al., 1989). Target yields are set by farming style and reflect variety choice and fertilizer level. Fish grow 10% per week if sufficient feed is supplied (related to 'style'). Common market prices (2004) are used for the produce. Only gross income is computed.

Calibration. Since it is impossible to collect sufficient basic data for each case for which the model will be applied, it is good practice to collect data from a number of trials and to compare them with actual observations for the purpose of calibration. Much of this still needs to be done and 'calibration' is so far only done by 'guestimation'; results should therefore be taken as indicative values only.

Outputs

SIMILE allows inspection of the values of all model variables at any time interval in output tables or graphs. Export of these variables is possible for further analysis with other programs, such as MS-Excel. The set of macro's for Scenario Analyses is called BoNam-SA.

Looking in great detail to individual variables is necessary when the model is build and tested. A comprehensive set of outputs could include weekly or monthly values of the soil relative water contents in the plots 3 and 4, levels of water stress in the crops, crop dry weights, and runoff between fields and from the farm, and the water level in the pond.

In the productive stage of modelling, however, one is interested in a few outputs only, such as the indicators of performance. We use four indicators of farm performance: (i) annual farm gross income (Baht yr^{-1}) as it results from rice, vegetables and fish; (ii) number of weeks per year that a pond is dry as a measure of risk; (iii) the quantity of irrigation applied ($m^3\ yr^{-1}$) that can be used to determine water use efficiency, and (iv) the quantity of runoff from the farm ($m^3\ yr^{-1}$) to see the consequences of choices on neighbouring farms. In the next section, we provide examples of the first two indicators.

Answering the questions

The question about the optimum size of the farm pond (question 1, Box 1) is relevant before a major investment of excavating a pond or constructing a reservoir and for detailing the conditions for a loan for this purpose. It can be answered by running the model for scenarios of relative pond sizes, and by inviting the farmer to select the answer that fits her/him. For an illustration of the type of results provided, we ran the model for relative pond sizes from 0.0 to 0.3 (m^2 pond surface m^{-2} farm) and for the four farm styles with otherwise the same input data and all management parameters set at default values. A first round of interactions with the FO Local Wisdom took place in Buriram (2004), and other rounds are planned.

The following graphs present three values for the indicator at each pond size. The middle one corresponds with the average level, the upper one with the level attained or exceeded in the best 25% of the years and the lower one with the level attained or not quite in the worst 25% of the years. The spread between the upper and lower values is a measure of the inter-annual variability in weather. Irregular patterns in the graphs are due to non-linear processes, such as failure or a second crop due to drought.

Results in Figure 4 for the indicator 'farm income' for the driest site (Korat) indicate that a pond size of 5-10% is optimal for the styles A-C, while 'no pond' is usually best for style D. There is no sharp optimum, and the value tends to be higher for the wetter years. Note also the difference in Y-axes: the styles B and C provide more income than style A and much more than D. The main reason why the income goes down at larger pond sizes is that the size of the vegetables plot, a major income earner, becomes small.

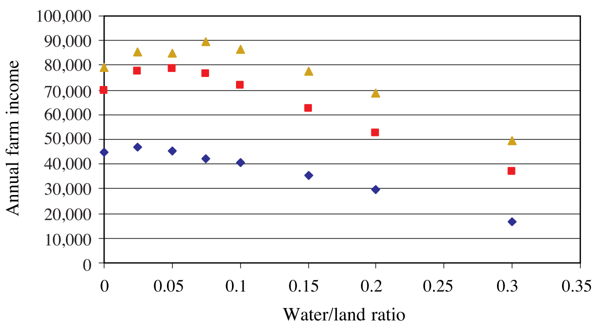


Figure 4a. Korat, style A

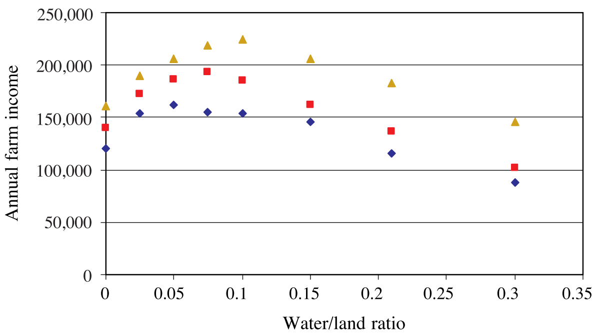


Figure 4b. Korat, style B

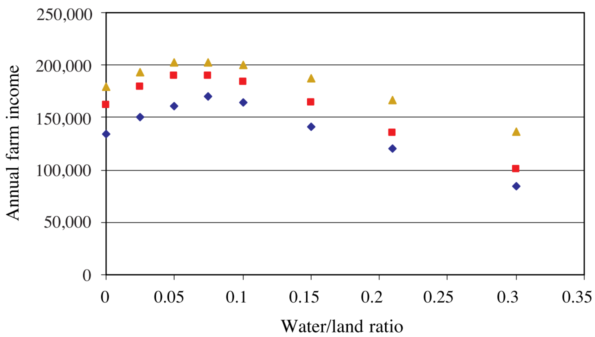


Figure 4c. Korat, style C

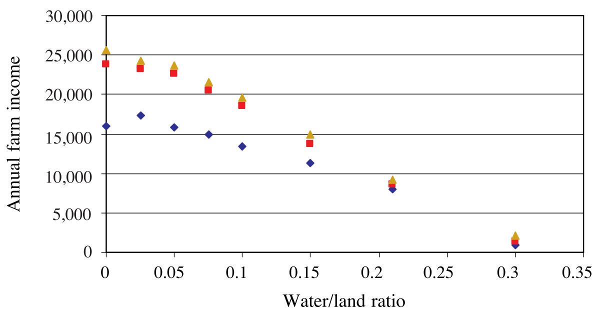


Figure 4d. Korat, style D

Figure 4 (a-d). The relation between pond size and average farm income in Korat under four farming styles

To illustrate the large difference between different parts of N.E. Thailand, we show in Figure 5 the indicator 'number of dry weeks', and give an indication of 'risk' related to climate. Selected are data from 2 locations (Korat, Ubon) and all for farming style B ('income'). It is clear that the chance of the pond running dry for several weeks a year is pretty large. The reason that the risk increase in Korat for large pondsizes is that the catchment area of water becomes too small. In Ubon, 15% of the farm area in pond keeps ample water for irrigation year round. Quite obviously: the best recommendations for sizes and farming practices between these regions differ significantly.

To demonstrate the value of the model for exploration of innovations, we reran the model for the same situations as in Figure 5, but reduced drainage from ponds to zero (as could be done with clay on the pond bottom, or with plastic sheets). The results are shown in Figure 6. The difference is not as large as might be expected because evaporation losses from the surface are as large as the (low) rate of drainage in Figure 5.

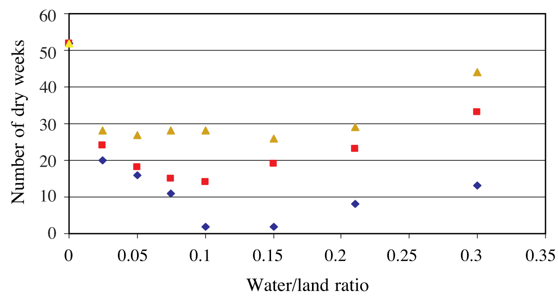


Figure 5a. Korat, style B

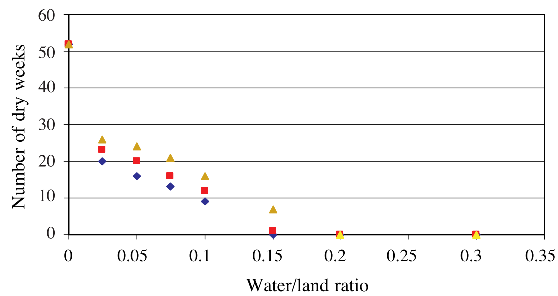


Figure 5b. Ubon, style B

Figure 5 (a, b). The number of weeks that the pond is dry under farming style B in Korat and in Ubon

Discussion

It is important to realize that in any situation the 'optimum pond size' is not the same for each of the four indicators. Moreover, the different styles, farmers give different weights to each of the indicators. As a result, determining 'the' optimum for a particular farmer cannot be done by reading only Figures 4, 5 or 6, and was suggested for brevity in the previous section. A more comprehensive set of graphs needs to

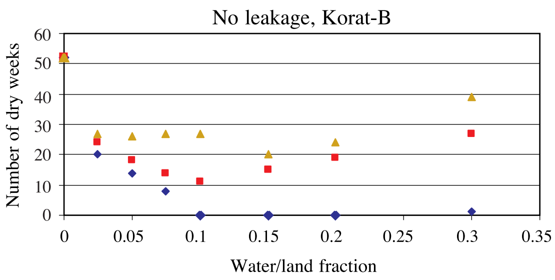


Figure 6a. Korat, style B, drainage prevented

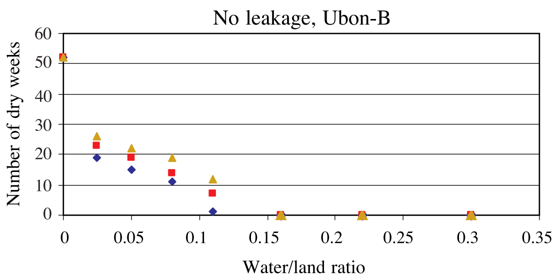


Figure 6b. Ubon, style B, drainage prevented

Figure 6 (a, b). The number of weeks that the pond is dry under farming style B but with sealed ponds to stop drainage

be considered together in a multi-criteria analysis. How this can be done effectively and interactively for this model with Thai farm advisors has still to be established.

This sample of results demonstrates some of the capacities of the BoNam model and present only indicative values. Limited calibration and feedback, however, are still a handicap to the practical value of the results. On-farm observations and interaction sessions are planned for the near future.

Shape of the pond was not mentioned so far even though farmers are interested in this feature. The shape of the pond (oval, rectangular, multiple small ones) does not affect much the results of simulations and any particular choice won't affect the results significantly. Practical advice, therefore, is to identify the shape(s) in agreement with landscape (lower parts of the farm and following the landscape). In low parts, upwelling of water from local acquifers could be very important. A factor farmers can influence is shading of the pond. This leads to a reduction of wind and hence of surface evaporation (but an increase of transpiration if trees provide shade) to reduce evaporation.

Local runon can be very significant. Yet, we observed on several occasions and different farms that farmers tend to overestimate the importance of rainfall in filling farm ponds and underestimate run-in; the quantities of drainage and upwelling are difficult to appreciate. A benefit of using the BoNam model can therefore be the refinement of the mental models FOs and farmers to in their daily operations with the farm water balance.

A model can also help to address consequences of variability and heterogeneity that otherwise can be difficult to judge. We avoided use of averaged rainfall data for simulation as Nonhebel (1994) found that use of such data may lead to overestimation of yields by 50% (unirrigated) to 15% (fully irrigated crops). However, there is still significant uncertainty in other important parameters, so that evaluation and calibration in the future needs more attention. Metselaar (1999) demonstrated clearly the importance of parameter inaccuracy in predictive modelling, and showed that calibration is indispensable before practical results can be obtained.

While it may be argued that the pond on every farm is customized in size and shape, in practice this cannot be handled at a large scale by the contractors who build them. They provide only the standard size and shape, where farmer can only determine where on the farm and, within limits, the linear. On a 1 hectare farm, the LDD standard volume (fixed value of 1,260 m^3) corresponds with a relative pond size of 4% (or about 15 × 25 m). Future scenario analysis should consider how to optimize for every growing season the use of the water in a pond of fixed size.

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Role of bio-resources in improving the fertility of coastal sandy soils for sustainable groundnut production

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Keywords: Sandy coastal soils, organic soil amendments, micronutrients, groundnuts

Abstract

The coastline of India is approximately 8,000 km in extent and is dominated by sandy light textured soils. Coastal sandy soils exhibit poor nutrient status especially micronutrients such as Zn and B due to leaching and low organic matter status. Groundnuts are one of the major crops grown by coastal farmers in the nutrient impoverished soils. An attempt has been made in the present investigation to improve the fertility of these coastal sandy soils with various bio-resources. A series of laboratory incubation, pot and field experiments were carried out using these coastal sandy soils. The soil used in these studies was representative of the sandy texture soils of the region (classified as Typic Udipsamments) with pH 8.38, electrical conductivity (EC) 1.12 dS m^{-1} with a low N, P, K, Zn and B status. Various bio-resources viz. Rhizobium, composted coirpith at 10 t ha^{-1} and lignite humic acid at 20 kg ha^{-1} along with $ZnSO_4$ at 25 kg ha^{-1} and Boron at 10 kg ha^{-1} constituting 16 treatments were studied in a factorial randomised block design with three replications using groundnut **(Arachis hypogea)** *as the test crop. Periodic soil and plant samples at the critical stages of the crop growth were sampled and the soil samples were analysed for various physico-chemical properties, nutrient availability, microbial population and enzyme activity viz. urease, phosphatase, dehydrogenase and cellulase. The results of the investigation showed that application of bio-resources significantly improved the soil chemical properties, available nutrients and microbial population. Enzymatic activities, an index of biological activity increased significantly and correlated positively with the microbial population of soil. A favourable soil environment created by way of improved physical, chemical and biological properties of the soil significantly increased the yield and nutrient uptake of groundnut in coastal sandy soils.*

Introduction

The coastline of India is approximately 8,000 km in extent and is dominated by sandy light textured soils. Poor nutrient status, low cation exchange capacity (CEC) and soil organic matter along with reduced microbial activity are the major constraints limiting crop production on these soils. Coastal sandy soils exhibit poor nutrient status especially micronutrients zinc (Zn) and boron (B) due to leaching and low organic matter status. Groundnut is one of the major crops grown by coastal farmers in the nutrient impoverished soils with relatively very poor yield. Hence, an attempt has been made in the present investigation to improve the fertility of these coastal sandy soils with various bio-resources.

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Materials and methods

To study the effect of various bio-resources in improving the fertility of the coastal sandy soils, a series of incubation, pot and field experiments were carried out during Feb. 2003 to April 2005 at the Department of Soil Science and Agricultural Chemistry, Annamalai University. The soil used in these studies was representative of the sandy texture soils of the region (classified as Typic Udipsamments) with pH 8.38, electrical conductivity (EC) 1.12 dS m^{-1} with a low N, P, K, Zn and B status. Various bio-resources viz. rhizobium, composted coirpith at 10 t ha^{-1} or humic acid at 20 kg ha^{-1} as organic sources and $ZnSO_4$ at 25 kg ha^{-1}, Boron at 10 kg ha^{-1} and their combinations constituting 16 treatments were studied in a factorial randomized block design (FRBD) replicated three times. Soil samples were taken at regular intervals and analysed for various physico-chemical properties such as pH, EC and nutrients viz. N, P, Zn and B using standard procedures as outlined by Jackson (1973). Based on the nutrient availability in the different treatments studied in the incubation experiment, the best bio-resource treatments, composted coirpith and humic acid and the inorganic treatment Zn + B were selected and evaluated for the performance in relation to groundnut production in the pot experiment. The treatments included for the pot experiment were: T_1- Absolute control; T_2- Recommended doses of fertilizers; T_3- T_2 + $ZnSO_4$ at 25 kg ha^{-1} + Boron at 10 kg ha^{-1}; T_4- T_3 + Composted coirpith at 10 t ha^{-1}; T_5- T_3 + Humic acid at 20 kg ha^{-1}; T_6- T_3 + Composted coirpith + Humic acid. To verify the validity of incubation and pot experiments, a field experiment was also carried out in coastal sandy soil. Soil samples (0-15 cm) were analysed for microbial populations viz. bacteria, fungi and actinomycetes as per the procedure proposed by Cynathia (2003). Enzymatic assay viz. urease (Tabatabai and Bremner, 1972), phosphatase (Tabatabai and Bremner, 1969), dehydrogenase (Casida et al., 1964) and cellulase (Denison and Koehn, 1977) were also estimated. The plant samples collected at critical stages were analysed for the concentrations of various nutrients like N, P, K, Fe, Zn and B using the procedures as given by Jackson (1973).

Treatment details

	Rec. fertilizer	Zn + B	CC	HA
T1	–	–	–	–
T2	+	–	–	–
T3	+	+	–	–
T4	+	+	+	–
T5	+	+	–	+
T6	+	+	+	+

Results and discussion

All the bio-resources evaluated were helpful in reducing the soil pH and EC of the coastal sandy soil. In the incubation study, the maximum reduction was observed with the application of composted coirpith at 10 t ha^{-1} (pH 8.12 and EC 0.76 dS m^{-1}). The combined application of composted coirpith and humic acid were the best treatment in reducing the pH and EC in pot experiment (pH 8.09 and EC 0.70 dS m^{-1}) as well as in the field experiment (pH 8.22 and EC 0.83 dS m^{-1} at harvest stage). The decomposition of applied bio-resources accompanied by the release of organic

Table 1. Effect of bio-resources on the physico chemical properties and available nutrient contents of soil in the incubation experiment

Treatments	pH	EC (dS m^{-1})	OC (%)	N (ppm)	P (ppm)	K (ppm)	Zn (ppm)	B (ppm)
A_1B_1	8.29	1.01	0.29	60.88	4.10	87.17	0.87	0.16
A_1B_2	8.29	1.02	0.30	66.77	4.50	88.50	0.90	0.17
A_1B_3	8.19	0.77	0.42	70.98	6.22	101.83	1.28	0.25
A_1B_4	8.15	0.85	0.38	68.02	6.03	97.17	1.20	0.21
A_2B_1	8.28	1.03	0.30	61.05	4.23	88.67	1.14	0.16
A_2B_2	8.30	1.01	0.32	67.52	4.58	90.17	1.25	0.17
A_2B_3	8.12	0.75	0.43	71.95	6.35	102.00	1.32	0.26
A_2B_4	8.20	0.84	0.39	68.42	6.10	97.50	1.36	0.21
A_3B_1	8.26	1.01	0.30	60.78	4.22	88.50	0.96	0.46
A_3B_2	8.30	1.02	0.31	67.08	4.53	89.83	0.97	0.39
A_3B_3	8.11	0.77	0.45	71.32	6.28	102.17	0.99	0.51
A_3B_4	8.17	0.85	0.40	67.62	6.02	98.83	0.98	0.44
A_4B_1	8.27	1.02	0.31	61.62	4.32	81.83	1.20	0.41
A_4B_2	8.31	1.00	0.33	67.60	4.59	90.67	1.29	0.41
A_4B_3	8.05	0.73	0.44	72.03	6.42	103.33	1.48	0.52
A_4B_4	8.15	0.81	0.40	68.73	6.33	100.17	1.46	0.48
S Ed	0.03	0.02	0.03	2.71	0.10	2.12	0.04	0.02
CD (p = 0.005)	NS	0.04	0.06	5.43	0.20	NS	0.08	0.04

A_1 – Control; A_2 – $ZnSO_4$ @ 25 kg ha^{-1}; A_3 – Boron @ 10 kg ha^{-1}; A_4 – $ZnSO_4$ + Boron
B_1 – Control; B_2 – Rhizobium; B_3 – Composted coirpith @ 10 t ha^{-1}; B_4 – Humic acid @ 20 kg ha^{-1}
CD – Critical Difference (Test of significance – Probability at 5% level)

Table 2. Effect of bio-resources on the physico chemical properties and organic carbon content of soil

Treatment	Pot experiment			Field experiment		
	pH	EC (dS m^{-1})	OC (%)	pH	EC (dS m^{-1})	OC (%)
T_1	8.41	1.00	0.30	8.42	1.00	0.29
T_2	8.40	0.99	0.31	8.41	0.99	0.30
T_3	8.41	0.98	0.30	8.41	0.99	0.30
T_4	8.14	0.80	0.40	8.26	0.87	0.38
T_5	8.28	0.84	0.38	8.30	0.91	0.36
T_6	8.09	0.70	0.43	8.22	0.83	0.41
S Ed	0.02	0.03	0.01	0.02	0.02	0.01
CD (p = 0.05)	0.04	0.05	0.02	0.03	0.03	0.02

T_1- Absolute control; T_2- 100% NPK; T_3- T_2 + $ZnSO_4$ @ 25 kg ha^{-1} + Borax @ 10 kg ha-^{1}; T_4- T_2 + T_3 + Composted Coirpith @ 10 t ha^{-1}; T_5- T_2 + T_3 + Humic acid @ 20 kg ha^{-1}; T_6- T_2 + T_3 + Composted Coirpith and Humic acid.

Table 3. Effect of bio-resources on the soil microbial population and enzymatic activity of soil

Treatment	Microbial population			Enzyme activity			
	Bacteria	Fungi	Actinomycetes	Urease	Phosphatase	Dehydrogenase	Cellulase
T_1	10.33	3.99	3.67	19.27	14.17	89.13	12.66
T_2	12.99	4.67	4.33	27.57	18.11	110.50	15.03
T_3	12.66	4.99	4.67	27.63	20.36	114.00	16.00
T_4	21.33	9.33	7.33	44.00	24.50	141.76	21053
T_5	18.67	7.67	5.33	42.13	21.57	135.50	18.43
T_6	22.67	11.00	8.33	51.70	27.50	151.90	24.50
S Ed	0.56	0.31	0.26	1.58	0.83	3.63	0.74
CD (p = 0.05)	1.02	0.62	0.52	3.15	1.65	7.26	1.49

Bacteria – 10^{-6}/g soil; Fungi – 10^{-5}/g soil; Actinomycetes – 10^{-4}/g soil
Urease – µg NH_4/g soil/24 hr.; Phosphatase – µg p-nitrophenol/g soil/hr.; Dehydrogenase – µg TTF/g soil/24 hr.; Cellulase – µg DNS/g soil/hr.

acids contributed its effect on reducing the soil pH and EC. Tolanur and Badunar (2003) obtained the results similar to this study.

In the present study, the influences of bio-resources in enhancing the availability of soil major and micronutrients was well evidenced in all the experiments. The results indicated the increased availability of major nutrients with the conjoint application of composted coirpith at 10 t ha^{-1} and humic acid at 20 kg ha^{-1}. In the field experiment a NPK content of 109, 18.9 and 163 kg ha^{-1} were recorded in comparison to 79, 5.2 and 132 kg ha^{-1} respectively in control

The combined application of composted coirpith and humic acid increased the availability of zinc and boron in post harvest soil. In the field experiment, a concentration of 1.27 ppm of Zn and 0.26 ppm of B were recorded as compared to 0.74 and 0.06 ppm in control (Table 4). The decomposition of applied bio-resources accompanied by weathering certain primary minerals, and greater multiplication of microbes has helped in the mineralization of the nutrient elements (Tolanur and Badanur, 2003). Further, the reduction in soil pH and reduced volatilization loss of N and increased solubility of P due to acid production with the application of composted coirpith and humic acid can be ascribed to the greater nutrient availability in the soil (Savithri and Hameed Khan, 1994).

The applied bio-resources were also helpful in creating a better soil biological environment of coastal sandy soil, and were well evidenced in the present study by the increased microbial population and enzymatic activity. The combined application of composted coirpith at 10 t ha^{-1} and humic acid at 20 kg ha^{-1} significantly increased the population of bacteria (22.67 × 10^6/g soil), fungi (11.0 × 10^5/g soil) and actinomycetes (8.33 × 10^4/g soil). The availability of readily mineralized C and N and improvement in the physico-chemical properties of the soil due to the application of bio-resources might have improved the microbial population of the soil (Baradwaj and Datt, 1995). The same treatment recorded 51.70 µg NH_4/g soil/24 hr. of urease, 27.50 µg p-nitrophenol/g soil/hr. of phosphatase, 151.90 µg TTF/g soil/24 hr. of

Table 4. Effect of bio-resources on the nutrient availability of soil

Treatment	Pot experiment (ppm)					Field experiment (kg ha^{-1})				
	N	P	K	Zn	B	N	P	K	Zn	B
T_1	38.73	4.28	64.47	0.63	0.09	79	5.2	132	0.74	0.06
T_2	45.37	4.52	71.63	0.65	0.11	93	16.5	143	0.77	0.07
T_3	44.53	4.53	69.50	1.06	0.15	91	16.4	139	1.13	0.18
T_4	55.23	5.05	78.67	1.18	0.23	101	18.3	157	1.23	0.22
T_5	52.70	4.93	75.93	1.12	0.21	96	17.5	152	1.19	0.20
T_6	59.47	5.13	79.97	1.21	0.27	109	18.9	163	1.27	0.26
S Ed	1.78	0.01	2.02	0.01	0.01	1.88	0.49	2.86	0.02	0.01
CD (p = 0.05)	3.55	0.03	4.03	0.02	0.02	3.75	0.98	5.72	0.03	0.02

Table 5. Effect of bio-resources on the growth and yield of groundnut

Treatment	Pot experiment				Field experiment			
(cm)	Plant height plant	No. of pods per	Pod yield (g pot^{-1}) (g pot^{-1})	Haulm yield (cm)	Plant height plant	No. of pods per	Pod yield (kg ha^{-1})	Haulm yield (kg ha^{-1})
T_1	42.47	12.33	22.00	33.52	51.56	16.99	1,225.2	1,740.8
T_2	52.70	15.67	25.19	39.37	58.76	17.33	1,390.6	1,935.7
T_3	49.67	16.00	26.95	39.46	58.96	17.66	1,425.5	1,947.8
T_4	58.50	20.67	31.03	44.64	61.33	21.00	1,605.7	2,150.0
T_5	55.23	18.33	29.71	41.76	59.76	18.66	1,525.8	2,098.3
T_6	63.10	22.00	34.40	48.07	62.96	23.66	1,670.0	2,214.4
S Ed	1.63	0.43	1.10	1.26	1.01	0.46	33.77	36.55
CD (p = 0.05)	3.25	0.86	2.19	2.52	2.04	0.92	67.53	73.10

Table 6. Effect of bio-resources on the major nutrient uptake by groundnut

Treatment	Pot experiment (mg pot^{-1})						Field experiment (kg ha^{-1})					
	N		P		K		N		P		K	
	Pod	Haulm	Pod	Haulm	Pod	Haulm	Pod	Haulm	Pod	Haulm	Pod	Haulm
T_1	774.00	653.15	73.41	82.95	201.97	543.90	41.99	35.72	3.97	3.16	11.52	39.81
T_2	975.92	784.06	105.27	121.14	272.14	679.50	54.37	42.53	5.48	5.21	14.91	46.48
T_3	990.38	802.34	110.33	125.94	281.89	692.59	55.16	43.71	5.92	5.49	15.16	47.60
T_4	1,325.1	967.56	150.23	161.19	351.57	824.12	76.86	55.27	7.94	7.34	18.94	53.97
T_5	1,185.8	870.93	129.28	145.65	314.30	733.22	69.32	51.82	7.17	7.09	16.27	48.18
T_6	1,437.4	1,098.3	172.32	189.32	379.91	879.78	81.33	62.99	8.48	9.04	19.83	56.83
S Ed	42.31	38.54	6.87	6.01	11.81	32.58	2.38	3.09	0.20	0.22	0.22	1.06
CD (p = 0.05)	84.62	77.10	13.74	12.03	23.62	65.16	4.76	6.17	0.38	0.41	0.43	2.11

Table 7. Effect of bio-resources on the micronutrient uptake by groundnut

Treatment	Pot experiment (mg pot^{-1})						Field experiment (kg ha^{-1})					
	Zn		B		Fe		Zn		B		Fe	
	Pod	Haulm	Pod	Haulm	Pod	Haulm	Pod	Haulm	Pod	Haulm	Pod	Haulm
T_1	10.95	16.65	46.77	147.71	57.43	91.04	0.59	0.84	0.21	0.42	0.32	0.77
T_2	13.25	19.85	65.81	183.51	66.13	107.24	0.75	1.13	0.37	0.51	0.36	0.83
T_3	13.68	20.46	68.30	201.17	70.76	107.74	0.79	1.13	0.37	0.52	0.38	0.85
T_4	16.48	24.19	91.68	260.50	88.20	126.28	0.90	1.24	0.52	0.76	0.47	0.88
T_5	14.48	21.43	83.36	229.45	80.13	114.12	0.83	1.17	0.49	0.68	0.43	0.86
T_6	17.15	25.14	105.54	284.36	95.88	130.96	1.04	1.26	0.54	0.82	0.52	0.92
S Ed	0.43	1.04	3.12	7.85	3.63	6.03	0.02	0.01	0.02	0.02	0.02	0.01
CD (p = 0.05)	0.86	2.08	6.23	15.70	7.25	12.15	0.03	0.02	0.03	0.03	0.03	0.02

dehydrogenase and 24.50 µg DNS/g soil/hr. of cellulase. The increase in the soil enzymatic activity may be ascribed to the easily biodegradable organic matter imposed in the soil, which stimulated the growth of soil microorganisms (Perucci, 1992).

The bio-resources significantly increased the yield of groundnut in coastal sandy soil. The highest pod and haulm yield of 34.40 and 48.07 g pot^{-1} in pot experiment and 1,670 and 2,214 kg ha^{-1} respectively in field experiments were recorded with the combined application of composted coirpith and humic acid along with Zn + B. The increased yield with the application of bio-resources along with micronutrients might be due to the increased production of Indole Acetic Acid (IAA) in plants, thereby contributing growth promotion and yield maximization. This finding corroborates the earlier report of Parasuraman and Mani (2003).

The uptake of N, P, K, Fe, Zn and B by groundnut was also significantly increased with the various bio-resources. In field experiment, the combined application of composted coirpith and humic acid recorded 81.33 kg ha^{-1} of N, 1.04 kg ha^{-1} of Zn and 0,54 kg ha^{-1} of B by pod and 62.99, 1.26 and 0,82 kg ha^{-1} of N, Zn and B by haulms respectively. The increased nutrient uptake by groundnut with bioresource application might be due to reduction of soil pH by the way of organic acid production and by the mechanism of chelation which favoured for greater nutrient availability and uptake by plants. This corroborates the earlier report of Savithri and Hameed Khan (1994).

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Performance of rice in lowland soils amended with humified sludge and organic manures

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Keywords: sludge, animal manures, fertilizer, rice yields, nitrogen use efficiency

Abstract

Experiments were conducted in 2002 in the Ashanti region, Ghana, to evaluate the effect of humified sludge (HS), poultry manure (PM), cattle manure (CM), mixture of humified sludge, poultry manure and cattle manure (MM) and inorganic fertilizer (IF) on growth, yield and nitrogen uptake, and use efficiency of rice, in three lowland soils.

The study revealed that soil amendment with organic fertilizer such as manures or humified sludge improved rice growth and the yield. Amendment brought forward flowering by more than 7 days in the vertisol. Humified sludge (HS), poultry manure (PM) and inorganic fertilizer (IF) tended to enhanced tillering compared to the cattle manure (CM) and the mixture of the manures (MM), especially in the vertisol. Mean grain yield was 17.4% better in the second season than in the first season, probably due to a second application of organic materials. For the first and the second season the effect of the amendments on grain yield was ranked HS>PM>MM>IF>CM>Control and HS>PM>IF>CM>MM>Control, respectively. The superiority of HS and PM to the IF may be attributed to balanced and gradual release of plant nutrients, which synchronized with the demand, at the different growth stages of the rice.

N uptake was significantly enhanced by nutrient amendments, with HS and PM producing more N uptake than CM during the second season. Soil type and nutrient amendment had little effect on both physiological nitrogen use efficiency (PNUE) and nitrogen harvest index (NHI). The highest N uptake was observed in the gleysol during the second season. Agronomic N use efficiency (ANUE) followed the order; Vertisol> Gleysol>Fluvisol in the second season. The observed differences in N uptake and ANUE among the treatments may be partly due to differences in the native fertility of the soils.

Introduction

High input prices, potential environmental problems related to the use of chemical fertilizer and the need for efficient utilization of natural resources have generated interest in the use of organic material in sub-Saharan Africa. Application of organic materials has long been known to improve soil physical and chemical properties especially providing nutrients. However, mineralization of soil organic N varies widely with soil properties (type, texture, pH…). Qi-xiao, 1984, Eneji et al., 2002). Due to urbanization, rice has become an important staple food in Ghana and rank second after wheat on the food import list of Ghana GLG/SOFRICO).

Soils of the inland valleys of West Africa are generally very poor in nutrients. The average exchangeable Ca, Mg and K, ECEC, clay content and available phosphorus of these soils are considerably lower than those in Southeast Asia and Japan (Hirose and Wakatsuki, 2002). Their fertility is therefore among the lowest in the world. Farmers in the inland valleys (IVs) of sub-Saharan Africa cultivate rice mostly under rainfed conditions with little or no bunding. Their fields alternate between flooded and droughty conditions, thus subjecting added inputs, particularly N, to leaching and surface runoff, leading to reduced N-use efficiency (Fashoola et al., 2001). The traditional low-yielding, non-responsive rice varieties are being replaced by improved high-yielding varieties in West Africa (IITA,1992). Balanced fertilization and availability of macro and micro-nutrients is essential to realize the yield potential of these modern varieties. The use of inorganic fertilizer is very low among rice farmers in West African due to

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its high cost. Keeping the production cost low is an important strategy for smallholder rice farmers in the area. Therefore, the use of low-cost external inputs, while maintaining stable rice yield is necessary. An experiment was conducted to evaluate rice growth, grain yield and N response under different soil amendments (viz. inorganic fertilizer, sewage sludge, poultry and cattle manure) in three lowland soils of Ghana.

Materials and Methods

The study was carried out in 2003 during the dry and rainy seasons at the Crops Research Institute, Kumasi, Ghana. The site is located in the semi-deciduous forest agro-ecological zone with a bimodal rainfall pattern. The major rainy season lasts from mid-March to the end of July, while the secondary rainy season begins in September and ends in mid-November (Figure 1). This is followed by a long dry spell which ends by mid-March. The soils used for the study were an Eutric Vertisol, an Eutric Fluvisol, an Haplic Gleysol Food and Agricultural Organization (1991), which represent the main lowland soils in Ghana. The physico-chemical properties of the soils are given in Table 1.

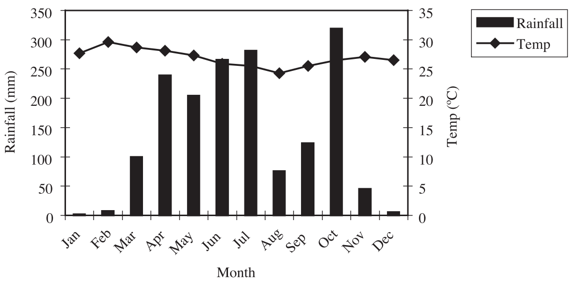


Figure 1. Monthly rainfall (mm) and mean temperature at Crops Research Institute, Kumasi, Ghana during the experiment

Pots (25 cm in diameter and 30 cm in depth) were filled with 8 kg of each of the soils. Three sources of organic manure (Table 2), – Humified sludge (HS), Poultry manure (PM), Cattle manure (CM), mixture of manures (MM=HS+PM+CM) and inorganic fertilizer (90 kg N + 45 kg P_20_5 and 45 kg K_20 ha^{-1}) constituted the treatments. The control treatments received neither manure nor inorganic fertilizer. The quantities of the manure applied were calculated to supply 90 kg ha^{-1} were mixed with the soil four weeks before the transplantation of the rice seedlings. There was total of 18 treatments (i.e. three soil types x five sources of plant nutrients and a control). The 18 treatments were replicated five times and arranged in a randomized complete block design.

Table 1. Characteristics of the Soil Used for the Study

	Soil type		
	Eutric Vertisol	**Eutric Fluvisol**	**Haplic Gleysol**
pH (H_2O) 1:2	7.5	4.7	5.0
Total C (gkg^{-1})	23.0	12.7	12.0
Total N (gkg^{-1})	2.1	3.3	1.3
Available P (mg kg^{-1})	2.1	1.8	2.9
Exc. Ca ($cmolckg^{-1}$)	13.3	6.4	8.2
Exc. K (cmol kg^{-1})	0.1	0.8	0.2
Exc. Mg (cmolc kg^{-1})	5.3	2.8	1.7
Exc. Na (cmol kg^{-1})	0.7	0.3	0.4
Exc. Acidity (cmol kg^{-1})	0.8	1.0	1.0
CEC (cmol kg^{-1})	28.5	11.2	11.9
Texture	DC	SiCL	SiL

DC = Dark clay; SiCL = Silty clay loam; SiL = Silty Loam

Table 2. Characteristics of the Organic Manutres Used for the Study

	Humifie Sludge	**Poultry Manure**	**Cattle Manure**
pH (H_2O) 1:2	6.1	8.0	7.5
Moisture (%)	69.2	72.0	77.7
Total C (gkg^{-1})	335.9	153.0	252.2
Total N (gkg^{-1})	57.4	35.0	19.0
P_2O_5 (gkg^{-1})	50.8	66.4	14.9
CaO (gkg^{-1})	18.9	28.0	18.2
K_2O (gkg^{-1})	5.3	21.8	24.1
MgO (gkg^{-1})	5.1	13.4	11.5
$ECdSm^{-1}$ (1:1)	1.8	7.5	7.1

For the inorganic treatment, a basal fertilizer rate of 45 kg N, 45 P_2O_5 kg and 45 kg K_2O ha^{-1} was applied to the pots before transplanting. The rest of the N was applied as top dressing at the panicle initiation stage. Twenty-one-day-old seedlings of the rice variety TOX 3108-56-4-2-2-2 were transplanted at the rate of two seedlings per pot. Water level was gradually raised from 2 cm to 5 cm 14 days after transplanting, then maintained at this level 10 days before harvest.

At maximum tillering (MT), heading and harvest period, the above ground biomass was sampled, dried (70°C), weighed and ground to pass a 0.42 mm sieve. Soil samples were also collected from the topsoil (0-15 cm), dried and ground to pass a 2 mm sieve before analysis. Total N and C content of both the plant and soil samples were analysed by the dry combustion method using an automated Yanaco CN coder (Model MT-700, Yanagimoto MFG. Co. Ltd. Kyoto, Japan). The rice grain weight was recorded at harvest and its moisture content was measured using a multigrain tester. Grain weight was then adjusted to 14% moisture.

Nitrogen use efficiency (NUE) was evaluated based on the agronomic N use efficiency (ANUE), the physiological N use efficiency (PNUE) and the nitrogen harvest indexes (NHI) using the following equations;

1. $$\text{ANUE} = \frac{\text{Grain yield with N application} - \text{Grain yield with no N}}{\text{N applied}}$$

2. $$\text{PNUE} = \frac{\text{Grain yield}}{\text{Total N uptake}}$$

3. $$\text{NHI} = \frac{\text{Grain N}}{\text{Total N content}}$$

Rice growth, yield and yield attributes (number of tillers, plant height, number of panicles, 1,000 grain weight, grain yield and weight of dry matter at maximum tillering, anthesis and at harvest) were recorded.

The data were statistically analysed as a factorial experiment following the general Linear Model (GLM) procedure of SAS/StatView package (1999). A probability of <0.05 was considered as significant and the mean separation was done by Duncan's multiple Range Test.

Results

A sharp increase in dry matter was observed from anthesis (AT) to grain maturity (MAT) Figure 2. However, amending the vertisol with PM in the

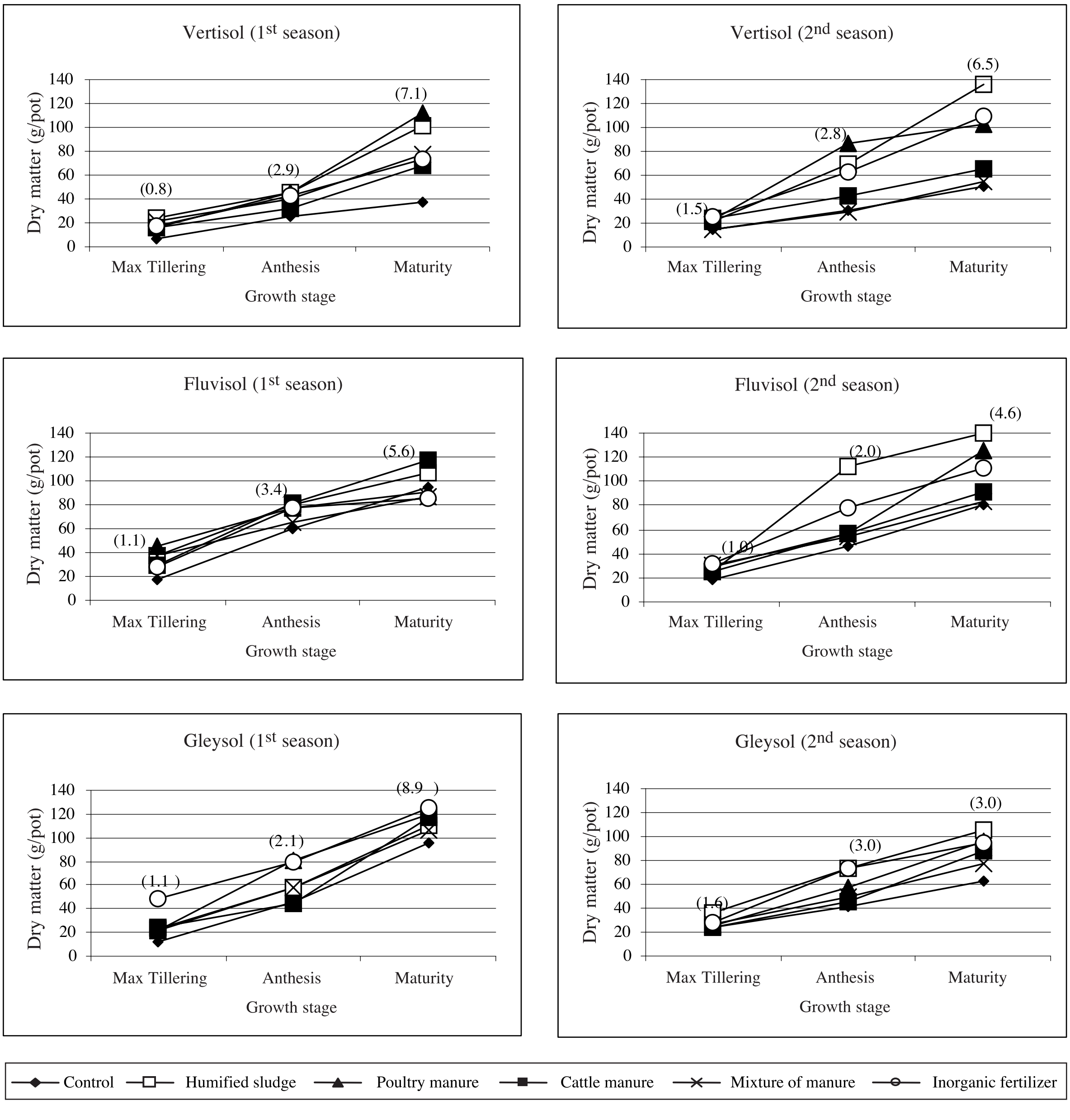


Figure 2. Dry matter accumulation at different growth stages of rice as affected by soil type and nutrient sources

1st season, and Fluvisol with IF in the 2nd season, resulted in a significant decreases in DM accumulation from AT to MAT. For all soils, CM and MM gave a relatively low DM accumulation towards maturity particularly in the 2nd season. DM accumulation was poorer when no amendments were made to the soils in both seasons. In dry season, the highest DM accumulation was observed in Gleysol amended with PM and IF treatments while for both seasons, HS application proved superior.

The average standard error of the six treatments at each growth stage is given in parenthesis.

The data for the number of effective tillers per hill are represented in Table 3. During the dry season, all treatments, but CM, significantly improved tillering in the vertisol. The fluvisol PM treatment gave significantly more tillers than the other treatments. For the gleysol tillering was best in the PM and IF treatments. During the rainy season HS produced more tillers than the other nutrient amendments under vertisol while HS, IF, PM gave more tillers under Gleysol. For the Fluvisol, PM, IF and HS produced more tillers than the other amendments. Based on soil type, tillering varied in the order fluvisol>gleysol> vertisol.

During the dry season all nutrient amendment of vertisol significantly increased plant height (Table 3), but height differences in fluvisol were not significant. Cattle manure, PM and MM had better effect on plant height under Gleysol. In the rainy season, HS and PM significantly increased plant height under the Vertisol while for Fluvisol, PM was superior to all other amendments. For both seasons the lowest plant eight was recorded under vertisol.

The data on days to 50% flowering are also shown in Table 3. Rice took a longer time to flower when the vertisol was not treated with manure or fertilizer during the two seasons. Flowering also was delayed when gleysol was amended with PM, CM and IF in the rainy season.

Difference in 1,000 grain weight among the soil types and plant nutrient inputs did not follow any trend during the dry season. However, in rainy season, all the treatments improved 1,000 grain weight than control in both vertisol and fluvisol (Table 4).

The number of rice grains per panicle is presented in Table 3. This was recorded only in rainy season. The differences among soil types are ranked: EF>EV>HG whereas based on nutrient sources the

Table 3. Effect of soils and manure type on growth and yield attributes of rice Values with different letters are significantly different

	Dry Season								
	Tillers/pot Soil Type			Plant Height (cm) Soil Type			Days to Flowering Soil Type		
Nutrient source	Vert	Fluv	Gley	Vert	Fluv	Gley	Vert	Fluv	Gley
Control	14^{a}	25^{a}	25^{a}	94.0^{a}	116.3^{a}	107.3^{ab}	112^{c}	103^{c}	100^{bc}
HS	21^{b}	33^{b}	23^{a}	120.3^{b}	121.3^{a}	103.7^{a}	97^{a}	99^{bc}	100^{bc}
PM	21^{b}	40^{c}	31^{b}	121.3^{b}	118.3^{a}	117.3^{c}	104^{b}	96^{ab}	104^{b}
CM	13^{a}	28^{a}	24^{a}	112.7^{b}	116.3^{a}	116.7^{bc}	95^{a}	96^{ab}	93^{a}
MM	19^{b}	26^{a}	22^{a}	118.7^{b}	117.0^{a}	117.7^{c}	103^{b}	98^{b}	98^{b}
IF	21^{b}	29^{a}	34^{b}	112.7^{b}	115.3^{a}	106.0^{a}	101^{b}	93^{a}	96^{ab}

	Rainy Season											
	Tillers/pot Soil Type			Height (cm) Soil Type			Days to Flowering Soil Type			No. of grains/panicle Soil Type		
Nutrient source	Vert	Fluv	Gley	Vert	Fluv	Gley	Vert	Fluv	Gley	Vert	Fluv	Gley
Control	10^{a}	18^{a}	14^{a}	112.6^{a}	110.0^{a}	103.3^{a}	111^{d}	100^{a}	99^{b}	121^{a}	135^{a}	127^{a}
HS	19^{b}	26^{a}	27^{c}	125.7^{d}	114.7^{a}	123.3^{c}	98^{a}	100^{ab}	100^{bc}	168^{c}	164^{c}	140^{a}
PM	18^{a}	24^{a}	22^{abc}	122.7^{d}	124.7^{b}	114.7^{b}	104^{b}	98^{a}	101^{c}	159^{bc}	156^{bc}	129^{a}
CM	12^{a}	18^{a}	16^{ab}	119.3^{bc}	111.7^{a}	118.3^{bc}	107^{c}	100^{a}	102^{c}	135^{a}	142^{ab}	135^{a}
MM	11^{a}	19^{a}	16^{ab}	107.6^{a}	117.7^{a}	102.0^{a}	108^{c}	98^{a}	96^{a}	132^{a}	144^{ab}	135^{a}
IF	17^{a}	25^{a}	24^{bc}	113.3^{ab}	116.3^{a}	105.3^{a}	100^{a}	99^{ab}	101^{c}	148^{b}	142^{ab}	131^{a}

(HS = humifed sludge; PM = poultry manure; CM = cattle manure; MM = mixture of manures; IF = inorganic fertilizer; Vert = eutric vertisol; Fluv = eutric fluvisol; Gley = haplic gleysol)

Table 4. Effect of sources of plant nutrients and soil type on 1,000 grain weight. Values with different letters are significantly different

	Grain weight (g)					
	Dry season Soil Type			Rainy Season Soil Type		
Nutrient source	Vert	Fluv	Gley	Vert	Fluv	Gley
Control	20.9^{a}	24.3^{b}	23.6^{ab}	23.0^{a}	23.3^{a}	27.0^{b}
HS	23.5^{ab}	24.1^{b}	22.3^{ab}	29.4^{b}	28.1^{b}	27.5^{b}
PM	23.5^{ab}	21.1^{a}	22.4^{ab}	29.1^{b}	28.8^{b}	28.5^{b}
CM	24.1^{b}	25.7^{b}	22.1^{a}	27.9^{b}	29.1^{b}	29.1^{b}
MM	23.9^{b}	22.6^{a}	22.9^{ab}	27.7^{b}	30.0^{b}	27.7^{b}
IF	22.9^{a}	24.5^{b}	25.0^{b}	29.0^{b}	29.1^{b}	27.7^{b}

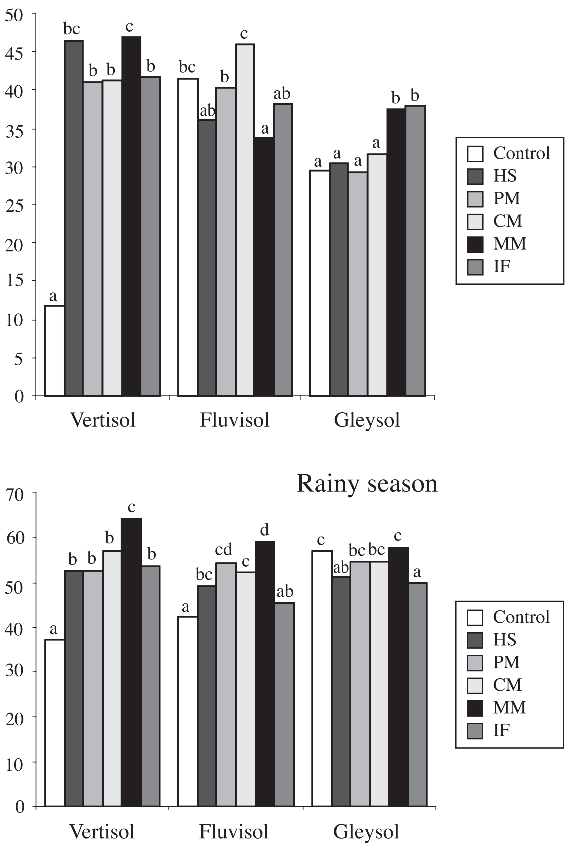
HS = humified sludge; PM = poultry manure; CM = cattle manure; MM = mixture of manures; IF = Inorganic fertilizer; Vert = eutric vertisol; Fluv = eutric fluvisol; Gley = haplic gleysol.

number of seeds per panicle varied in the order: HS>PM>IF>CM>MM>CONTROL

The effect of different soils and manure types on rice yields for the dry and rainy seasons' trials, are shown in Figure 3. In the dry season the manure effect on rice yield was ranked HS>PM>MM>IF>CM>CONTROL. Among the soils, the rice grain yield differed in the following order: EF>HG>EV. The best grain yields were recorded when HS and PM were incorporated in the vertisol. Grain yield was lowest in the unfertilized vertisol. Yield response to all nutrient amendments except MM was similar for fluvisol and gleysol during the dry season. Generally grain yield of rice in rainy season exceeded that of the dry season by 17.4%. Differences in yield among the soils followed a similar trend as the dry season trial. However among nutrient sources the trend differed in the order; HS>PM>IF>CM>MM>CONTROL. HS and PM produced similar yields under Fluvisol. For the two seasons, HS and PM amendment increased rice yield more than the inorganic fertilizer.

The greatest harvest index (64.1%) was obtained from vertisol amended with MM as shown in Figure 3. Under Fluvisol MM gave the lowest HI in the dry season but in the rainy season HI was lowest under IF and control treatments. In the dry season, the IF-treated Gleysol gave the lowest HI. Gleysol treated with mixed manures had the best HI among the treatments in the two seasons.

Nutrient amendments significantly improved nitrogen (N) uptake in both the grain and the straw (Table 5) but the uptake differed significantly among soil types and nutrient sources (P <0.01). In the 2[nd] season, total N uptake due to HS incorporation was



(HS = humified sludge; PM = poultry manure; CM = cattle manure; MM = mixture of manures; IF = inorganic fertilizer).

Figure 3. Influence of different sources of plant nutrient and soil type on Harvest Index. Bars with the same letters are not significantly different

significantly higher than in all other treatments across soil types. However, in the straw, N uptake due to HS and IF application was similar. During the 1[st] season, N uptake was higher under Gleysol than the other soil types. Soil type did not have effect on N uptake in all plant parts in the 2[nd] season.

For both seasons, the highest agronomic nitrogen use efficiency (ANUE) was obtained from HS amendment (Table 6). ANUE was best under vertisol. In 2[nd] season ANUE varied among soil types in the following order: Vert>Gley>Fluv. Regardless of the soil type, no significant differences were observed among nutrient sources in the 1[st] season. However a significant interaction was observed between nutrient sources and soil types. The trend in 2[nd] season with respect to nutrient application followed the order: HS>PM>IF>CM>MM.

Generally nutrient source or soil type did not substantially affect the ratio of grain production/total N (i.e. PNUE). The influence due to nutrient treatment was significant only in the 1[st] season (Table 6).

Table 5. Influence of soil and manure type on N uptake in rice grain and straw

haplic gleysol) Nutrient source (N)	First (Dry) season			Second (Rainy) season		
	N uptake in grain (g/kg)	N uptake Straw (g/kg)	Total N uptake in plant (g/kg)	N uptake in grain (g/kg)	N uptake Straw (g/kg)	Total N uptake in plant (g/kg)
Control	0.41c	0.47b	0.88b	0.50d	0.34c	0.84d
HS	0.67a	0.73a	1.41a	1.16a	0.65a	1.81a
PM	0.65ab	0.67ab	1.32a	1.00b	0.56b	1.56b
CM	0.56b	0.61ab	1.17a	0.76c	0.38c	1.14c
MM	0.61ab	0.53ab	1.14ab	0.76c	0.34c	1.10c
IF	0.62ab	0.61ab	1.23a	0.87c	0.69a	1.56b
Soil type (S)						
Vert	0.56a	0.42c	0.98b	0.79a	0.45a	1.24a
Fluv	0.57a	0.51b	1.09b	0.91a	0.55a	1.46a
Gley	0.62a	0.88a	1.5a	0.82a	0.48a	1.30a
N × S	**	*	**	**	**	**

* Significant at 0.05 level; ** Significant at 0.01 level
NS = not significant; HS = humified sludge; PM = poultry manure; CM = cattle manure; MM = mixture of manures; IF = inorganic fertilizer; Vert = eutric vertisol; Fluv = eutric fluvisol; Gley = haplic gleysol
In a column under the same layer, means followed by a common letter are not significant at 5% level by DMRT.

Table 6. Effect of soil and manure type on Agronomic nitrogen use efficiency (ANUE), Physiological nitrogen use efficiency (PNUE) and Nitrogen harvest index of rice

Nutrient source (N)	First (Dry) season			Second (Rainy) season		
	ANUE (g rice per N applied)	PNUE (g rice per N absorbed)	NHI (%)	ANUE (g rice per N applied)	PNUE (g rice per N absorbed)	NHI (%)
Control	–	21.5b	46.4a	–	35.7ab	59.2c
HS	51.9a	29.5a	48.9a	96.0a	36.1ab	64.1b
PM	48.5a	30.4a	50.4a	74.7ab	37.2a	64.1b
CM	36.0a	30.4a	50.0a	39.1cd	39.0a	66.8ab
MM	45.1a	33.9a	54.4a	33.9d	38.7a	70.3a
IF	48.8a	32.2a	51.2a	60.6bc	33.4b	56.1c
Soil type (S)						
Vert	82.5a	30.7a	55.9a	91.8a	36.4a	64.6a
Fluv	62.3a	33.6a	53.2a	15.3c	36.6a	62.1a
Gley	37.6b	24.7a	41.6a	31.1b	37.0a	63.6a
N × S	**	**	*	**	**	**

* Significant at 0.05 level; ** Significant at 0.01 level
NS = not significant; HS = humified sludge; PM = poultry manure; CM = cattle manure; MM = mixture of manures; IF = inorganic fertilizer; Vert = eutric vertisol; Fluv = eutric fluvisol; Gley = haplic gleysol
In a column under the same layer, means followed by a common letter are not significant at 5% level by DMRT.

No statistically significant change in nitrogen harvest index (NHI) occurred as a result of soil amendment in the 1st season. A similar observation was made among soil types in both seasons (Table 6). The best NHI value was recorded in the 2nd season with MM amendments. However this did not differ significantly from the value recorded under CM treatment. IF incorporation recorded the lowest NHI in all soil types as compared with the organic amendments in the 2nd season. There was an interaction between nutrient source and soil type for all parameters shown in Table 6.

Discussion

Generally, a greater number of effective tillers were obtained with PM, HS. This was possibly due to continuous and adequate release of plant nutrients particularly nitrogen for development of tillers and panicles. Mae and Shoji (1984) reports close correlation between the number of tillers and amount of N absorbed during tillering and panicle initiation. Poor physical condition and probably NH^{+}_{4} fixation in the vertisol may explain the poor tillering of rice in the unfertilized control compared to the other soil types of the same treatment. The number of days to 50% flowering was increased by about 7 days during both seasons in the un-amended vertisol. Nutrient amendment and soil type did not have much influence on 1,000-grain weight, although some lower values were obtained with control only during the rainy season. Test weight is a varietal character strictly controlled by the hull of the particular variety and thus cannot grow beyond the size allowed by the size of the hull (Mae 1997). This might explain the marginal influence of the treatments on the 1,000-grain weight.

There was a high yield response to organic amendment in both seasons. The relatively high yield obtained from the unamended fluvisol and Gleysol compared to vertisol suggests relatively higher inherent fertility in these soils. According to Norman et al. (1998) rice grown on clay soils (e.g. Vertisol) requires 35-65 kg N ha^{-1} more fertilizer than does rice on silty loam to achieve similar grain yield due to NH^+_4 fixation and diffusion constrains in the former. Also in Vertisol P is hardly available to plants since it is usually bound in the insoluble form of Ca-P (Ae et al., 1991). The improved grain yield recorded with the incorporation of HS and PM in the soils suggests adequate release of N and other essential nutrients such as P to meet the demand of the rice crop. According to Snapp (1995) high quality organic materials provides readily available N, energy (carbon) and nutrients to soil ecosystems, besides its role in retaining mineral nutrients such as N, S, and micronutrients in the soil. The higher yields obtained in the 2nd season as compared to the first season could be due to residual effects of previous organic amendments and rice root biomass left after harvest of the first crop. According to Qi-Xiao (1984), the annual contribution of rice root to soil organic matter content in China was about 211 kg/ha with 46% carbon. In long-term studies manures have been shown to improve soil fertility, N supply capacity and physical parameters (Rasmussen et al., 1980).

Generally, as reported by Mae (1997), rates of leaf expansion and dry matter accumulation are the greatest during the period from panicle primordial initiation stage to late stage of spikelet initiation. Norman et al. (2003) reported dramatic increase in dry matter after heading due to grain filling. In this study, organic materials affected dry matter accumulation pattern in the growth stages. The higher DM value observed mostly with the application of HS and PM may partly be ascribed to its ability to synchronously release N to rice, compared with CM and MM, although DM accumulation differed among soil types. There were some peculiar patterns observed for DM accumulation: (a) a linear increase from MT to MAT as with IF and control treatments and (b) a sharp increase from MT to AT and gradual increase from AT to MAT, as with HS treatment in Fluvisol and PM treatments in Vertisol during 2nd season (Figure 2).

The lower N content of the straw at maturity in comparison to the content in the grain especially in 2nd season (Table 5) clearly indicates N remobilization from the vegetative parts. Mae and Shoji (1984) reported that remobilized N from the vegetative organs to the panicles accounted for 70-90% of the total N, with the leaf blade alone contributing 60% of the remobilized N. The higher N uptake in the grain of rice fertilized with HS, PM and IF reflected the extent and pattern of N release for absorption by plant from seedling stage to grain filling stages (Norman et al., 2003). Perhaps the relatively high C/N ratio of CM, 13.3, compared to HS and PM, (5.9 and 4.4, respectively), caused N immobilization in soil, hence the low N uptake. The differences in N uptake observed among the soils especially the higher uptake in fluvisol and gleysol could be either due to the native N supply capacity of the soils associated with soil organic carbon and total soil N (Sahrawat, 1982) or probably a result of high fixation of NH_4^+ and diffusion restriction associated with 2:1 clays such as found in vertisol (Trostle et al., 1998).

The high ANUE observed for all nutrient inputs under vertisol in comparison with values under fluvisol and Gleysol was mainly due to very low rice grain yield in the control treatment in vertisol. The low ANUE values of fluvisol and gleysol especially in the second season (Table 6) indicate that relatively high native N fertility reduced crop responsiveness to added N from external sources. This suggests the need to reduce the amount of N applied to soils with higher native N to improve fertilizer use efficiency. The carry-over effect of the first season amendment increased grain yield for most of the treatments. Based on nutrient sources, the ANUE generally increased in the second season. The probable reason could be that the amount of N applied in the second season was in reality higher than that used for the calculation considering the characteristically gradual N release from organic materials and the carry-over effect from the 1st season. In addition this carry-over effect seemed to increase the rate of DM accumulation from MT to AT in Vertisol in 2nd season (Figure 2). Nutrient amendment had little effect on ANUE in both Fluvisol and Gleysol particularly in the 2nd season probably due to relatively high native soil fertility. According to

Bufogle et al. (1997a, 1997b), at maturity there is similar amount of fertilizer N and native N accumulated by the rice plant with 50 to 70% of the N in grain depending on N fertilizer rate and seeding method. Contribution of native N to grain production was thought to be very high in Fluvisol and Gleysol.

The relatively high N uptake due to HS and PM application, particularly in the 2nd season (Table 5), resulted to low PNUE and NHI. This observation may indicate that N supplies from HS and PM was in excess of the N needed by the variety at the current N fertilizer rate. According to Eagle et al. (2000), when available N was in excess, much of the additional N uptake is partitioned within the straw, resulting in a lower ratio of grain N/total plant N (i.e. NHI) and a lower ratio of grain production/total plant N (i.e. PNUE). It could therefore be inferred that in a relatively N limiting system, such as in zero N, CM and MM fertilized pots, any increased N uptake was partitioned to the grain, resulting in higher ratios although their grain and straw yields were lower than the other treatments.

Conclusion

The results show that rice grain yield can greatly be improved by use of organic waste particularly humified sludge in soils of low fertility status such as the West African lowland soils. However the low potassium content of humified sludge needs to be supplemented with external potassium input to prevent mining of this deficient element in the soil. The Significant increase in grain yield during the second (rainy) season indicate that long term application of organic waste may improve overall soil fertility status and lead to added benefit caused by more efficient utilization of plant nutrients.

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Paddy use and status of water resources in a first order watershed in a sandy soil area of Northeast Thailand

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Keywords: mini-watershed management, paddy field, rainfed

Abstract

The upper watershed area of the Korat Plateau is used for upland and paddy rice cultivation. Precipitation in Northeast Thailand exhibits a widely fluctuating rainfall pattern from year to year. Sugarcane and cassava are the main upland crops, present in the field throughout the year. However, paddy rice is planted only once a year, in the rainy season, so rice production is affected by the variable nature of the precipitation pattern of each year and hence results in yield instability. We monitored precipitation, land use, dates of rice planting, and water level in paddy fields and adjacent farm ponds weekly in a first order watershed in a sandy soil area of Northeast Thailand over three years, 2002 to 2004, to determine relationships between precipitation and the time and extent of rice planting. Each of the three years exhibited a different precipitation pattern in the rainy season, and paddy field use consequently varied each year. In 2002 and 2003 when there was less than 100 mm/month of precipitation in June and July, rice planting was delayed until September, the proportion of total paddy area planted was less than 80%, and 40% of the upper paddy area was not planted. Conversely, in 2004 when there was comparatively more rain, approximately 165 mm/month in June and July, rice planting was completed by the end of July. In this case, nearly 100% of total paddy area, including upper paddy fields, was planted. In all three years, in the lower paddy fields, almost 80% of the paddy area was covered with ponded water at the maximum level, however in the upper paddy field, only 60% of the paddy area was covered with water. These results indicate that upper paddy fields are unable to perform adequately the function of water storage that is essential for a paddy field to support rice production.

Introduction

Topography of the upper watershed area of the Korat Plateau is undulating and the soil is sandy. The top of the ridge and upper part of the valley wall are used for upland, and bottom of the valley and lower part of the valley wall are used for rainfed paddy rice cultivation. Sugarcane and cassava are the main upland crops, being present in the field throughout the year. However, paddy rice is planted only once a year, in the rainy season so rice production is affected by the variable nature of the precipitation pattern of each year and hence results in yield instability.

Precipitation in Northeast Thailand exhibits a widely fluctuating rainfall pattern from year to year. The fluctuation is exhibited by not only annual precipitation but also distribution of monthly precipitation, beginning and end of the rainy season. The process of the rice planting differs each year in the upper area of watershed. And rice planting size of the area is also different. The annual productivity of rice is not only dependent on the yield per unit area, but also on the quantity of planting area.

We survey the situation of crop planting, paddy and pond water and precipitation in a first order water shed in Nong Saeng Village, Khon Kaen Province, Northeast Thailand.

This study is component of the Rainfed Agriculture project, a collaborative effort of Japan International Research Center for Agricultural Sciences (JIRCAS), Ministry of Agriculture and Cooperatives of Thailand and Khon Kaen University. The purpose of this project is to develop agriculture technologies for effective water use. Therefore, we are investigating actual farm land use and water situation at each plot level in first order water shed. This paper reports this investigation.

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Site and Method

The research site, Nong Saeng Village is located approximately 30 km South of Khon Kaen City. Nong Saeng is undulating topography area with paddy and upland fields in small watersheds.

Two watersheds were selected as the research areas (called NS-1 and NS-2) in the village. The two areas are 1.5 km apart. The direction of each research area was in the first order watershed from the riverhead.

We monitored precipitation, land use, dates of rice planting, and water level in paddy fields and adjacent farm ponds weekly from rainy season of 2002 to dry season of 2005.

The monitoring of paddy field use was carried out by field surveys. The objects of survey were all paddy fields in each of the research area. The observations of paddy and pond water level were undertaken on the same day as the observation of paddy use. The data of each paddy lot were input into GIS data base (Suzuki et al., in print), and classified into 3 categories of paddy, lower, middle, upper paddy. Figure 1 shows each category of paddy. Precipitation was measured with an automatic rain fall gauge. We installed rainfall gauges in each research area. These gauges are built in data-logger and recording every 0.2 mm rainfall.

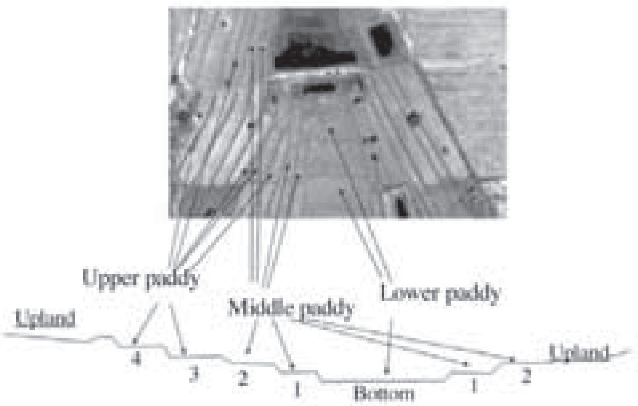

Figure 1. Classification of paddy fields

Result and discussion

Characteristics of precipitation pattern in research period

Figure 2 shows 10 days precipitation in NS-1 from May 2, 2002 to December 31, 2004. The yearly precipitation during the three years exhibited different

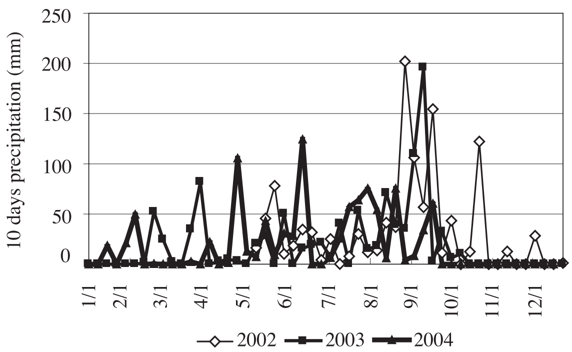

Figure 2. 10 days precipitation in NS-1

pattern. The precipitation during the research period was characterized as follows:

1. Little precipitation in early rainy season in 2002 and 2003.
2. The highest record in September in 2002.
3. Little precipitation in the late rainy season in 2004.
4. Late end to the rainy season in 2002.
5. Precipitation in dry season in 2003 and 2004

Paddy field use

Figure 3 shows the relation between expansion of rice planting area, water ponding area and accumulative precipitation. Rice planting area includes nursery. Final rice planting areas are shown in Table 1.

Table 1. Ratios of rice planting area

Area	Location	2002	2003	2004
NS-1	Whole	78%	89%	97%
	Lower	93%	98%	100%
	Middle	78%	87%	97%
	Upper	60%	79%	94%
NS-2	Whole	79%	81%	98%
	Lower	98%	100%	96%
	Middle	88%	88%	100%
	Upper	49%	55%	98%

In 2002 and 2003, precipitation was less than 100 mm/month in June and July, and with rice planting beginning in the middle of July. The pace of the planting area expanding was different by location. Pace was delayed in the middle and the upper paddy field and plantings were carried out progressively. Planting continued until September. Moreover, planting was done in almost all of the lower areas, however it was limited in the upper paddy field, although planting continued until September. Especially in the upper paddy field in NS-2, planted area was less than 55%.

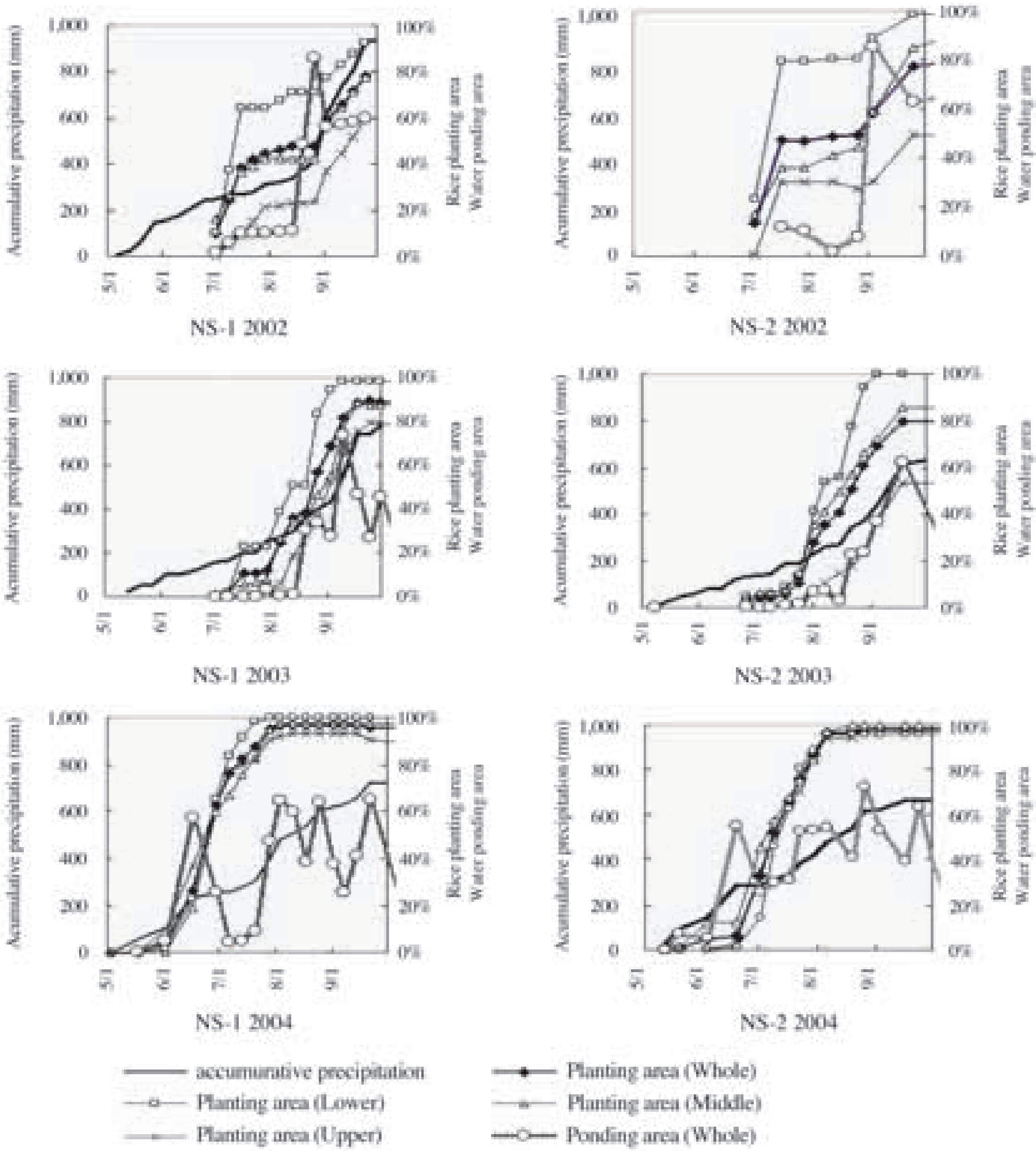

Figure 3. Rice planting and water ponding area in paddy field and precipitation

While in 2004, precipitation was approximately 165 mm/month in June and July, rice planting started in the middle of June and planting was completed by the end of July. Consequently harvest was advanced approximately on a weekly basis. The pace of the planting area expanding was not different by location. And final planting area was over 90% including upper and middle paddy.

Transplanting was only selected for the method of rice planting in 2002. However, direct seeding was introduced in both areas in 2003 and 2004. Figure 4 shows the ratio of direct seeding area in upper and lower paddy.

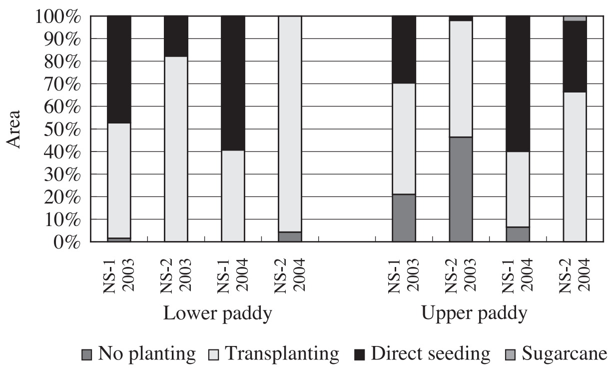

Figure 4. Ratio of direct seeding to other forms of cultivation and sugarcane production for the different watersheds and years

In 2003, Paddy field in NS-1 area, only direct seeding was practiced before the beginning of August. Transplanting was practiced after the middle of August. Direct seeding introduced in 30% of the paddy field area. However in NS-2 area, 20% was transplanted by August 1st. Especially, in the lower paddy, 34% was transplanted. And final area of direct seeding was 9%. In 2004, direct seeding was introduced from the beginning of rice planting season of June in the both of the research areas. The 58% of paddy field in NS-1 was seeded in June. However in NS-2 area, direct seeding was not introduced in the lower paddy. Expansion of direct seeding area in both areas was stopped and transplanting was started in July.

Paddy field and pond water

The changes of water ponding area of paddy were similar in NS-1 and NS-2. However changes were quite different each year. The ponding area did not exceed 10% of the whole area by August in 2002 and 2003 and in June in 2004. After exceeding 10%, ponding area expanded rapidly and reached maximum. However, high rate of water coverage did not continue even in the lower paddy except in 2004.

The ponding area of the lower paddy exceeded over 80% of the maximum every year. However the ponding area of upper paddy was only 60% at maximum and water ponding area decreased rapidly. Water ponding area was under 20% after October every year.

From the beginning of rainy season, water storage of ponds in research areas continuously decreased or kept around the same level every year. After the middle of rainy season, water level changed to increase rapidly. Increase occurred after ponding area of paddy field expanded. After water level changed to increase, water storage rose to the maximum level within a short term except in 2004.

Problems of paddy use and water resources

Results of the survey revealed the problem of the upper paddy field, while over 93% of the lower paddy area was planted every year. However, 40% of the upper paddy area was not planted in 2 years during 3 years of research term. The upper paddy was not utilized efficiently. The primary factor affecting yields was the availability of water (J.S. Caldwell et al., 2002). All of the upper paddy was not covered by ponding water, moreover ponding area changed smaller soon. The upper paddy does not have enough function of keeping water that is considered as one of the basic functions of paddy field.

Many ponds were constructed in the research area. As a result of interviews with farmers, newly constructed ponds located near upper paddy were contributing to reduce the unplanted area. Actually, part of storage water was pumped up and used for nursery and soil puddling in the paddy include upper paddy. This stored water from ponds is used not only for rice planting but also used for supplemental irrigation in the flowering stages of rice. And ponds are used for fish cultivation, livestock, horticultures and second crops in dry season and domestic water (Ogura and Sukchan, 2002). However, water level rising of ponds did not occur before suitable rice planting season in 2002 and 2003. Hence, it is difficult to increase planting area of upper paddy by only construction of new reservoirs.

In and around Nong Saeng Village including research areas, upland rice planting was introduced and area for upland rice planting was increasing in these 3 years. And introduction of direct seeding was also increasing. Direct seeding is one of the measures to use more the upper paddy efficiently. Introduction of direct seeding was triggered for the first time due to water shortage in 2003. However reason of introduction was also due to labour induced problems. These two problems are not presumably to be a separate problems. Farmers have pointed out that yield of direct seeding area was lower than transplanting area. It is necessary to discuss how to use the upper paddy more effectively.

Conclusion

As a result of observation in the two first order watersheds in Nong Saeng Village, Khon Kaen Province, Northeast Thailand, rice planting term was different each year. And pace of rice planting and final planting area were different by location in the year when a limited precipitation was recorded in June and July. The upper paddy does not have enough function of keeping water and it was not utilized efficiently. Construction of reservoirs and introduction of direct seeding contributed to increase planting area. However, it is necessary to discuss methods to use the upper paddy more effectively.

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Overview of sandy soils management in Vietnam

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Keywords: Vietnam, sandy soils, and management

Abstract

In Vietnam, more then 36% of agricultural soils are classified as light textured degraded soils that have a low inherent nutrient supplying capacity, low organic matter content and limited water holding capacity. Among these soils, about half a million hectares are sandy soils mainly located in coastal areas. Communities that are economically marginalized and have few viable options available to address issues of food insecurity, poverty and unsustainable resource management often dominate these soils. This has a direct negative impact on the economic and social fabric of communities that are dependant on natural resources for goods and services in order to sustain already tenuous livelihoods.

In this paper, the authors report the results collected from different studies on sandy and light textured soil management in Vietnam including a cooperation project with Belgian universities focused on coastal sandy soils of Central Vietnam and a North Vietnam sandy soils monitoring project. The main physico-chemical characteristics of sandy soils, nutrient problems and Vietnamese farmers’ experiences on mineral and organic fertility management of sandy soil to overcome the shortages in food and toward a sustainable production are described.

The management of these soils requires integrated practices that can increase fertility, and the nutrient and water holding capacity of these soils. Biological management of these soils can be an effective way to increase soil quality through management of biomass, i.e. farmyard manures, crop residues, green manures, and alley cropping. In addition, the effective management of these soils needs careful consideration of appropriate techniques that not only address the issue of low productivity, but to also protect the environment. These soils are prone to significant losses of nutrients through leaching, so that any intensification of production needs to recognize this potential adverse effect and develop management strategies that minimize off-site pollution. These technologies need to be assessed in pilot demonstration plots under local conditions prior to recommending their adoption by the wider agricultural community in coastal areas.

Introduction

The total territory of Vietnam is 32.92 million ha but only 35% of it is utilizable for agriculture of which, 95% was already used (9.41 million ha). More then 36% of agricultural soils are classified as light textured degraded soils (such as arenosol and acrisol) that have a low inherent nutrient supplying capacity, low organic matter content and limited water holding capacity. Among these soils, about half a million hectares are sandy soils mainly located in coastal areas. Sandy soil occupied only 1.61% of the territory and 4.61% of agricultural soil but have more than 10 millions people (14% Vietnam population) dependent on them.

In Vietnam, sandy soils are distributed mainly in coastal provinces including Thanh Hoa, Nghe An, Ha Tinh, Quang Binh, Quang Tri, Thua Thien Hue, Ninh Thuan, Binh Thuan and along some big rivers where soil developed *in situ* are derived from sandstone and granite rocks. According to Vietnam soil association (1996), the Vietnamese group of sandy soils may be classified mainly into 3 units: white and yellow sand dune soils; red sand dune soils and sandy marine soils (Table 1).

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Table 1. Area of Vietnam costal sandy soil

Fao Unesco	Local name	All Vietnam	Coast central areas
Arenosols	Coastal sandy soil	533,434	339,339
Luvic Arenosols	Yellow & white sandy dune soil (Cc)	222,043	134,113
Rhodic Arenosols	Red sandy dune soil (Cd)	76,886	75,000
Haplic Arensols	Sandy marine soil (C)	234,505	130,277
Percentage %		100	63.6

Source: Viet nam Soil Association, 1996.

Table 2. Selected physicochemistry of representative Vietnam sandy soil

No	Item	Unit	Mean	Std	n
1	pHH_2O		4.61	0.48	75
2	pHKCl		4.10	0.47	75
3	Bulk density	$gram/cm^3$	1.51		24
4	Density	$gram/cm^3$	2.65		24
5	Porosity	%	43.0		24
6	Texture				
	2-0.2 mm	%	66.60	18.1	75
	0.2-0.02 mm	%	19.85	10.2	75
	0.02- 0.002 mm	%	7.08	6.35	75
	<2 µm	%	5.59	5.36	75
7	OC	%	1.08	0.67	300
8	CEC	cmolc/kg	4.52	3.79	75
9	Ca^{++}	cmolc/kg	0.69	0.74	75
10	Mg^{++}	cmolc/kg	0.25	0.36	75
11	K^+	cmolc/kg	0.03	0.16	300
12	Na^+	cmolc/kg	0.28	0.79	75
13	Al^{3+}	cmolc/kg	0.59	0.67	75
14	H^+	cmolc/kg	0.06	0.09	75
15	N	%	0.06	0.03	300
16	P	%	0.02	0.01	300
17	K	%	0.18	0.24	75
18	P (Bray II)	mg P/kg	28.8	21.9	75

In this paper, the authors report the results collected from different studies on sandy and light textured soil management in Vietnam including a cooperation project with Belgian universities focused on coastal sandy soils of Central Vietnam and a North Vietnam sandy soils monitoring project. The main physico-chemical characteristics of sandy soils, nutrient problems and Vietnamese farmers' experiences in the use of mineral and organic fertility management of sandy soil to overcome the shortages in food and the establishment of sustainable production systems are described.

Vietnam Sandy Soil fertility status

Beside two alluvial soils of Vietnam (Red River fluvial soil and Mekong River fluvial soil), soil fertility in Vietnam is not very high. Throughout soils in Vietnam have low pH, low C, low N and very low CEC. It is especially true of soils that are light textured such as sandy soils or acrisol. The dominant feature of the coastal sandy soil (Haplic Arenosol) is shown in Table 2. Results of routine soil testing conducted recently reveal that, most of Vietnamese sandy soils had low organic matter content. All of the studied soil samples are deficient in N, P, Ca and 50% in Mg.

Acidity and organic content

As it is not easy to increase clay content of sandy soil, acidity and organic content are usually cited as two main critical chemical characteristics when managing sandy soils. Acidity of sandy soils depends on type of sandy soil formation and profile. Generally, sandy soils are acidic with the pH_{KCl} below 5 but in particular cases, pH_{KCl} of Vietnam sandy soil may reach more than 6.0 units. Analysing 300 cultivated sandy soil samples from Thua Thien Hue Province, results showed a very large variation of organic content. The average was 1.08 with the standard deviation of 0.67. Both acidity and organic carbon content of sandy soil may be influenced by agronomy activity, waterlogging condition, rate of organic material mineralization and sea water contamination. Figures 1 and 2 show pH and organic carbon content (OC) distribution of sandy soils in Thua Thien Hue Province.

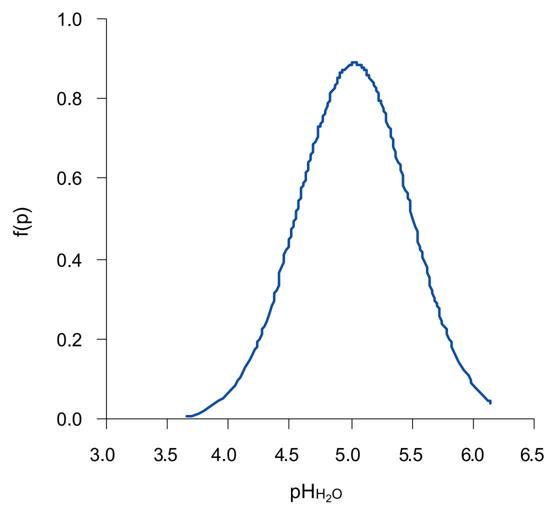

Figure 1. Distribution function of pH_{H2O} of sandy soil as indicated by Normal distrubution (n = 300)

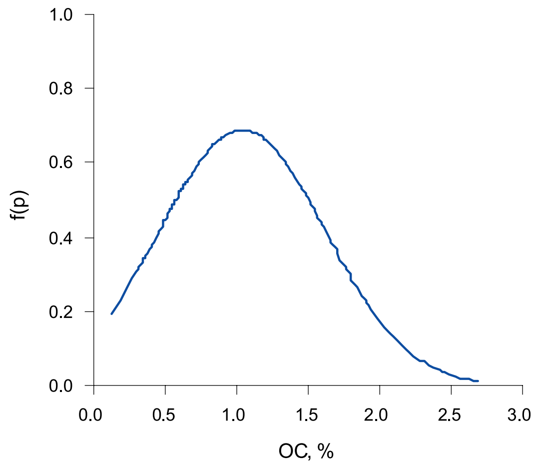

Figure 2. Distribution function of OC% of sandy soil as indicated by Normal distribution (n = 295)

Coastal population, poverty and land use management

As mentioned, about half a million hectares are sandy soils mainly located in coastal areas and communities that are economically marginalized often dominate these costal areas. Farmers have few viable options available to address issues of food insecurity, poverty and unsustainable resource management.

Poverty has a strong spatial dimension in Vietnam. Despite reduced poverty visible in all regions, some regions are still very poor. Taken as a whole, central highlands and north central coast is the poorest region in Vietnam (Table 3, Anonymous, 2004). The low living standard of the peasants' household in sandy soils areas results from a particular difficulty of natural condition (serve climate, poor soils) as well as rural socio-economic management reasons.

Topography of sandy coastal soil may be distinguished by flat forms or moving dunes; flat sandy with coarse grain layers are managed to foods and different foodstuff crops; while moving dune sandy with fine grain is most difficult to manage. Management of sandy soil in Vietnam is usually sequenced in different steps.

1. *Land use planning*

Land use planning is probably the first important step in managing sandy coastal areas and sandy soil. Normally, government takes firstly action. Land use planning should be realized at different scales, both at regional and farm level. Land management at regional or provincial level may follow

Table 3. Poverty across regions in Vietnam (%)

In percent	1993	1998	2002
Poverty rate	58.1	37.4	28.9
Northern mountainous	81.5	64.2	43.9
Northeast	86.1	62.0	38.4
Northwest	81.0	73.4	68.0
Red River Delta	62.7	29.3	22.4
North Central Coast	74.5	48.1	43.9
South Central Coast	47.2	34.5	25.2
Central Highland	70.0	52.4	51.8
Southeast	37.0	12.2	10.6
Mekong Delta	47.1	36.9	13.4
Food Poverty	29.4	15.0	10.9
Northern Mountainous	42.3	32.4	21.1
Northeast	29.6	17.6	15.4
Northwest	26.2	22.1	46.1
Red River Delta	24.2	8.5	5.3
North Central Coast	35.5	19.0	17.5
South Central Coast	22.8	15.9	9.0
Central Highland	32.0	31.5	29.5
Southeast	11.7	5.0	3.0
Mekong Delta	17.7	11.3	6.5

Source: Anonymous, 2004.

national program approach such as afforestation program, national action plan for anti-desertification or eradication of poverty campaign. At farm level, farmers should adapt and analyse what may fit the family's requirement in food and in cash and it depends on their capital and labour capability. It depends also on local weather conditions and variations of the market. Farmers' decision is very much influenced by their need in food. At the country level, Vietnam is at safe food security but it is not true for every household in coastal areas. It is suggested that in such cases land use planning should be undertaken in a participatory way that involves both the need and the capability to make action both by authority and inhabitants. Study reported by Nguyen Thuc Thi (2003) showed an example of sandy soil use planning projection by 2010 for three provinces in central coast where dominated sandy soils (Table 4).

2. *Field engineering and management*

About 27% of sandy areas are still not used (Vu Nang Zung et al., 2005). There are several reasons, but one of them is the area is not yet managed. It is clearly agreed that, water field engineering including canal irrigation and drain system, making ridges, reforest tree for fixing moving sandy soil are most important key works. Management in sandy soil should involve both water management together with forestry and agriculture management (Phan Lieu, 1981).

Table 4. Sandy soil use planning projection in 2010 for three provinces (Quang Binh (QB), Quang Tri (QT), Thua Thien Hue(TTH))

Land use type	Total (ha)	%	QB (ha)	QT (ha)	TTH (ha)
Rice-Rice	11,150	9.4	3,000	1,750	6,400
2 Rice + 1 cash crop	1,000	0.8	200	500	300
1 Rice + 2 cash crops	1,900	1.6	1,000	700	200
Rice + cash crop	1,250	1.1	700	400	150
Cash crop only	6,000	5.1	1,000	2,500	2,500
Perennial/fruit tree	250	0.2	150	50	50
Fishery Forestry	550	0.5	100	100	350
Eucalyptus, Casunarinas	72,104	60.8	25,512	21,782	24,810
Total	118,504	100	37,162	34,582	46,760

Source: Nguyen Thuc Thi, 2003

3. Choice of suitable crops and cropping systems

Choice of suitable crops and cropping sequence are often very delicate. Casunarina (*Casuarina equisetifolia*), Eucalyptus (*Eucalyptus sp*), Photina (*Phitinia prunifolia*), Kapok tree (*Alba pentandra*), Guava (*Psidium guajava*/*Myrtacea*), Jack fruit (*Artocarpus heterophyllus*); Vetiver (*Vestiveria sp*) are frequently cited as plant species that can firstly grown on sandy and using as fixing tree for wooden, fuel, fruit or medicinal purposes.

Cashew (*Anacardium occidentale L/Anacardiacea*); Mango (*Mangifera indica L*), Coconut (*Cocos nucifera L)*, Dragon Fruit Tree (*Hylocereus undatus*), Citrus/ Citron Orange (*Cistrus reticulata Blanto*) are also adapted and grown in some coastal areas. These trees were very well developed on sandy soils with a good cultural practice such as fertilization for cashew, lighting regulation for dragon fruits.

Permanent dry sandy soils may be used for cash crops such as peanut, maize, sesame while seasonal or permanently flooded areas are very well adapted for rice crops. Tables 5 and 6 show different land use types

Table 5. Cropping system in Vietnam sandy soil by 2004

Crops	Percentage
Rice-Rice	7.8
1 Rice	0.9
1 Rice-1 cash crop	8.2
Cash crop only	13.5
Fruit and perennial tree	5.0
Fishery	0.14
Forestry	27.1
Others	10.5
Total used	72.5
Non used	27.5

Source: Vu Nang Zung et al. 2005.

Table 6. Detail of crop yield and cash value equivalent

Crop/items	Yield range (tonne/ha year)	Cash value in Vietnam 10^6\$/ha year
Spring rice[1]	4-6	8-12
Summer Rice[1]	3-5	6-10
Peanut[1]	1.2-1.8	0.96-1.4
Soybean[2]	4.0-6.5	3.5-5.7
Sesame[1]	0.8-2.3	16-46
Maize[1]	2.5-3.5	3.8-5.3
Sweet potato[2]	2.48-18.2	2.5-18.2
Cassava[2]	4.7-22.2	5.6-26.6
Dragon fruit[2]	15-30	90-180
Cashew[2]	1.0-1.5	17-25.5
Vegetable[1]	30-50	30-50
Shrimps/Fish[2]	0.9-30	9-300

Source: [1] Pham Quang Ha, 2005 (un publised data)
[2] Statistical data in Website: http://www.mard.gov.vn

in Vietnam on sandy soils, their yields and economic value. Fishery seem to be a most interesting option for maximization economic return but this type of land use accounts for only 0.14%. Forestry is at the lowest economical value land use type and it accounts for 27.1% of land used. Rice based cropping dominates all types of sandy land uses.

4. Balance fertilization in relation to organic fertilizer

Integrated nutrient management is the efficient use of all types and forms of nutrients, both those originating from the field or farm and those from outside the field or farm (Nguyen Van Bo et al. 2003). Balanced fertilization is achieved when the cropping system is supplied with the correct proportions of N, P, K, Mg and other nutrients.

There are three main approaches to soil fertility and plant nutrition management:

- Plant crops adapted to indigenous soil nutrient supply
- Improve the soil fertility to meet the crop’s requirement
- Fertilization with organic and inorganic materials

Crop residue management and farmyard manure is an area that is the subject of studies and should be practiced on light texture soil. Returning crop residues to soil improves significantly soil physico-chemical properties. However, inappropriate agricultural practices and continuous cropping without adequate nutrient additiona are occurring in many places. The management of sandy soils requires particularly integrated practices that can increase fertility, and the nutrient and water holding capacity. Biological management of soils can be an effective way to increase soil quality through management of biomass, i.e. farmyard manures, crop residues, green manures, and alley cropping. In addition, the effective management of the soils needs careful consideration of appropriate techniques, not only to address the issue of low productivity, but also to protect the environment from, for example, nitrate leaching and heavy metal accumulation. Synthesis studies (Table 7) from National Institute for Soils and Fertilizers (NISF, Hanoi, 1996-2000, un published data) showed clearly crop yields in sandy soils are damatically affected by farmyard manure. Crop yields increased by between 158-200% when treated with FYM compared with control treatments. In practice, different types of green or farmyard manures are used. In Thua Thien Hue Provinces for example farmers use buffalo manure, chicken manure, pig manure or even rice straws with urine and ash.

Table 7. Crop yield (tonne/ha) as affected by farmyard manure (FYM)

Treatment	Sesame	Peanut	Rice	Maize
NPK	0.6 (0.2)	1.2 (0.5)	2.5 (0.3)	1.8 (0.2)
NPK + FYM	1.2 (0.4)	1.9 (0.3)	4.3 (0.6)	3.4 (0.3)
Percentage (%)	200.0	158.3	172.0	188.8

Source: NISF, unpublised data (1996-2000)

Conclusion

The paper presented here is based on a synthesis approach drawing on the Vietnamese experiences on sandy soil management. As the situation is complex and sandy soil management needs not only logistic input but also time consuming for biogical process. The management of these soils requires integrated practices that can increase fertility, and the nutrient and water holding capacity of these soils. Biological management of these soils can be an effective way to increase soil quality through management of biomass, i.e. farmyard manures, crop residues, green manures, and alley cropping. In addition, the effective management of these soils needs careful consideration of appropriate techniques to address not only the issue of low productivity, but to also protect the environment. These soils are liable to significant losses of nutrients through leaching, so that any intensification of production needs to recognize this potential adverse effect and develop management strategies that minimize off-site pollution. These technologies need to be assessed in pilot demonstration plots under local conditions prior to recommending their adoption by the wider agricultural community in coastal areas.

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Carbon mineralization in coastal sandy tracts under semi dry rice production

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Keywords: *Ipomea cornea* composted, rice production, semi-arid climate, sandy soils

Abstract

Experiments were conducted during 2002-2004 to explore the possibility of recycling a common weed in the study area, (East costal region in Southern peninsular India) ***Ipomea cornea*** *as green manure for semi dry rice. A laboratory based incubation study was conducted in year 2002. The incubation study revealed that* ***Ipomea cornea*** *composted with poultry manure recorded lower CO_2 evolution and wider C:N ratio as compared to* ***Ipomea cornea*** *composted with cattle manure. Field experiments were conducted for three years (2002-2004) in coastal sandy tracts in Ramanathapuram District, Tamil Nadu State of India with rice-rice cropping sequence under semi-dry condition to study the impact of* ***Ipomea cornea*** *compost on rice yield and soil organic carbon status. The field study indicated that the application of* ***Ipomea cornea*** *composted with poultry manure recorded the highest rice grain yield and soil organic carbon status as compared to* ***Ipomea cornea*** *composted with cattle manure. During the crop growing period, the soil organic matter status and soil temperature were negatively correlated. With increase in soil organic matter status a decrease in soil temperature was observed.*

Introduction

In general in agro-ecosystems, soils receive considerable carbon inputs from a variety of sources including leaf fall, stubbles, roots and root exudates as well as through external sources including farmyard manure and compost. The study area, Ramanathapuram District of Tamil Nadu State, India located in east coastal area of southern peninsular India at longitude (E) 78º10′-79º27′ and latitude (N) 9º05′-9º56′. This district covering a geographical area of 408,957 ha. The semi-dry system of rice cultivation is mainly confined to tracts that depend on rains and have no supplementary irrigation facilities. In this semi-dry system part of the rice crop's life cycle passes under aerobic conditions and part under anaerobic conditions. In the conventional rice cultivation practiced in irrigated areas, rice crops' life cycle occurs completely under anaerobic condition. The amount and quality of organic carbon are crucial factors influencing soil productivity. The endemic deficiency of organic matter in tropical sandy soils particularly those under the influence of arid and semi-arid climates are a major factor contributing to their low productivity. Experiments were conducted to explore the possibility of recycling a common weed in the study area, *Ipomea cornea* as green manure for semi dry rice.

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Materials and methods

In 2002, under laboratory conditions, 5 kg of the green leaves of *Ipomea cornea* was composted with cattle manure and poultry manure @ 0.625, 1.25, 1.88 and 2.50 kg anaerobically for 30 days. The matured compost was obtained at the end of composting period (30 days). The nutrient contents of the organic materials composted are furnished in Table 1. In summary, the green leaves of *Ipomea cornea* harvested from wastelands near the experimental site were chopped and mixed with cattle/poultry manures and wetted with deionized water to bring the mix to 60 percent moisture content. The moisture content was maintained at 60 percent. Since the composting was done under anaerobic condition, the mix was not turned. The 'mix' was subsequently maintained at this anaerobic condition. A total of nine treatments were replicated for five times. The CO_2 _C evolution was measured at weekly intervals. (Bundy and Bremner, 1972). Separate containers were kept for each of the 5 sampling intervals so that once opened for CO_2 _C measurement, the container could be discarded.

Field experiments were conducted for three years (2002-2004) in coastal sandy tracts with rice-rice cropping sequence under semi-dry condition. The experimental soil (Typic Tropaquept) was alkaline in soil reaction (soil: water ratio 1:2) (pH 8.7), low in N (Subbiah and Asija, 1956) (90 kg ha^-), P (Olsen

Table 1. Nutrient contents of manures (mg g^{-1} of dry matter) used in the Study (Mean values)

Nutrients	Cattle manure	Poultry manure	*Ipomea cornea*
N	32.5	45.0	11.6
P	7.0	16.5	3.8
K	16.0	18.5	3.1
Ca	6.5	43.0	1.2
Mg	6.5	5.5	3.8
S	3.5	5.5	2.7
Organic carbon	112	238	601
Organic matter	193	410	1,036

et al., 1954) (4.2 kg ha^{-1}) and high in available K (Stanford and English, 1949) (324 kg ha^{-1}. The initial soil organic carbon content was 1.2 g kg^{-1}. The *Ipomea cornea* compost obtained from another batch of composting was applied basally (10 kg/plot) as per the treatment schedule. The experimental plot size was 5 × 4 m^2. The design of the experiment was a randomized block design with three replicates. The oxidizable soil organic carbon content was measured (Walkely and Black, 1934) in various growth stages of rice, tillering, panicle initiation, flowering and harvest stages. At harvest stage, rice grain and straw yields and soil temperature were recorded.

Result and discussion

Incubation Experiment CO_2_C evolution

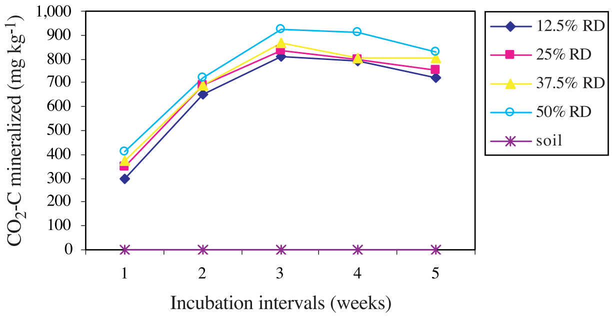
Rapid mineralization followed by a steady decline in the rate of mineralization with time was observed. Initially, the mineralization was faster; with increase in the period of composting, there was a steady decline in the mineralization rate. The exponential nature of carbon mineralization from soil organic matter and added plant residues was previously reported by Vanlauwe *et al.*, (1994). At all sampling intervals, the lowest amount of C was mineralized from poultry manure and the highest from cattle manure. The pattern of C mineralization from *Ipomea cornea* compost was similar to that of the control soil from fourth week after incubation onwards; indicating that most of the C added through compost had been mineralized within four weeks of incubation (Figure 1). High rates of CO_2_C evolution from the *Ipomea cornea* – cattle manure compost immediately after incubation was noticed. This could be due to the presence of easily decomposable organic compounds in the cattle manure as compared to less easily decomposable organic compounds in the poultry manure. Poultry manure contains large amounts of $CaCO_3$, struvite and other basic compounds (Bril and Solomons, 1990). Low level of decomposition in *Ipomea cornea*-poultry

Table 2. Estimated quantity (kg ha^{-1}) of nutrients added to the soil through the manures evaluated in this study

Treatments	Amount of cattle/poultry manure added (t ha^{-1})	Nutrients added through manures (kg ha^{-1})		
		N	P	K
Cattle manure				
12.5% of RD*	0.625	20.31	4.38	10.00
25.0% of RD	1.250	40.63	8.75	20.00
37.5% of RD	1.875	60.94	13.13	30.00
50.0% of RD	2.500	81.25	17.50	40.00
Poultry manure				
12.5% of RD*	0.625	28.13	10.31	11.56
25.0% of RD	1.250	56.25	20.63	23.13
37.5% of RD	1.875	84.38	30.94	34.69
50.0% of RD	2.500	112.50	41.25	46.25

(*RD = Recommended dose-5 t ha^{-1})

(i) *Ipomea cornea* – cattle manure compost



(ii) *Ipomea cornea* – poultry manure compost

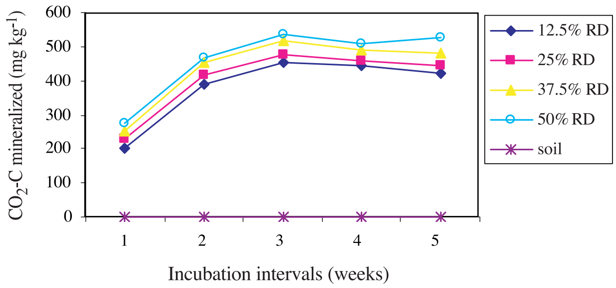


Figure 1. Cumulative CO_2-C mineralization (mg kg^{-1}) in the compost

manure compost could be attributed to high concentration of Ca and neutralization of organic acids and H^+ by Ca and buffering reactions (Mahimairaja *et al.*, 1995).

Field Experiment

Oxidizable soil organic carbon content

At all stages of crop growth, significant improvements in oxidizable soil organic carbon content were observed in the *Ipomea cornea*-poultry manure compost treatments as compared to in the control and *Ipomea cornea*-cattle manure compost treatments. Highest oxidizable soil organic carbon content (4.30 g C kg^{-1}) was recorded for the *Ipomea cornea*-poultry manure (50% RD) compost treatment (Table 3). Many studies have revealed a direct linear relationship between soil organic carbon storage and gross annual C input to soil (Halvin et al., 1990; Paustian et al., (1992). With increase in the level of Poultry manure (50% RD) used in the compost, Oxidizable soil organic carbon content was increased.

Table 3. Oxidizable soil organic carbon in crop growing period (g kg^{-1} soil)

Treatments	Tillering	Panicle Initiation	Flowering	Harvest
Cattle manure				
12.5% of RD	1.4	1.6	1.7	1.9
25.0% of RD	1.7	2.0	2.2	2.5
37.5% of RD	1.9	2.3	2.6	3.0
50.0% of RD	2.3	2.5	2.8	3.1
Poultry manure				
12.5% of RD	1.6	2.0	2.2	2.5
25.0% of RD	2.1	2.3	2.6	3.2
37.5% of RD	2.5	2.7	2.9	3.4
50.0% of RD	2.8	3.3	3.6	4.3

Yield of rice

Application of *Ipomea cornea*-poultry manure compost (37.5% RD) recorded higher grain (3,550 kg ha^{-1}) and straw yields (4,260 kg ha^{-1}) which was on par with the application of *Ipomea cornea*-poultry manure compost (50% RD) (Table 4). This could be due to the higher amount of $CaCO_3$ in the poultry manure. Calcium in poultry manure exchange with Na in the soil exchange complex, thereby reduce the ill effects of Na on soil and plant. The experimental site was alkaline in soil reaction. Despite a higher nutrient content in the poultry manure as compared to cattle manure the presence of $CaCO_3$ in poultry manure could have favourable effect on the experimental soil. Low yield in *Ipomea cornea*-cattle manure compost applied plots could be due to the lesser amounts of nutrients added through cattle manure.

Soil Temperature

At harvest stage a negative linear correlation between soil temperature and soil organic matter status was observed (Figure 2). As soil organic matter status increased, decrease in soil temperature was noticed.

Table 4. Yield (Kg ha^{-1}) as influenced by the incorporation of organics

Treatments	Grain	Straw
Cattle manure		
12.5% of RD	2,320	2,784
25.0% of RD	2,574	3,063
37.5% of RD	3,265	3,918
50.0% of RD	3,097	3,685
Poultry manure		
12.5% of RD	2,725	3,270
25.0% of RD	3,287	3,912
37.5% of RD	3,550	4,260
50.0% of RD	3,425	4,110
SEd	137	164
CD (P:0.05)	325	389

Conclusions

Ipomea cornea is one of the most rapidly spreading weeds in southern peninsular India. It is fast encroaching cultivated lands, water reservoirs and waste lands. A significant amount of time, effort and money has been used for its eradication. Recycling of this weed *Ipomea cornea* could serve dual purpose of its eradication and serving as a better organic material. *Ipomea cornea* could be composted with animal manures and used as manure for semi-dry rice cultivation. Between cattle manure and poultry manure, *Ipomea cornea* composted with poultry manure recorded lower CO_2 evolution, wider C:N ratio and higher rice yield and organic carbon status.

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A decision support framework for the sustainable management of sandy soils

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Keywords: decision support, sandy soils, soil management, hazard maps

Abstract

Sustainable agricultural systems are based on managing soils according to their capabilities and environmental constraints. A soil’s productive capacity is determined by key properties – some intrinsic (such as texture and structure), and others (such as pH and organic matter content) that can be manipulated by management. Knowledge of the intrinsic properties of a soil enables inferences to be made about properties such as CEC and pH buffer capacity. From these inferences, management strategies can be developed for maximising the productive capacity of the soil.

To facilitate the interpretation of properties of upland soils for identifying soil constraints and appropriate management strategies, a decision support framework ‘Soil Constraints and Management Package’ (‘SCAMP’) has been developed. Utilising a database approach, inputs of basic soil data (both field and laboratory) are processed to output soil constraints to productivity (using alpha-numeric descriptors) and to identify appropriate management strategies. Where spatially referenced soil data are available, maps of constraints can be readily produced in a GIS.

SCAMP was applied to soil data from a Land Use Evaluation and Planning Study of three communes in Binh Thuan Province, Vietnam, and to a spatially referenced soil survey of the Herbert River catchment, Queensland, Australia. For the sandy soils in the Vietnamese study, SCAMP identified constraints of limited plant available water, low nutrient holding capacity, low pH buffer capacity and generally low nutrient fertility. Suggested management strategies included trickle/drip irrigation, organic amendments, addition of high activity clays, and regular liming. From the Australian data, attributes of the representative soil types of the Herbert River catchment were used to produce a map identifying areas of low pH, high acidification risk and low nutrient holding capacity. These two applications demonstrate the usefulness of SCAMP for linking soil data to management strategies for sustainable productivity at both plot and catchment scale. This link is often not made with the information collected in soil surveys.

Introduction

Sustainable agricultural systems are based on managing soils according to their capabilities and environmental constraints. The productive capacity of a soil is determined by key soil properties – some intrinsic (such as texture and structure), and others (such as pH and organic matter content) that can be manipulated by management. Knowledge of the intrinsic properties of a soil enables inferences to be made about derived properties such as CEC and pH buffer capacity. From these inferences, management strategies can be developed for maximising the productive capacity of the soil.

Inferring soil management practices from soil attributes is the principle on which the Fertility Capability Classification System (FCC) of Sanchez *et al.* (1981) is based, and using the FCC it has been shown that:

(a) soils in one FCC unit may belong to different categories in a classification system (orders, suborders, great groups, subgroups or families);

(b) the number of FCC units in a given area is much smaller than soil classification units, thereby simplifying interpretations; and

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(c) making fertilizer recommendations based on FCC units is more profitable than making generalised recommendations.

To facilitate the interpretation of upland soil properties for identifying soil constraints and appropriate management strategies, a decision support framework 'Soil Constraints and Management Package' ('SCAMP') has been developed. Utilising an Access database, inputs of basic soil morphological, chemical and physical data are firstly used to identify intrinsic soil constraints to long-term productivity, and then to indicate management practices that will minimise the impacts of these constraints on productivity. SCAMP can be applied at plot, farm or catchment scale, and where geo-referenced soil data are available, maps of constraints can be produced.

SCAMP builds on the Fertility Capability Classification of Sanchez *et al.* (1981, 2003) by:

(a) considering a wider range of soil properties to determine constraints to productivity;

(b) utilising surrogates to infer several key soil properties; and

(c) including a temporal assessment of the pathways of water flow for identifying the risk of off-site nutrient movement.

The SCAMP Framework

SCAMP can be applied at three 'levels' of complexity, depending on the availability of key soil attribute data (Table 1). Level 1 uses only observations made on a soil 'mini-pit' in the field. Level 2 utilises field observations and some simple field measurements. Level 3 utilises field observations and measurements and a range of diagnostic laboratory analyses. Soil management strategies that can be inferred from the SCAMP assessment become more comprehensive as the application level of SCAMP moves from Level 1 to Level 3.

Table 1. Attributes determined for each application level of SCAMP

SCAMP Level	Attributes
Level 1	Texture, colour, structure and consistence, drainage class, permeability class, slope, signs of erosion
Level 2	Level 1 plus field pH, field EC, dispersion class, infiltration rate
Level 3	Level 2 plus organic C, ECEC, P buffer capacity, pH buffer capacity, plastic limit

Briefly, Level 1 attributes are recorded for a representative 'mini-pit' approximately 15 cm square and 50 cm deep. Field texture, soil structure and soil consistence are described using established nomenclature (e.g., Euroconsult 1989, McDonald *et al.* 1990) and colour can either be described using the Munsell system, or more simply as 'black', 'white', 'red', 'yellow', 'brown' or 'gleyed/grey'. Permeability class (rate of water movement into the profile) and drainage class (rate of water movement through the profile) are rated from a consideration of structure and pores (permeability) and texture and the presence and persistence of a watertable (drainage) as indicated by mottles/gleying in the 'mini-pit' (McDonald *et al.* 1990). Level 2 attributes are also determined in the field, and involve measurements using hand held pH and EC meters, with dispersion class based on the behaviour of aggregates placed in water (Emerson 1967), and infiltration rated according to the time taken for a known volume of water to enter the soil from a plastic ring inserted into the soil surface. Level 3 attributes are determined in the laboratory following standard analytical methods.

The first SCAMP descriptor of a soil is the texture class – either sandy (*S*), loamy (*L*) or clayey (*C*), of the plough layer (generally 0-20 cm) and the subsurface layer (20-50 cm). If there is a change in texture class, then the descriptor uses both classes (e.g., if texture class changes from *S* in the plough layer to *L* in the subsurface layer, then the soil is classified as *SL*). Following the texture class descriptor, the SCAMP framework then defines a series of 'constraint' descriptors based on criteria that use the values of the attributes listed in Table 1 (Table 2). Constraints are grouped under the general headings of: water regime constraints, soil pH and acidity constraints, cation constraints, clay fraction constraints, landscape constraints, and soil structural constraints.

The constraint descriptors follow the texture class descriptor to give a SCAMP notation for the soil. For example, many Ferralsols would be described as *C a e i k* (i.e. clayey, strongly acidic, low CEC, high P-fixation by iron, low K-reserves), many Vertisols as *C d v b* (i.e. clayey, ustic or aridic soil moisture regime, vertic, calcareous), whereas a young Fluvisol with no constraints is simply classified as *L* (loamy soil). The absence of constraints suggests no major limitations to productivity, other than nitrogen deficiency.

Applications of SCAMP

Two applications of SCAMP will be described, the first based on a land use evaluation and planning

Table 2. SCAMP descriptors and the attributes used to determine the descriptors

SCAMP descriptor	Soil attributes
S, L, C (texture)	Field texture or clay content
*d, d^* (ustic, aridic or torric moisture regime)	Period of subsurface dryness
*g, g^* (aquic moisture regime)	Period of saturation or drainage class
*a, a^* (acidity, Al toxicity)	Field pH or Al saturation
ar (acidification hazard from low to high)	Pedotransfer function using organic C and clay content to calculate pH buffer capacity
b (calcareous)	Field pH
e (low nutrient retention)	Effective CEC
s, s^ (salinity)	Field or laboratory EC
*n, n^* (sodicity)	Dispersion class or Na saturation
k (low K reserves)	Exchangeable K, nitric acid extractable K
i (P fixation)	P buffer capacity using a single point P sorption index
v (vertic properties)	Field observation or clay content and CEC/clay ratio
om (organic C rating from low to high)	Organic C content
vc (variable charge characteristics)	Soil pH in $CaCl_2$ and KCl
slope	Slope
er (erosion hazard)	Field observation
p (permeability rating from 1 to 4)	Field observation
d (drainage rating from 1 to 6)	Field observation
hs (hard setting)	Field texture and CEC/clay ratio
comp (compaction layer)	Field observation

study of three communes in Vietnam, and the second based on the spatially-referenced soil survey of a catchment. In the former study, SCAMP was used to identify the constraints of the major soil types to sustainable production. This information was required to enable the establishment of field experiments to develop appropriate management strategies for dealing with these constraints. In the latter study, SCAMP was used to identify areas most at risk of rapid soil acidification and leaching loss of nutrients so that an awareness program could be undertaken with landholders to improve fertilizer management practices.

Land Use Evaluation and Planning Study

A land use evaluation and planning study was undertaken on three communes in the Bac Binh District, Binh Thuan Province, Vietnam (Vinh 2001). A soil survey (1:50,000) had previously been carried out for the district, and this survey was used to select sites of the major soil types of the district in the three focus communes: Phan Hoa (agricultural land: 159 ha), Hoa Thang (agricultural land: 3,817 ha), Phan Tien (agricultural land: 201 ha) and Phan Thanh (agricultural land: 2,391 ha). At each site, a pit was dug and several soil attributes described. Soil samples were collected and analysed for some parameters in the laboratory. Attributes were then used to derive SCAMP descriptors.

Spatially Referenced Soil Survey

A spatially referenced soil survey (1:8,000) was available for the Herbert River Catchment, Queensland, Australia (Wood and Bramley 1996). The soil survey covered an area of 52,200 ha. Using the soil survey to select sites, soil samples were collected from representative profiles of the 24 major soil types of the catchment, and surface (0-20 cm) and subsurface (40-60 cm) samples were analysed in the laboratory for several chemical and physical attributes.

Results and Discussion

Land Use Evaluation and Planning Study

The SCAMP attributes derived from the field and laboratory data are presented in Table 3. Unfortunately limited information was available on field texture, permeability and drainage, and no data were available for P buffer capacity or clay content. This lack of data prevented a fuller assessment of the soil constraints.

For the soils classified as *S* (sandy), the following constraints are common across all sites (Table 3): *d* (ustic or aridic soil moisture regime), *e* (low nutrient retention), and *k* (low K supply). In addition, some of the sites had either *a* (acidity) or *a^* (high Al saturation) constraints. Across all *S* soils, *ar* (acidification risk) was high or very high, and *om* (organic matter content) was low or medium.

These constraints indicate that the following management strategies could be implemented in these sandy soils for sustainable productivity:

Table 3. SCAMP descriptors for soils sampled in Bac Binh District, Vietnam

Sample No.	Soil type	Crops	SCAMP constraints
PH7a	alluvial	rice	*C g^ a ar(low) s^ n^ k om(medium) hs*
PH8	?	rice/beans	*C a ar(moderate) n k om(medium) hs*
HT3a	sand	peanut, watermelon, Eucalypt, Acacia	*S d ar(very high) e k om(low) comp*
HT6a	sand	cashew	*S d ar(very high) e k om(low)*
PT1a	alluvial	rice	*L g a^ ar(moderate) e n k om(medium) hs*
PT3	?	fruit trees	*C ar(low) om(medium)*
PTh1	sand	cashew	*S d a ar(high) e k om(low) comp*
PTh2	sand	cashew	*S d ar(high) e k om(medium)*
PTh3	alluvial	rice	*C g^ a ar(low) s^ n^ om(medium) hs*

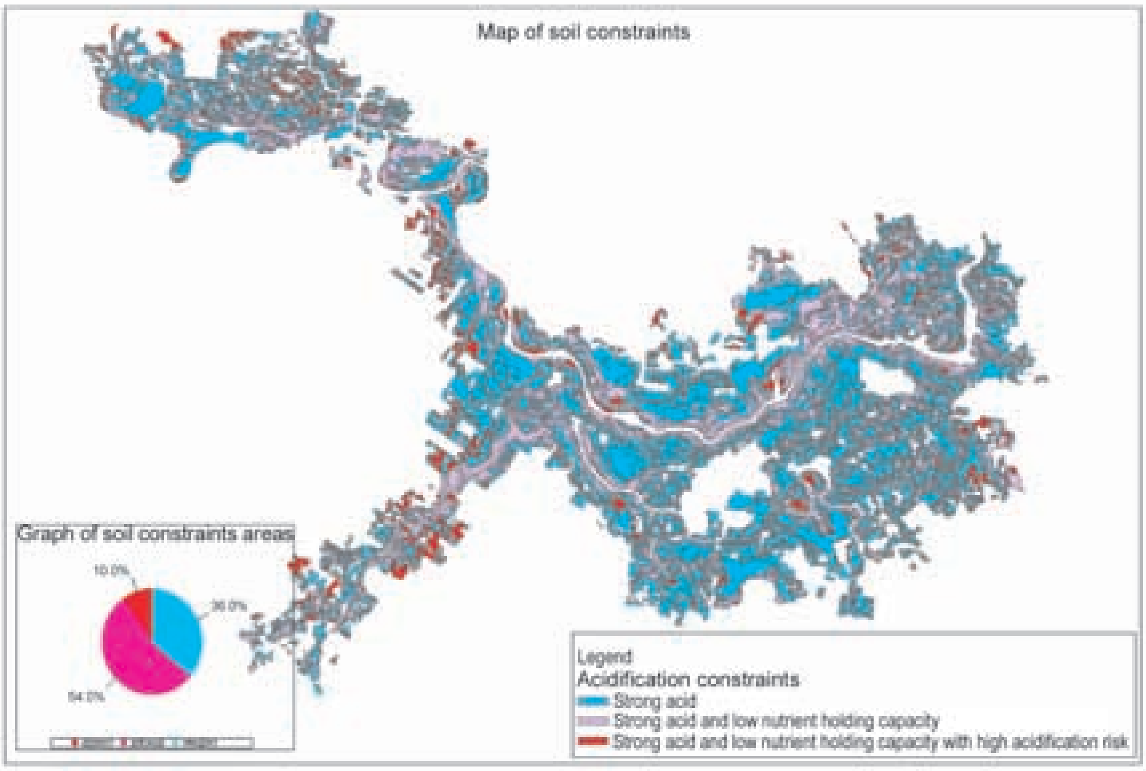

Figure 1. Map of soils in the Herbert River catchment that are strongly acid [pH(water)<5.5], with low nutrient holding capacity (ECEC <4 $cmol_c$/kg soil), and high acidification risk (pH buffer capacity <1.5 kmol H^+/kg.pH unit)

d: Trickle or drip irrigation will be required to grow crops during the dry season. Adding soil conditioners to improve the water holding capacity of the soil could be investigated.

e: CEC should be increased by addition of organic residues in association with a liming program to increase soil pH and therefore variable charge (e.g., Aitken *et al.* 1998) and/or high activity clays could be added to increase permanent charge (e.g., Noble *et al.* 2004).

k: Potassium fertilizers or organic amendments having a significant content of K will need to be applied. If applying K fertilizer to a soil with the *e* constraint, fertilizer applications should be split and only low rates applied on each occasion.

a or *a^*: Acid tolerant crops should be grown as a short term response to this constraint. For long term sustainability, a liming program should be commenced with regular monitoring of soil pH.

ar(high-very high): With an acid addition rate of 3.4 kmol H^+/ha.yr [which occurs with many agricultural systems (Moody and Aitken 1997)], the pH(water) of the 0-20 cm layer of these soils will decrease by 1 pH unit in a period of less than 10 years. Strategies for countering this acidification would be a regular liming program and/or using agricultural systems with low net acid addition rates.

om(low-moderate): Improving levels of organic matter in these soils would improve nutrient supply, increase CEC, increase water holding capacity and increase pH buffer capacity.

It is noteworthy that many of the *C* (clayey) soils were poorly drained with salinity and/or sodicity constraints and often were compacted or hard setting (Table 3). The soil with least constraints (PT3) was also the only one supporting fruit trees such as lemon.

Spatially Referenced Soil Survey

In order to identify areas of the Herbert River catchment most at risk of rapid acidification and also loss of nutrients (cations, nitrate) by leaching, it was reasoned that soils with the following constraints would be most susceptible to these processes: *S* (sandy) and/or *a* with *ar(high)* (strongly acidic soils with a low pH buffer capacity), and/or *e* (low ECEC). A map was produced of soils with these constraints (Figure 1). It can be seen that large areas of strongly acidic soils with low ECEC occur along the riverbanks. A liming program will be required to maintain the long term productivity of these soils and fertilizer (particularly nitrogen) management will need to minimise the potentially high risk of off-site nutrient movement.

Conclusion

The two applications described above demonstrate the usefulness of SCAMP for identifying soil constraints at plot and catchment scale. At plot scale, management strategies for addressing these constraints can be suggested and trialled. This information also allows the landholder to move from regional or district fertilizer recommendations and land management practices to soil-specific management, thus improving productivity, profitability and sustainability.

At catchment scale, constraints can be mapped to identify 'hot spots' which can be targeted for remediation or awareness programs for the landholders. Catchment scale maps can also be used by government and catchment management authorities for the purposes of land use planning and risk assessment for such off-site issues as nutrient movement (with impacts on water quality) and on-site land degradation issues such as soil acidification.

Thus SCAMP can be used at different scales, making use of all available soil information such as field observations and soil survey data. SCAMP is multi-purpose, transparent and flexible, making it a very useful tool for obtaining the most from soil information.

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Managing organic inputs for enhancing biological and physico-chemical soil health in the West African savannas

Vanlauwe, B.[1]

Keywords: soil organic matter, decomposition, organic matter quality

Abstract

Numerous soils in the West African savannas contain less than 20% silt and clay. Soil organic matter (SOM) is a valuable resource in cropping systems with minimal external inputs, as it contributes to plant nutrition by supplying nutrients through mineralization and by favouring the soil cation exchange properties. The quality of the applied organic resources may affect those SOM-driven properties. The objectives of this paper were to investigate the relationships between N contained in various SOM fractions, obtained through particle size separation after soil dispersion and the soil N supply and to assess the impact of residue quality on the cation exchange capacities of such SOM fractions. In an initial microplot field experiment, a highly significant (P <0.001) relationship between the residue derived N (RDN) present in the SOM between 2 and 0.053 mm or the particulate organic matter (POM) and the uptake of RDN by maize. In an associated pot experiment indicated the relatively higher availability of RDN in the POM compared to the SOM <0.053 mm. In a second multilocational alley cropping trial, N uptake by maize was shown to be more closely related to N contained in the POM material as compared to N belonging to SOM fractions with smaller particle size. No clear relationships between the quality of organic inputs and the quality of the POM could be established. In a third long term arboretum with promising agroforestry species, the organic fractions had the highest CEC, expressed on dry matter basis, and the CEC of the fraction between 0.053 and 0.020 mm, the silt and the clay fractions was inversely related to their particle size: clay > fine silt > coarse silt. An important effect of the quality of the litter material on the charge characteristics of the fine and coarse silt fractions emerged as organic inputs with a high C/N and lignin/N ratio produced SOM with the highest CEC.

Introduction

Soil organic matter (SOM) is a valuable resource in cropping systems with minimal external inputs, as is the case for the major part of the West African savanna, where external inputs are scarce and/ or expensive. It contributes directly to plant nutrition by supplying nutrients through mineralization and indirectly by favouring the soil cation exchange properties. SOM is not a homogeneous pool, but consists of organic components with a wide range of turnover times. For a clear understanding of the contribution of SOM to the soil nutrient status and exchange properties, it is necessary to fractionate the total SOM pool into distinct fractions with similar characteristics and to determine the contribution of individual fractions to the various aspects of the overall soil fertility status.

Addition of fresh organic matter is one possible way to manage the size and quality of the SOM pool. In the short-term organic resources release nutrients, may enhance soil moisture conditions (Vanlauwe et al., 2001), or improve the soil available P status (Nziguheba et al., 2000). In the long term, continuous inputs of organic resources influence the levels of soil organic matter and the quality of some or all of its pools (Vanlauwe et al., 1998; Cadisch and Giller, 2000). Residue quality has been shown to modify the residue decomposition process (Vanlauwe et al., 2005) and may be an important factor in regulating the impact of fresh organic matter on the various SOM fractions. Most studies undertaken to date on the contribution of SOM to soil fertility have concentrated on decomposability, mineralization, or nutrient release. However, SOM quality should also include characteristics relating to the contribution of SOM to the physico-chemical health of the soil.

The objectives of this paper are (i) to investigate the relationships between N contained in various SOM fractions, obtained through particle size separation after soil dispersion, and N supply as affected by the biochemical quality of freshly added plant materials

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(ii) to assess the impact of residue quality on the cation exchange capacities (CEC) of those SOM fractions. In the first part of the paper, the concept of organic resource quality is highlighted with supporting evidence from laboratory and field studies.

The organic resource quality concept

Unlike mineral fertilizers, the release dynamics of plant available nutrients from organic resources vary widely and are less predictable. Such uncertainties may hinder the most efficient use of these organic resources or even their adoption by small-scale farmers. A range of quality characteristics has been found to affect the decomposition and mineralization process of organic resources. Originally, the C/N ratio was seen as a good predictor of decomposition and N availability (Waksman and Tenney, 1928). Subsequently, Vallis and Jones (1973) reported that soluble polyphenols affect N mineralization dynamics of organic resources. Mellilo et al. (1982) showed that the N and lignin content of hardwood leaf litter residues significantly affected their decomposition; while Handayanto et al. (1994) showed that the content of soluble polyphenols that were actively binding proteins was better related to decomposition than the total soluble polyphenol content.

As a result of a Symposium in 1995 (Cadisch and Giller, 1997), efforts were made to consolidate information on residue quality – N dynamics relationships resulting in an Organic Resource Database (ORD). The ORD contains information on organic resource quality parameters and N mineralization dynamics from almost 300 species found in tropical agro-ecosystems (Palm et al., 2001). Analysis of the information in the ORD has led to the development of a Decision Support System (DSS) for organic matter (OM) management (Figure 1) (Palm et al., 2001). The DSS makes recommendations for appropriate use of organic materials, based on their N, polyphenol, and lignin contents resulting in four classes of organic resources (Palm et al., 2001).

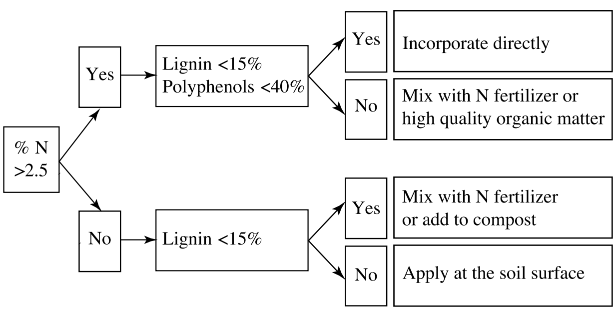

Figure 1. The Decision Support System for organic N management, leading to 4 classes of organic resources (adapted from Palm et al., 2001)

To test the DSS, various trials with inputs of organic resources of varying resource quality were implemented in West, East and Southern Africa with maize as a test crop (Vanlauwe et al., 2002). Responses to organic inputs were expressed in field fertilizer equivalency values. Data from these trials showed the percentage fertilizer equivalencies (% FE) values for organic materials with a low polyphenol content (<4%) and a N content >2.3% were positively related to their N content (Figure 2). The critical level of N for increasing crop yield was 2.3%, confirming the initial value hypothesized by Palm et al. (2001). Organic matter with a high polyphenol content (>4%) still led to positive % FE values, but the increase with increased N content was less and the N content needed to improve maize yield was 2.8 rather than 2.3% (Figure 2). Polyphenol – N interactions seem to delay the immediate availability of N as concluded by others from data obtained under controlled laboratory or greenhouse conditions (Palm and Sanchez, 1991, Oglesby and Fownes, 1992). While from the current data polyphenols appeared to be under certain conditions important modifiers guiding initial N release from organic materials, the lignin content was not observed to improve on the derived equations. This does, however, not exclude their importance in medium to long term N dynamics.

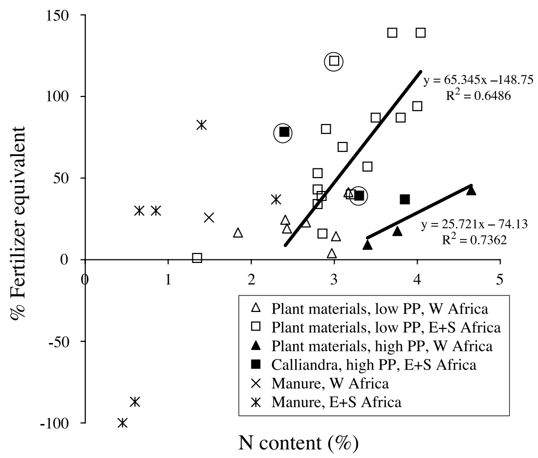

Figure 2. Relationship between the N fertilizer equivalent and the N content of plant residues and manure for a series of sites in West (W), East and Southern (E+S) Africa. The linear regression equations were calculated separately for the plant materials with low and high polyphenol (PP) content. Encircled values were excluded from the regression analysis. Source: Vanlauwe et al. (2002)

Fractionation of soil organic matter following particle-size classes

In all experiments, the soil organic matter pool was fractionated following particle size after chemical dispersion. The soil was dispersed by reciprocal shaking for 16 hours at 144 rpm after adding a Na-hexametaphosphate/Na-carbonate mixture. After dispersion, the soil slurry was wet-sieved to separate the fractions >2 mm, between 0.250 and 2 mm and between 0.053 and 0.250 mm. The organic components were separated from the mineral fraction for each of these particle-size classes by careful decantation. The slurry passing through the 0.053 mm sieve was manually passed through a 0.020 mm sieve to separate the coarse silt fraction (0.020-0.053 mm). The fine silt fraction (0.002-0.020 mm) was separated after four sedimentation cycles, while the clay fraction (<0.002 mm) was collected after four flocculation cycles with $CaCl_2$, followed by dialysis in distilled water. The particulate organic matter (POM) includes the organic material larger than 0.053 mm. More details are given by Vanlauwe et al. (1998b). Samples to be used for CEC measurements were dispersed with only Na-carbonate, avoiding the use of Na-hexametaphosphate because of its high inherent charge. The methodology to measure CEC as a function of pH and at low ionic strength is based on the Silverthioureum (AgTU) method (Oorts et al., 2000). For measuring the CEC of the whole soil, a buffered AgTU-solution was used. In view of the limited amount of material available, the CEC of the fractions was measured at different pH-levels using the same sample. This was achieved by gradually acidifying the mixture sample-AgTU-solution and taking subsamples of the solution at different pH-levels. More details are given by Oorts et al. (2000).

The experiments

In a first microplot experiment, ^{15}N-labeled high quality *Leucaena leucocephala* and low quality *Dactyladenia barteri* residues were applied in microplots installed in *Leucaena* and *Dactyladenia* alley cropping plots on a Ferric Lixisol at a rate of 128 and 79 kg of N ha^{-1}, respectively. The fate of the leaf residue N was followed in the soil, crop, and hedgerow of the respective alley cropping systems during three maize and two cowpea seasons. At regular intervals, soil was sampled at 0-5 and 5-10 cm and the SOM fractionated. A subsample of dried soil, collected at each sampling time was used for a bioassay study with maize in the greenhouse to determine the residual ^{15}N uptake by maize. A complete description of the field plot layout and experimental methods is given by Vanlauwe et al. (1998a). In a second multilocational experiment, alley cropping trials were established between 1989 and 1991 in Bouaké and Ferkéssedougou (Côte d’Ivoire), in Glidji, Amoutchou, and Sarakawa (Togo), and in Niaouli (Benin Republic) to assess crop productivity of the alley cropping systems relative to a no-tree control. More details are given by Aihou et al., 1999, Tossah et al., 1999, and Vanlauwe et al., 1999. Soils were collected between 1994 and 1996 in the various treatments for SOM fractionation. Multiple regression analysis was used to express maize N uptake as a function of N additions and SOM N-content at the start of the season. In an additional pot experiment, soil was taken from a selected number of treatments per site and grown with maize to determine relationships between SOM fractions and maize N uptake. Soils from an alley cropping trial, established in 1986 in Ibadan (Nigeria) on a Ferric Lixisol were also included in the pot experiment. In a third experiment, soil was taken in 1995 from the surface 10 cm under *Leucaena leucocephala*, *Dactyladenia barteri*, *Afzelia Africana*, *Pterocarpus santalinoides*, and *Treculia africana* in an arboretum, established in 1979 in Ibadan, Nigeria.

Soil organic matter fractionation and soil N supply

In Experiment 1, initially, most of the residue derived N (RDN) was recovered in the fraction between 0.250 and 2 mm in both the *Leucaena* and *Dactyladenia* treatments. The proportion of the total amount of RDN recovered in the SOM fractions smaller than 2 mm shifted towards the smaller particle size classes towards the end of the experimental period. Although the total amount of RDN in the POM was larger for the *Leucaena* than for the *Dactyladenia* treatment, the turnover of RDN incorporated in the POM was similar for both the high-quality *Leucaena* and the low-quality *Dactyladenia* residues, probably because maize roots were present in both cases as a source of POM. Highly significant (P <0.001) relationships between the native N and the RDN present in the SOM between 2 and 0.053 mm or the particulate organic matter (POM) and the uptake of RDN by maize in the associated pot experiment confirmed the relatively higher availability of RDN in the POM compared to the SOM <0.053 mm. Moreover, the regression slopes were not significantly different for the *Leucaena* and *Dactyladenia* treatments, confirming that most likely maize roots masked any presumed relationships between the quality of the inputs (high quality *Leucaena* vs low quality *Dactyladenia*) and the turnover of the POM fraction. The weak relationships between the native N and the RDN in the SOM <0.053 mm and maize RDN uptake indicated the lower availability of N in the finer SOM fractions.

The pot trial, described under experiment 2, confirmed the relatively higher availability of N contained in the POM material compared to N associated with smaller particle size classes for a wider range of soils (Figure 3). Although the POM material in treatments with tree species having a higher N content (e.g. *Leucaena*) seemed to have a larger N concentration compared with treatments with lower quality tree species (e.g. *Senna siamea*), it was not possible to establish a clear relationship between the quality of the organic inputs and the quality of the POM material. This was caused most likely by the wide range of organic inputs in alley cropping systems (ranging from high quality leaves to low quality maize roots) and the different times of inputs relative to the soil sampling schedule. Although the N applied with the different prunings explained the largest part of the variation in obtained maize N uptake patterns in Experiment 2, the total amount of N in the POM fraction at the start of the growing season and the POM N concentration explained respectively about 14 and 5% of the observed variation (Table 1). This was surprisingly higher than the variation explained by N fertilizer (3%).

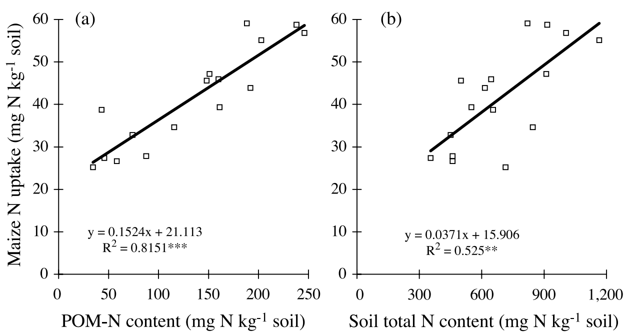

Figure 3. Relationships between the maize shoot N uptake and the particulate organic matter (POM) N content (a) and the total soil N content (b) for a series of West-African moist savanna soils taken under a selected number of treatments described in Experiment 2

Soil organic matter fractionation and soil exchange properties

For all treatments in Experiment 3, the organic fractions had the highest CEC, expressed on dry matter basis, and the CEC of the fraction between 0.053 and 0.020 mm, the silt and the clay fractions was inversely related to their particle size: clay > fine silt > coarse silt. A good correlation existed between the slope of the fitted CEC-pH relationships and the organic carbon content of the fractions. The clay and fine silt fractions were responsible for 85 to 90% of the CEC. An important effect of the quality of the litter material on the charge characteristics of the fine and coarse silt fractions emerged (Table 2). Organic inputs with a high C/N and Lignin/N ratio produced SOM with the highest CEC. More resistant organic residues thus had a combined positive effect on both quantity and the quality of SOM in terms of its charge characteristics.

Table 1. Stepwise multiple regression analysis of maize N uptake for the fields described under Experiment 2 (R^2 of the regression model = 0.692)

Independent variables	Regression coefficient	Prob > F	Partial correlation
– N content of prunings 1, 2, and 3 (kg N ha^{-1})	+ 0.092	0.0001	0.273
– Rainfall during growing season (mm)	+ 0.066	0.0001	0.167
– POM N content (kg N ha^{-1})	+ 0.130	0.0018	0.143
– POM N concentration (%)	+ 30.9	0.0231	0.048
– Fertilizer N addition (kg N ha^{-1})	+ 0.318	0.0490	0.033
– Soil silt + clay content (%)	+ 0.848	0.0629	0.028
– Constant	-106.4		

Table 2. Multiple regressions for CEC of the fine (0.020-0.002 mm) and coarse (0.053-0.020 mm) silt organic matter fractions in Experiment 3

	Regression equation	R^2
Fine silt	CEC = 0.81 + 0.59* pH	0.459
	CEC = -5.76 + 0.69* pH + 0.22* (C/N)	0.847
	CEC = -1.58 + 0.61* pH + 0.09* (Lignin/N)	0.834
Coarse silt	CEC = 1.16 + 0.48* pH	0.368
	CEC = -4.66 + 0.55* pH + 0.20* (C/N)	0.678
	CEC = -0.95 + 0.50* pH + 0.07* (Lignin/N)	0.643

Conclusions

Fractionation of the SOM pool into different fractions with varying particle size yielded fractions with distinct features related to N supply and cation exchange properties. While the coarser material appeared to be more closely related to N supply, the finer fractions were more relevant for exchange properties. Although the N concentration of the POM material seemed to positively influence N uptake by maize, no clear relationships between the quality of fresh organic inputs and POM could be established, due to the wide range of fresh organic materials in alley cropping systems and due to the incorporation of residue derived N in other organic materials before entering the POM pool. Contrarily with N supply, residue quality seemed to influence the CEC characteristics of the coarse and fine silt material. This was not the case for the clay fraction because of the relatively high contribution of its mineral components to the CEC.

There is a need for a user-friendly method to determine the quality of the SOM fractions following a similar approach as for fresh organic inputs. Care should be taken of the per definition differences in particle size of the different SOM pools, as residue particle size interferes with the outcome of the ‘traditional’ residue quality procedures for plant residues (Vanlauwe et al., 1996a). Furthermore, it is not clear whether the impact of the quality of a single organic input is consistently masked by the wide range of other inputs in a realistic cropping system (roots, weeds, crop residues, etc.). Determination of the variation in POM quality and N release during the growing season could help evaluate the former point. The impact of the location of the POM material within the soil structure on its N release characteristics needs to be evaluated. Lastly, the exact contribution of each SOM fraction to maize N uptake as a function of above-mentioned parameters (quality, location in the soil matrix) should be the ultimate goal in attempting to unravel the N supply characteristics of the SOM pool.

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Re-evaluation of fertility status of sandy soil in Northeast Thailand with reference to soil-plant nutrient budgets

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Keywords: Maize, sandy soils, inorganic fertilizer, cow manure, plant nutrient uptake

Abstract

*Sandy soils are generally regarded as very fragile with respect to agricultural production due to their very low nutrients and organic matter content. Limited information is available, however, on the fertility status of soils especially with reference to soil-plant relationship. The objectives of this study were, therefore, to examine the relationship between the nutrient contents in sandy soil and the amount of plant uptake for a variety of fertilizer applications and to evaluate the nutrient budget between soil and plant. A field experiment was undertaken at the experimental farm of Khon Kaen University, located in the central region of Northeast Thailand. Maize was grown during the rainy season (May – September) in 2004 on a sandy soil (*Quartzipsamments*). Six treatments were applied with three replications: NPK (equivalent to 100 kg ha*$^{-1}$*), PK, NK, NP, control and NPK + manure treatments. Soil samples were collected and available and total contents of N, P and K were determined in addition to general soil properties. Plants were sampled at harvest and the contents of N, P and K determined.*

Aboveground biomass was 7.35 t ha^{-1} *for the NPK treatment. Biomass was 48%, 37%, 10% and 50% lower in PK, NK, NP and control treatment, respectively, indicating that N was the dominant limiting factor, followed by P and K. The amount of N, P and K in the aboveground biomass amounted to 53, 16 and 38 kg ha*$^{-1}$ *for the NPK treatment. More than 80% of the root biomass was observed in the top 20 cm of the soil, where 19 kg ha*$^{-1}$ *of mineralizable N, 72 kg ha*$^{-1}$ *of available P and 77 kg ha*$^{-1}$ *of exchangeable K were stored. These amounts corresponded to 40%, 57% and 20% of the nutrients stored within 1 m, suggesting high concentration of P and N on the surface soil. Relatively high ratios with respect to the amount of plant uptake to soil nutrients were also indicated, suggesting relatively low sustainability of the agricultural system without proper management.*

Introduction

Sandy soils are generally regarded as very fragile with respect to agricultural production due to their very low nutrients and organic matter content (Boul et al. 2003, Wambeke 1992). Agricultural productivity on such soils is hence considerably low. In Northeast Thailand, for example, agricultural systems have been developed on such sandy soils and paddy rice has been cultivated in the lowlands and various field crops such as maize, cassava and sugarcane have been cultivated in the uplands. After continuous cultivation of such crops, yield decline has been observed mainly in the uplands. Decline in soil fertility has also been related to the decline of soil nutrients and organic matter. Nevertheless, limited information is available on the fertility status of soils especially with reference to soil-plant relationship, even though analysis of nutrient balance or soil-plant nutrient budget is important and inevitable to assess the sustainability of agricultural ecosystem (Vidhaya et al. 2004). The objectives of this study were, therefore, to examine the relationship between the nutrient contents in soil and the amount of plant uptake for a variety of fertilizer applications and to evaluate the nutrient budget between soil and plant of the agricultural system established on marginal sandy soil.

Materials and methods

Experimental field

A field experiment was carried out at an experimental field in Khon Kaen University, located in

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the central region of Northeast Thailand (latitude: 16º28′N, longitude: 102º49′E, 207 m above sea level) with a mean annual temperature and precipitation of approximately 26 and 1,200 mm, respectively. The field examined was slightly undulating with an area of 0.36 ha (60 m × 60 m). The soil of the field was classified as *Quartzipssamments* (Soil Survey Staff 2003) or Nam Phong series according to the soil survey in Thailand.

Experimental design

Maize (*Zea Mays* L., CP-888) was grown for 114 days during rainy season in 2004. Seeds of maize were sown on May 15 and plant samples were collected on September 5. In the experiment, to investigate the effect of NPK management on plant growth and nutrient uptake, six treatments were randomly setup with three replications, i.e. NPK treatment, PK (-N) treatment, NK (-P) treatment, NP (-K) treatment, control (-NPK) treatment and manure (NPK + cow dung manure) treatment. Chemical fertilizers were applied at rates equivalent to 100 kg ha^{-1} of N, P and K as urea, Triple superphosphate and potassium chloride, respectively. Half of them was applied at the beginning of the experiment (May 15) and the rest was applied about 3 weeks later (June 11). Cow dung manure was applied as an example of organic matter fertilizer at rate equivalent to 10 t ha^{-1} (165 kg N, 36 kg P and 301 kg K ha^{-1}) in addition to inorganic NPK fertilizers at the beginning of the experiment (May 15). They were applied manually by spreading on the ground and mixing with surface soil within 20 cm depth. The area of each plot was set to be 49 m^2 (7 m × 7 m). In each plot 9 rows were prepared at an inter row spacing of 75 cm, and in each row 23 plants were established 30 cm apart.

Soil sampling and analysis

Soil samples were collected before and after the experiment. At the beginning of the experiment, soil samples were collected from the plow layer (0-20 cm) as composite samples and also from several layers of a 1 m deep profile horizontally. After the experiment, soil samples were collected from the bulk, rooting zone and rhizosphere part of the plow layer in each plot. Here the soil located far from plants, attached to the root system of plants weakly and strongly were regarded as bulk, rooting zone and rhizosphere samples, respectively.

All the soil samples were air-dried and sieved through 2 mm sieve before the analyses. The electrical conductivity (EC), pH, total C content, total N content, C/N ratio, contents of mineralizable N, inorganic N, available P, exchangeable Ca, Mg, K and Na, CEC and particle size distribution were measured as general properties of the soil. In addition total P and K contents were measured as the potential pool of P and K in soil. The electrical conductivity (EC) and pH were determined electrochemically (CM 30S, TOA Electronics; and pH/ion meter Model 225, Denver Instrument) in a 1:5 soil:water suspension. Total C content, total N content and C/N ratio were determined by the dry combustion method (Sumigraph NC analyser NC-800, Sumika Chem. Anal. Service). Mineralizable N content was obtained as the difference between the amount of N extractable with 2 M KCl solution before and after incubation at 30º for 4 weeks at field capacity. In the analyses, the concentrations of NH_4^+ and NO_3^- were determined by the indophenol method and Griess-Ilosvay method, respectively (Mulvaney 1996). Available P content was determined by a colorimetric method after extraction by the Bray No. 2 method (Bray and Kurtz 1945). Contents of exchangeable Ca and Mg were determined by atomic absorption spectrometry (AA-660, Shimadzu Corp.) and contents of exchangeable K and Na by flame emission spectrometry (AA-660, Shimadzu Corp.) after extraction with a neutral 1 mol L^{-1} ammonium acetate solution. Cation exchangeable capacity was determined by measuring ammonium concentration of the extract of ammonium saturated soils with a 1 mol L^{-1} NaCl solution. Particle size distribution was analysed by the sieving and pipetting methods. Total P and K contents were determined by a colorimetric method and frame emission spectrometry, respectively, after wet digestion with conc. HNO_3 and $HClO_4$.

Plant sampling and analysis

Plant aboveground and belowground samples were collected at the end of the experiment. Five aboveground samples were collected from each plot and separated into corn, stem and leaf subsamples. Roots were washed out carefully from soil excavated in the control and manure treatments around one plant stand every 10 cm depth up to 1 m (30 cm × 75 cm for 0-50 cm depth and 30 cm × 37.5 cm for 50-100 cm depth).

All the corn, stem, leaf and root samples were oven dried at 70º for 24 hours and weighed to determine dry biomass. The grain component was weighed to calculate grain yield and then ground to a powder. The C and N contents were determined by the dry combustion method (Sumigraph NC analyser NC-800, Sumika Chem. Anal. Service). The P and K contents were determined by a colorimetric method and flame emission spectrometry (AA-660, Shimadzu Corp.), respectively, after wet-digestion of the plant samples with HNO_3 and $HClO_4$. The amount of N, P and K taken up by plants were then calculated as the product of dry weight and their contents in plants.

Results and discussion

Plant

Plant growth and yield The dry weight of corn was highest (5.18 t ha^{-1}) for the NPK treatment, followed by the -K treatment, -P treatment, -N treatment, and lowest (2.54 t ha^{-1}) for the control treatment (Figure 1). The dry weight for the NPK treatment was significantly higher than those for the -N, -P and control treatments ($p < 0.05$). The dry weight of corn for the manure treatment was higher than that of the NPK treatment, suggesting the positive effect of organic matter application in addition to inorganic fertilizer application. Corn was the dominant part of aboveground biomass and contributed to about 70% of the total aboveground biomass regardless of the treatments. Similar tendencies were observed for the other parts of the aboveground biomass, and hence, for the total aboveground biomass: 7.35, 6.64, 4.65, 3.84, 3.71 t ha^{-1} for the NPK, -K, -P, -N and control treatments and 8.88 t ha^{-1} for the manure treatment, respectively. Aboveground biomass was, therefore, 48%, 37%, 10% and 50% lower in -N, -P, -K and control treatment, respectively, than that in the conventional treatment, indicating that N was the dominant limiting factor, followed by P and K. On the contrary, biomass was 21% higher in manure treatment. Yield also showed similar tendencies, suggesting that soil nutrients and fertilizers affect not only the biomass but also crop production of the corn grown on this low-fertility sandy soil: 4.02, 3.58, 2.41, 2.16, 1.97 t ha^{-1} for the NPK, -K, -P, -N and control treatment and 4.74 t ha^{-1} for the manure treatment, respectively.

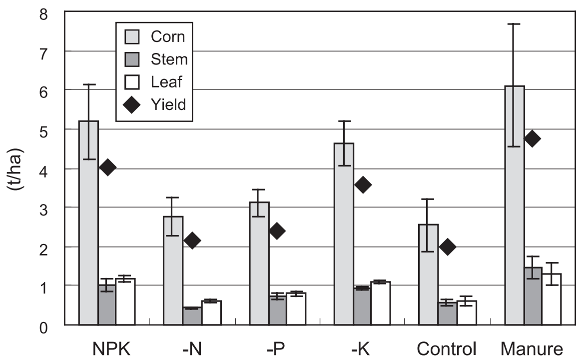

Figure 1. Dry weight and yield of plant components

On the contrary, dry weight of the belowground biomass to 1 m soil depth was 0.7 and 1.8 t ha^{-1} for the control and manure treatment respectively, suggesting considerable amount of biomass (about 16%) was located in the soil.

N, P and K concentrations of the plants. N concentration of the aboveground biomass was about 7 g kg^{-1}, and relatively higher in the corn and relatively lower in the stem part. P concentration of the aboveground biomass was about 2 g kg^{-1}, and that of the corn part was relatively higher than those of the stem and leaf parts. K concentration of the aboveground biomass was about 4-6 g kg^{-1}, and relatively higher in the corn part and relatively lower in the leaf part. The effects of the treatments on these concentrations were not so prominent, suggesting that concentrations of nutrients are more or less intrinsic characteristics of the plants.

Amounts of N, P and K taken up by the plants The amount of N, P and K in the aboveground biomass amounted to 53, 16 and 38 kg ha^{-1} for the NPK treatment, and 23, 7 and 15 kg ha^{-1} for the control treatment, respectively (Figure 2). The amount of N of the -N treatment and that of P of the -P treatment were similar to those of the control, suggesting the dependency of plants to fertilizers, whereas the amount of K of the -K treatment was between those of the NPK and control, suggesting relatively high contribution of soil K to plant uptake. It should be also noted that about 80% of N, 90% of P and 80% of K were in the corn, indicating that considerable part of the nutrients in the plants has been removed at harvesting every year.

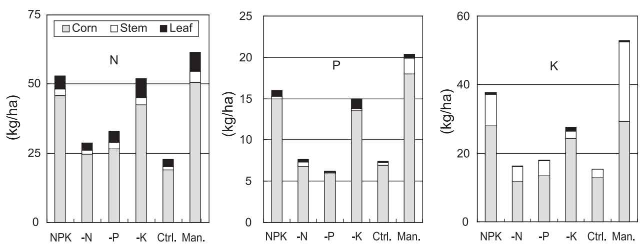

Figure 2. Amount of N, P and K taken up by plants

Root distribution Figure 3 shows the root distribution of the control and manure treatment. About 61% and 80% of the total dry weight of the roots were located within the surface 10 cm of the soil for the control and manure treatment, respectively. Within 20 cm they amounted to 81 and 91%, respectively. These results suggest that considerable amount of roots were spread within the plow layer where more

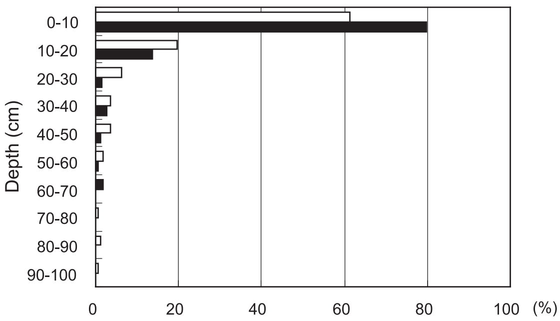

Figure 3. Root distribution in soil

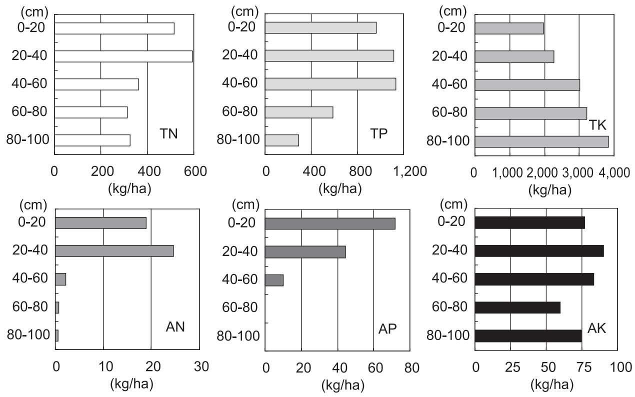

Figure 4. Distribution of total and available N, P and K stored in soil. TN, TP and TK designates Total N, P and K, and AN, AP and AK designates available N, P and K respectively

nutrients and organic matter were stored as discussed later, and that the percentage increased with the application of fertilizers onto the soil surface.

Soil

General properties of the soil Surface soil (Ap1, 0-20 cm) had the pH of 5.5, EC of 21.7 μS cm^{-1}, CEC of 2.14 cmolc kg^{-1}, total N of 0.26 g kg^{-1}, and about 90% of sand, suggesting relatively low soil nutrients, organic matter and capacity to store nutrients (Table 1). There was slight decrease in organic matter and increase in clay content with soil depth. However, very low status of soil fertility was observed throughout the soil profile. In general this soil was regarded as one of the representative sandy soils found in Northeast Thailand, as reported by Tulaphitak et al. (1996a, 1996b).

Amounts of N, P and K in the soil before the experiment The amounts of total and available N, P and K stored in the soil profile are shown in Figure 4. Here the mineralizable N, available P and exchangeable K were regarded to be the available fractions of N, P and K, respectively. The amounts of available N, P and K within 1 m depth amounted to 46.9, 126 and 384 kg ha^{-1}, respectively, whereas those of total N, P and K within the same depth were 2,109, 2,764 and 14,275 kg ha^{-1}, respectively. Therefore, available fractions of N, P and K corresponded to 2.2, 4.6 and 2.6% of the total, suggesting that only a small portion of the nutrients were readily available to plants. Distribution of the nutrients also varied according to the nutrients. Namely, the amounts of total N and P gradually decreased with depth whereas that of total K showed gradual increase with depth. These would be related to the same tendencies of organic matter content and clay content within the profile, respectively (Table 1). Accordingly, the amountf of total N, P and K within 20 cm or within plow layer amounted to 25, 27 and 14% of the nutrients stored within 1 m, respectively. On the contrary, the amounts of available N, P and K within 20 cm or within plow layer amounted to 18.9, 71.8 and 76.8 kg ha^{-1} and corresponded to 40%, 57% and 20% of the nutrients stored within 1 m, respectively. This indicated high

Table 1. General properties of the soil

Horizon	Depth (cm)	EC (μS/cm)	pH	CEC (cmolc/kg)	Exchangeable bases (cmolc/kg)			
					K	Na	Mg	Ca
Ap1	0-20	21.7	5.50	2.14	0.08	0.01	0.60	0.74
Ap2	20-32	25.0	5.37	2.54	0.08	0.06	0.55	0.83
Bw1	32-58	16.1	5.11	3.71	0.06	0.03	0.60	0.91
Bw2	58-84	16.3	4.90	5.14	0.05	0.02	0.39	0.87
C	84-125+	17.6	4.85	2.12	0.06	0.00	0.38	0.71

Horizon	Depth (cm)	Total N (g/kg)	Total C (g/kg)	Available P (g/kg)	Particle size distribution		
					Sand (%)	Silt (%)	Clay (%)
Ap1	0-20	0.26	5.6	0.04	89.9	7.1	3.0
Ap2	20-32	0.37	6.1	0.04	89.6	5.0	5.3
Bw1	32-58	0.18	1.8	0.01	78.5	16.1	5.4
Bw2	58-84	0.16	1.6	0.00	76.1	16.9	7.1
C	84-125+	0.16	1.6	0.00	73.6	19.3	7.1

concentration of available P and N on the surface soil and relatively even distribution of available K within the profile. In this sense, therefore, erosion of surface soil may lead to rapid depletion of P and N in the soil-plant system, and hence, rapid decrease in sustainability of this agricultural ecosystem.

Amounts of N, P and K in the soil after the experiment The amounts of available N, P and K of the bulk, rooting zone and rhizosphere soil were measured to investigate the effect of plant growth on the distribution of nutrients in the soil in accordance with the distance from the plant roots. On average, clear differences were not observed among the bulk, rooting zone and rhizosphere soil (data not shown). There was, however, a slight decrease in available N and slight increase of available K in the rhizosphere, suggesting depletion of N around the roots. This result was in accordance with the fact that N was the main limiting factor for plant growth in this agricultural system. Further study is needed to investigate more thoroughly the chemical and positional availability of nutrients in this low-fertility sandy soil, as proposed by Moritsuka et al. (2003).

Soil-plant relationship

For the control treatment, the amount of N, P and K in corn was 18.9, 6.9 and 12.9 kg ha^{-1}, respectively, and the amount of available N, P and K stored within 1 m of soil was 46.9, 126.4 and 384.4 kg ha^{-1}, respectively. These results suggest that about 40%, 6% and 4% of soil available N, P and K could be removed by just one cultivation of maize without any fertilization. It means basically low sustainability of this agricultural system, especially for N, without proper management even though capacity factor of soil fertility such as replenishment of nutrients in the soil solution from soil-solid phase should be carefully taken into account. The apparent increase of nutrient uptake by NPK fertilization, calculated as the difference between the NPK and control treatments, was 30.2, 7.9 and 22.4 kg ha^{-1} for N, P and K respectively. These values also indicate apparent fertilizer use efficiency because 100 kg ha^{-1} of inorganic NPK fertilizers was added. It suggests that the efficiency was not high, especially for P, due to heavy rainfall and low capacity to retain nutrients in the soil. In order to improve sustainability of agricultural production, therefore, countermeasures should be taken to increase fertilizer use efficiency, such as proper incorporation of organic matter in combination with fertilizer application in this agricultural system. To minimize erosion of surface soil would be another prerequisite because considerable portion of stored N and P are found within 20 cm of the soil profile.

Conclusion

In this agro-ecosystem, N was the dominant limiting factor for crop production. A considerable part of the available N and P was located within 20 cm of the soil, suggesting the importance of surface soil on nutrient cycling between soil and plant. Relatively high ratio of the amount of plant uptake to soil nutrients strongly suggested the need for proper management for the maintenance of the sustainability of the system.

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Addition of clay based soil ameliorants to light textured soils to reduce nutrient loss and increase crop productivity

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Keywords: **Sandy soils, remediation, high activity clay additions, CEC, increased production, sugarcane, sorghum**

Abstract

Productivity decline occurs in many agronomic systems due to loss of soil organic matter and a consequent decline in soil fertility. This is pronounced in light textured soils, which even in their pristine state can have low levels of fertility. High temperatures and leaching conditions in tropical environments further exacerbates this poor fertility. In order to facilitate agronomic production on these soils, significant amounts of organic or inorganic fertilizers are required to maintain economic yields. However, the inherent low cation exchange capacity (CEC) of these soils limits their ability to retain nutrients such as Ca^{2+}, Mg^{2+} and K^{+}. The addition of inorganic fertilizer is often beyond the means of resource poor farmers and has the potential negative impact on the environment due significant leaching losses associated with the high hydraulic conductivity of light textured sandy soils.

This paper reviews results from field experiments designed to assess the efficacy of bentonite (high-activity clay with a high CEC) additions on improving crop productivity and reducing nutrient loss. A number of field trials were established on light-textured soils in Northern Australia, Northeast Thailand and Hainan Province in China. Treatments and crop species (including sugarcane and various forage crops) differed at each of the study locations and included a range of rates (from 10 to 60 t ha^{-1}), different application methods (broadcast, banded and slotted), and in some trials a comparison with other commonly used field amendments (e.g. various organic materials and termite mound material). These field trials demonstrated significant increases in crop biomass and yields associated with clay additions. Additional glasshouse studies support the observed increases in biomass observed in the field trials, and suggest that the yield increases were due to a combination of increased water-holding capacity, nutrient availability and reduced nutrient loss. These results support the notion that degraded light textured soils can be highly productive if intrinsic properties are addressed through clay additions.

Introduction

It is well recognised that when soils are cleared of their native vegetation and cultivated, chemical degradation of inherent chemical properties occurs. In general, a decline in soil organic matter (SOM) reduces the soil's capacity to retain exchangeable cations, resulting in accelerated soil acidification and nutrient depletion. The consequent decline in soil fertility can be pronounced in light textured soils, which even in their pristine state can have low levels of fertility. This poor fertility can be further exacerbated by the high temperatures and leaching conditions found in tropical environments.

The impact on soil chemical properties following land clearing and continuous cropping can be illustrated by results obtained from a 'paired site' study, carried out as part of an ACIAR[4] funded project investigating the development of technologies to alleviate soil acidification in legume based production systems in the tropics of Asia and Australia. Results from selected sites from Northeast Thailand and Hainan, China are presented in Table 1. The decline in

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Table 1. Soil chemical properties of the surface 0-10 cm depth interval from selected paired sites from Northeast Thailand and Hainan, China

Site No.	Parent material	Vegetation	Years under prod.	pH	OC %	Ca^{2+}	Mg^{2+} cmol$_{(+)}$/kg	K^-	CEC	pHBC cmolH$^+$/ kg.unit pH
				Hainan, China						
AC01	metamorphic	eucalypts	40	4.61	0.87	0.18	0.24	0.1	2.75	1.60
AC01	metamorphic	peanuts/sweet potato	10	4.88	0.71	0.74	0.14	0.04	1.94	1.16
AC07	granite	eucalypts	20	5.07	0.93	0.25	0.25	0.22	1.14	1.12
AC07	granite	pepper	3.5	4.88	0.64	0.3	0.11	0.32	1.23	1.20
AC05	granite	eucalypts	20	4.8	1.25	0.41	0.19	0.09	1.99	1.62
AC05	Granite	pepper	13	4.78	0.78	0.21	0.09	0.07	1.37	1.33
AC09	Marine	pine	na	5.07	0.5	0.05	0.05	0.02	0.60	1.01
AC09	Marine	kinggrass	na	5.11	0.52	0.05	0.03	0.02	0.62	1.04
AC06	Sandy	eucalypts	18	4.78	0.59	0.09	0.15	0.05	0.96	0.93
AC06	Sandy	pineapples	2	4.90	0.32	0.11	0.03	0.03	1.00	0.94
AC04	Fluvial	coconuts	36	5.22	0.85	0.91	0.31	0.06	1.53	1.00
AC04	Fluvial	cowpeas/chillies	20	5.42	0.43	1.6	0.11	0.52	1.31	1.09
				Northeast Thailand						
C1	Alluvium	Diterocarp forest	comm. forest 14 yrs	5.18	0.67	0.74	0.40	0.09	1.57	0.92
C1	Alluvium	cassava	40+	5.00	0.33	0.25	0.11	0.03	0.83	0.63
C2	Alluvium	Diterocarp forest	comm. forest 14 yrs	5.05	1.08	0.80	0.45	0.07	2.09	1.14
C2	Alluvium	cassava	40+	5.02	0.43	0.34	0.11	0.04	0.91	0.83
C3	Alluvium	Diterocarp forest	comm. forest 14 yrs	5.08	0.65	0.59	0.37	0.05	1.64	1.07
C3	Alluvium	cassava	38	5.25	0.28	0.30	0.11	0.03	0.73	0.59
R3	Alluvium	Diterocarp forest	nat. reserve forest	4.72	0.96	0.25	0.19	0.09	1.67	1.32
R3	Alluvium	rice	37	5.09	0.67	0.60	0.11	0.04	1.21	0.76
R4	Alluvium	Diterocarp forest	spiritual forest	4.87	0.85	0.34	0.20	0.07	1.34	1.07
R4	Alluvium	rice	50+	5.18	0.21	0.14	0.03	0.04	0.48	0.41
R5	Alluvium	Diterocarp forest	spiritual forest	5.16	1.06	1.44	0.45	0.06	2.52	1.23
R5	Alluvium	rice	100+	5.03	0.29	0.16	0.05	0.02	0.67	0.45

organic carbon (OC), cation exchange capacity (CEC) and pH buffering capacity (pHBC) is clearly demonstrated in the soil attributes of the long-term cultivated systems when compared to their adjacent forest sites.

The Thailand sites exhibited a greater degree of degradation compared to the Hainan sites, as true 'undisturbed' forest sites were not available in Hainan. At the time of sampling in Hainan, all 'undisturbed' sites had been under a permanent tree crop for 20 years or more. This shift back to a more permanent tree crop system, plus a more regular use of organic waste materials in the crop production systems of Hainan may be providing a degree of reversal to degrading processes commonly observed in most changed land use systems. However, despite this, it is clear that these sandy soils from both Thailand and China have generally low fertility and low capacity to retain nutrients and that this has been further exacerbated by long term cultivation.

Many of the crop production systems studied require significant amounts of inorganic fertilizers to sustain economic yields. However, adding sufficient nutrients to ensure adequate plant growth can be difficult as the inherently low CEC of these soils limits the ability of the soil to hold nutrients such as calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+), and these can be rapidly lost through leaching. Under these conditions, the addition of fertilizers can be expensive, wasteful and have the potential to cause significant environmental harm as many of the applied nutrients can be lost from the system through leaching into the underground aquifers and runoff into streams, ultimately affecting water quality.

To attempt to counteract this degradation and the consequences of nutrient depletion and soil acidification remediation strategies are often implemented. The addition of organic amendments such as manure or compost can be effective but short-lived in tropical environments, requiring large quantities and regular additions. Effort has also gone into strategies to remediate surface soil acidification and increasing CEC through the addition of liming materials. However, on light textured sandy soils containing low activity clays with limited buffering capacity, the rate of re-acidification after liming is invariably high due to the low inherent resistance of the soil to acid input (Lesturgez et al., 2005). An alternative approach to increasing the nutrient retention properties of the soil has been demonstrated in recent studies (Noble *et al*; 2001; Noble *et al*; 2003; Noble *et al*; 2004) where the addition and incorporation of high-activity clay has been shown to permanently increase the CEC of the soil and provide positive yield benefits.

This paper discusses the efficacy of the use of high activity clays, either used alone or in association with other amendments, as a potential soil amendment/conditioner for increasing the nutrient holding capacity of light textured soils. The results reported here incorporate the outcomes of a number of glasshouse studies and field trials that were established using light-textured soils from Northern Australia and Hainan Province in China, and confirm previously reported responses (Noble *et al*; 2001; Noble *et al*; 2003; Noble *et al*; 2004). Treatments and crop species (including sugarcane and various forage crops) differed at each of the study locations. Treatments generally included a range of rates of high-activity clay (from 10 to 60 t/ha), different application methods (broadcast, banded and slotted), and in some trials, comparison with various organic materials commonly used as field amendments. In addition, recent results from farmer field based assessments in Thailand are presented to demonstrate the positive response of this approach under farmer field conditions.

Experimental Details

Australia

Two field trials were established at Ingham in North Queensland, on a river plain alluvial sand with minimal soil development (80% coarse sand, 14% fine sand, 3% silt and 3% clay). The high-activity clay used in both trials was a Ca^{2+} dominated bentonite enriched with dunder (a by-product from the distillation of molasses) to increase its K^+ content. The bentonite mix contained 46, 28, 10 and 10 $cmol_c$/kg of Ca^{2+}, Mg^{2+}, K^+ and Na^+ respectively.

Field trial 1: The first trial was planted to sorghum, and included five rates of bentonite (0, 5, 10, 20 and 40 t ha^{-1}). All bentonite treatments were broadcast evenly over the whole plot (3 m $\times$ 10 m) and incorporated with a small rotary hoe to an incorporation depth of approximately 20 cm. Nitrogen (N), phosphorus (P) were applied following standard fertilizer recommendations, and K^+ applied at variable rates depending on levels supplied by the bentonite/dunder mix. Crop biomass yields were recorded from the plant and ratoon crop.

Field trial 2: The second trial was planted to sugarcane, and included a control treatment (0 bentonite) and three rates of bentonite (10, 30 and 60 t ha^{-1}), applied as either a broadcast or banded treatment. The bentonite in the ‘broadcast’ treatments was spread evenly over the whole plot (6 m $\times$ 10 m) and incorporated with a rotary hoe to an incorporation depth of approximately 20 cm. The bentonite in the ‘banded’ treatments was first applied to a pre-prepared furrow, approximately 20 cm deep and then incorporated with a rotary hoe. The effect of incorporating the bentonite applied in the furrows was to distribute it relatively evenly in a concentrated band of soil, visually estimated to be approximately 20 cm deep and 50 cm wide. This concentrated band of soil equated to a higher rate of bentonite per unit of soil, such that within that ‘band’, the 10, 30 and 60 t ha^{-1} bentonite additions could approximately compare to a ‘broadcast’ rate of 30, 90 and 180 t ha^{-1}. The planting row for the ‘banded’ treatments was within the band of treated soil. Nitrogen and P was applied following standard recommendations, and K applied only to the control plots receiving no bentonite.

Glasshouse pot trial: Using the same soil from the field site, a glasshouse pot trial was established using fives rates of bentonite (at 0, 1.25, 2.5, 5 and 7.5% bentonite in 2,000 g soil, equivalent to 0, 12.5, 25, 50 and 75 t ha^{-1} assuming a soil bulk density of 1 g/cm^3 and an incorporation depth of 10 cm). The bentonite used was a blend of three bentonites; a Ca-dominated, Mg-dominated bentonite and a bentonite which had been beneficiated using potassium chloride making it a K-dominated bentonite. Inorganic nutrient solutions of $CaCl_2$, $MgSO_4$ and K_2SO_4 were added to the treatments at rates inversely proportional to the rate of bentonite used, bringing the soil cation levels to a minimum of 2.7, 0.68 and 0.45 $cmol_c$ kg^{-1} soil for Ca^{2+}, Mg^{2+} and K^+ respectively. The difference in soil CEC due to bentonite addition was equivalent to 1.89, 3.30, 4.31, 6.48 and 8.33 $cmol_c$ kg^{-1} soil for bentonite rates of 0, 12.5, 25, 50 and 75 t ha^{-1} respectively. Micronutrients N and P were added based on standard recommendations. The pots were sown to forage sorghum.

Three sets of these treatments were established so that three watering regimes could be imposed after plants were well established (watering to 'field capacity' daily, 'drying down', and 'leaching' by watering in excess of 'field capacity' by the equivalent of 25 mm rainfall daily for six days). Plant available water (PAW) was calculated in the laboratory by determining water retention curves at 0, 5, 10, 30, 300 and 1,500 kPa, and calculating the PAW as the difference between 10 and 1,500 kPa. Water uptake and growth measurements were recorded daily for all treatments during the drying down and leaching phases of the experiment, and total biomass recorded at the end of the experiment. Leachate volumes were recorded and chemical analysis carried out on leachates, soil and plant material.

China

Field trial: A field trial was established Weng Tein, in Wenchang county on the northeastern side of Hainan Island in 2001. The soil at the site was a sand of marine origin with approximately 88% coarse sand, 7% fine sand, 1% silt and 3% clay. The trial was initially planted to maize and then replanted to King Grass. Treatments included a control, bentonite (40 t ha^{-1}), manure/compost (at 10, 20 and 40 t ha^{-1}), bentonite (at 20, 40 and 60 t/ha, with each rate also having the manure/compost mix added at 20 t ha^{-1}), and filtermud (40 t ha^{-1}) a by product from the processing of sugarcane. The bentonite used in this trial had a CEC of 48 $cmol_c$ kg^{-1} with approximately 16 $cmol_c$ Ca^{2+} kg^{-1} and 12 $cmol_c$ Mg^{2+} kg^{-1}. Crop dry matter yields were recorded and the soil was sampled following amendment application to examine the impact of the treatments on soil chemical properties.

Glasshouse pot trial: Soil was collected from the Wenchang field site and used to establish a glasshouse pot trial, where bentonite was added at 0, 10, 20, 40 and 80 t ha^{-1}, and 'fresh water filterpond mud' (FWFPM) added at 0, 10, 20, 40, 80 and 160 t ha^{-1}. Pots were free draining, and King Grass was transplanted into the pots using trimmed rooted sections taken after division from large clumps collected from the field. Nitrogen, phosphorus and potassium were added to each pot at rates equivalent to 100, 50 and 200 kg ha^{-1} of N, P and K respectively, once at establishment, and again after the third biomass harvest. A total of five plant biomass harvests were taken at approximately 3 monthly intervals and the soil was sampled after the final biomass harvest (approximately 16 months after establishment) and analysed for a range of soil chemical properties.

Thailand

Field trials that had been established previously in Northeast Thailand have been reported elsewhere (Noble *et al*., 2004) and for brevity are not reported here. An assessment of water productivity associated with the range of field studies is undertaken here as well as the presentation of results from farmer field assessments that were undertaken in the 2004 growing season. These farmer field studies were undertaken by a number of farmer based networks that are present in the region. The object of the assessment was to first sensitize members in these farmer networks to the degree of degradation that their soils had undergone followed by showing them the results of structured field trials through visits to trial sites. Once general agreement was achieved to trial the clay materials, networks were provided with bulk samples of the locally sources clay to be distributed to members willing to participate in the assessment. The design of the individual farmer studies was left to the farmers themselves so as not to influence the process of learning by trialling. Participating farmers were asked to collect relevant data on rates of application and yields. The result reported here are from those farmers who were prepared to collect the relevant data. As in any participatory process these is significant attrition with respect to participation.

Results and Discussion

Australia

Field Trial 1: The yields (t ha^{-1} fresh weight) from both sorghum crops grown in the first trial demonstrated a strong and highly significant response to increasing rates of bentonite. The response was still linear at 40 t ha^{-1}, indicating that yield could have been further improved by higher application rates. Yield responses were strongly correlated with the increase in CEC of the soil in the 0-20 cm depth increment (Figure 1).

The bentonite significantly increased CEC (an increase equivalent to 0.27 $cmol_c$ kg^{-1} for every 10 t ha^{-1} bentonite added) and the level of plant available Ca^{2+}, Mg^{2+} and K^+, and the yield response can

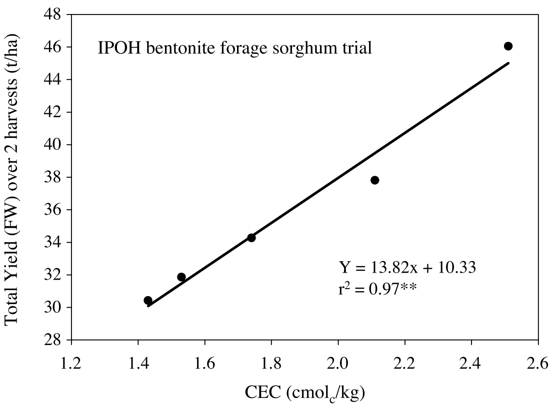

Figure 1. Yield response (t ha^{-1} FW) of forage sorghum to the CEC (cmol/kg) of the soil in the 0-20 cm depth increment. Results from the field site at Ingham, Australia

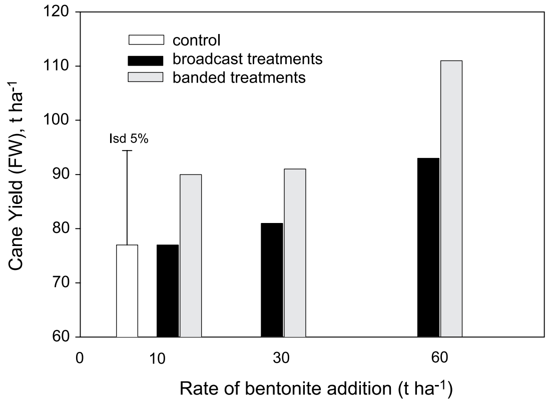

Figure 2. Yield response (t ha^{-1} FW) of millable cane to increasing rates of broadcast or banded bentonite additions. Results from the field site at Ingham, Australia

be directly attributable to these increases. It is very difficult to retain added nutrients in light textured sandy soils similar to that in this trial, however, it is clear that although the sorghum crop was not planted until 7 months after the bentonite was applied, the increase in soil CEC associated with the bentonite additions has reduced or prevented the loss of the added nutrients.

Field Trial 2: In the second trial, planted to sugarcane, increases in soil cation concentration and CEC with increasing rates of bentonite are within keeping with the changes observed in the sorghum trial. A rate of 60 t ha^{-1} bentonite increased the CEC of the soil to 2.61 cmol$_c$ kg^{-1} compared to the CEC of 0.97 cmol$_c$ kg^{-1} in the control soil. It is of interest to note that within 4 weeks of applying inorganic K fertilizer to the soil surface of the control plots, the K had already started to move through the profile. The concentration at 10-20 cm was 0.36 cmol K kg^{-1} compared to 0.14 cmol K kg^{-1} at 0-10 cm. In contrast, although it was 10 months since the bentonite was applied, the soil concentration of K in the top 20 cm of the all bentonite treatments remained high and consistent with the amount of K that would have been added with the bentonite addition (ranging from 0.22 to 0.33 cmol K kg^{-1} depending on the rate of bentonite used). There was a steady increase in yield with increasing rates of bentonite additions. At the bentonite addition rate of 60 t ha^{-1}, the yield increase, when compared to the control treatment, was 16 t ha^{-1} (17% yield increase) and 34 t ha^{-1} (30% yield increase) for the broadcast and banded treatments respectively (Figure 2).

The effect of concentrating the amount of bentonite added by applying in a band within the planting row area, is evident by the higher yields achieved at all rates of application (Figure 2). As discussed, this concentrated band of soil equated to a higher rate of bentonite per unit of soil, such that within the 'incorporated band', the 10, 30 and 60 t ha^{-1} bentonite additions could approximately compare to a 'broadcast' rate of 30, 90 and 180 t ha^{-1}. The yield increase is significantly correlated to this 'equivalent' rate of bentonite ($r^2 = 0.90$).

Glasshouse pot trial: Previous glasshouse trials have used open pot systems enabling leaching to occur and providing an assessment of the nutrient retention capacity of the bentonite added. However, it can be argued that water holding capacity would increase with increasing bentonite addition and, even with very regular watering, there would be an effect of increasing available water with increasing bentonite rate and that some of the yield increase may be due to increased plant available water (PAW) capacity. The aim of this study was to ascertain the reason(s) for the responses to bentonite, and attempt to separate the nutritional from the soil physical effects.

Water retention curves demonstrated a significant increase in PAW with increasing rates of bentonite. Additions of bentonite equivalent to 0, 25, 50, and 75 t ha^{-1} provided PAW contents of 0.085, 0.086, 0.090, 0.117 g cm^{-3} (equating to a change in gravimetric water content of 5.5, 5.6, 5.9 and 7.6% respectively at the soil bulk density of 1.53 g cm^{-3}) (Figure 3). During the first stage of the trial all pots were watered by weight, adding sufficient water to bring the soil to a water content assumed to be the moisture content at 'field capacity' (10 kPa). Pots were watered to weight daily, either once or twice a day, depending on rate of water use, so that plants were never exposed to water stress.

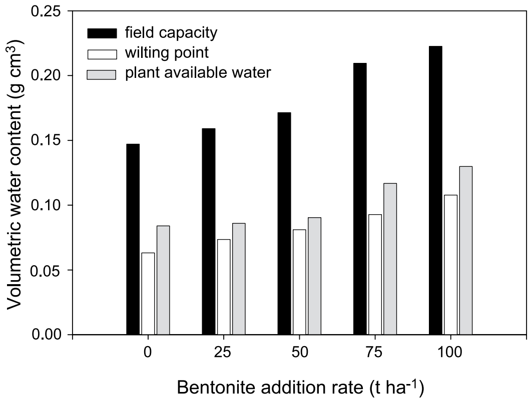

Figure 3. Volumetric water content (g cm^3) at ‘field capacity’, ‘wilting point’ and ‘plant available water’ for soil with bentonite added at rates equivalent to 0, 25, 50, 75 and 100 t ha^{-1}. Soil used was from the field site at Ingham, Australia

Despite adequate water and nutrients, during this stage of growth, there was a growth response to bentonite additions, with bentonite rates >25 t ha^{-1} having taller plants with thicker stems. It is unlikely that this early response was nutritional, and although the plants had adequate readily available water to ensure good growth, it is plausible that these growth responses were in part due to the availability of the slightly larger amounts of PAW available in the bentonite treatments during these early stages of growth. If so, this potential for a higher PAW due to bentonite addition may prove to be an important factor in the early stages of germination and establishment of a crop in the field. This aspect was considered by Suzuki et al. (2005) in their assessment of changes in the water retention curves associated with the addition of clay materials.

When the plants were fully established, three differing watering regimes (drying down, maintaining at field capacity, and leaching) were imposed over a period of 6 days, by which time the plants in the drying down treatment were stressed and there had been no leaf extension for 2 days. During this period the ‘leaching’ treatment had received the equivalent of 25 mm rainfall per day. At the end of this period, as expected, the plants in the drying down treatment had significantly less biomass than the other two watering regimes where water supply was adequate. This decrease in biomass tended to be over the full range of bentonite rates, but the difference in the control treatment receiving no bentonite being the most significant (Table 2). These results again suggest that the greater amount of PAW due to the bentonite additions has had a positive impact on sustaining growth during short periods of water deficit.

Table 2. Total plant biomass (DW g pot^{-1}) at harvest for plants grown under three watering regimes and with a bentonite addition rates of 0, 12.5, 25, 50 and 75 t/ha, from the glasshouse trial using soil from the Ingham field site, Australia. The figures represent the mean of 4 replicates and significant difference between treatments are shown using the ‘least significant difference of the means (lsd) at the 5% level of significance

Watering Regime	Bentonite addition rates (t ha^{-1})					
	0	12.5	25	50	75	lsd 5%
dry-down	4.7	6.3	10.4	11.4	10.6	1.4
field capacity	5.9	7.4	12.0	11.7	11.7	1.2
leaching	6.0	7.5	12.2	12.2	11.6	1.2
lsd 5%	1.1	n.s	n.s	n.s	0.8	

The pots in the ‘leaching’ treatment were subjected to the equivalent of 150 mm rainfall over a weekly period, which is typical of rainfall events in a tropical environment. The majority of the major nutrients (original present in soil or added via the bentonite additions or supplements of inorganic nutrient solutions) could be accounted for at harvest following chemical analysis of the soil, leachate, and plant material. Approximately 70% of the added N could be accounted for and was clearly taken up by the plant prior to leaching taking place, as there was very little N collected in any of the leaching events. However, under these leaching conditions, the increase in CEC with bentonite addition rate significantly increased the retention of the soil cations Ca^{2+}, Mg^{2+} and K^+ (Table 3).

Table 3. Cations (Ca^{2+}, Mg^{2+} and K^{+}) collected in the leachate, taken up by the plant, and remaining in the soil collected at harvest, all expressed as a percentage of the initial levels. Results are from the glasshouse trial using soil from the Ingham field site, Australia

Cations as a % of initial soil levels	Bentonite addition rates (t/ha)				
	0	12.5	25	50	75
Ca^{2+}					
% leached	31	11	0	0	0
% plant uptake	5	3	3	3	2
% remaining in soil	67	92	117	111	130
total	103	106	120	114	132
Mg^{2+}					
% leached	31	20	2	2	2
% plant uptake	10	7	9	5	4
% remaining in soil	31	71	97	94	123
total	72	98	107	101	129
K^+					
% leached	44	28	8	12	8
% plant uptake	46	45	57	43	32
% remaining in soil	25	26	25	42	75
total	114	98	90	97	115

Results from field and glasshouse trials demonstrate that the improved retention of soil nutrients due to bentonite additions has immediate yield benefits, but over time, has the potential to reduce the requirement for inorganic fertilizer inputs. An important and additional benefit is the potential to reduce the negative impact on the environment due to significant leaching losses associated with the high hydraulic conductivity of light textured sandy soils.

China

Field Trial: Unfortunately both the maize and King Grass crops grown at the Wenchang field site were severely damaged by root feeding grubs and rats, and despite dry matter harvests being undertaken on a number of occasions, there were no significant treatment responses due to the very high coefficients of variation (>65%) resulting from the uneven crop growth. However, analysis of soil samples collected approximately 12 months after addition of the various amendments demonstrate the impact of the bentonite additions, with the CEC of the soil increasing from 0.63 $cmol_c\ kg^{-1}$ for the control to 0.66, 1.02 and 1.29 $cmol_c\ kg^{-1}$ following the addition of 20, 40 and 60 t ha^{-1} bentonite respectively. All these additions of bentonite were accompanied by 20 t ha^{-1} of a compost/manure mix. However additions of compost/manure on its own at 10, 20 and 40 t ha^{-1} had little or no impact on increasing soil CEC, so it is assumed that the increase in CEC is due to the bentonite alone. This is supported by the treatment where bentonite was added at 40 t ha^{-1} without additional compost/manure and had a CEC of 0.98 $cmol_c\ kg^{-1}$. Addition of 40 t ha^{-1} filtermud, a waste product from sugarcane milling, resulted in a similar increase in soil CEC, being 1.03 $cmol_c\ kg^{-1}$.

Glasshouse trial: Because of the difficulties encountered in the field trial, soil was collected from the site so that selected amendment treatments could be tested in a glasshouse pot trial. In the pot trial, a filtermud (FWFPM) treatment was included, but in this case, unlike the field trial the material used was waste material derived from fresh water prawn aquaculture industry. Increasing rates of both bentonite and FWFPM significantly increased the CEC of the soil. The trial was continued for approximately 16 months in freely watered, free-draining pots, and during this time there were 5 biomass harvests, removing a substantial amount of soil nutrients. Despite this, soil samples collected at the final harvest show there was still high levels of cations remaining in the soil, in particular for the bentonite rates >40 t ha^{-1}. There were significant increases in total plant biomass (sum of DW (g/pot) for the 5 harvests) for the higher rates of both

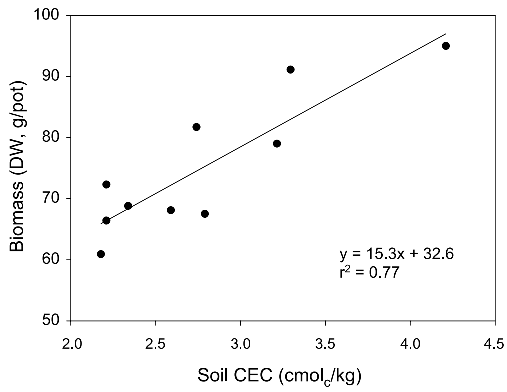

Figure 4. Increase in biomass of King Grass (g/pot DW) due to an increase in soil CEC ($cmol_{(+)}$/kg resulting from additions of bentonite or FWFPM to soil collected from the Wenchang field site, China

bentonite and FWFPM, but over all rates of amendment addition, biomass was significantly correlated with the increase in CEC, regardless of the amendment used to achieve this CEC (Figure 4).

Thailand

The previous discussion has focused on the impact of added bentonites on the surface charge characteristics of the soil of light textured sandy soils. In addition, there is clear evidence to support the notion that the addition of bentonites to soils can have a significant impact on the water retention properties of soils (Suzuki et al., 2005). A common characteristic of all of the field trials reported here and elsewhere (Noble et al., 2005) is that they were undertaken under rainfed conditions. A significant risk associated with the production of broadacre crops on these light textured soils is the potential for entire crop failure associated with drought stress. This has been observed in trials undertaken in Northeast Thailand (Noble *et al.*, 2005). By increasing the productivity of these degraded production systems significant positive benefits accrue including an enhancement in water productivity (i.e. WP = kg dry matter per unit rainfall) of these rainfed production systems. Using data collected from several field trials undertaken in Northeast Thailand where the addition of bentonite was assessed, the WP of these systems was significant increased (Figure 5).

Water productivity increased from a mere 0.20 kg mm^{-1} on the unamended soil treatments to over 14.75 kg mm^{-1} in those treatments receiving a combination of bentonite and compost (Figure 5). This clearly indicates the degraded nature of these soils, but more importantly demonstrates the positive impact of addressing soil chemical and physical constraints on WP.

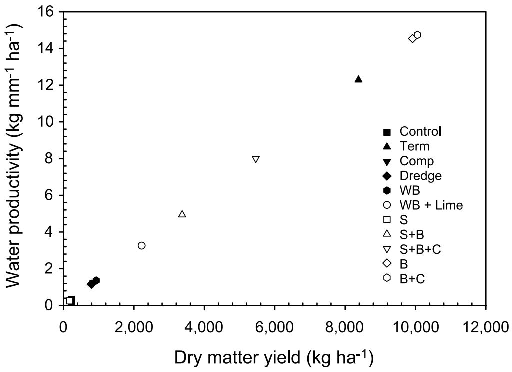

Figure 5. Relationship between dry matter production and water productivity for a range of soil based treatments in Northeast Thailand. Control = current practices; Term = termite mound soil at 120 ton ha^{-1}; Comp = leaf litter compost at 10 t ha^{-1}; Dredge = dredged material at 240 tonne ha^{-1}; WB = acid waste bentonite at 50 t ha^{-1}; WB + Lime = acid waste bentonite at 50 t ha^{-1} + 5 t ha^{-1} lime; S = Slotting; S+B = Slotting + 50 t ha^{-1} bentonite; S+B+C = Slotting + 50 t ha^{-1} bentonite + 10 t ha^{-1} compost; B = Local bentonite at 50 t ha^{-1}; B+C = Local bentonite at 50 t ha^{-1} + compost at 10 t ha^{-1}. (Adapted from Noble *et al*., 2004)

Whilst the activities to date have focused on understanding the processes contributing to lower productivity on these degraded light textured soils with the objective of developing management strategies based on the introduction of clay based materials to address these problems, an initial attempt to transfer this technology to farmers was undertaken in 2004. Using farmer network groups in Northeast Thailand extensive consultation was undertaken to demonstrate to farmers the concept of using clay based materials to improve their degraded production systems. Clay material was supplied in bulk to selected networks prepared to trial clay on their farms. The rates and methods of application were left to the farmers to decide upon with the only stipulation that farmers record their yields. For brevity the results from a group of organic rice growers in the Yosthon region of the Northeast are presented in Table 4. Substantial increases in yield over traditional practices were observed with relatively low applications of bentonite (0.63-10 t ha^{-1}) in combination with their current practices. Taking into account the costs associated with the purchase and application of bentonite, in 13 out of the 15 cases presented in Table 4 farmers were still ahead financially. These results are encouraging as they indicate that modest rates of application of bentonite can have a significant impact on the financial viability of these rice based systems. In addition, as these rice based systems would not be subject to water limitations it is assumed that the response to bentonite application is a function of enhanced fertility.

Table 4. Yield responses of rainfed lowland organic rice to applications of bentonite under farmer field conditions in Northeast Thailand during the 2004 growing season

Co-operating farmer/network	Bentonite rate (t ha^{-1})	Rice yield farmer practice (t ha^{-1})	Rice yield farmer practice + bentonite (t ha^{-1})	Net profit farmer practices (Baht ha^{-1})*	Net profit farmer practice + bentonite (Baht ha^{-1})	Net profit from the application of bentonite over farmer practices (Baht ha^{-1})
Mr. Sen Sookprasert	1.25	1.00	2.00	10,000	18,750	8,750
Mr. Chai kaewnonghee	1.25	1.50	3.00	15,000	28,750	13,750
Mr Yod Ketsipong	0.63	2.00	2.60	20,000	25,370	5,370
Mr. Noojee Yodnamkam	1.25	2.50	4.01	25,000	38,850	13,850
Mr. Suthinan network	5.00	3.45	4.76	34,500	42,600	8,100
Don Hee Farmer Field school	1.56	2.11	2.71	21,100	25,540	4,440
Ban Yae Farmer Field school	1.25	1.20	2.23	12,000	21,050	9,050
Non Haad Farmer Field school	3.13	0.68	1.10	6,800	7,870	1,070
Kudstian Farmer Field school plot 1	1.25	3.00	5.61	30,000	54,850	24,850
Kudstian Farmer Field school plot 2	1.25	1.54	1.66	15,400	15,350	-50
Laohansai Farmer Field school plot 1	10.00	0.97	2.00	9,700	10,000	300
Laohansai Farmer Field school plot 2	10.00	1.51	1.85	15,100	8,500	-6,600
Srikaew Farmer Field school	2.50	0.80	1.51	8,000	12,600	4,600
Kudchiangmee Farmer Field school	1.25	1.19	2.00	11,900	18,750	6,850
Nonpakha Farmer Field school	1.56	1.03	1.67	10,300	15,140	4,840

* Current price of organically grown rice is 10 Baht/kg.

Current estimates of the cost of locally sourced bentonite delivered and applied is 1,000 Baht/tonne.

Conclusions

The degradation of light textured sandy soils of the tropics has been the focus of significant research in the past (Aweto *et al*., 1992; Noble *et al*., 2000; Noble *et al*., 2004). One of the key drivers of declining productivity is a reduction in the capacity of soils to retain and provide essential nutrients to the developing crop along with reduced soil water holding capacity. It is well recognized that organic matter has essential biological, physical and chemical functions in soils and is one of the primary indicators of soil quality both for agriculture and environmental functionality (Robert, 2001). Biological conservation methods are an effective means of addressing the decline in fertility of soils as well as protecting them from the physical effects of erosion (Stocking, 2003). These conservation methods focus on the management of biomass through crop residues, green manures and alley cropping. The advantage of biomass management is that it not only influences the fertility status and surface charge characteristics of soils but also results in the sequestration of carbon. However, the principal limitation to effectively initiating such conservation measures in developing countries is the availability of organic materials and the human resources required to manage these systems at the smallholder farming level. In addition, under tropical climatic conditions where continuous mixing of the soil occurs on a routine basis, significant mineralization of carbon will occur, thus requiring regular inputs of organic matter to replenish these losses.

The addition of bentonite clay to degraded sandy soils has clearly demonstrated the potential role of these materials in restoring the productive capacity of soils within a single season. These have been verified both in field and greenhouse studies. Moreover in studies over a 3 year period the responses to this form of intervention are persistent and continue to increase (Noble *et al*., 2004). The mechanisms associated with the enhancement in productivity are an increase in the cation exchange capacity of soil and concomitant nutrient supplying capacity; and changes in the water retention/physical properties of these soils. Suzuki et al., (2005) have shown that not only is the plant available water content increased with the application of bentonite but also the stability of aggregates. In this study the former is confirmed.

Whilst bentonites were used as a model to demonstrate the effect of increasing the fertility status of soils, this should not preclude the use of other indigenous technologies or other locally available sources of clay materials. It is plausible that the introduction of soil improvement technologies as discussed may be best suited to improving household food security through the rejuvenation of small areas along with the introduction of small scale inexpensive supplemental irrigation systems. This technology would also allow an incremental expansion of the area rejuvenated as and when the individual has adequate resources. Based on the productivity increases and persistence in response, it is suggested that such a strategy may be a viable option to resource poor farmers that would significantly improve food security at the household level as well as assist in improving the financial status of farmers. Such an approach would allow crop intensification that may have positive benefits associated with reduced land required for food production (environmental benefits); stable yields (food security); crop diversification to higher value and nutritious crops (financial and health benefits); and reduced labour requirements through growing crops on a smaller area. The results from field trials under rainfed conditions also effectively demonstrate the concept of ‘more crop per drop’ that in these climatically variable agrozones offers a potential solution to crop variability and hence risk. As rain-fed agriculture is practiced on approximately 80% of the agricultural land globally and will remain the dominant source of food production during the foreseeable future (Rockström *et al*., 2003; Parr *et al*., 1990), increasing the productivity of these production systems in order to take advantage of annual rainfall is an important priority in maintaining global food security.

Finally, a rather cursory attempt to demonstrate the cost effectiveness of this approach using examples of organically grown rice clearly demonstrates that there are significant financial benefits to be achieved within the first year, with the full cost of purchasing and applying the bentonite being recovered. This has been demonstrated under farmer field conditions that represent actual farmer practice. These results are encouraging and with additional research and development further advances can be made regarding the most cost effective means of application, economic rates of application under contrasting agro-ecozones and the long-term implications of such strategies in enhance the productivity of degraded light textured soils.

Acknowledgments

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Effect of organic and inorganic fertilizers on yield and quality of ruzi grass (*Brachiaria ruziziensis*) grown on saline sandy soils of the Northeast, Thailand

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Keywords: organic fertilizer, inorganic fertilizer, ruzi grass, saline soil, sandy soil

Abstract

*Most soils in the Northeast of Thailand are sandy in texture. They are poor both in physical and chemical properties. Saline soils currently occupy an area of approximately 17% of the region and are increasing annually. These saline sandy soil can be detrimental to plant growth and result in low yields, this being mainly due to low fertility, high soluble salts and low water holding capacity. To grow crops successfully, these soils must be improve. The objective of this study is to elucidate the effect of organic and inorganic fertilizers on yield and quality of ruzi (*Brachiaria ruziziensis*) grass on saline sandy soils of the Northeast Thailand.*

Experiment design was factorial in RCBD with 3 replications. Factors were 3 rates of chicken manure (0, 1.87 and 3.75 t/ha), 2 rates of rice husk (0 and 5 t/ha) and 3 rates of 15-15-15, inorganic fertilizer (0, 156 and 312 kg/ha). Ruzi grass seedlings were transplanted in to 2 × 3 m plot on a Typic Natraqualfs soil at a 30 × 30 cm spacing. Both fresh and dry weight of grass was measured at harvest. For dry weight, increasing rates of manure resulted in an increase in yield. These was significantly different between control and 3.75 t/ha. Rice husk also gave significant dry weight differences between control and 5 t/ha rate. For the 15-15-15, inorganic fertilizer, the application at 156 kg/ha increased dry weight significantly from control. There was a significant interaction between rice husk and inorganic fertilizer. It was concluded that chicken manure at 3.75 t/ha together with rice husk at 5 t/ha and fertilizer at 156 kg/ha was the best combination rate to give highest grass dry weight under this saline and sandy condition. Grass quality such as crude protein, neutral detergent fiber and acid detergent fiber were analysed. Soil chemical properties such as pH, EC, OM, total N, available P, exch, K and exch, Na were also analysed before and after the experiment.

Introduction

Most soils in the northeast are sandy in texture. They are poor in physical, chemical and biological properties. Saline soils currently occupy an area of approximately 17% of the region and are increasing annually. Most saline soils are also sandy, these saline sandy soils can be deleterious to plants and result in low yields, due to low fertility, high soluble salts especially sodium chloride, low water holding capacity and low cation exchange capacity. To grow crops successfully, these soils must be improve. The objective of this study is to elucidate the effect of organic and inorganic fertilizers on yield and quality of ruzi grass as well as the changes in soil properties used in the experiment.

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Materials and Methods

Experiment design was factorial in RCBD with 3 replications. Factors were 3 rates of chicken manure (0, 1.87 and 3.75 t/ha), 2 rates of rice husk (0 and 5 t/ha) and 3 rates of 15-15-15, inorganic fertilizer (0, 156 and 312 kg/ha). Ruzi grass seedlings were transplanted into 2 × 3 m plot of Kula Ronghai series soil (Ki, Typic Natraqualfs) with 30 × 30 cm spacing. Both fresh weight and dry weight of grass were measured as well as grass quality. Soil properties before and after the experiment was also measured.

Results and Discussion

Some properties of Kula Ronghai series soil (Ki, fine-loamy, mixed, active, isohyperthermic, Typic Natraqualfs) before the experiment are shown in Table 1. This soil is slightly saline soil with high soil reaction (pH) low in plant nutrients but high in sodium and sandy in texture.

Table 1. Soil properties before the experiment

Series	pH (1:1, H_2O)	EC_e (dS/m)	OM (%)	Total N (ppm)	Available P (ppm)	Exch. K (ppm)	Exch. Na (ppm)	Texture
Ki	9.8	2.35	0.19	115	12	39	668	0-15 cm LS 15-30 cm SL 30-50 cm SCL

Table 2. Some properties analysis of chicken manure (M) and rice husk (R)

	pH (1:5, H_2O)	EC_e (dS/m)	OM (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
M	8.4	45	26	1.8	2.0	1.8	8.2	0.8
R	6.0	1	12	0.5	0.3	0.7	210 (ppm)	0.6 (ppm)

Table 3. Effect of chicken manure (M) rice husk (R) and chemical fertilizer (C) on fresh weight of Ruzi grass (t/ha)

C (kg/ha) (C)	M (t/ha) (A)											
	0				1.87				3.75			
	0	156	312	ave	0	156	312	ave	0	156	312	ave
R (t/ha) (B)												
0	2.06	2.94	3.05	2.69	2.48	3.75	3.97	3.40	2.59	4.11	3.88	3.52
5	2.10	4.69	4.97	3.92	2.67	5.09	5.60	4.46	3.94	6.21	7.19	5.78
Mean	2.08	3.82	4.01	3.30	2.58	4.42	4.79	3.93	3.26	5.16	5.54	4.65
CV. (%)	**20.56**											
F-test	**A**, B**, C**, AB^{ns}, AC^{ns}, BC*, ABC^{ns}**											

Some properties of chicken manure and rice husk used in the experiment are shown in Table 2. Chicken manure is slightly basic with a pH 8.4, has a high electrical conductivity, organic matter and available plant nutrients relative to other organic fertilizers. Rice husk got very low electrical conductivity and was also low in organic matter and other nutrients.

The effect of chicken manure, rice husk and chemical fertilizer on fresh weight of Ruzi grass were shown in Table 3. There was highly significantly different between the different levels of manure, rice husk and chemical fertilizers, the interaction took place only for rice husk and chemical fertilizer.

Table 4 also clearly shows the effect of chicken manure, rice husk and chemical fertilizer on fresh weight of Ruzi grass. Manure at both rates gave higher fresh weights that were significantly different from the control. Treatments receiving rice husk at a rate of 5 t/ha also gave significantly different from control and similarly chemical fertilizer also gave higher fresh weights that were significantly from control.

The effect of chicken manure, rice husk and chemical fertilizer on dry weight of Ruzi grass were shown in Table 5, there was highly significantly different between the different levels of manure, rice husk and chemical fertilizer, again the interaction took place only for rice husk and chemical fertilizer.

Table 4. Effect of chicken manure (M), rice husk (R) and chemical fertilizer (C) on fresh weight of Ruzi grass (t/ha)

Materials	Fresh weight (t/ha)		
M (t/ha) (A)	0	1.87	3.75
Mean	3.30b	3.93a	4.65a
R (t/ha) (B)	0	5	
Mean	3.20b	4.72a	
C (kg/ha) (C)	0	156	312
Mean	2.64b	4.47a	4.78a
CV. (%)	**20.56**		
F-test	**A**, B**, C****		

The effect of chicken manure, rice husk and chemical fertilizer on dry weight of Ruzi grass are shown in Table 6. There was no significant difference between manure rate at 0 and 1.87 t/ha, 1.87 t/ha and 3.75 t/ha but there was a significantly different between 0 and 3.75 t/ha. Rice husk at 5 t/ha also gave significantly different on dry weight basis. Chemical fertilizer at 156 kg/ha gave higher and significantly different dry weight as well as at 312 kg/ha from the control.

Table 5. Effect of chicken manure (M), rice husk (R) and chemical fertilizer (F) on dry weight of Ruzi grass (t/ha)

C (kg/ha) (C)	M (t/ha) (A)											
	0				1.87				3.75			
	0	156	312	ave	0	156	312	ave	0	156	312	ave
R (t/ha) (B)												
0	0.48	0.67	0.75	0.64	0.60	0.81	0.76	0.72	0.56	0.86	0.85	0.76
5	0.52	1.54	1.06	1.04	0.76	1.06	1.22	1.01	0.91	1.23	2.32	1.15
Mean	0.50	1.10	0.90	0.84	0.68	0.94	0.99	0.87	0.74	1.05	1.09	0.96
C.V. (%)	**13.24**											
F-test	**A**, B**, C**, AB^{ns}, AC^{ns}, BC*, ABC^{ns}**											

Table 6. Effect of chicken manure (M) rice husk (R) and chemical fertilizers (C) on dry weight of Ruzi grass (t/ha)

Materials	Dry weight (t/ha)		
M (t/ha) (A)	0	1.87	3.75
Mean	0.84b	0.87ab	0.96a
R (t/ha) (B)	0	5	
Mean	0.70b	1.07a	
C (kg/ha) (C)	0	156	312
Mean	0.64b	1.03a	0.99a
C.V. (%)	**13.24**		
F-test	**A**, B**, C****		

It could be concluded at this point that the best combination rate for manure, rice husk and chemical fertilizer for grass fresh weight was 1.87 t/ha, 5 t/ha and 156 kg/ha while for grass dry weight was 3.75 t/ha, 5 t/ha and 156 kg/ha respectively. In other word, to increase dry weight significantly, more manure was needed.

The effect of chicken manure rice husk and chemical fertilizer on Ruzi grass quality were shown in Table 7. Manure at 3.75 t/ha with 312 kg/ha of chemical fertilizer gave highest crude protein whether with or without rice husk. For neutral detergent fiber the values from different treatments gave similar result but manure at 3.75 t/ha with or without rice husk at 5 t/ha gave the highest value for neutral detergent fiber. Manure at 3.75 t/ha with rice husk at 5 t/ha and 312 kg/ha of chemical fertilizer gave the lowest value needed for acid detergent fiber.

The effect of chicken manure, rice husk and chemical fertilizer on soil properties before and after the experiment were shown in Table 8. It seems to be that soil pH was increased after added manure, rice husk and chemical fertilizer. Electrical conductivity and Na of soil were also increased, this could be the result from more ions lefted from the experiment as

Table 7. Effect of chicken manure (M), rice husk (R) and chemical fertilizers (C) on Ruzi grass quality (% of dry weight)

	M (t/ha)	–	R (t/ha)	–	C (kg/ha)	CP (%)	NDF (%)	ADF (%)
1	0	–	0	–	0	7.25	54.95	23.84
2	0	–	0	–	156	7.67	52.32	22.56
3	0	–	0	–	312	8.11	53.41	22.99
4	0	–	5	–	0	7.38	52.87	23.16
5	0	–	5	–	156	8.14	55.40	23.35
6	0	–	5	–	312	8.73	51.59	23.57
7	1.875	–	0	–	0	7.49	54.90	23.45
8	1.875	–	0	–	156	8.30	52.18	23.97
9	1.875	–	0	–	312	8.89	54.97	24.25
10	1.875	–	5	–	0	7.85	54.87	23.74
11	1.875	–	5	–	156	8.33	53.76	23.76
12	1.875	–	5	–	312	9.07	52.18	21.81
13	3.75	–	0	–	0	7.99	55.49	23.76
14	3.75	–	0	–	156	8.42	53.30	22.87
15	3.75	–	0	–	312	9.51	52.31	22.01
16	3.75	–	5	–	0	8.06	55.84	24.09
17	3.75	–	5	–	156	7.85	53.87	23.45
18	3.75	–	5	–	312	9.75	52.53	21.28
ave.						8.26	53.70	23.10

CP = Crude Protein, NDF = Neutral Detergent Fiber, ADF = Acid Detergent Fiber.

Table 8. Total effect of chicken manure, rice husk and chemical fertilizer on soil properties before and after the experiment

	pH (1:1, H_2O)	EC_e (dS/m)	OM (%)	Total N (ppm)	Available P (ppm)	Exch. K (ppm)	Exch. Na (ppm)	Texture
Before**	9.8	2.35	0.19	115	22	122	1,270	Same
After**	10.2	3.15	0.28	175				
Control (after)	10.4	3.60	0.02	16	7	40	2,128	Same

well as more Na from the capillary action of brine in the soil. Organic matter as well as N, P and K after the experiment were also higher. This could be the residual effect of chemical fertilizer. When comparing these values with control after the experiment. The control treatment was higher in electrical conductivity and very high Na, while lower in other plant nutrients. This suggested that to grow crop successfully and to maintain soil fertility, organic materials as well as chemical fertilizer should be applied at proper rates.

Conclusions

Saline sandy soils which are poor in physical and chemical properties as well as low in fertility can be used for pasture in the northeast, if managed correctly. The objective of this study is to elucidate the effect of organic and inorganic fertilizer on yield and quality of ruzi grass grown on saline sandy soils of the northeast. Factors involved were 3 rates of chicken manure, 2 rates of rice husk and 3 rates of inorganic fertilizer. For dry weight of ruzi grass, increasing rates of manure could increase yield. There was significantly different between control and 3.75 t/ha of manure rate. Rice husk also gave significant dry weight differences between control and 5 t/ha rate. For the 15-15-15, inorganic fertilizer the application at 156 kg/ha could increase dry weight of grass significantly from control. It could be concluded that manure at 3.75 t/ha with rice husk at 5 t/ha and fertilizer at 156 kg/ha was the best combination rate to give the highest dry weight of grass under the studied condition but for fresh weight lower rate of manure seem to be better.

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Positive impact of traditional rice cropping on geochemical qualities of saline sandy soil in Northeast Thailand

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Keyword: sandy soil acid, rice farmer practice, salinity, pH, reduction, soil column

Abstract

The majority of soils in Northeast Thailand are of low fertility and acidic to depth. Moreover 17% of cultivated soils in the region are affected by salinity that has its origin in saline groundwater that has risen to within 1 m of the soil surface. Traditional rice growing techniques are not well adapted to these kinds of soil constraints that often results in the abandonment of entire fields or areas within fields due to salinization. A study was undertaken to determine the effects of rice cropping on these saline sandy soil with respect to changes in the geochemical attributes of the soil solution and their consequences on soil conservation.

An accurate assessment of geochemical changes and associated mechanisms, including the effects of reducing conditions on soil solution composition, is difficult to undertake under field conditions. Thus we established a laboratory experiment where conditions similar to those in the field could be simulated. Four undisturbed soil columns of 50 cm in height and 24.5 cm in diameter we collected from Northeast Thailand, two of which were saline (S) and two non-saline (NS). Rice was transplanted into one of the columns from each of soil salinity types. The columns were designed to continuously monitor pH, Eh and the chemical composition of solution at three depths namely -7, -24, -40 cm. An increase in pH was observed within the acidic NS column with the pH rising to almost neutrality within the surface horizon. This increase in pH is controlled by iron reduction. At the second depth interval (i.e. -24 cm) manganese reduction control changes in pH along with changes in the partial pressure of CO_2*. The highest increase in pH was measured in the NS columns cropped with rice whilst the smallest increase in pH was observed in the un-cropped S soil. On these sandy soils the production of rice using farmers practices contributes to increases in pH and temporarily controls the expansion of salinity by diluting the salt above the soil. Continued traditional rice cropping contributes to limiting the expansion of degradation on these soils.*

Introduction

Soil salinisation is a global problem that is estimated to affect 6.5% of the earth's soil surface is (Cheverry et al. 1998). In Northeast Thailand, problems of salinisation and soil degradation have attained an important level (Kohyama et al., 1993). The soils of the region soils are sandy (Mitsuchi et al., 1986; Yuvaniyama, 2001), with very low nutrient supplying capacity (Ragland and Boonpuckake, 1988) and low organic matter (OM) contents (Arunin1986). Around 17% of this area's soils are affected and a further 108,000 km^2 which is more than twice the size of Switzerland are potentially at risk by the same phenomenon. Upland deforestation leading to a rise of the saline watertables has been the main cause of the increase in soil salinisation (Williamson *et al.*, 1989). This problem is of increasing importance to national stakeholders concerned over their continued use of these soils for agricultural. A decrease in rice production yield due to the occurrence of saline patches could have serious affects on this area's ability to satisfy the rising food demands of its increasing population (Fukui, 1991; Kono, 1991). Moreover, rice cropping forms a distinct cultural element in communities of northeast that has significant implications on the socio-economic status of the region (Formoso et al., 1997). Hence a decline in rice yields would have serious consequences.

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Salinity issues have been studied for many years in this region of Thailand (Arunin, 1984), (Brinkman et al., 1977). However, there are still unanswered questions on the dynamics of saline patches and the respective soil development. It was therefore decided to study the impact that rice cropping has on these impoverished, sometimes acidic soils that are subject to salinisation. The first results of this study show significant differences in terms of acidity, notably during the dry season, between the saline and non-saline zones. In previous studies Grunberger (2002) observes saline zones having a neutral pH of 6.5-7 and non-saline having a pH of 4.5-5. The discrepancy between pH levels would suggest a modification in behaviour between saline and non-saline patches situated in close proximity to one another (a few metres) on soils of identical origin. Therefore, an evaluation was undertaken using undisturbed columns collected from cultivated and non-cultivated soil with the objective of identifying the effects of traditional rice cropping on soil geochemistry notably the role of plants and salinisation. Since pH is an important indicator of soil quality, variations in pH and Eh are studied in the first months following submersion.

Methods

Experiments were conducted on cultivated plots in Pra Yuhn, near Khon Kaen, Northeast Thailand (16º21′12.744 North and 102º36′29.8″ East).

In the saline patches the exchangeable complex is dominated by sodium. The region has a tropical Savannah climate with a mean annual rainfall of 1,200 mm from May to October. Evaporation is greater than precipitation, except at the height of the rainy season from July to September (Bolomey, 2002). Soil is regularly saturated by solutions of NaCl as the water table rises and conductivity has an average value of 20 dS m^{-1} at a pH of 6.82. The water table is near the soil surface at the end of the rainy season and draws down by 2 m in the dry season.

The study was conducted in the laboratory for optimal control of conditions and ease of monitoring. Four undisturbed soil columns (47 cm high and 24.5 cm in diameter) were tested; two from within the saline patch and two from outside. Rice was planted on one column from each of the two sites. Thus four distinct types were possible; non-saline/non-cultivated C4 (NS NC), non-saline/cultivated C3 (NS C), saline/non-cultivated C1 (S NC) and saline/cultivated C2 (S C).

Efforts were made to reproduce field conditions and ensure that all interventions and measures were conducted in the same way on each column. Measurement and sampling equipment was installed to control the water flow, measure pH and Eh and to study chemical evolution of soil solution. Different measuring equipment was installed at three levels; at 7 cm, less than 24 cm and at 41 cm from surface (Figure 1).

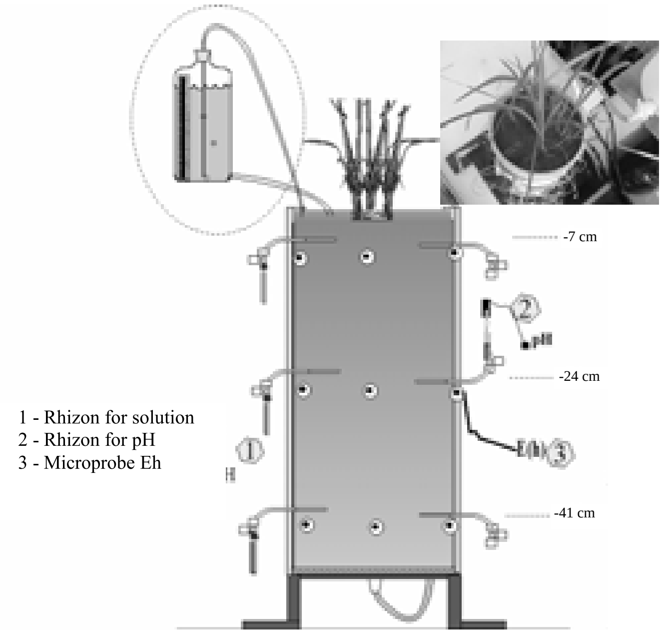

Figure 1. Diagram of a soil column with instrumentation installed to monitoe pH, Eh, chemical composition of the solution, at three depths

The soil has a sandy loam texture (Grunberger, 2002), less than 10% clay content and low, superficial levels of organic matter (OM) (Table 1). The soil was classified as an Ultisols (Roi Et series in the Thai classification system) having a low cation exchange capacity, less than 5 $cmol_c$ kg^{-1} of soil (Table1).

After a week’s saturation, the soil surface of the columns was flooded to a predetermined level using a Marriotte device. Deionised water was used so as to simulate rainwater that under natural conditions irrigates the field plots. Five rice plants were transplanted in two columns to simulate a tuft of plants in the field. Weekly samples of water were taken and analysed. The pH and Eh were measured twice a week, always at the same time.

Studies on reduction in saturated soil and evolution of pH have demonstrated the important roles of microorganisms, certain minerals such as iron and manganese hydroxides and also the partial pressure of CO_2 (p CO_2) (Berthelin, 1998; Ponnamperuma, 1972; Zhi-Guang, 1985; Sumner, 2000).

Table 1. Selected chemical and physical properties of soil collected from Pra Yuhn

Depth (cm)	Interior of the salt patch						External to salt patch					
	Sand %	Silt %	Clay %	CEC ($cmol_c.kg^{-1}$)	pH H_2O	C %	Sand %	Silt %	Clay %	CEC ($cmol_c.kg^{-1}$)	pH 1:5	C %
0-9	66	28	6	1.4	7.0	0.4	55	40	4	2.0	4.4	0.4
15-20	60	34	6	1.5	6.7	0.1	63	31	6	2.0	5.7	0.1
25-35	63	31	6	1.5	6.4	0.0	60	34	5	2.4	5.9	0.0
45-55	48	29	14	4.7	7.5	0.0	44	42	15	2.5	5.6	0.0

Analysis for this study is based on two important equations that characterise the transformation of iron and of manganese when undergoing oxidation and reduction.

Equation 1 shows the stochiometry of the reaction between iron hydroxides (i.e. goethite dissolution) and protons that result in an increase in pH (Chamayou, 1989).

1. $Fe\ OOH + 3H + e = Fe^{2+} + 2H_2O$

where the reduction of Fe (III) to Fe (II) consumes H^+ and causes an increase in pH. Similarly, as for the iron, the reduction of manganese consumes protons (Sigg *et al*., 1992).

2. $MnO_{2(s)} + 4H^+ + 2e = Mn^{2+} + 2H_2O$

Results

All soil samples show an initial acid pH (Figure 2). This is followed by a rapid reduction in the Eh of the soil profile, reaching as low as -0.35V for the non-saline/cultivated soil column (C3 NS C). For this column the kinetics of reactions was extremely rapid. The pH and Eh of the saline samples (S NC and S C) developed less rapidly. The level of salinity can influence microbial activity by slowing down the development of populations thereby influencing the reduction processes within the soil profile. Iron plays the major role in the in these reaction in the surface horizons of the soil profile, where the presence of Fe (II) is found (Figure 3). This is partly caused by a reduction reaction of Fe (III) to Fe (II) (equation 1).

The presence of ferrous iron is demonstrated by the results of chemical analysis in Table 2.

For the deeper soil layers (24 to 41 cm) the four columns have higher potential for Eh than the surface layer.

Manganese reduction tends to occur before iron in the order of reaction. It appears in the transition phase of soil that is changing from the oxidised to the

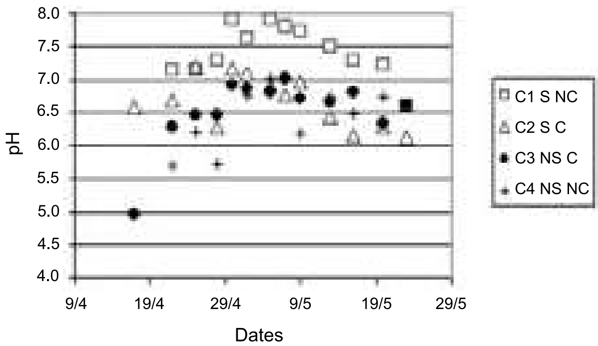

Figure 2. Soil solutions pH development over time at a depth of 7 cm for the four undisturbed columns

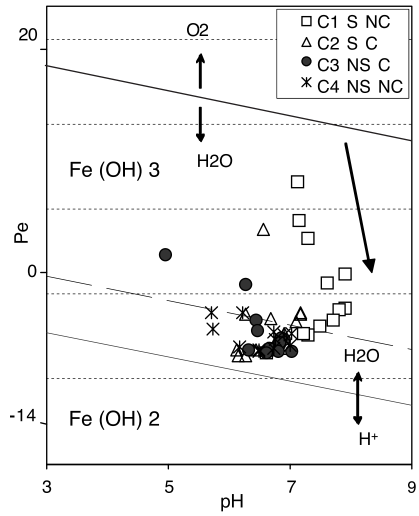

Figure 3. Relationship between pH and pe for soil solutions, of the four columns within the 7 cm layer

reduced state (Sumner, 2000). However, only high levels of manganese in the soil profile can produce a significant effect. The abundance of manganese in this soil can be confirmed, due to the presence of nodules of manganese when the soil was sieved. It was also found when analysing the soil solution (Table 2). This confirms that in this soil, manganese is mobilised and precipitates as shown by the oxydoreduction of the soil. As for the iron, the reduction of manganese consumes protons (Equation 2). The influence of Mn is demnonstrated in the depth layers of >24 cm, and is presented in Figure 4. A strong correlation between the presence of Mn in solution and pH development is

Table 2. Soil solutions composition

	Date	Al me/L	Ca me/L	Fe me/L	Mg me/L	Mn me/L	Na me/L	Cl me/L	EC mS/cm	Calculated alkalinity me/L	Analyse alkalinity me/L
C1 S NC -7 cm	22-April	0.04	0.09	0.04	0.86	0.00	2.25	0.98	0.36	1.1	1.9
	25 April	0.11	0.22	0.17	0.18	0.01	6.60	4.13	0.67	2.9	
	29 April	0.56	0.64	0.19	0.50	0.01	13.93	13.05	1.58	1.0	
	06 May	0.97	0.25	0.41	0.11	0.03	8.62	4.06	0.75	5.6	4.9
	13 May	0.67	0.25	0.33	0.07	0.03	8.60	3.54	0.96	6.1	6.4
C2 S C -7 cm	22-April	0.01	0.31	0.22	0.39	0.01	15.23	5.69	1.61	10.2	12.9
	25 April	0.00	0.43	0.17	0.55	0.01	16.64	3.74	2.00	13.3	14.4
	29 April	0.00	0.49	0.11	0.48	0.01	15.99	3.64	1.06	12.7	14.9
	06 May	0.00	1.02	0.32	0.44	0.04	11.98	2.53	1.32	10.5	12.9
	13 May	0.00	1.46	0.67	0.32	0.07	5.84	1.16	0.81	6.4	
C3 NS C -7 cm	22-April	0.00	0.16	0.08	1.20	0.01	4.99	3.46	0.68	0.6	
	25 April	0.00	0.32	0.36	0.84	0.07	5.98	1.26	0.77	4.4	5.4
	29 April	0.00	0.85	1.28	1.28	0.26	8.16	0.93	1.00	9.6	10.4
	06 May	0.00	1.87	0.94	1.13	0.59	9.20	0.71	1.13	12.8	
	13 May	0.00	2.35	0.58	0.76	0.75	9.38	0.63	1.24	12.7	11.9
C4 NS NC -7 cm	15 April	0.01	0.08	0.00	0.33	0.00	2.86	1.71	0.42	-0.1	
	22-April	0.30	0.25	0.09	0.35	0.00	7.76	6.62	0.88	1.6	
	25 April	0.03	0.06	0.15	0.80	0.00	2.98	0.68	0.42	2.1	2.9
	29 April	0.02	0.19	0.54	0.87	0.02	4.54	0.55	0.44	4.6	5.4
	06 May	0.01	0.64	1.95	0.69	0.11	6.60	0.52	0.81	8.9	7.9
	13 May	0.00	1.10	3.17	0.42	0.20	6.91	0.51	0.80	11.3	8.9
	Irrigation water	0.04	0.01	0.01	0.00	0.00	0.17	0.21	0.03	0.0	

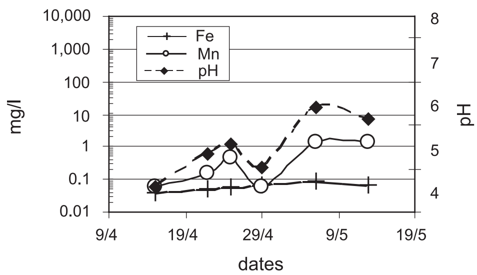

Figure 4. Relationship between the Fe, Mn and pH with time in soil solution from the 24 cm depth interval in treatment C3 C NS

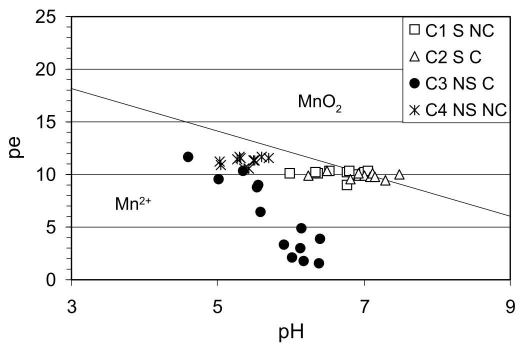

Figure 5. Relationship between pe- pH and the equilibrium line between MnO_2 and Mn^{2+} at 24 cm depth interval for all columns

clearly evident. These observations can be used to construct phase equilibrium diagrams for the different forms of Mn that are present in solution and solid phases, namely, MnO_2 and Mn^{2+} for the profiles at the 24 cm depth interval (Figure 5). Equilibrium between solid and solution phases depends on the log of activity for Mn^{2+} in soil solution and is written in the following way (Sigget al., 1992):

$$4pH + pe + \log(Mn^{2+}) = 43.6$$

Using the Phreeqc simulation model (Parkhurst *et al*., 1999), the activity of Mn^{2+} was calculated for the different soil solutions.

Figure 5, presents the phase diagram for solutions collected from the 24 cm depth interval and demonstrates the influence of reduced conditions on the presence of MnO_2 and Mn^{2+}. This is probably the mechanism controlling the pH and pe of these soils. Alkalinity and the partial pressure of CO_2 interact and control pH. In a closed system, if the pCO_2 increases, the pH diminishes. If however, in this confined medium, the pCO_2 equilibrates with atmosphere after reoxydation, pH will rise (Bourrié, 1978).

In this study, using the Phreeqc model, partial pressure of CO_2 was calculated near the soil surface where alkalinity was measured (Figure 6). The pCO_2 values do not differ with changes in soil salinity. They have values of around 1000 times higher than pCO_2 atmospheric values, which is $10^{-3.5}$atmosphere. Only the C1 S NC column differs, by having a lower pCO_2, closer to the atmosphere’s and less alkalinity for this profile. An empirical relation exists which, based on the partial pCO_2 pressure, allows the pH of an iron rich, submersed soil to be calculated;

$$pH = 6.1 – 0.58 \log pCO_2 \text{ (atm)}$$

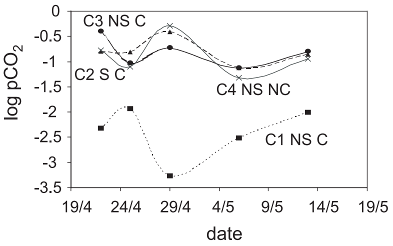

Figure 6. Log of the partial pressure of CO_2 of surface laye for all columns

This relation was derived using measurements made in the field and laboratory. This equation was applied to this study’s measurements from soil surface (Figure 7).

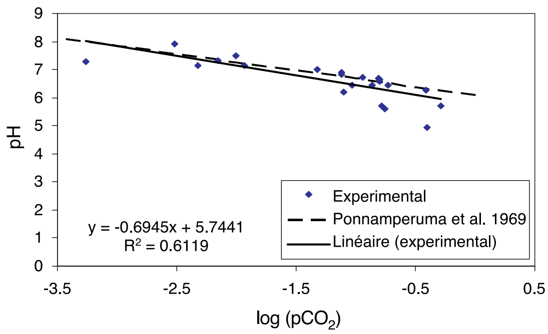

Figure 7. Relationship between predicted pH and the log pCO_2

The relation could be applied to the data of this study. The small differences observed between measured and predicted was probably due to the abundance of manganese in soil and its affect on the control of pH. Subsequent measures made in the field after this first experiment, show similar results on the controlling influence of pH.

Conclusions

In the four soil columns saline, non-saline, with or without plants, pH values of soil solutions converge towards neutrality. The reduction dynamics and pH evolution are related to the availability of carbon provided around the rice roots, to feed the reductive microbial populations. The pH of the soil has an acid tendency before reduction, which changes towards neutrality under the influence of iron and manganese and assures more favourable conditions for the development of rice plants.

The differences of pH values during submerged and dry conditions are important. These cyclic evolutions, which follow the seasons, cannot perhaps bring a return to initial state but may produce a differentiation of pH values. The dissolution of salt through the maintenance of submergence by fresh water on the surface of the rice crop, produces favourable conditions for plant development and rapidly enables reduction to take place. The effect of contact from the rising saline water table under pressure, (Maeght *et al.*, 2005) can also be reduced by dilution in the layer of fresh water.

Traditional rice growing on poor, sandy soil can contribute to temporary pH improvements in soil by rapidly bringing about reduction in the soil surface. It can also assist, during submergence, in controlling the expansion of salinity, by diluting the influx of the rising saline water table in paddy fields. Extensive soil degradation of these impoverished soils can therefore be limited by continuing these traditional rice-cropping methods and in the absence of alternative solutions, should be strongly encouraged.

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Significance of soil management practices on degradation and/or conservation of upland sandy soils in semi-arid West Africa

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Keywords: crust, Sahel, soil erosion, soil management practices, thin layers in soil profile

Abstract

Semi-arid West Africa, known as the Sahel, is one of the front lines of desertification. There are a vast distribution of sandy soils developed on ancient dunes and the foot slopes that biomass production is largely dependent on. Due to the potential fragility derived from the sandy texture, soil management practices significantly influence either degradation or conservation of upland field. One of the characteristics of sandy soils in the Sahel is the presence of thin layer(s), which is a few milimeters thick and consists of finer soil particles, in the profile and at the immediate surface of soil. Field observation revealed that the thin layer(s) in the soil profile has a self-protection mechanism against wind erosion. The thin layer formed at the surface of soil through tillage practice, known as a crust, accelerates water erosion.

The case of Central Mali suggest that a mould-board plow, which is used for weeding, disrupted some thin layers and encouraged a crust formation at the soil surface. Although the plow is efficient for weeding, the management practice resulted in increased runoff and selective loss of finer soils which generate a vicious cycle of soil degradation. A hint to solve the problem was found in the case of Northeast Burkina Faso where management practices utilize a push-hoe. The push-hoe, a simple tool traditionally used for weeding, disturbed only a few centimetres of surface soil without disruption of the thin layers. Tools and the ways of soil management practices are influential in the conservation of the thin layers in soil and the prevention of crust formation at the surface, thus the degradation of the Sahelian sandy soils.

Introduction

Semi-arid West Africa, known as the Sahel, is one of the front lines of desertification. UNCCD (1994) clearly defined, desertification/land degradation is “human-induced”. Serious aspect of desertification in the Sahel are caused through daily activities, such as crop cultivation, that are undertake by local people to maintain basic needs and to improve livelihoods.

Among soil management practices, tillage is one of the most influential practices that changes the condition of the soil surface where erosion processes take place. This study, therefore, focuses on the behaviours of surface soil under different tillage practices. Morphological characteristics and functions of sandy upland soil in the Sahel are firstly explained in relation to the processes of soil degradation. Then, the significance of soil management practices on both degradation and conservation are discussed referring to the cases of the field studies in Mali and Burkina Faso.

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Materials and methods

Field observation and measurements

Soil profiles were described to identify the soil names. Movement of surface soil associated with a series of soil management practices and rainfall events was observed in the field. The temporal changes of the soil surface undulation after tillage were measured by a line-measuring method (Tanaka, 1996). Details of local husbandry systems, e.g. cropping and livestock keeping, were described through the interview from farmers and field observation. By blowing air onto the soil surface under different condition, movement of sand grains was observed in order to assess the susceptibility to wind erosion. Degree of water erosion was assessed by measuring the height between the current level of land surface and the former level which was remained at the electric poles installed 20 years ago.

Laboratory analyses and micro-morphological observation

General soil properties, e.g. pH, texture, CEC, T-C, T-N and T-P, were measured in the laboratory. Undisturbed soils were collected from the soil surface and the profile, and thin section specimens prepared using the procedures described by Tanaka et al. (1992). To assess the effect of thin layer of finer particles on water permeability, clay suspension was added to the sand bed in a grass column filled with water and, then, the rate of water discharge from the column was measured (Tanaka, 1996).

Results and Discussion

General aspects of the study areas

Sahel streches over a vast area from the Atlantic coast of West Africa to Northeast Africa. With annual rainfall ranging between 250 and 500 mm, there are several local husbandries including crop cultivation and pastoralism under diverse agro-ecologcal condition. The rainy season is four months which is basically affordable to maintain crop/grass production, though the Sahel is frequently hit by drought/flooding due to irregular rainfall distribution. From satelite imagery, bands of ancient dunes can be identified extending east to west with some 10 km to 100 km long which overlaps with major places of crop/grass production (Tanaka et al., 2005). Table 1 shows the descriptive characteristics of the study sites in Mali and Burkina Faso. The soil of the site in Mali is classified as *Typic Kandiustalfs* (pHw: 5.0-5.5, Sand: 80-95%, CEC: 1.5-6.2 cmol/kg, T-C: 0.7-1.7 g/kg, and T-N: 0.03-0.14 g/kg) and that in Burkina Faso as *Typic Quartzipsamments* (pHw: 5.0-6.3, Sand: 90-95%, CEC: 1.0-3.0 cmol/kg, T-C: 0.4-1.3 g/kg, and T-N: 0.05-0.16 g/kg) referring to Soil Survey Staff (1996).

Table 1. Descriptive characteristics of the study site

Features/Site	Thiongoni (Mali)	Takabangou (Burkina Faso)
Agro-ecological zone[1]	Transition Sudan – Sahel	Sahel zone
Annual rainfall	550 mm	400 mm
Wet years	600~650 mm	450~500 mm
Dry years	400~450 mm	300~350 mm
Landscape	upland plain (<2%)	ancient dune
Management practices	Sudan type[2]	Sahel type[2]
Farming tool	hoe, plow	push-hoe
Soil disturbance	over-turning (15 cm)	scratching (3-5 cm)
Fertility recovery	glass fallow, *parcage*[3]	glass fallow, *parcage*[3]
Habitants (ethnic)	Bambara and Fulbe	Songai, Fulbe and Bela

[1] Classified referring to Nicholson (1980). [2] Sudan type associates soil disturbance in weeding and Sahel type is basically no-tillage system (Ohji, 1990). [3] *Parcage* is French term referring to a patch of land in cultivated field where cattle herds are kept and feces are dropped during dry season.

Remarkable micro-morphological characteristics

In the Sahelian sandy soils, two types of remarkable micro-morphological structure can be identified, i.e. thin layer(s) and crust(s) of finer soil particles respectively found in the profile and at the surface of soil. These thin structures have different functions in terms of prevention/acceleration of desertification processes.

Thin layer(s) in soil profile: The key characteristic in the Sahelian sandy soil is the presence of thin layer(s), which is a few milimeters thick and consists of finer soil particles, found in the soil profile (Figure 1).

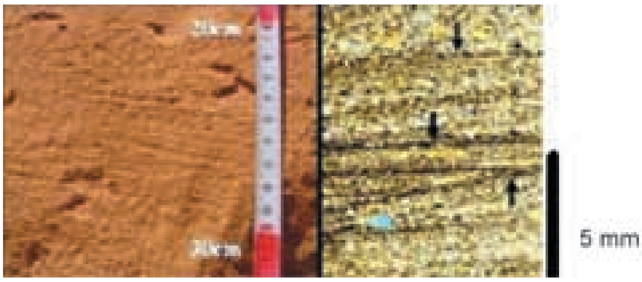


Figure 1. Micro-morphology of the soil profile in the study site, Burkina Faso (left: close-up of the profile, right: thin layers indicated in arrows)

Surface soil is usually disturbed and loosened through tillage activities and tramping by animals and people. Some loosen soils are removed by wind during dry season and the one of the thin layers is exposed to the surface. Field observation revealed that the soil was not removed by blowing air to the surface of the exposed thin layer. Once the thin layer was scratched, however, soil was removed until the next thin layer appeared. This emprical finding suggests that the thin layers in the profile of sandy soil inherently has a mechanism of self-protection against wind erosion.

Crust formation at the soil surface: Field observation revealed that particles of sandy soil were tend to be easily seggregated when they moved under the impact of raindrops and runoff water. It was also observed that the seggregated finer soil particles were sedimented and fromed a thin layer (crust) at the immediate surface of soil as shown in Figure 2.

Soil management practices and its influences

Case studies in Mali and Burkina Faso revealed that a type of farming tool has an influential impact on accerelation or slowing-down of soil erosion.

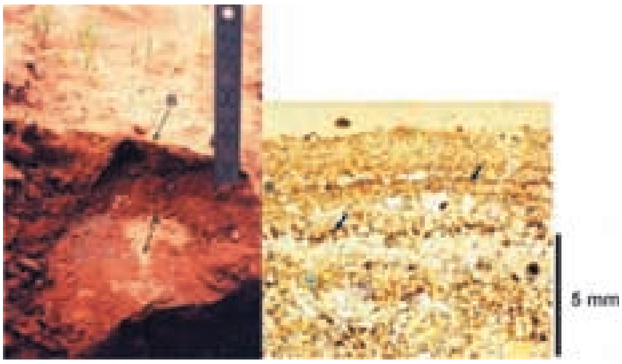
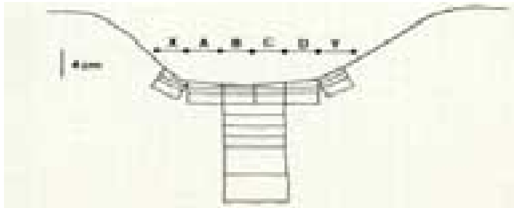


Figure 2. Micro-morphology of the soil profile in the study site, Mali (left: surface of the ridge where a crust was formed, right: crusts, indicated in arrows, found at the immediate surface of the ridge)

A case in Thiongoni Village, Central Mali: Mould-board plow is widely used for weeding in rain-fed millet cultivation. The plowing is repeated three times, once for ridge-making and twice for weeding, during the cropping season. In plowing, the soil was disturbed to a depth of 15 cm and the thin layers were observed to be broken. In addition, ridges were also formed with exposed subsurface soil, which relatively rich in finer particles, to the surface. When the ridge collapsed under rainfall, a crust was formed in the immediate surface of soil as shown in Figure 2. Figure 2 shows a patterns of combined thin layers of finer and coarser particles, and this micro-morphological feature is evidence that some soils moved with runoff water from the ridge to the inter-ridge space. The measurement of temporal changes of the surface unduration also suggested that the ridge soil collapsed and moved with runoff water. A laboratory experiment demonstrated that an additon of approximately 10 mg/cm^2 of clay, which was a small portion of clay contained in the removed soil, decreased the initial water permeablilty of 7.2 mm/min to less than 0.1 mm/min, suggeting the increase of water runoff.

Figure 3 shows the selective loss of finer particles from the surface soil. More than 60% of the finer particles were selectively removed from the top 4 cm.

These processes, which is initiated by the use of a mould-board plow, are repeated every year. Although no direct evidence was found between these proceses and soil erosion, the field measurement estimated that the rate of soil loss in the study site ranged between 5.1 and 19.5 mm/year. The mould-board plow, originally used for cotton cultivation in Sudan savanna zone, is effective and efficient for weeding in cultivated field of heavy texture soil. Due to the merits, the use of the tool



Depth (cm)	x	A	B	C	D	Y
0-1	3.9 (-69.8)	1.4 (-89.1)	1.0 (-92.2)	1.9 (-85.3)	2.3 (-82.2)	2.4 (-81.4)
1-2	3.8 (-70.5)	3.0 (-76.7)	1.9 (-85.3)	2.2 (-82.9)	2.1 (-83.7)	3.0 (-76.7)
2-4	3.8 (-70.5)	4.1 (-68.2)	4.5 (-65.1)	4.9 (-62.0)	4.4 (-65.9)	3.7 (-71.3)
4-6	7.4 (-42.6)					
6-8	10.3 (-20.2)					
8-10	11.1 (-14.0)					
10-12	12.0 (-7.01)					
12-17	17.4 (+34.9)					
17-22	9.3 (-27.9)					

Figure 3. Selective loss of finer particles estimated from the particle size distribution in the inter-ridge soil. (the value is the % of silt + clay; the value in parentheses is the % of lost silt + clay from the original soil)

is recommended by government authority and widely accepted by cultivators, unfortunately even in the Sahel, despite of potential risk to accerelate soil erosion as suggested in the case study.

A case in Takabangou Village, Northeastern Burkina Faso: Contrarily, minimum tillage using a traditional push-hoe is commonly practiced in the vast area of the Sahel for weeding. Disturbance of soil is limited to a few centimetres of the surface, and most of the thin layers in the soil profile are conserved intact. The traditional tillage with this simple tool is, thus, well suited under the Sahelian condition to minimize the soil loss by wind erosion, although there are some disadvantages, i.e. low efficiency and heavy work-load. Improvement of the soil-friendly tool will be one of the next study issues.

Conclusion

Micro-morphological study revealed that there are thin layers consist of finer particles in the profile of the Sahelian sandy soil. Simple field examination and observation suggested that the thin layer has an inherent role of self-protection against wind erosion. The traditional tillage practice for weeding with a push-hoe minimizes the disruption of the thin layers. Contrasting this, tillage with a mould-board plow disrupts the thin layers and makes ridges at the soil surface. Field and micro-morphological observation revealed that movement of soil from the ridge with water under rainfall event encourages the formation of crust in the immediate surface of soil, leading to a drastic decrease of water permeability, runoff water and selective loss of finer soil particles.

This comparative study showed that selection of tools and the associated tillage practices have great influences on the conservation and/or disruption of the thin layers in the soil profile and the formation of crust in the soil surface, thus, the degradation and/or conservation of upland sandy soils in the Sahel.

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Management solution for improving soil organic matter for crop productivity and environmental quality in the tropical island of Guam

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Keywords: Soil quality, Organic Matter Content, Compost, Soil Fertility, Soil Degradation, Soil Productivity, Sustainable, Agricultural systems

Abstract

One of the major problems of agricultural soils in tropical regions of the Pacific is the low organic matter content. Composted organic material is applied to agricultural fields as an amendment to provide nutrients and also to enhance the organic matter content and improve the physical and chemical properties of the cultivated soils. Land application of composted material as a fertilizer source not only provides essential nutrients to plants, it also improves soil quality and effectively disposes of wastes. In our soil program at the University of Guam, we are evaluating the use of organic material as an alternative to synthetic fertilizers. Our goal is to develop management strategies and use available resources for improving crop productivity while conserving resources and preserving environmental quality. Our case study project is designed to improve soil fertility status by using composted organic wastes and assessing how nitrogen and other essential nutrients contribute to long-term soil fertility and crop productivity without application of inorganic fertilizers. In our pilot project compost is produced from milled typhoon debris mixed with animal manure, fish meal, shredded paper and other organic wastes. Mature compost is then applied to the field at rates of 0, 5, 10, 15, and 20 t ha^{-1} as a soil amendment on an eroded Cobbly soil of Southern Guam. Corn was planted and monitored for growth performance and yield. The effect of land application of composted material on the soil organic matter (SOM) content and other properties as the soil quality indices are being evaluated in this pilot study.

Introduction

Now more than ever the importance of an adequate supply of plant nutrients to ensure efficient crop production is being recognized. Growers are continually striving to overcome nutrient deficiencies and adopt improved management practices in order to increase yields for more profit. Great progress in fertilizer technology and the use of plant nutrients has been made in recent years, and a wider understanding of plant and soil chemistry has led to improved fertilization and farming practices that have improved crop yields worldwide (Tisdale et al., 1985). However, over-application of commercial fertilizers may reduce farm profits, create a risk of soil degradation, and cause environmental pollution (Tisdale et al., 1985). The ease of applying synthetic fertilizers and the lack of knowledge for matching fertilizer applications to the nutrient requirements of certain crops have added to the problem.

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Among the problems inherent to tropical soils, soil acidity, characterized by low pH, excessive aluminum, deficient calcium, and low organic matter are the most serious (Hue, 1992). Tropical soils are often unproductive because some of these soils are prone to strong phosphate fixation that renders phosphorus unavailable to plants. Soils that are prone to such phosphate fixation (adsorption of P to oxides and clay minerals) often require extremely high phosphate fertilizer applications in order to alleviate the effect of phosphate fixation. Selvi et al. (2003) reported that the application of rock phosphate with organic manure enhances the dissolution of rock phosphate in the soil and thus increases the plant availability of P. As referred to by Selvi et al. (2003), Bagavathiammal and Mahimairaja (1999) reported that the organic acids produced during the decomposition of organic manure supply protons for rock phosphate dissolution.

Soil acidity and mineral deficiencies can be corrected by lime and fertilizers but, these are not always viable options for small or resource-poor farmers (Hue, 1992). However, Hue (1992) reported that green manures and composted organic material increase soil organic matter and provide plant nutrients, alleviate aluminum toxicity, and render phosphorus more available to crops. This increased availability of phosphorus is believed to be the result of the reaction of organic matter-derived molecules with soil minerals (Hue, 1992).

In the hot and humid tropical environment, weathering of soils is rapid; thus, large areas of Ultisols and Oxisols occur in these regions (Motavalli, 1997). Thus the inherent poor chemical properties of Ultisols and Oxisols pose problems for agriculture in these regions. The fertility of these soils is often limited by properties that evolve from high iron and aluminum content, low activity clay, and low organic-matter content. These limitations are often manifested by the following properties:

- High phosphate-fixing capacity.
- Low pH and high exchangeable Al.
- Low CEC and low base saturation that is further complicated by the zero or net positive charges brought about by variable-charge Fe and Al Oxide/Hydroxide colloids.

In humid tropical climates, the loss of basic cations and the related acidity and aluminum toxicity require special management techniques. Heavy rainfall and high temperatures in these regions also promote rapid organic matter decomposition, which may also release H^+ ions that acidify the soil and increase exchangeable Al to toxic levels that limit root growth in the subsoil.

One of the most important nutrients limiting crop yield in the tropics is nitrogen (N). The concentration of native available N in tropical soils fluctuates considerably in response to seasonal changes (Sanches, 1976). Fertilizer recommendations, cropping calendar and the farming system therefore need to take into account the seasonal availability of N. Nyamangara et al. (2003) reported that nitrogen uptake from the organic waste material (animal manure) was greater in the second season compared with the first season. This implied that the N from the organic fertilizer became more available (through mineralization) for plant uptake in the second year compared with first year (Nyamangara, et al., 2003). In addition to nutrient value, the application of aerobically composted organic waste (manure) to soil does not pose an environmental concern regarding NO_3^- leaching presumably due to the high degree of stabilization that occurs during the decomposition of the organic waste (Nyamangara et al., 2003). Nyamangara et al. (2003) reported that the organic waste (composted manure) application actually enhanced the use efficiency of mineral N fertilizer by crops when the two were applied in combination.

In the hot and humid environment of tropical regions in the Pacific the soil organic matter is minimal due to rapid decomposition. In addition to its slow release nutrient capability, organic matter is largely responsible for aggregation, soil moisture holding capacity and other improved physical properties of the soil. Thus, increasing soil organic matter content must be the first step in any farming practice in the Pacific region. Fuller (1951) stated that the continued productivity of the soils depends largely upon the replenishment and maintenance of the soil organic constituents. Organic matter additions are the only means of making some soils economically productive (Cook and Ellis, 1987). Well-decomposed organic matter has a very high cation-exchange capacity that adds to the buffer capacity of the soil. Hence, an adequate supply of soil organic matter makes it safe to apply rather large applications of fertilizer at planting time and thus avoid the need for a second application (Cook and Ellis, 1987).

Among the practices recommended for improvement of the soil quality and soil fertility in tropical regions is the application of composted organic wastes, which slowly release significant amounts of nitrogen and phosphorus (Muse, 1993; Zibilske, 1987; Eghball, 2001). In addition to supplying plant nutrients, organic compost has been shown to increase soil organic matter, enhance root development, improve germination rates and increase water-holding capacity of soils (Muse, 1993; Zibilske, 1987). Application of organic material promotes biological activity, enhances nutrient exchange capacity, improves water balance, increases organic matter content and improves the structure of the soil (Muse, 1993; Zibilske, 1987).

In our soil program at the University of Guam, we are evaluating the use of composted organic material as an alternative to synthetic fertilizers to increase yield and enhance crop productivity. More specifically, we are studying the effect of organic matter and inorganic soil constituents in order to improve soil quality for agricultural sustainability. Our goal is to develop management strategies and use available resources to increase soil organic matter for improving crop production while conserving natural resources and preserving environmental quality. Our case study project is therefore, designed to improve soil fertility status by using composted organic wastes as soil amendment and assessing how the nitrogen and other essential nutrients contribute to long-term soil fertility and crop productivity without application of synthetic fertilizers.

Material and Methods

Composting of readily available materials was undertaken at the Inarajan Agricultural Experiment Station in the district of Inarajan Village in Southern Guam. In our case study at the research station of the University of Guam, tree trimmings from the roadsides, chicken, hog and horse manure from local farmers and ranchers and wood chips from typhoon debris were used for compost production.

Passively treated compost piles were supplied with air through perforated pipes embedded in the pile, with occasional mixing of the compost using a backhoe. Samples were collected from different sections of the compost pile for nutrient characterization before the compost was applied on the treatment plots. Seven samples were collected randomly and were mixed to produce one composite sample and brought to the lab for analysis. Total Kjeldahl nitrogen (Page et al., 1982) and NO_3 by Lachate was determined. Soluble phosphorus was determined colorimetrically by using sodium bicarbonate (Olsen and Sommers, 1982). The pH was determined in a 1:5 soil:water paste using a combination electrode.

In the second stage of the experiment we applied the composted organic material to plots as a source of fertilizer in order to evaluate the agronomic value of the organic compost on crop production. In addition, the effect of compost as soil amendment for enhancing soil quality and improving soil properties was evaluated.

Twelve field plots (7.6×5.5 m^2) were set up at the Inarajan experiment station in Southern Guam for this project. The soil under study is the Akina series (Very fine, kaolinitic, isohypothermic Oxic Haplustalf) formed on residuum derived from the volcanic deposit (USDA-SCS, 1988). Composted organic wastes were applied 0 (control), 5, 10, 15, and 20 t ha^{-1} and each rate were replicated three times.

Results

The compost characteristics and range of compositional values for each time before the land application of the organic material are presented in Table 1. As shown in Table 1, the carbon to nitrogen ratio of the compost before land application ranged from 37 to 47 over the two sampling periods. The compost was incorporated 10 cm into the soil one week before the corn was planted in order to allow the carbon to nitrogen ratio to stabilize itself during this period. Vigorous growth during the growing season reflected sufficient nitrogen release by the compost indicating that the initial high carbon to nitrogen ratio did not suppress plant growth.

The results indicated that under the unique climatic conditions of Guam, land application of organic compost enhanced soil quality and increased soil fertility considerably. As shown in Tables 2, 3, and 4 considerable improvements in bulk density, soil organic matter content, soil pH, nutrient distribution, and other soil quality parameters occurred with the increased application of composted organic material on the soil under treatment.

Table 1. Some of the characteristics of compost at the time of application

Compost Application Phase	pH	Moisture Content (%)	Carbon Content (%)	Total N (%)	C/N Ratio	Nitrate (NO_3) (mg kg^{-1})	Phosphate (PO_4)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)
Nov. 2003	7.27	49.6	25.1	0.672	37.4	231.5	162.70	5,362.1	3,672.3	1,174.6
April 2004	7.48	50.3	29.5	0.618	47.7	173.8	151.94	4,761.2	5,612.4	9,840.4

Table 2. Measured soil parameters after different rates of compost application – April/May 2003

Compost Application Rate	pH	Bulk Density (gm/cm^3)	Moisture Content (%)	Organic Matter (%)	Nitrate (NO_3) (mg kg^{-1})	Phosphate (PO_4) (mg kg^{-1})	Potassium (K) (mg kg^{-1})	Calcium (Ca) (mg kg^{-1})	Magnesium (Mg) (mg kg^{-1})	CEC (meq/ 100 g soil)
0 t/ha	8.0	1.18	26.01	5.36	32.8	30.09	206.83	3,416.17	171.40	1.90
5 t/ha	7.6	1.01	25.86	5.64	49.6	52.34	744.97	3,779.88	297.59	2.33
10 t/ha	7.6	0.98	28.07	6.57	58.9	61.02	1,053.36	4,748.70	431.20	2.98
20 t/ha	7.7	0.91	32.16	9.46	160.1	76.65	1,418.71	5,492.18	787.92	3.77

Table 3. Measured soil parameters after different rates of compost application – Nov./Dec. 2003

Compost Application Rate	pH	Bulk Density (gm/cm^3)	Moisture Content (%)	Organic Matter (%)	Nitrate (NO_3)	Phosphate (PO_4)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	CEC (meq/ 100 g soil)
					(mg kg^{-1})					
0 t/ha	7.9	1.03	37.59	3.43	13.3	17.82	217.03	3,178.61	182.63	2.17
5 t/ha	7.8	0.98	37.70	4.56	41.8	35.83	485.40	3,300.61	337.88	2.62
10 t/ha	7.8	1.03	40.54	5.43	57.6	44.63	748.54	3,495.12	511.26	3.24
20 t/ha	7.6	1.01	44.60	7.18	79.3	58.43	1,064.72	4,312.43	807.02	4.16

Table 4. Measured soil parameters after different rates of compost application – April/May 2004

Compost Application Rate	pH	Bulk Density (gm/cm^3)	Moisture Content (%)	Organic Matter (%)	Nitrate (NO_3)	Phosphate (PO_4)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	CEC (meq/ 100 g soil)
					(mg kg^{-1})					
0 t/ha	8.2	1.16	34.11	2.78	9.8	18.93	390.41	3,694.64	172.66	2.09
5 t/ha	8.0	1.04	39.18	5.52	16.6	42.43	859.30	4,875.00	375.42	2.97
10 t/ha	7.9	1.02	44.64	7.40	22.9	57.68	1,265.00	5,608.87	601.48	3.63
15 t/ha	7.6	0.99	42.77	10.30	88.0	64.69	1,950.20	5,835.57	849.49	4.12

Data obtained from the first trial indicated that as the compost application rates were increased from 0 (control) to 5, 10 and 20 t ha^{-1}, the soil CEC (cation exchange capacity), one of the major soil quality indexes, was also increased, indicating a considerable improvement in nutrient exchange capacity of the soils treated with organic matter amendments (Table 2, 3, 4). A significant yield increase (Figure 1A, 1B, 1C) in plots with compost application of 10 and 20 tonnes per hectare provides evidence of these improvements.

Following the first harvest in May 2003, the plots were re-planted during the wet season (August to December) of 2003. The same soil quality enhancement occurred following the second round of the compost application on the treated soils (Table 3). Yield results from the dry season trial showed an even higher increase in crop yield as the compost application rate was increased from 0 (control) to 5, 10, and 20 t ha^{-1} (Figure 1). It should be noted that the yield results from the second trial reflect the effect of previous compost application on these plots. In addition to yield increase, the quality of the corn crop also improved as a result of the increasing compost application rate (Figure 2). Data from the second corn harvest (December of 2003), however, showed that the yield increase from 10 t ha^{-1} was not significantly different from the 20 t ha^{-1} (Figure 1) indicating that the highest rate of compost application only promotes vegetative growth (Figure 3) at the expense of grain production. Therefore, the application rate from 20 tonnes per hectare was adjusted to 15 tonnes per hectare on the third trial for the same crop (Figure 1C). The results from the third trial were then used to establish an optimum level of the compost application rate, which can then be recommended to the local farmers who are currently using organic material as the source of soil nutrient for their crops.

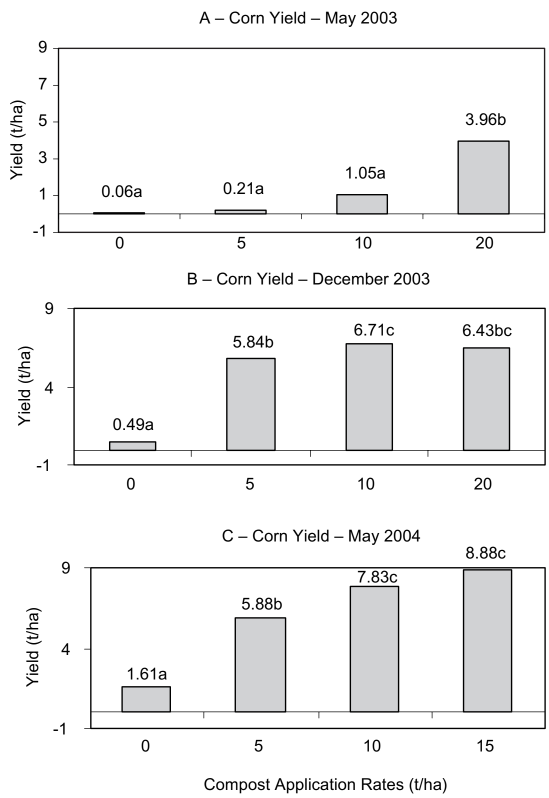

Figure 1. Yield results showing gradual increase as compost application rates were increased [*Mean shown on the columns followed by the same letter are not significantly different according to Fisher's LSD multiple comparison test (P <0.05)]

Figure 2. Showing that in addition to yield increase, quality of corn crop was also improved as the result of increased compost application rate

Figure 3. Showing lush green leave production (left: 20 tonnes/ha, right: 0 tonnes/ha) during the wet growing season that might have suppressed the grain production for fall harvest

As was evidenced by the data evaluated, land application of compost organic wastes enhanced soil quality/fertility significantly. Data obtained from this experiment shown that with continued application of compost prior to each planting event, the soil quality was further enhanced and the yields were increase as well.

Concluding Remarks

The results and observations from this experiment indicate that composted organic material is certainly a good substitute for inorganic fertilizers both in terms of enhanced soil fertility and improved soil quality indices. As indicated, the composted organic wastes are generally rich in organic matter and they improved physical as well as chemical properties of the soil under study.

For sustainable agricultural systems within small-scale farming enterprises in the Pacific islands, composting can be a viable option for developing effective plant nutrient management strategies in many situations. Transitioning farming practices in the Pacific into sustainable agricultural systems is desirable. However, the real or perceived economic incentives to use composted organic material as a soil amendment need to be introduced with greater emphasis among the small scale farmers of Guam and the other farmers in the Pacific region with similar environmental conditions. Ongoing research programs are designed to specifically address the soil conditions and nutrient status that are unique for Guam and other island of the Pacific with similar environmental conditions. Some of the unique soil properties, such as phosphate fixing capacity or aluminum toxicity that are common in Guam and the other islands of the Pacific may be corrected by implementing management strategies that include application of organic material to improve the fertility status of these soils without the use of commercial fertilizers. Our findings clearly indicated that productivity can be improved by proper use of composted organic materials, and that the environment benefits as well through the reuse of organic wastes that otherwise would be buried in landfills. Evaluation of sustainability is an integral facet of our research projects, and our plant and soil testing and analysis programs are geared to address the problems associated with the unique properties of soil in Guam and other neighbouring islands that have low fertility as a result of insufficient organic matter content.

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Session 7

“Successes and failures: Stakeholders and development agencies perspectives in enhancing the livelihoods of communities on light textured sandy soil”

The "Dr soils" program of the Land Development Department, Thailand

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Abstract

The Land Development Department (LDD), Ministry of Agriculture and Cooperatives, Thailand has been highly successful in transferring soil management technologies to Thai farmers through the "Dr. Soils" programs. Dr. Soils are farmers selected from each village who are trained in the basic soil testing program, soil mapping units and land development techniques. They are representatives of LDD's officers whose role is to assist farmers in implementing proper land management practices. They are also messengers that distribute information about land development to villages and transfer message regarding land use problems from farmers back to LDD.

After twelve years of operations since 1992, there are now 66,000 Dr. Soils from 67,000 villages. Dr. Soils are volunteers who are not paid a salary, but are provided with a small farm pond and a distinctive yellow jacket. They are also provided with LDD soil improvement products, legume seed, and grow the legumes as a seed crop, selling the harvested seed to LDD. Dr. Soils also have the opportunity to propagate vetiver grass seedlings, which they sell to LDD.

The Dr. Soils program is now serving farmers all over Thailand. Some of them are provided with Soil Test Kits to test soil samples for basic recommendation for crop growing. Farmers are taught how to take soil samples and it is recommended that samples are collected one or two weeks before testing, so that the samples have time to dry. On the day when the team is scheduled to visit their village, farmers take their soil samples to be analysed at a central point, such as the local temple or school.

The vans also serve as mobile laboratories, and analyse soil samples in the village. When farmers hand in their samples in the morning, they are interviewed to find out details about the management history of the field, the current land use, and any problems they are experiencing. While farmers are waiting for the samples to be analysed, LDD staff take the opportunity to educate farmers about soil testing and fertilizer use. Each van unit can analyse about 100 samples in one morning. In the afternoon, when the analysis is finished, farmers are given an appointment to hear outcomes of the test.

Crop and soil management under integrated farming systems in Northeast Thailand: an individual farmers experience

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Abstract

*This paper presents the experiences of an individual farmer who gave up a career as a policeman to return to farming as his main form of livelihood. What is interesting in this situation is to see how he accessed knowledge that was required for him to become a successful farmer. Mr. Chaiyasit Sitti is 65 years old and lives of Bungsim Village, Muang District, Khon Kaen Province. There are 3 persons in his family and he has a single son. Currently he lives with his wife and works full time on the farm. His farming components included rice monocropping, vegetables monocropping, mixed cropping of mango, banana, guava and guinea (**Panicum maximum**) grass, raising cattle, and fish culture in the pond. Apart from fish, other outputs from the pond are lotus cultivation for sale into local markets. There are a number of indigenous and new innovations that he has adopted to support his farming operations. For example he used a pruning technique to produce mangos in off-season; wood vinegar produced through the distillation of tar generated in the production of charcoal is used to repel insects from crops. The farmer has improved soil fertility through the incorporation of cattle manure mixed with bio-extract which he produces on-farm. **Sesbania rostrata** is grown prior to the annual rice crop and incorporated as green manure crop. Paddy fields act as grassland area of the feeding of cattle in the dry season. In the wet season, various grass species available on the farm provide forage which is cut and carried for feeding to cattle. Vegetable wastes and banana stem are put into the pond to feed the fish. Farm products that are produced are used for household consumption as well as selling into markets in order to generate incomes. In general, the middleman buys the farm products at the farm gate. His household income is derived through the sale of farm products which is sufficient to cover living expense as well as contribute to savings. In order to achieve success with respect to integrated farming practices several factors are required to be present. Firstly, enough water and efficient use of irrigation water on the farm throughout the year. Secondly minimizing a dependence on external farming inputs. This is achieved by recycling organic wastes back to the farm. Thirdly, dedication to the tasks of farming; work hard and developing new technologies through trial and error. Further, the adoption of improved technologies introduced by researcher and extension worker is important. By adapting these new innovations to fit their existing farm resources, improvements in productivity are achieved.*

Sustainable intensification of crop-livestock systems on sandy soils of Latin America: trade-offs between production and conservation

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Keywords: legume pastures, Cerrados, productivity livestock

Abstract

Large areas in Latin America are covered by coarse-textured (sandy) soils that are under extensive livestock systems, annual cropping systems and forest plantations. Low levels of soil organic matter and limited availability of water and plant nutrients, in particular phosphorus and nitrogen, are the major soil constraints to agricultural productivity. These sandy soils are also highly susceptible to massive topsoil losses through wind and water erosion. Because of this, large and small-scale farmers face the challenge of developing sustainable agricultural systems in this type of soils. The present paper discusses the technical potential and socio-economic viability of two resource management technologies that were developed in the Brazilian Cerrados to enhance livelihoods of small and large farmers and productivity of sandy soils: crop-pasture systems with high use of inputs and legume-based pastures for dairy systems with low use of inputs. These technologies were developed, tested and monitored with the active participation of individual farmers, local organizations and researchers from EMBRAPA and CIAT. The two technologies described in this paper increased productivity and profitability of large and small-scale production systems in the short-term and improved resource conditions in the long run. In spite of their economic and environmental soundness, their massive adoption is constrained by socio-cultural factors, the lack of economic incentives and continuous technical backup and policies to support sustainable intensification of these soils.

1. Introduction

Sandy soils are considered marginal for agricultural activities. Many studies have shown the complexity of soil fertility problems and the challenges in developing sustainable management options, particularly on small holders farms. Because of the limited capacity of building soil organic matter (SOM) and hence nutrient stocks, farmers have to rely heavily on the use of external inputs on a seasonal basis (Giller et al., 1997). However, most of the smallholder farmers use sub-optimal amounts of fertilizer due to cash limitations and poor access to fertilizer markets. Large-scale farmers also face the challenge of replenishing nutrients that were removed from the system by both leaching losses and crop extraction. This calls for increased efficiency in use and recycling of both exogenous and endogenous nutrient pools in the cropping systems (Mapfumo and Mtambanengwe, 2004). In practice, soil conservation and crop production technologies for sandy soils have resulted in a wide range of impacts, not all favourable from an economic and environmental point of view, thus, in many cases resulting in little adoption of resource management technologies (Smith et al., 1999).

The objective of this paper is to highlight the factors driving the decisions made by farmers to intensify production of crop-livestock systems on sandy soils that rely on high or low inputs. Two case studies from Brazil were selected to illustrate the process. The conclusions presented in this paper are an attempt to generalize observations and opinions given by farmers about constraints and potential for adoption of the improved management systems.

2. Geographical distribution of sandy soils in Latin America

Extensive areas of the tropical savannas in Latin America are covered by coarse-textured soils. Quartzose sands (Entisols) occupy 30 million ha (Mha) or 15.2% of the Brazilian Cerrados. Chemically, they are characterized by having a low base saturation, low

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carbon levels (0.5%) and low pH of <5.5 (Adamoli et al., 1986). Sandy soils in the Colombian and Venezuelan savannas occupy roughly 20% of the whole area (4 Mha) and are scattered in patches along the main physiographic land units: upper plains, rolling lands and alluvial plains (Rondón el al, 2004). Mean SOM values reported for sandy areas where agricultural intensification is occurring are: 1.6% for sandy textures of the Colombian Llanos (Hoyos et al., 2004) and 0.5-0.8% for the sandier Ultisols of the central Llanos (Hernandez and Lopez, 2002). In general, the Eastern Llanos in Venezuela have a higher proportion of sandy soils and lower C values.

3. Land use changes in Savanna and Cerrado agro-ecosystems

Before the mid-1960's, the Brazilian Cerrado was an empty area characterized by a low population density and the presence of extensive cattle ranching systems based on native pastures and some subsistence agriculture concentrated in the most fertile soils along the rivers. During the 70's occupation of this area was encouraged by the Brazilian government through the POLOCENTRO and PRODECER Development Projects. Thousands of farmers from the South of Brazil moved to the Cerrados and established crop and pasture systems taking advantage of the long-term loans and ample subsidies provided by the government to purchase land, fertilizers and machinery. During the period of America 1975-80 the POLOCENTRO project incorporated 2.4 million has for agricultural production and financed 3,373 projects including the development of large-scale farming systems, construction of roads and grain storage facilities and the formation of farmer Cooperatives (Cunha, 1994). All this led to the accelerated occupation of the Cerrados. Today, there are more than 60 Mha of large scale mechanized crop systems located primarily on extensive plateaus with heavier (clay) soils, extensive cattle ranches on undulating sandy areas and small dairy farms located in the downstream in riparian areas (Ayarza, et al., 1993).

The savannas of Colombia and Venezuela experienced similar changes though at a much lower scale (Rondón, et al, 2004). By the mid 50s, they were used for extensive cattle ranching, with cattle feeding on native low quality grasses. In the mid 1960's, the Venezuelan government promoted the introduction of large-scale tree plantations (pines, eucalyptus) and some commercial crops (rice, cotton and peanuts under irrigation). More than 0.5 Mha were planted with, *Pinus caribbea* in the Venezuelan Eastern Llanos. In Colombia in the 1970s, research led by CIAT and the Instituto de Investigacion agropecuaria, ICA, encouraged the intensification of livestock activities through the introduction of improved grasses (mainly Brachiaria species introduced from Africa) in association with forage legumes (*Arachis pintoi*, *Stylosanthes capitata, Desmodium ovalifolium, Centrosema acutifolium*). More recently, rapid agricultural expansion is taking place in Colombia as well as livestock intensification in Venezuela. The most important land use in the Llanos of both countries is introduced grasses (5 Mha in Venezuela and 1 Mha in Colombia). However, recently areas with lower slopes (less than 3%) have been converted to mechanized cropping (sorghum, maize) taking advantage of irrigation projects developed in the region. Forest plantations have replaced the patches of deciduous forest in Venezuela. In the process, large areas of sandy soils have also been incorporated to agricultural production.

4. Problems of the expansion of agricultural activities

The accelerated expansion of agricultural activities in the Cerrados of Brazil and savannas of Colombia and Venezuela led in a short time to an impressive increase in the export of grain, meet and milk from the region. Unfortunately, it also contributed to serious environmental problems that are associated with soil degradation, water losses and contamination and increasing costs to control pests and diseases. Intensive tillage operations in continuous cropping systems resulted in serious soil loss of physical stability and a rapid SOM mineralization in sandy and loamy soils (Lopes et al., 2004; Amézquita et al., 2002; Silva et al., 1994). Inadequate pasture management resulted in rapid pasture degradation. As much as 50 Mha in the cerrados are at some level of pasture degradation (Macedo, 1995). The degradation process was greater on sandy soils.

Individual farmers are confronting the challenge of maintaining/improving the profitability of their production systems while, at the same time, responding to the increasing pressure of society to minimize pollution and improve the quality of the soil and the water. Funding agencies and development banks are providing greater support to projects with focus on environmental protection rather than increasing agricultural productivity. However, the challenge is to optimize productivity for greater environmental sustainability.

5. Description of the case studies

Most activities reported in this paper were carried out on farms around the Municipalities of Uberlândia and Prata, State of Minas Gerais, Brazil. This region has undergone rapid intensification of land use in recent years (Oliveira Schneider, 1996). Although most of the soils are deep and well structured Red-Yellow and Dark-Red Latosols (Anionic Acrustox and Typic Haplustox, respectively, according to the USDA classification system), there are extensive areas dominated by coarse-texture soils with low natural fertility and high susceptibility to erosion. Average annual rainfall is 1,600 mm, concentrated between November and March. The dry season, from June to September, is very marked, with relative humidity dropping to less than 15%.

The work focused on developing farmer-led prototypes of two major production systems: (i) agro-pastoral systems with high inputs, and (ii) legume-based pasture systems for dairy production with low inputs for sandy and clayey soils. For the purpose of this work we will concentrate only on results from sandy soils. Previous research indicated that there are numerous advantages of the integration of crops and pastures and in the use of forage legumes to increase the sustainability of production systems (Spain et al., Boddey et al., 1996; McCown et al., 1993; Thomas et al., 1995).

Case 1: Agropastoral system for high input systems

A monitoring work was conducted in the Santa Terezinha farm located 30 km from Uberlândia. The farm has 1,000 ha and the soils are very sandy (Table 1). A team of researchers from EMBRAPA and CIAT worked in close collaboration with the owner of the farm to organize, and synthesize historical information about land use changes over time and space with the introduction of crops and improved pastures for a period of 17 years (1979-1996). The exercise allowed assessing the economic efficiency and environmental impact of the introduced systems or changes in land use pattern. It was also a good opportunity to capture drivers behind farmer's decisions for change.

Because of its inherently low fertility and productivity potential the owner decided in 1979 to establish an extensive livestock system. After few years, he noticed that pasture productivity was declining sharply and consequently the capacity of the farm to maintain the same herd size. This crisis coincided with the return of his son from school after graduating in agronomy. Both of them decided then to plant crops to reclaim degraded pastures. With the introduction of agricultural activity on the Santa Terezinha Farm in 1983, the original system of calf fattening was transformed into an integrated system, in which cycles of crops and pastures were alternated over time and space. By 1992, all the original pastures of *B. decumbens* cv. Basilisk at some state of degradation had been replaced by pastures of P. maximum, planted simultaneously with maize after a 3 to 4-year cycle of cropping. From this time onward, the proportion of area under pastures remained at 40% of the total farm area (Figure 1). Despite the reduction in pasture area, the size of the herd was maintained almost constant, resulting in twofold increase in the number of calves per hectare and a 60% increase in the gross margin income as compared to the traditional systems (Table 2).

The new production system also improved soil quality. During the crop cycle, soil fertility increased as a result of using fertilizers and amendments. During the pasture cycle, soil aggregation recovered, and SOM increased by 30%, compared with areas that had been

Table 1. Chemical properties of the Fazenda Santa Terezhina near Uberlandia, M.G., Brazil (mean of thirty soil samples)

Soil Depth	Sand	Clay	pH	Al	Ca+Mg	K	Al+H	P	M.O
	-----%-----			-----meg/100 g-----				(ppm)	%
0-10	82	13	5.4	0.38	0.41	0.04	1.90	1.6	0.97
10-20	79	15	5.2	0.36	0.19	0.04	0.78	0.6	–
20-30	74	13	5.2	0.31	0.13	0.02	0.69	0.4	–

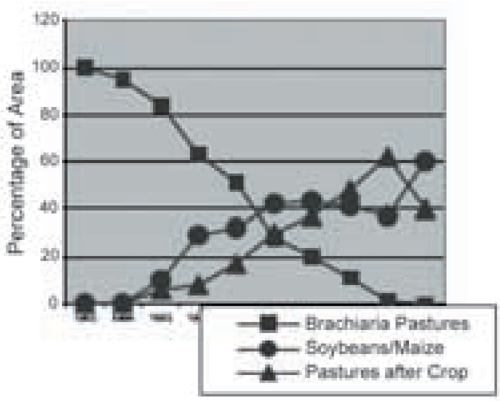

Figure 1. Dynamics of land use change in the Santa Terezinha farm as a result of the integration of crops and pastures over time and space

Table 2. Economic efficiency of calf production in three production systems with different degrees of intensification

Parameter	Management System		
	Traditional[1]	Improved[2]	Crop/pasture
Pasture reclaimed/year (%)	1	10	25
Age of pasture (years)	15-20	10	5
Hectares/cow	1.85	1.3	0.96
Calves/ha	2.8	5.7	6.6
Gross income/ha (US$)	43	95	110
Area in pastures	1,728	2,110	416
Total gross income (US$)	74,304	200,459	45,760

[1] Extensive livestock system based on *Hyparrhenia* grass
[2] Extensive livestock system based on Brachairia grasses + fertilization maintenance
Source: Fisher (unpublished)

planted to crops for 4 years (Ayarza et al., 2004). Lilienfein (1996) found that C, N, and P contents of the macro-aggregates were enriched during the pasture cycles.

The control of pastures for the planting of crops was initially achieved by conventional tillage, at the end of the rainy season. With the progress made on no-till systems the farmer decided to plant crops on pasture residues chemically controlled. The main goal of the farmer was to take advantage of the improved soil fertility and minimize tillage operations.

Case 2: Legume based-pasture systems with low inputs

The work was conducted in dairy farms near the Municipio of Prata, 30 km west from Uberlândia. This region is located at the lower part of the watershed formed by the Paranaiba and Rio Grande rivers. Most of the region has sandy soils with low pH (<5.5) and low availability of P. Relief is gentle in the top of the "Chapadas", however, it is pronounced toward many streams and rivers present in the region. Cultivated pastures have replaced most of the native Cerrado vegetation and now they account for 64% of total area (0.32 Mha). More than half of the 24,000 inhabitants of the Municipality in 1964 were devoted to produce milk. Milk was collected and commercialized through the Cooperative of Producers of Prata "CORPRATA". This is a farmer-led organization created to provide credit, technical assistance and inputs to 554 associates.

Most of milk produced in the wet season was obtained on degraded Brachairia pastures. During the dry season, milking cows were fed with supplements based on cutting grass, sugarcane and concentrate. Farmers interviewed during the work mentioned that their priority was to increase milk production and reduce cost in the use of concentrate particularly during the dry season.

In order to improve performance of dairy systems and income of farmers of the region, the EMBRAPA-Cerrados Center and the Tropical Lowlands Project of CIAT developed a collaborative project between 1996-1998 to test the potential of the forage legume Stylosanthes cv. Mineirao to increase milk production during the dry season. Previous research showed that this legume is well adapted to low soil fertility soils and is capable to remain green during long dry season (EMBRAPA, 1993; Barcellos and Vilela, 1994; Ramos et al., 1996). One ha paddocks of Stylo + Brachaiaria grass pasture were established in twelve farms varying in size, herd size and productivity per cow (Table 3). A common problem in all farms except one was very low level of milk productivity per cow (3.8 l/day on average).

Table 3. Characteristics of the farms selected for the evaluation of *stylosanthes guianensis cv.* Mineirao

Farm type	Area (ha)	Herd size	Milking cows	Production (lt/day)	
				Total	Per cow
1	63	75	17	80	4.7
2	64	27	5	20	4.0
3	29	50	8	40	5.0
4	116	70	24	72	3.0
5	28	78	13	40	3.0
6	22	35	4	15	3.7
7	77	100	30	130	4.3
8	16	38	13	80	6.2
9	77	65	20	45	2.2
10	11	36	11	40	3.6
11	58	57	28	66	2.3
12	80	100	12	100	8.3
Mean	53	60	15	60	4.2

Daily production of two milking cows grazing the grass + legume paddocks was recorded during four periods of eight days each during the dry season of 1997. Production was compared to that obtained from the same cows for a similar period of time just before they started grazing the legume.

Stylosanthes cv. Mineirao had a positive effect on milk production (Table 4). Impact was greater with

Table 4. Milk production of cows grazing Stylosanthes Mineirao during the dry season in small dairy systems in several farms in Prata. M.G., Brazil (mean of four periods of eight days)

Productivity level (lt/day)	Con-centrate	Stylo	Mean production	Increase (%)
Low	+	–	3.5	
(2-3)	+	+	5.0	45
Medium	+	–	6.0	
(4-6)	+	+	7.0	15
High	+	–	8.0	
(8-10)	+	+	8.4	5

cows having lower productivity potential. These types of animals are common in dual-purpose systems in small farms. None of the farmers participating in the work was ready to substitute the concentrate by the use of Stylosanthes. However, during the second year some of them started reducing by half the use of concentrate without losing milk production. Others decided to keep using Stylo as a complement of the animal diet. In both cases there was a significant effect on production costs.

Farmers also saw additional benefits of grazing the legume during the wet season since the recovery of lactating cows and their calves was faster as compared to the traditional degraded pastures. Milk increments were modest but significant for small farmers. Larger-scale farmers did not put much importance on milk output but on the benefit of grazing pastures during the dry season and the improved conditions of the pastures during the wet season.

6. General discussion

Crop-pasture integration

The integration of crop and livestock activities is relatively new to cerrado farmers but it seems to be the best option for sustainable management of sandy and clayey soils. In the case of the Fazenda Santa Therezinha the owner perceived the economic and environmental advantages of this technology and accepted the challenge to adjust his traditional production system to an innovative one with the support of his son who was returning from school with a B Sc degree in Agronomy. The introduction of crops such as soybeans and maize allowed him to improve the short-term profitability of the production system while the increased pasture productivity improved even further the long-term profitability of the livestock component. Good and stable prices of commodities in the market and credit to purchase machinery and inputs were major incentives for the change. The results of monitoring crop-livestock systems confirmed the beneficial effect of integration on the system’s productivity and on soil quality.

Despite its great potential, only a few farmers have adopted this system. This is partly because changes are needed in infrastructure and management to handle both activities. In addition, a change in mentality is needed from both grain farmer and livestock owner, who are accustomed to working with just one activity (Spain et al., 1996).

Apparently, this change is now beginning to take place among grain farmers in the Cerrados, as they are beginning to perceive the economic benefit of crop/ pasture integration, even when both activities are carried out in separate areas. Smith el al. (1999) conducted a survey to assess the factors driving land use change in the Cerrados near Uberlândia. They found that about half of the farmers interviewed, had dairy and beef cattle. During the rainy season, the animals remain in the cultivated pastures. During the dry season, the animals are confined and supplemented with silage and feed concentrates, usually produced from crops on the farm. This type of integration has made it possible to take advantage of areas unsuitable for agriculture and increase the farmers’ income through milk and meat production. In this case, farmers perceived livestock as complementing rather than substituting their principal activity of grain production.

During the last 10 years, the system is expanding to remote areas in the North of the Cerrados. Framers are using this technology to reclaim degraded pastures and improve economic efficiency of the system.

Legume based pastures

The introduction of Stylosanthes cv. Mineirao in low input systems of small dairy systems is a good example of an innovation that can generate benefits with respect to productivity and soil quality in both the short and long term, without causing major structural changes to the production system. This technology requires only small quantities of seed to establish (0.7-1.5 kg/ha), does not need additional soil pre-paration tasks, and requires very few inputs (Ayarza et al., 2004). These characteristics and the capacity of cv. Minerirao to provide green forage during the dry season give this legume clear advantages to improve the productivity of the system, during critical times. In addition to improving milk production and, the availability of N in the soil-plant system increases and permits greater stability of pastures over a longer term. Stylosanthes is very sensitive to initial competition and therefore it is important to control regrowth of companion grasses through proper grazing management to have a good establishment of the legume. Input of researchers to solve this problem was important.

Participating farmers were most of the time impressed by the outstanding performance of the legume during the dry season. They perceived the superior forage availability and the better condition of animals grazing the cv. Minerirao plots. However, they were cautious to move to this technology because of economic limitations, lack of knowledge about its management and availability of adequate seed in the market. After they perceived the benefits during the first year they were enthusiastic about having more cv. Mineirao in their farms.

Although technologies supported by the cooperative (sugarcane, urea and concentrate) helped to increase milk production during the dry season their cost was equal or even higher than the returns obtained by small farmer by selling the milk produced. For this reason they were enthusiastic about using cv. Mineirao. However, none of the farmers participating in the work substituted the use of concentrate during the first year of evaluation. Rather, they were interest to prove that cv. Mineirao could increase even further milk production. In the second year some of them started to reduce the use of concentrate.

The major challenge for researchers working in the project was to convince farmers that the legume would be a cheaper solution than the use of supplement and concentrate. The only way to overcome this problem was by involving, as much as possible, farmers in the evaluation process. Farmers had enough freedom to select the areas they wanted to have the legume, to participate in the evaluation process and even quit if they loose interest. On the other hand, the Cooperative requested for a continuous process of capacity building to provide technical assistance once the project was over.

Constraints for adoption

As with all new technologies and management options there are some difficulties and obstacles to their widespread adoption. Below we briefly discuss these aspects.

a) Economic, social and cultural aspects

Integrated crop-livestock systems appear to be sound from the economical and ecological points of view. However, its massive adoption will require a change in the structure of the production system. It will also require incentives, credit and a "new type" of producer empowered with tools, information and managerial skills to optimize short and long-term benefits according to market demands.

Small farmers devoted to produce milk confront the problems of lack of financial resources, education and health services. Furthermore, they are pressed to improve the short-term profitability of the system to satisfy the demands of the family. All these factors restrict their capacity to adopt any technological innovation without outside support (financial, technical, etc.). Land tenure is often mentioned as a constraint for the adoption of technologies. In this case it was not so important since most farmers in the cerrados own their own land.

b) Technological aspects

The biggest limitation for the massive adoption of improved legumes such as Stylosanthes cv. Mineirao was the lack of good seed. Some of the small farmers in Prata area tried to harvest seed from their small paddocks with little success. This bottleneck is often ignored when developing crop technologies. Alliances with the private sector and farmers organization are needed to support seed production.

Lack of continuous technical assistance to ensure good establishment and management of legume-based pastures is another constraint. Legume based-pastures require a skillful management for maintaining a proper balance between grass and legume components.

c) Favourable policy environment

New technologies and management options will require more favourable policy environments to be successful. Better dialogues amongst farmers, researchers, extensions and policy makers are essential and require much more effort from the agricultural research community.

d) Lack of effective participation of farmers

Even though there has been a considerable effort for the development of better technologies in the region by various national and international institutions, the true "explosion" in technology implementation was more a result of the effort of the farmers themselves. Farmer-to-farmer communication and farmer cooperatives were the main driving forces behind the transfer and adaptation of the experiences obtained in the southern temperate region in Brazil (Landers, 1996). Farmers need to be engaged in a dialogue on how they can arrive to solutions that suit their requirements and circumstances. An entry point for truly interdisciplinary research would be experimentation based on farmers own practices.

To better match precision of farming systems to technologies, technology design must involve the intended beneficiaries earlier. That is moving from formal to more farmer-led as soon as the comparative advantage shifts from researcher to farmer.

Main conclusions

Land use policies and land management practices are in general designed with a long-term objective, while farmers are generally more concerned with the short-term benefits for the continuing survival. Therefore it is appropriate to identify entry points where short-term benefits could be created. Resource management technologies for sandy soils should be conceived on the need to improve livelihoods of farmers, while ensuring that the environment inherited by future generations is not degraded. A favourable policy environment is needed during the transition periods of technological change.

The strategy of on-farm research make possible to incorporate the farmer early on in the generation and assessment of the new technologies. In addition, it provides an opportunity of identifying problems earlier, and of conducting research under a broad range of conditions, as in our study, for which conditions ranged from high input to low input systems and large-scale to small-scale farmers.

A better understanding of the driving forces behind land use change at the farm and other levels is required in order to ensure that new technological and management options are appropriate and are acceptable to farmers. Adoption of legumes depends on the comparative advantage over other crops and other alternatives. The market demand, price incentives, labour, pests and diseases limit scaling up and out of legume-based technologies.

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Technologies for sustainable management of sandy Sahelian soils

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Keywords: Sandy soils, inorganic and organic fertilizers, microdose, fertilizer pleacement, water harvesting

Abstract

Soil fertility is the most limiting factor for crop production in the Sahelian zone of West Africa. Over 95% of soils in this region are sandy and pose a great challenge to sustainable management. The poor structure and coarse texture of sandy soils results in low water holding capacity. Nutrient contents and nutrient retention are low, thus causing a low inherent fertility status for agricultural production.

In the recent past, scientists have evaluated the potential of different technologies in addressing the soil fertility problems in the sandy Sahelian soils with the aim of increasing food production. Research results have shown that yields can be increased three to five times with the improvement of soil fertility using organic and inorganic fertilizers. Combinations of these materials also improve an array of other soil properties such as organic carbon content, cation exchange capacity (CEC) and pH. The main constraint to combining inorganic-organic materials is the high costs of inorganic fertilizers and the low availability of organic fertilizers at the farm level. Crop rotation and intercropping systems have also shown potential in increasing food production and improving soil fertility. Rotation systems increase biological nitrogen fixation and improve fertilizer use efficiency. The use of locally available phosphate rock, which could be an alternative to the use of high cost imported P fertilizers, has also shown potential for alleviating soil P limitations in these sandy soils, improving yields and the efficiency of N and water use. Hill placement of inorganic fertilizers and manure is superior to broadcasting. Fertilizer applied to crops in "micro-doses" and hill placed, combined with the use of crop residues and/or manure offers profitable natural resource management technologies to farmers. Successful experience from Niger has shown that adoption of microdose technology can increase production by more than 100% and farm incomes by 50% but requires supportive and complementary institutional innovation and market linkage. Combined water harvesting techniques and integrated nutrient management (INM) in the drier areas of the West African region clearly shows that higher yields can be achieved. In the Central Plateau of Burkina Faso, stone bunds alone doubled sorghum yield compared to the control and could reduce risks of crop failure in erratic rainfall years.

A bottleneck to the use of these profitable soil fertility-enhancing technologies is the low capacity of farmers to invest in these technologies. In order to have these technologies to reach millions of farmers, a new integrated soil fertility management (ISFM) paradigm has been adopted which integrates biological, physical, chemical, social, economic and political factors. Future research challenges include strategies to increase the legume component for a better integration of crop-livestock production systems, exploiting genetic variation for nutrient use efficiency and integration of socio-economic and policy research with the technical solutions. Another very important issue for research is how to increase crop biomass availability at farm level to alleviate the constraint of non-availability of organic amendments. Use of decision support systems, modeling, and GIS are important in order to extrapolate research findings to other areas in which successful technologies can be expanded/scaled out to reach more farmers.

Introduction

The Sahelian zone of West Africa is the home of the world's poorest people, 90% live in villages and gain their livelihood from subsistence agriculture. Per capita food production has declined significantly over the past three decades. According to the FAO, total food production in Sahelian countries grew by an impressive 70% from 1961 to 1996, but it lagged behind the population which doubled causing food production per capita to decline by approximately 30% over the same period. High population densities have necessitated the cultivation of marginal lands that are prone to erosion. Consequently, present farming systems are not sustainable.

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Sahelian countries produce 80% of their total cereal production under very difficult conditions. Rainfall is generally low, variable and unreliable (Toupet 1965) with a growing period of 60-100 days (Sivakumar, 1986). The average annual rainfall of the cultivated zones varies from 300 to 900 mm and the ratio of annual rainfall to annual potential evapo-transpiration varies from 0.20 to 0.65.

The rainfall in West Africa shows a significant north-south gradient because of the inter-seasonal movement of the inter-tropical convergence zone, north and south of the equator. The rainfall in the Sudano-Sahelian zone is low, variable, and unreliable. Time-dependent variations in rainfall are quite common in the region with coefficient of variation of annual rainfall ranging between 15-30% (Figure 1). Nicholson (1981) showed that in 1950, rainfall over West Africa was above normal, at some locations as high as 250% above normal. However, in 1970, rainfall was below normal throughout the region. As a result of rainfall variability average yields of sorghum and pearl millet have shown significant inter-annual variability (Figure 2).

In addition to the unpredictable climatic conditions, the region is experiencing declining production as a result of negative nutrient balances reported for most cropping systems. Stoorvogel and Smaling (1990) reported that in 1983 49 kg/ha or an average of 9.3 million kg of nutrients was lost in sub-Saharan Africa. Projections for the year 2000 showed that nutrient losses will increase to 60 kg per year. In Burkina Faso, with a cropped area of 6.6 million ha,

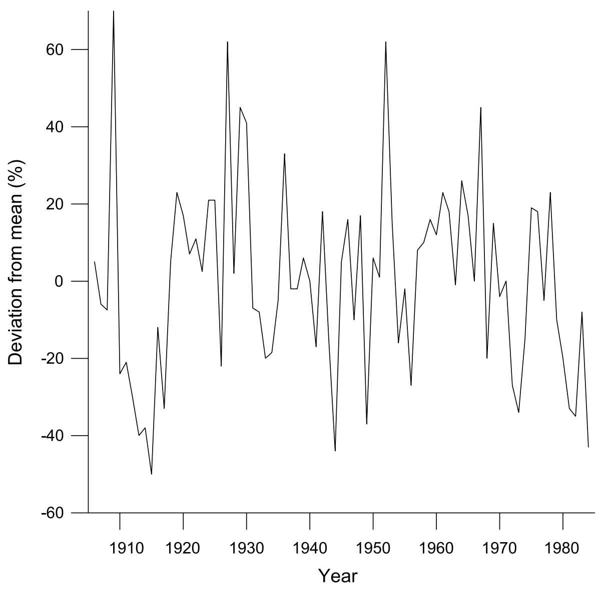

Figure 1. Percentage deviation of annual rainfall from the mean at Niamey, Niger

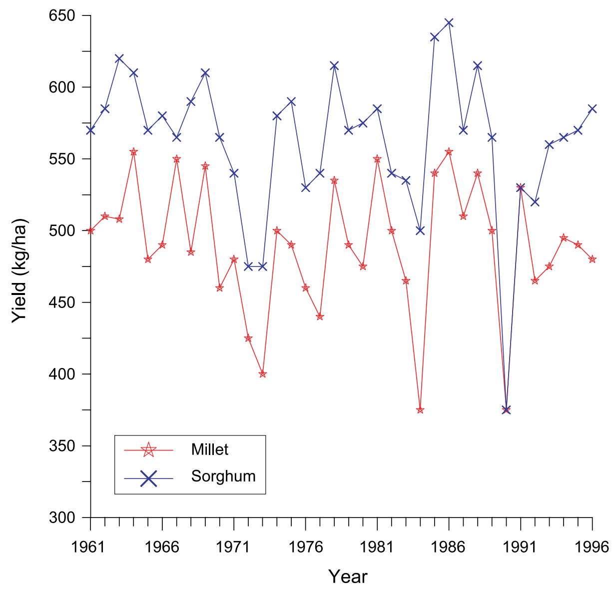

Figure 2. Sorghum and millet yields in the Sahel over the period 1961 to 1996

Table 1. Nutrient losses for some West African countries

Country	Area (1,000 ha)	Losses for the region (10^5 tonnes)		
		N	P	K
Benin	2,972	41,388	4,530	26,967
Burkina Faso	6,691	95,391	12,128	65,357
Ghana	4,505	137,140	14,121	75,093
Mali	8,015	61,707	7,817	55,382
Niger	985	176,120	24,180	121,692
Nigeria	2,813	1,107,605	138,392	785,310

the nutrient losses were estimated at 95,000 tonnes of N, 12,128 tonnes of P and 65,357 tonnes of K or the equivalent of US$159 million for the purchase of N, P and K fertilizers (Table 1).

This situation has stemmed from increasing population pressure, and soil degradation in particularly drought-prone region where the soils are naturally infertile. Currently over a quarter of West Africa sub-region's population of two hundred million inhabitants are threatened by food insecurity. It is estimated that the productivity of land currently under cultivation should increase by at least 3% per annum in order to meet the food demands of the regions population. Any program aimed at reversing the declining trend in agricultural productivity and preserving the environment for present and future generations in West Africa should begin with soil fertility restoration and maintenance.

This paper highlights various soil fertility restoration technologies tested in the sandy sahelian zones of West Africa. The paper discusses the crop production environment in West Africa, the combined use of organic and inorganic nutrient sources, fertilizer application technologies, cropping systems management, combined water harvesting and nutrient management (INM), phosphate rock utilization and plant genetic utilization for drought resistance before presenting future research challenges and conclusions.

Crop production environment

The most common cropping systems in the Sudano-Sahelian zones involve growing several crops in association as mixtures or intercrops. This practice provide the farmer with several options for returns from land and labour, often increased efficiency with which scarce resources are used, and reduce dependence upon a single crop that is susceptible to environmental and economic fluctuations. Types of crop associations differ from place to place, with ecological zone, farm size, human population, and soil fertility as well as with cultural and socio-economics factors.

In the Sudanian zone, sorghum based cropping systems are common. Millet, maize, groundnut, and cowpea are important components of this system (Steiner, 1984); whereas in the Sahelian zone, the cropping system is millet based, with millet/cowpea and millet/groundnut being the most important cropping patterns. While considerable information is available on fertilizer requirements for single crop species, little is known for intercropping.

The increase in production of pearl millet and sorghum has been due to the expansion of area cultivated and not to the increase of productivity per unit area. In Nigeria, whereas the area under cultivation doubled between 1979 and 1994, the yield per hectare declined from 1 tonne to 0.89 tonne over the same period. Groundnut and cowpea are the two predominant grain legumes in the Sudano-Sahelian zone. Groundnut occupies 2.7 million hectare of arable land and cowpea 6 million. The countries of West Africa have been traditional exporters of groundnut, but production has declined recently. Cowpea production on contrary has increased over the years, and in some countries such as Niger, it has more than doubled, largely because of an increase in area cultivated. Yields of cowpea grain are generally low, ranging between 50 and 300 kg/ha in marked contrast to yields of over 1,000 kg/ha obtainable on research station and by large scale commercial enterprises in Northern Nigeria. The potential for increased yields in the region is therefore high.

Crop livestock interaction

Crop-livestock interactions are evolving in West Africa, in relation to increased human and livestock populations and the resultant agricultural intensification (Smith et al., 1997). Such scenarios tend to force closer integration of crops and livestock, such that soil fertility replenishment depends on manure and urine from livestock, which in turn depend heavily on crop residues for feed. The most intense and integrated crop-livestock interactions occur in the drier parts of West Africa, in the Sudano-Sahelian zone, where annual rainfall is less than 800 mm. Over 50% of the ruminant population of West and Central Africa is found in the dry savannas and Sahel and the numbers of these livestock are predicted to increase at a rate of about 2% per annum between 1988 and 2025 (Winrock, 1992).

Interactions between crops and livestock can be beneficial or, if resources are limiting or overexploited, competitive. The transfer of nutrients from rangelands to cultivated fields by livestock provides the means for a redistribution of nutrients in time and space. Land that is unsuitable for cropping can be grazed thereby producing manure that in turn may make other land more suitable for crop production because livestock transform poor quality, bulky vegetation into products of high economic and nutritive value (Delgado *et al*., 1999). More specifically, direct positive contributions of livestock to soil fertility through manure and urine may include improved organic matter content, supply of nutrients (especially N and P), improved nutrient retention capacity, and a better soil physical condition as a result of improved water holding capacity.

It is also important to be aware of the potential negative effects of livestock on soils in order that these could be minimized. Livestock can contribute to vegetation removal and, through trampling, soil compaction, thereby accelerating soil runoff and erosion which may be associated with increased soil bulk density and decreased infiltration rates (Delgado *et al*., 1999). Through voiding ingested nutrients, especially N in urine, which is subsequently volatilized, livestock may induce nutrient loss to the system (Mohamed-Saleem and Fitzhugh, 1995).

Soil types and their fertility status

The sandy Sahelian soils are dominated by low activity clay soils consisting mainly of Entisols and Alfisols (Kang 1985). Entisols are mainly composed of quartz sand. Alfisols have a clay accumulation horizon and a high base saturation because of lower rainfall and leaching. Both soils have poor structural stability, low water retention and nutrient holding capacity, low organic matter content and low effective cation exchange capacity (ECEC) and are highly susceptible to drought (Kang 1985, Bationo and Mokwunye 1991). Phosphorus is the most limiting factor to crop production in these sandy soils of Sahelian zone followed by nitrogen. Available P in these soils is less than 2 mg P/kg while the amount of total P ranges between 25 to 340 mg/kg with a mean of 109 mg/kg (Manu *et al.*, 1991). These soils therefore present major constraints for arable production.

Nutrient balances are negative for many cropping systems suggesting that farmers in West African countries are mining their soils (Table 2). In Burkina Faso, estimates indicate that in 1983, for a total of 6.7 million hectares of land cultivated, soil nutrient mining amounted to a total loss of 95,000 tonnes of N, 12,100 tonnes of P and 65,000 tonnes of K. The significance of these figures is alarming when it is realized that productivity of these soils in their native state is already low because of low native plant nutrient fertility levels.

Table 2. Aggregated nutrient budgets (losses) for some West African countries

Country	Area (1,000 ha)	Losses for the region (10^5 tonnes)		
		N	P	K
Benin	2,972	41,388	4,524	26,980
Burkina Faso	6,691	95,391	12,111	65,389
Ghana	4,505	137,140	14,101	75,111
Mali	8,015	61,707	7,806	55,395
Niger	985	176,120	24,146	121,721
Nigeria	2,813	1,107,605	138,202	85,499

There is a close relationship between the main dominant soil types in the various agro-ecological zones, while Ferrasols are dominant in the humid zones, Lixisols and Arenosols constitute the major part of in the Sudano-Sahelian zones.

The main physico-chemical features of these soils are as follows:

- Arenosols (Psammients in the American classification).
- Arenosols mainly consist of quartz with low water retention capacity and low nutrient content. These soils account for about 6%, 15%, 10%, 30%, 13% and 30% of the area of Burkina Faso, Mali, Mauritania, Niger, Nigeria and Senegal respectively.
- Lixisols (Alfisols in the American classification).

They form 80%, 46%, 52%, 55%, 34% and 59% of the total area of Benin, Burkina Faso, Ghana, Guinea Bissau, Nigeria and Togo respectively, these are soils which have a horizon characterized by the accumulation of clay with a low nutrient accumulation capacity but are well saturated in cations.

A survey of the physical and chemical properties of selected soils from West Africa was undertaken and multivariate analysis techniques such as discriminate analysis to compare the pearl millet producing soils with the sorghum/maize soils used (Table 3).

Most of the millet, sorghum, and maize-producing soils in West Africa are sandy and it influences the physical and chemical characteristics of these soils. A majority of the West African soils have low levels of organic matter, total nitrogen, and effective cation exchange capacity (ECEC). The main source of nitrogen is accumulated organic matter and its naturally low level of ECEC could be attributed to low organic matter and clay contents, the correlation being higher with organic matter content. The kaolinitic mineralogy of the soil systems also influenced ECEC.

Nitrogen sources and management

Bationo and Mokwunye (1991) reported a very significant relationship between soil organic matter (SOM) and total nitrogen in the Sudano-Sahelian. Soil organic matter is highly correlated with the clay content of soil and as result of the sandy nature of the soils in the Sudano-Sahelian zone, total organic matter remains very low in most of the soils in the region. In many cropping systems, little or no agricultural input is added to the soil. This leads to a decline in soil nitrogen which frequently results in lower crop yields or soil productivity. As predicted by Stoorvogel and Smaling (1990) countries like Burkina Faso, Mali, Niger and Senegal lose as much as 14, 8, 16, 12 kg N/ha per year respectively (Table 4).

In the Sudano-Sahelian zone, there is a flush of N at the beginning of the wet season. The magnitude of this flush seems to be proportional to the duration of the preceding dry season (Semb and Robinson, 1969). This flush may range between 13 to 183 kg N/ha, but to what degree this release of N will be beneficial to the subsequent crop depends on the intensity and the frequency of the rains early in the

Table 3. Univariable analysis of variance of the pearl millet and sorghum/maize soils groups

Variables	Millet		Sorghum/Maize	
	Range	Mean	Range	Mean
pH H_2O	5.2-68	6.09	4.9-76	6.34
pH KCI	4-5.8	4.86	4-6.8	5.41
Organic matter (%)	14-1.9	0.93	8-5.01	2.52
Total N (mg/kg)	31-336	184	181-1,476	723
Exchangeable cation (cmol/kg)				
Ca	0.15-264	1.15	0.34-16	4.78
Mg	0.02-0.94	0.39	0.12-216	1.13
K	0.03-0.33	0.12	0.05-1.13	0.41
Na	0.02.-0.09	0.38	0.01-0.06	0.035
Exchangeable acidity (cmol/kg)	0.05-0.45	0.138	0.02-1.13	0.226
Effective exchange capacity (cmol/kg)	0.54-3.6	1.83	1.77-19.20	7.56
Base saturation (%)	36-98	86.5	36-99	92.3
Maximum P sorbed (mg/kg)		81		180
Aluminum saturation (%)	0-14	1.9	0-46	4.6
Al dithionite (mg/kg)	110-2,509	738	312-5,100	1,481
Fe dithionite (mg/kg)	1,500-25,100	8,535	3,400-15,625	9,795
Fe oxalate (mg/kg)	111-1,500	484	539-3,155	1,554
Al oxalate (mg/kg)	49-502	286	202-1,056	1,056
Bray P1 (mg/kg)	1-112	4.9	1.4-05	16
Total P (mg/kg)	25-191	95	71-941	244
Sand (%)	0.70-0.90	88	2.7-71.94	86
Clay (%)	70-90	2.97	7.8-27.14	5.41

Table 4. N, P, and K losses in selected West African countries

Country	Cultivated area 10^3 ha	Fallow (%)	N	P	K
			(kg/ha cultivated area)		
Benin	2,972	62	-14	-1	-10
Burkina Faso	6,691	50	-14	-2	-10
Gambia	326	29	-14	-3	-16
Mali	8,015	72	-8	-1	-6
Mauritania	846	79	-7	0	-5
Niger	10,985	47	-16	-2	-11
Nigeria	32,813	18	-34	-4	-24
Senegal	5,235	53	-12	-2	-10
Togo	1,503	49	-18	-2	-12

Sources: Stoorvogel and Smaling 1990

season. Annual crops will not have developed sufficiently to utilize a significant proportion of the N flush early in the season hence, most of it is susceptible to losses through leaching (Ssali *et al*. 1986).

Due to a lack of synchrony between nutrients released by soil organic matter and mineral fertilizer, nutrients especially N, are lost through leaching, volatilization, and denitrification. As pointed out by Myers *et al*. 1994, synchrony can be promoted by manipulating plant demand (controlling planting date, duration of crop to be grown, use of crops with different growth patterns in multiple cropping systems).

For many years several scientists in the Sudano-Sahelian zones initiated research to assess the efficiency of N fertilizers in order to increase food production (Christianson and Vlek 1991, Bationo *et al*. 1989, Bationo and Vlek 1998). Urea and calcium ammonium nitrate (CAN) are the most common sources of N used by farmers. Results of trials undertaken to evaluate these two sources and methods of application of nitrogen led to the conclusions that: 1) fertilizer N recovery by plants was low; 2) there is a higher loss of N at the placement point of urea (>50%) and the mechanism of N loss is believed to have been associated with ammonia volatilization; 3) losses of N from CAN were less than from urea because one-half of the N in CAN is in the non-volatile nitrate form; 4) although CAN is a lower N analysis fertilizer than urea, it is attractive as an N source because of its low potential for N loss via volatilisation and its low soil acidifying properties (Table 5) (Bationo *et al*. 2003). Point placement of CAN outperformed urea point placed or broadcast and ^{15}N data from similar trials indicate that uptake by plants was almost three times higher than that of urea applied in the same manner (Figure 5).

Table 5. Recovery ^{15}N fertilizer by pearl millet applied at Sadore, Niger, 1985

N source	Application method	^{15}N Recovery Grain (%)	Stover	Soil	Total
CAN	Point incorporated	21.3	16.8	30.0	68.1
CAN	Broadcast incorporated	10.9	10.9	42.9	64.7
Urea	Point incorporated	5.0	6.5	22.0	33.5
Urea	Broadcast incorporated	8.9	6.8	33.2	48.9
Urea	Point surface	5.3	8.6	18.0	31.9
S.E.		1.2	2.0	1.9	2.4

Sources: Christianson and Vlek, 1991

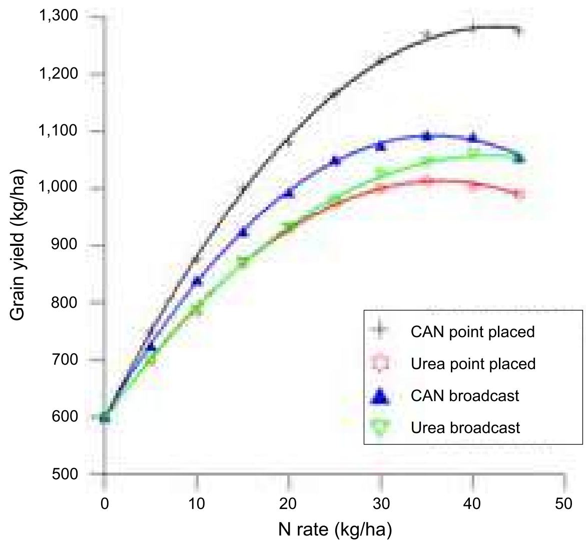

Figure 3. Effect of broadcast and point application methods for Urea and CAN on grain yield of pearl millet Christianson and Vlek (1991) found that the optimum N rate for sorghum is 50 kg/ha and 30 kg/ha for pearl millet

Nitrogen use efficiency can be increased through rotation of cereals with legumes and through the optimization of planting density. Bationo and Vlek (1998) reported a N-use efficiency of 20% in the continuous cultivation of pearl millet but the value increased to 28% when pearl millet was rotated with cowpea. In a study by Bationo *et al*. (1989) found a strong and positive correlation between planting density and response to N fertilizer.

Crop rotation

Rotation of cereals and legumes is a cheaper means of improving N availability. Cereal/legume rotation effects on cereal yields have been reported by several researchers (Bagayoko *et al*. 1996; Bationo *et al*. 1998; Bationo and Ntare 1999). Table 6 shows the effect of cowpea-millet rotation on millet grain and total biomass production. In a period of three years, there was an increase of about 3 t/ha of total dry matter production when millet was grown in rotation with cowpea.

Table 6. Millet grain and total dry matter yield at harvest as influenced by millet/cowpea cropping system at Sadore (Niger)

Cropping system	Grain yield 1996	1997	1998	Total dry matter yield 1996	1997	1998
	kg ha^{-1}					
Continuous millet	937	321	1,557	4,227	2,219	6,992
Millet after cowpea	1,255	340	1,904	5,785	2,832	8,613
P > F	<0.001	0.344	<0.001	<0.001	<0.001	<0.001

Source: Bationo and Ntare, 2000

Nitrogen use efficiency increased from 20% in continuous pearl millet cultivation to 28% when pearl millet was rotated with cowpea. Nitrogen derived from the soil is better used in rotation systems than with continuous millet (Bationo and Vlek 1998). Nitrogen derived from the soil increased from 39 kg N/ha in continuous pearl millet cultivation to 62 kg N/ha when pearl millet is rotated with groundnut. Those data clearly indicate that although all the above biomass of the legume will be used to feed livestock and not returned to the soil, rotation will increase not only the yields of succeeding cereal but also its nitrogen use efficiency (Bationo and Vlek 1998).

The response of legumes to rotation was also significant and legume yields were consistently lower in monoculture than when rotated with millet (Figure 4). This suggests that factors other than N alone contributed to the yield increases in the cereal-legume rotations.

Phosphorus sources and management

Among soil fertility factors, phosphorus deficiency is a major constraint to crop production in the Sudano-Sahelian zone. For many years, research has been undertaken to assess the extent of soil phosphorus deficiency, to estimate phosphorus requirement of major crops, and to evaluate the agronomic potential of various phosphate rock (PR) from local deposits (Bationo *et al.*, 1990). About 80% of the soils in sub-Saharan Africa are short of this critical nutrient element and without the use of

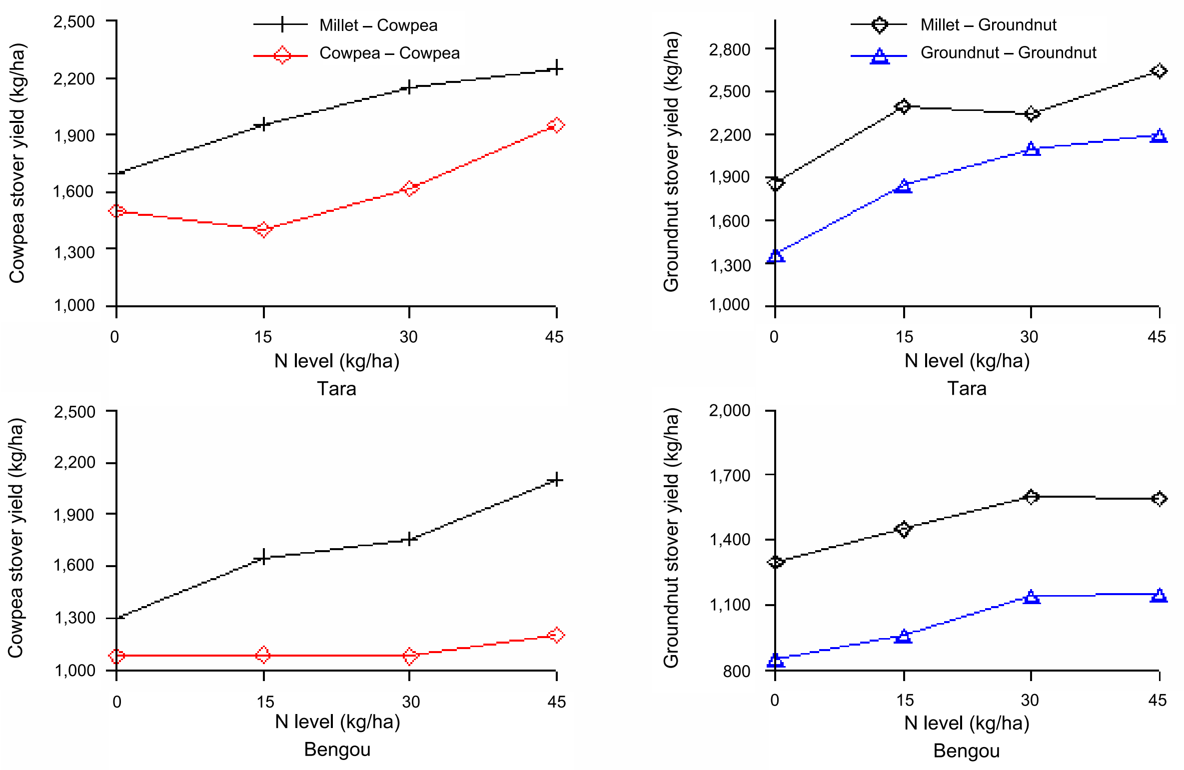

Figure 4. Effects of nitrogen and rotation on legume stover yield (kg/ha), average of four years (1989-1992) at Tara and Bengou, Niger

phosphorus, other inputs and technologies are not effective. However, sub-Saharan Africa use 1.6 kg P/ha of cultivated land as compared to 7.9 and 14.9 respectively for Latin America and Asia. It is now accepted that the replenishment of soil capital phosphorus is not only a crop production issue, but an environmental issue and P application is essential for the conservation of the natural resource base.

Availability and total P levels of soil are very low in the sandy Sudano-Sahelian zones of West Africa (SSZWA) as compared to the other soils in West Africa (Manu et al. 1991). For the sandy Sahelian soils total P values can be as low as 40 mg P/kg and the value of available P less than 2 mg P/kg. A study of the fertility status of selected pearl millet producing soils of West Africa, (Manu et al. 1991) found that the amount of total P in these soils ranged from 25 to 340 mg/kg with a mean of 109 mg/kg. The low content of both total and available P parameters may be related to several factors including 1) parent materials, which are mainly composed of aeolian sands, contain low mineral reserves and lack primary minerals necessary for nutrient recharge; 2) a high proportion of total P in these soils is often in an occluded form and is not available to crop (Charreau, 1974); 3) low level of organic matter and the removal of crop residue from fields. Organic matter has a favourable effect on P dynamics of the soil; in addition to P release by mineralization, the competition of organic ligands for Fe and Al oxides surface can result in a decrease in P fixation of applied and native P.

The P sorption characteristics of different soil types have been investigated and compared to the soils of the more humid regions. The soils of the SSZWA have very low capacity to fix P (Sanchez *et al.*, 1980). For pearl millet producing soils, Manu *et al.* (1991) fitted the sorption data to Langmuir equation (Langmuir 1918), values of maximum P sorbed ranged from 27 mg/kg to 253 mg/kg with a mean of 94 mg/kg.

Phosphorus deficiency is a major constraint to crop production and responses to nitrogen applications are substantial only when both moisture and phosphorus are not limiting. Field trials were established to determine the relative importance of N, P and K fertilizers. The data in Table 7 indicates that from 1982 to 1986 the average control plot yield was 190 kg grain/ha. The sole addition of 30 kg P/ha without N fertilizers increased the average yield to 714 kg/ha. The addition of only 60 kg N/ha did not increase the yield significantly over the control and the average grain yield obtained was 283 kg/ha. The data clearly indicate that P is the most limiting factor in these sandy Sahelian soils and there is no significant response to N

Table 7. Effect of N, P, and K on pearl millet grain and total dry matter (kg/ha) at Sadoré and Gobery (Niger)

Treatments	1982		1983		1984		1985	1986	
	Sadoré		Sadoré	Gobery	Sadoré		Sadoré	Sadoré	
	Grain	TDM	Grain	Grain	Grain	TDM	Grain	Grain	TDM
N0P0K0	217	1,595	146	264	173	1,280	180	180	1,300
N0P30K30	849	2,865	608	964	713	2,299	440	710	2,300
N30P30K30	1,119	3,597	906	1,211	892	3,071	720	930	3,000
N60P30K30	1,155	3,278	758	1,224	838	3,159	900	880	3,200
N90P30K30	1,244	3,731	980	1,323	859	3,423	1,320	900	3,400
N120P30K30	1,147	4,184	1,069	1,364	1,059	3,293	1,400	1,000	3,300
N60P0K30	274	2,372	262	366	279	1,434	290	230	1,500
N60P15K30	816	2,639	614	1,100	918	3,089	710	920	3,100
N60P45K30	1,135	3,719	1,073	1,568	991	3,481	1,200	980	3,500
N60P30K0	1,010	3,213	908	1,281	923	3,377	920	910	3,400
S.E.	107	349	120	232	140	320	162	250	400
C.V. (%)	24	22	26	30	24	22	28	32	25

N.B. Nutrient applied are N, P and K kg/ha

TDM = Total dry matter

without correcting first for P deficiency. When P is applied the response to N can be substantial and with the application of 120 kg N/ha pearl millet grain yields of 1,173 kg/ha were obtained as compared to 714 kg/ha when only P fertilizers were applied. Over all years the addition of potassium did not increase significantly the yield of both grain and total dry matter of pearl millet.

The use of alternative locally available phosphate rock

Phosphate Rock utilization

Despite the fact that deficiency of P is acute on the soils of West Africa, local farmers, use very low amounts of P fertilizers partly because of the high cost. The use of locally available phosphate rock (PR) could be an alternative to imported P fertilizers. Bationo *et al*. (1987) showed that direct application of local PR could be more economical than imported water-soluble P fertilizers. Bationo *et al*. (1990) showed that Tahoua PR from Niger was suitable for direct application, but Parc-W from Burkina Faso had less potential for direct application. The effectiveness of local phosphate rock depends on its chemical and mineralogical composition, the most important feature being the ability of carbonate ions to substitute for phosphate in the apatite lattice which influences the solubility, and controls the amount of phosphorus available to crops (Smith and Lehr, 1966). As shown in Table 8, in medium to long-term experiments, Tilemsi PR which is a medium-reactive rock with a total P_2O_5 of 29%, was practically equivalent to TSP per unit P (Zapata and Roy, 2004). Its relative agronomic effectiveness averaged about 80% compared to TSP.

Table 8. Yield of Millet, groundnut, sorghum, cotton and maize with Tilemsi PR and TSP in Mali, 1982-87

Fertilizer treatment	Grain yield (kg/ha/yr)	Productivity (kg/P/year)
Control with N and K applied	676	
Tilemsi PR basal application 120 kg P/ha	1,110	3.6
TSP annual application 30 kg P/ha	1,302	3.4

Phosphorus (P) placement and P replenishment with Phosphate rock

Fertilizer management practices also play an important role in increasing P use efficiency. The data in Table 9 clearly shows that hill placement of small qualities of P fertilizers resulted in a higher phosphorus use efficiency (PUE) when compared to the broadcasting of 13 kg P/ha as recommended by the extension services.

Single Superphosphate (SSP), Tahoua Phosphate Rock (TPR) and Kodjari Phosphate Rock (PRK) were broadcast (BC) and/or hill placed (HP). For pearl millet grain P use efficiency (PUE) for broadcasting SSP at 13 kg P/ha was 18 kg/kg P but hill placement of SSP at 4 kg P/ha gave a PUE of 83 kg/kg P. Whereas the PUE of TPR broadcast was 16 kg grain/kg P, the value increased to 34 kg/kg P when additional SSP was applied as hill placed at 4 kg P/ha. For cowpea fodder PUE for SSP broadcast was 96 kg/kg P but the hill placement of 4 kg P/ha gave a PUE of 461 kg/kg P. Those data clearly indicate that P placement can drastically increase P use efficiency and the placement of small quantities of water-soluble P fertilizers can also improve the effectiveness of phosphate rock (Table 9).

PUE in the sandy soils of West Africa can also be dramatically increased with the adoption of improved crop and soil management technologies. Whereas the absolute control recorded 33 kg ha^{-1} of pearl millet grains, 1,829 kg ha^{-1} was obtained when phosphorus, nitrogen and crop residue was applied to the ridge and fallowed leguminous cowpea in the previous season. Results indicate, for the grain yield, that PUE increases from 46 with only P application to 133 when P is applied in combination with nitrogen, crop residues and the crop is planted on ridges in a rotation system (Table 10).

Combined organic and inorganic nutrient sources

Combined application of organic resources and inorganic inputs resources in agricultural production has gained increasing popularity in the recent years. Farmyard manure and crop residues are frequently the most widely used because of their availability to farmers. Although most of these are often low in N and

Table 9. Effect of P sources and placement on pearl millet and cowpea yield (kg/ha) and P use efficiency (PUE) (kg/kg P)

Treatments		Millet in 2001		Cowpea in 2001		Millet in 2002		Cowpea in 2002	
P sources and methods of placement		Grain yield	PUE	Fodder	PUE	Grain yield	PUE	Fodder	PUE
1	Control	468		1,406		634		1,688	
2	SSP (BC)	704	18	2,656	96	887	19	2,375	134
3	SSP (BC) + SSP (HP)	979	30	4,468	180	1,898	74	3,125	147
4	SSP (HP)	798	83	3,250	461	1,026	98	2,969	584
5	15-15-15 (BC)	958	38	4,250	219	1,110	37	3,813	245
6	15-15-15 (BC) + 15-15-15 (HP)	1,559	64	6,500	300	2,781	126	5,156	266
7	15-15-15 (HP)	881	103	4,062	664	1,196	141	3,531	724
8	TPR (BC)	680	16	2,531	86	744	8	2,094	112
9	TPR (BC) + SSP (HP)	1,048	34	3,781	140	1,039	24	3,375	161
10	TPR (BC) + 15-15-15 (HP)	1,065	35	4,281	169	1,242	36	3,844	189
11	PRK (BC)	743	21	2,468	82	745	9	2,469	141
12	PRK (BC) + SSP (HP)	947	28	4,750	197	1,002	22	3,219	152
13	PRK (BC) + 15-15-15 (HP)	1,024	33	5,125	219	1,171	32	3,688	180
S.E.		46		120		60		222	
C.V.		18%		11%		10%		14%	

SSP: Single Superphosphate, 15-15-15: N2 P2O5 K2O compound fertilizer
TPR: Tilemsi Phosphate Rock, PRK: Kodjari Phosphate Rock
BC: Broadcast at 13 kg P/ha, HP: hill placed at 4 kg P/ha
PUE: P use efficiency kg yield/kg P applied

Table 10. Effect of mineral fertilizers, crop residue (CR) and crop rotation on pearl millet yield (kg/ha) and phosphorus use efficiency (PUE) Sadore, Niger, 1998 rainy season

Treatment	Without CR, Without N				Without CR, With N				With CR, Without N				With CR, With N			
	TDM Yield	PUE	Grain Yield	PUE	TDM Yield	PUE	Grain Yield	PUE	TDM Yield	PUE	Grain Yield	PUE	TDM Yield	PUE	Grain Yield	PUE
Control	889		33		2,037		58		995		61		1,471		98	
13 kg P/ha	2,704	140	633	46	4,339	177	1,030	75	4,404	185	726	51	240	4,594	1,212	86
13 kg P/ha + ridge	2,675	137	448	32	4,057	155	946	68	3,685	210	785	56	4,530	235	1,146	81
13 kg P/ha + rotation	5,306	340	1,255	94	6,294	327	1,441	106	5,392	338	1,475	109	6,124	358	1,675	121
13 kg P/ha + ridge + rotation	5,223	333	1,391	104	5,818	291	1,581	117	6,249	404	1,702	126	7,551	468	1,829	133
S.E.	407		407		407		407		407		407		407		407	

CR = Crop Residue; N = Nitrogen; TDM = Total Dry Matter; PUE (kg grain/kg P); TDM = Total dry matter

P, numerous research reports show large crop yield increases resulting from combination of organic resources and mineral fertilizers in the Sahelian zone of West Africa (Abdullahi and Lombin 1978; Bationo *et al*., 1993; Bationo *et al*., 1998; Pieri, 1989).

Manure plays a substantial role in enhancing crop yields on nutrient poor West African soils (Sedogo, 1993). According to Bationo *et al.* (2004), studies conducted in Mali, Burkina Faso and Niger show that manure collected from stables and applied alone produced about 34-58 kg of cereal grain dry matter (DM)/t manure and 106-178 kg of DM/t manure in stover. The application of manure together with inorganic fertilizer gave yields of 80-90 kg of grain DM/t manure and 84-192 kg of stover DM/t manure. Combined use of manure and mineral fertilizer show a long-term increase of sorghum yields over years (Figure 5). Bationo and Mokwunye (1991) have also shown that manure can help supply P when they found no difference between applying 5 t/ha of FYM and 8.7 kg P/ha as Single Superphosphate. According to Palm (1995) for a modest yield of 2 t/ha of maize the application of 5 t/ha of high quality manure can meet the N requirement but this cannot meet the P requirements in areas where P is deficient.

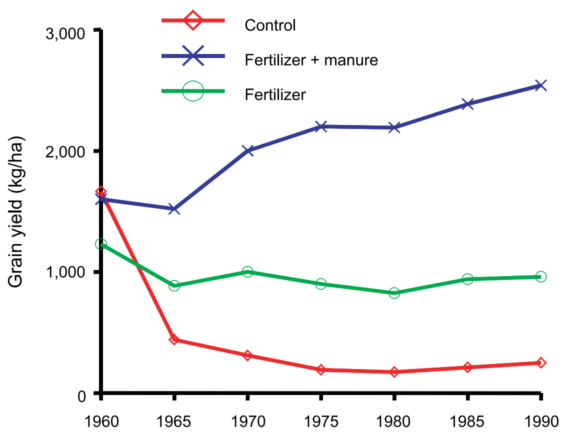

Figure 5. Sorghum grain yield as affected by mineral and organic fertilizers over time. Source: Sedogo (1993)

A significant effect between crop residue and mineral fertilizer on crop yield has also been reported (Bakayoko *et al*. 2000). From a long-term experiment initiated in 1984 in Sadore, Niger, Bationo *et al.* (1993) found that grain yield declined to 160 kg/ha in un-mulched and unfertilized plots as compared to 770 kg/ha with a mulch of 2 t crop residues per hectare and 1,030 kg/ha with 13 kg P plus 30 kg N/ha. Further, the combination of crop residue and mineral fertilizers resulted in grain yield of 1,940 kg/ha. Table 11 shows that, at the same level of target P, treatments with combined mineral and organic fertilizers had the highest yields demonstrating the advantage of combined nutrient application. In 2004 for example, the use of only inorganic P sources yielded respectively 1,350 kg/ha and 3,156 kg/ha of cowpea fodder whereas the same rate in the combined organic-inorganic form (6 t manure, 3 kg P and 30 kg N/ha) gave 2,088 kg/ha and 4,219 kg/ha at Banizoumbou and Karabedji respectively (Table 11).

Table 11. Optimum combination of plant nutrients for millet grain and cowpea fodder (kg/ha) at Banizoumbou and Karabedji, Niger, 2004 cropping season

Treatments	Banizoumbou		Karabedji
	Millet grain yield	Cowpea fodder yield	Cowpea fodder yield
Absolute Control	432	481	2,125
30 kg N/ha	661	650	2,813
12 kg P/ha	1,036	719	3,625
8 tonnes manure + 30 kg N/ha	1,359	1,888	3,562
6T manure + 3 kg P + 30 kg N/ha	1,172	2,088	4,219
4T manure + 6 kg P + 30 kg N/ha	1,255	1,869	3,719
2T manure + 8 kg P + 30 kg N/ha	1,510	2,025	3,344
12 kg P + 30 kg N/ha	1,396	1,350	3,156
S.E.	75	182	140
C.V.	14%	26%	12%

In different parts of SSA, application of organic residues has been shown to increase soil P availability due to the complexation of iron and aluminium by organic acids (Sahrawat *et al.*, 2001; Kretzschmar *et al.*, 1991), resulting in better root growth (Hafner *et al.*, 1993), improve potassium (K) nutrition (Rebafka *et al.*, 1994), protect young seedlings against soil coverage during sand storms (Michels *et al.*, 1995), increase water availability (Buerkert et al., 1996), and reduced soil surface resistance by 65% and topsoil temperature by over 4°C (Buerkert *et al.*, 1996), maintain soil organic carbon in the topsoil, increase the ECEC and subsequently the nutrient holding capacity of these soils (Bationo and Mokwunye 1991; De Ridder and van Keulen 1990). The application of 4 t of crop residue per hectare for example maintained soil organic carbon at the same level as that in an adjacent fallow field in the top soil but continuous cultivation without mulching resulted in drastic reduction organic carbon (Figure 6). These effects are stronger especially in the Sahelian zone, but weaker in other areas with lower temperatures, higher rainfall and heavier soils (Buerkert *et al.*, 1996). Organic amendments have also been reported to reduce the capacity of the soil to fix P

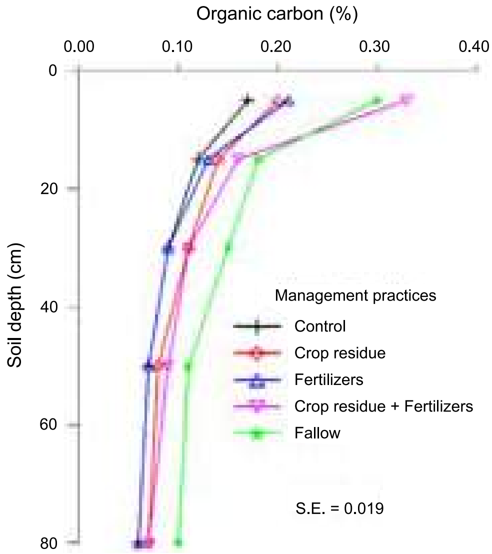

Figure 6. Effect of different management practices on soil organic carbon content after 14 years of cultivation, Sadore, Rainy season 1997

thereby increasing P availability for uptake and hence higher P use efficiency (Sahrawat *et al*., 2001).

Availability of organic inputs in sufficient quantities and quality is one of the main challenges facing farmers and researchers today (Bationo and Buerkert 2001). On fields of unfertilized local cultivars, grain yield averaged only 236 kg/ha and mean residue yields barely reached 1,300 kg/ha. In light of many competing uses for biomass such as fodder and fuel for cooking, it is unlikely that the recommended levels of crop residue could be available for use as mulch. At planting, although farmers require at least 2 t/ha of crop residue for mulch, only 250 kg/ha of crop residue is presently available.

Cropping systems management

Widespread use of cereal/legume rotations or intercrops has been suggested as a means to sustainably meet increasing food demands in West Africa (Alvey *et al*., 2001). Integration of cereals and legumes in production systems has been tested in order to utilize the N fixation ability and the P solubilization potential of legumes. Nitrogen-15 (^{15}N) for example used to quantify the amounts of nitrogen fixed by cowpea under different soil fertilization levels has shown that nitrogen derived from the air (NDFA) varies from 65 to 88% and can reach up to 89 kg N/ha (Bationo and Vlek 1998). The legume-cereal rotations will increase both the yield of succeeding cereal crops and its nitrogen use efficiency. In addition to that, the above-ground legume biomass is high quality forage for livestock.

Rotation of cereals and legumes is a cost effective means of improving soil fertility and productivity. Field experiments at several sites in West Africa have shown cereal yield increases in cereal/legume rotations of between 15 and 79% compared with continuous cereal systems. Rotation of cereals with legumes increases N use efficiency. For example, Bationo and Vlek (1998) have shown that nitrogen use efficiency increased from 20% in continuous pearl millet cultivation to 28% when pearl millet was rotated with cowpea. However, the degree to which N is involved as a driving force in these effects remains unclear (Bagayoko *et al*., 2000; Bationo *et al*., 1998). It has been assumed by many workers that the positive effect of rotations arises from the added N from legumes in the cropping system. Some workers, however, have attributed the positive effects of rotations to an improvement of soil biological and physical properties and the ability of some legumes to solubilize occluded P and highly insoluble calcium bounded phosphorus by legume root exudates (Arhara and Ohwaki 1989; Sahrawat et al. 2001) and to the lower amounts of plant parasitic nematodes (Pierce and Rice, 1988). Other advantages of crop rotations include soil conservation (Stoop and Staveren 1981), organic matter restoration (Spurgeon and Grisson 1965) and pest and disease control (Sunnadurai 1973; Pierce and Rice, 1988).

The data in Figure 7 illustrate the response of pearl millet grain to the crop rotation and to different inputs of organic and inorganic fertilizers. Farmer's practices yielded 161 kg/ha with no fertilizer and 631 kg/ha with the application of 13 kg P and 45 kg N/ha However, when these mineral fertilizers were combined with 2.7 t/ha of manure or crop residue in rotation with cowpea, yields of 1,504 kg/ha were achieved. The highest yield was observed in treatments involving rotation as opposed to no rotation treatments at the same rate of manure or crop residue.

Changes in soil chemical properties from long-term cropping system management trials, monitored in different agro-ecological zones of the Sudano-Sahelian region showed that rotations resulted in significantly higher soil pH, total N and effective cation exchange capacity (ECEC) (Bationo *et al*. 1995). In the long-term cropping system management studies in the Sahel, rotation systems were found to have higher levels of organic carbon compared to the continuous cropping system (Figure 8). This could partially be due to the contribution made by the fallen leaves of the cowpea crop in the crop rotation.

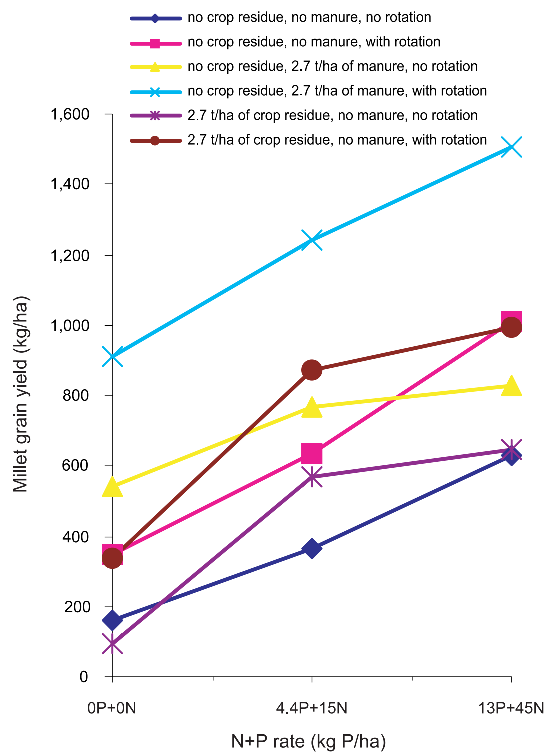

Figure 7. Effect of different N and P rates on pearl millet grain yield, Sadore, Niger, 2004 rainy season

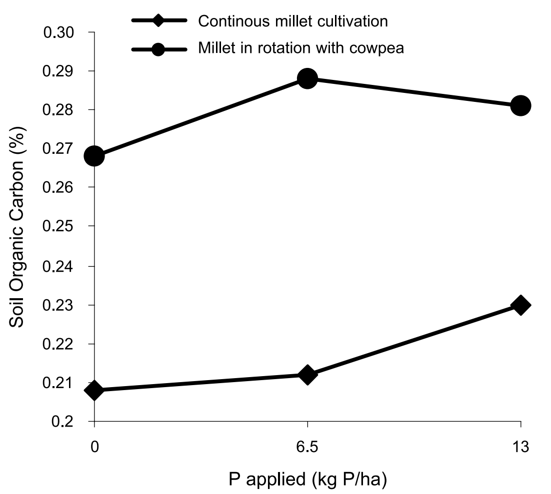

Figure 8. Effect of phosphorus and cropping system on soil organic carbon, Sadore, Niger, 1995

Combined water harvesting and integrated nutrient management (INM)

The intensification of crop production requires an integration of soil, water and nutrient management that is locally acceptable and beneficial for smallholder farmers (Zougmore, 2003a). Some methods such as terraces, minimum tillage, contour plots, tied ridges, stone bunds/lines, vegetative bands/diguettes, buttages, and Zaï (half moons) are used in the semi-arid lands of West Africa. According to Rockstrom *et al*. (2001) the keys to improved water productivity and mitigating intra-season dry spells in rainfed agriculture are maximizing the amount of plant available water and plant water uptake capacity. This implies systems that partition more incident rainfall to soil storage and less to runoff, deep percolation and evaporative loss, as well as crops that provide more soil cover and root more deeply (Rockstrom *et al*., 2001). In the Central Plateau of Burkina Faso stone bounds alone doubled sorghum yield compared to plots without stone bounds and therefore, can reduce risks of crop failure in erratic rainfall years (Zougmore, 2003a). Taonda *et al*., (2003) found that water harvesting alone with stone bunds did not improve yields but the combination of water harvesting with stone bunds or zai plus manure more than doubled sorghum yields when compared to the control (Table 12).

Table 12. Variation of the grain yields of the sorghum during four years (kg/ha)

Treatments	2000	2001	2002	Average
Control	353	393	215	331
Stone bunds	394	574	504	397
CP + Manure	1,026	1,168	1,072	789
Zaï + Manure	1,188	176	1,267	805

Source: Adapted from Taonda et al., (2003)

A study by Zougmore and Zida (2000) has clearly shown the effects of the spacing between installations of stone bunds on decreasing runoff, erosion and increasing yields. A spacing of 50 m reduced runoff by 5%, a spacing of 33 m by 12% and that of 25 m by 23%. Yield losses were reduced by 21% with a spacing of 50 m and 61% with a spacing of 25 m. With lower rainfall than normal, whereas yield increases were 58% with spacing of 50 m, it increased up to 343% with a spacing of 25 m. In a normal year increases were however not as much and the trend was even negative in years when rainfall was higher than the long-term average.

Zougmore et al. (2003a) found an average reduction in runoff of up to 59% in plots with barriers alone, but reached 67% in plots with barriers + mineral N and 84% in plots with barriers + organic N. On average, stone bunds reduced soil erosion more than grass strips (66% versus 51%). Integrated water and nutrient management may help to alleviate poverty and may empower smallholder farmers to invest in soil management for better crop production (Zougmore, 2003a).

The higher yields with Zai only (1,968 kg/ha) compared to N (1,490 kg/ha) and P (1,524 kg/ha)

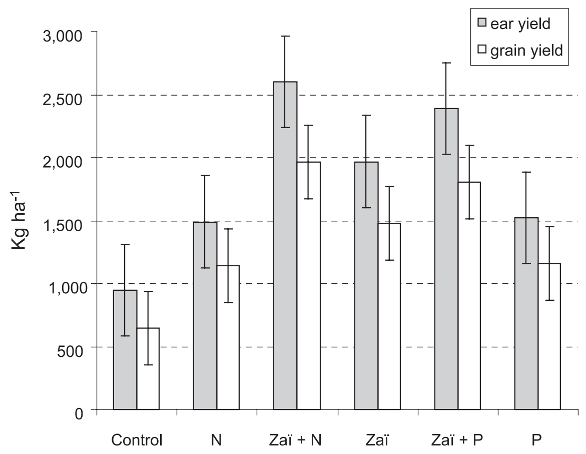

Figure 9. Effect of Zai, N and P on sorghum ear and grain yield in Tougouri, Burkina Faso, 2004 (Badiori et al. unpublished data)

treatments showed that water is the most limiting resource to crop production in the West African Sahel (Figure 9). Higher yields were observed when water harvesting techniques using Zai were combined with either N or P pointing to better fertilizer use efficiency.

Restoring favourable soil moisture conditions by breaking up the surface crust to improve water infiltration (half-moon technique) with appropriate nutrient management could be an effective method for the rehabilitation of degraded soil and improving productivity (Zougmore *et al*., 2003b). Animal drawn rippers and subsoilers could increase water productivity by increasing water infiltration and storage as well as root penetration (Rockstrom *et al*., 2001). Considerable yield increases above "farmers' practices" (i.e. flat cultivation and no fertilizer) could be realized by combining tied-ridged tillage with inputs of mineral N and P fertilizer, reaching maize grain yield levels of six times the prevailing yield under farmers' practices of approximate 1 t/ha (Jensen *et al*., 2003).

Conclusions

The use of rotation systems, organic and inorganic nutrients combinations and water harvesting technologies are an attractive alternative to the traditional farming systems in the Sahel, not only for increased food production but also for soil fertility improvement. However, few resource poor farmers have adopted the technologies proposed by researchers because of their capacity to invest in onerous soil fertility management and other socio-economic factors. To be adopted, researchers have to test their technologies in a participatory approach with land users. Consideration of the economic benefits of the technologies may be an important prerequisite for the success of adoption of the technologies. Besides, markets are increasingly becoming part of the research process since farmers have to trade cash crops and excess food crops produced.

Future research challenges include combining rainwater and nutrient management strategies to increase crop production and prevent land degradation, increasing the legume component for better integration of crop-livestock production systems, exploiting the genetic variation for nutrient use efficiency and integration of socio-economic and policy research with the technical solutions. Another very important issue for research is how to increase crop biomass availability at the farm level to alleviate the constraint of non-availability of organic amendments in order to maintain adequate soil organic matter levels for favourable soil conditions. Providing farmers with appropriate technologies and alternatives to soil mining and integrating the above and below ground resources conservation will contribute to the maintenance of soil quality. Selection of genotypes that can efficiently associate with Vesicular-Arbuscular Mycorrhizal (VAM) for better utilization of P applied as indigenous phosphate rock will increase benefits from these resources and increase their appeal to farmers. Use of decision support systems, modeling, and GIS is important in order to extrapolate research findings to other areas in which successful technologies can be expanded/scaled out to reach several farmers.

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Farmer perceptions, choice and adoption of soil management technologies in maize-based farming systems of Malawi

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Keywords: Farmer adoption, new technologies, maximum livelihood estimation, participatory research methods

Abstract

Rapidly declining soil productivity amidst diminishing per capita holdings of arable land poses a severe threat to sustainability of agricultural production and livelihoods for the majority of the farming population in Southern Africa. Due to their heavy dependence on agriculture, efforts to sustain the soil resource base are critical to stimulating economic development in these countries. Unfortunately, adoption of improved recommendations still remains very minimal while efforts to understand farmers' decision-making environment with regard to adoption of soil conservation technologies have been sidelined.

Consequently, a research project was commissioned with funding from the Rockefeller Foundation to better understand the socio-economic and technological factors that shape adoption decisions of soil management technologies in an increasingly vulnerable environment. Farmer Participatory Research Methods (FPR) and Maximum Likelihood Estimation Procedures (MLE) were employed to understand the effects of farmers' perceptions, knowledge and socio-economic orientation on subsequent adoption of a wide range of soil management technologies.

Results from all research sites indicated that the majority of smallholder farmers did experience soil degradation problems though most of them were unaware of the soil management technologies that could help to reverse this trend. Sand and sandy loam soils were the most common soil types present in their farms and due to the nature of these soils, farmers expressed difficulties in identifying specific technologies to address the rampant soil degradation prevalent in these fields. The most common management practices used by farmers to restore soil fertility were the use of green and grain legumes, application of inorganic fertilizer and compost manure. Common practices to control soil erosion ranged from use of vetiver grass, construction of box and contour ridges to the use of agroforestry techniques. Factors such as access to credit, food security, literacy levels, on-farm income and extension services were critical in influencing adoption of these soil management practices.

Introduction

Soil Fertility Initiatives in Malawi

Declining soil fertility ranks high among the factors limiting smallholder arable crop production in Malawi (Snapp *et al.*, 1998). This problem has been caused by diminishing land holding sizes as a result of the ever-increasing population growth rate currently at 3.2%. The problem has of late been exacerbated by continuous cultivation on the same piece of land as well as cultivation of fragile hill slopes with little or no application of inorganic fertilizers due to escalating prices as a result of removal of input subsidies.

The Risk Management Project and the Soil Fertility Network for Southern Africa have been working in Central Malawi at Chisepo Extension Planning Area between 1999-2004 growing seasons in collaboration with Bunda College of Agriculture, a constituent college of the University of Malawi. The two projects aimed at developing sustainable resource-conserving farming methods in collaboration with smallholder farmers in Malawi by integrating modeling, economic analysis as well as farmer participatory research in identifying viable soil fertility technologies for small scale farmers.

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Study Location

The study was conducted in Chisepo, Central Malawi, in 2002-2004 seasons. Chisepo is located in Kasungu Agricultural Development Division (KADD) North of Lilongwe, in the mid-altitude area of the Lilongwe-Kasungu plains. The most common soils are sandy loamy soils (60%) and sandy soils (30%). These soils are generally low in soil organic matter (0.25%), total nitrogen (0.1%) and range in pH from 5.6 to 5.8. Without soil fertility management technology interventions the soils barely produce adequate crops. The main crops grown in the area are maize and tobacco. Maize yields range from as low as 0.1 t ha^{-1} to 2.5 t ha^{-1}. Annual rainfall is 600-800 mm (Kamanga 2002). Farmers produce a wide range of crops such as Maize (dominant food crop), tobacco (dominant cash crop), groundnuts, soyabeans, beans, cassava, sweet potato and vegetables.

Farmer experimentation, trial design and data collection

The Mother-Baby trial approach was used in the experimentation process. This allowed quantitative data from researcher managed on-farm 'mother trials' to be systematically cross-checked with farmer-managed 'baby trials' with similar themes. The mother trials tested different soil fertility management technologies mainly the incorporation of grain and green legumes and fertilizer management trials.

The mother fields were placed on sandy soils and red (*katondo*) soils. In each mother trial, farmer chosen legumes were put in intercrop with maize and as sole legumes planted at the same time. The mother trial was replicated three times. Farmers also chose legumes based on what they prefer. The legumes chosen were planted in the baby trials. In this case, farmers wanted all the ten legumes to be subjected to intercropping or rotation with maize. The legumes were *mucuna, pigeon pea, bambara, soybean, groundnut, cowpea* (Determinate and indeterminate), *tephrosia, grahamiana and sunhemp*. Each mother trial was set in a simple way intercropping maize with legumes and sole legumes. In the baby trials, each farmer chose four legumes from the mother trials to plant in their fields. Follow up was made to see how each farmer had planted the legumes where they planted them and why they did what they had done.

Two sets of data was collected, namely, agronomic data sets which included soil sampling for nitrogen status, texture, soil pH, phosphorous status; and crop performance as measured by grain yield and harvest indices. Socio-economic data which is the major focus of this report was also collected using farmer participatory methodologies (FPR) which included focus group discussions and pairwise ranking. Farmer groups averaging 20-25 members per group who participated in these on-farm farmer research trials were consulted. Additionally, a short structured questionnaire was administered to all the participating farmers (70 farmers in total). Information collected included farmer derived taxonomies for soil and fertility status, farmer socio-economic characteristics, perceptions of the various soil fertility technologies as well as the factors that constrained increased adoption of these technologies.

Results and discussions

Socio-economic characteristics of farmers in the studied area

The majority of the smallholder farmers working on the project were men (76%). Very few women farmers took part in the experimentation process and the main reason for this was lack of interest from the women farmers. Most of the women farmers were suspicious of the project at first, as they did not understand the benefits of hosting the trials. Most farmers were illiterate and did not use manure in their farming system because of a reduction in stock levels of late due to theft. Very few farmers also applied inorganic fertilizer in their farms mainly due to increased prices of the commodity as a result of the market liberalization and removal of subsidies. More socio-economic characteristics as reported by farmers are presented in Table 1 below.

Table 1. Selected Socio-economic Indicators of farmers in the study area

Variable	Figure
Mean household size (number of members)	5.20
Consumer: worker ratio (dependency ratio)	1.30
Average land holding size (ha)	1.90
Male (%)	76.00
Illiteracy levels (%)	54.60
Primary education of household head (years)	4.10
Fertilizer use on maize (%)	30.00
Manure use on maize (%)	18.00
Maize yield-Hybrid (t ha^{-1})	1.42-3.25
Livestock ownership (%)	15

Soil characterization and fertility management in Malawi

Farmers classified soils based on what they saw and felt about that particular soil. There were certain inherent factors which farmers used to classify and characterize soil types. The most important ones were color, fertility, land type and depth of the soil. Characteristics such as slope, water holding capacity, ease of tilling, physical properties such as stickiness or firmness were also used. The actual fertility status of the soil was also determined by the location and previous soil management techniques that the farmer had been using previously on that piece of land.

The most common soils in the area were sandy clay loam soils (*Katondo)* and sandy soils (*Mchenga)*. The low fertility of sandy soils was the major factor causing reduced biomass and crop production in the smallholder farming sector. Sandy soils inherently have low amounts of nutrients, low soil organic matter and are weakly structured (Grant, 1981). Farmers reported that most of the fields in the area are infertile due to continuous cropping, which had put pressure on land. However, the farmers were quick to suggest ways of managing and replenishing soil fertility in their fields such as application of compost manure, planting tree species and leguminous plants (e.g. *Tephrosia vogelli)*, incorporating crop residues during land preparations, leaving fields to fallow as well as applying inorganic fertilizer.

Analysis of soil parameters showed no significant differences between sites, but indicated that in both sites there were low levels of SOM and soil N content (Table 2). The levels show that growing maize without fertilizer would be risky. Without alternative means of producing maize in such areas, more and more farmers' especially female-headed households would be food insecure. At the same time, the fertility status may indicate upon further calculations the level of external inputs needed for smallholders to break even in food production.

Table 2. Initial soil (0-20 cm) fertility status of the Chisepo

Field Types	Soil Parameters			
	% OM	%N	pH (water)	P (ppm)
Mbingwa	0.6	0.03	6.3	43.4
Kamphenga	0.5	0.04	6.6	44.2
Mean	0.6	0.04	6.4	43.8
C.V. (%)	43.42	45.67	12.49	27.69

Maize response to residual nitrogen

Figure 1 shows maize yields from the one of the mother trials conducted to investigate the effect of different legume incorporation on subsequent maize yields. Farmers planted MH 18 maize varieties in all

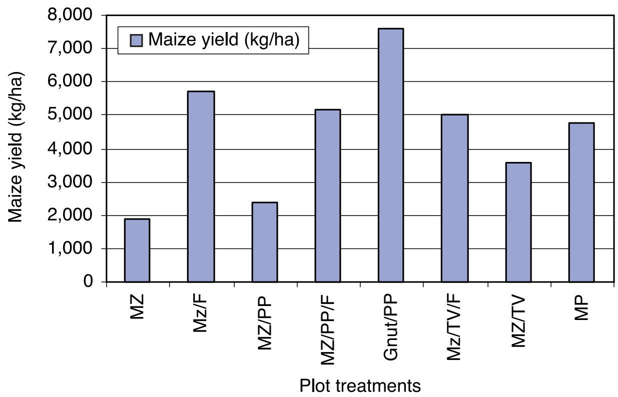

Figure 1. Maize yield response to residual N in the mother trial plots in 2002/2003

the plots. The groundnut/pigeon pea intercrop followed by maize recorded the highest maize yields (7,615 kg ha^{-1}) followed by maize plus fertilizer plots (5,695 kg ha^{-1}), maize/pigeon pea (5,175 kg ha^{-1}), maize/tephrosia (5,035 kg ha^{-1}) and mucuna/maize rotation (4,750 kg ha^{-1}). Lowest yields came from the continuous maize plots (1,870 kg ha^{1}). The yield increments were expected since the plots had cumulative effect of residual nitrogen from legume systems planted in the 2001/2002 growing season.

Similarly, maize yield response to residual nitrogen in the baby trial plots managed by farmers showed that pigeon pea-based plots compared well with the maize plus fertilizer plots. For example, highest maize yields were obtained from maize/pigeon pea plots followed by maize/tephrosia plots. The groundnut/pigeon pea plots in the farmers' trials performed the same way as the fertilized maize plots. The maize yields however, varied from one farmer to the other. These variations were expected since some farmers supplemented the residual nitrogen with fertilizer while other farmers did not. Four farmers planted tobacco in the baby trial plots. These farmers said that they wanted to take advantage of the legume residual nitrogen to improve their tobacco yields, which was their major cash crop. This showed that farmer had developing confidence in using legumes to improve their soil fertility even for cash crop production in the area.

Results from the intercrop systems showed that legumes such as pigeon pea, tephrosia, and groundnuts were very suitable for intercropping with maize as was indicated by the maize yields shown above. Since land holding sizes were smaller for most farmers (average 1.90 ha), having more legume best bets suitable for intercropping with maize would increase farmers' options for improving soil fertility and maize yields.

Farmer perception of the soil fertility and food security benefits of the legumes

Farmers were asked to give reasons for growing a particular legume crop in 2003/2004 growing season. The majority of farmers (48.2%) indicated that they chose the legumes as a source of food followed by those who stated that they grew it to improve their soil fertility status. However, when asked how they knew the legume improved soil fertility, they indicated that extension staff employed by the project organized a field day where they saw higher maize yields in plots where previously there were certain legume crops. Most farmers grew cowpeas than any other legume (23.6%), followed by mucuna and pigeon peas both grown by 19.1% of the farmers (Table 3).

Table 3. Farmer knowledge and practices of improving soil fertility

Soil fertility practice	% Aware of the practice*	% Farmers practicing
Legume residue incorporation	62 (48%)	55 (42%)
Application of animal manure	20 (28%)	18 (25%)
Agroforestry techniques	4 (8%)	2 (4%)
Fertilizer application	7 (14%)	4 (9%)
Compost manure (pit & heap)	3 (6%)	1 (2%)
Practice intercropping	62 (48%)	55 (42%)
Fallowing	5 (7%)	3 (6%)

* Total percentage more than 100 because of multiple responses

Traditional legumes were mainly grown for their food values. Cowpeas leaves were eaten as vegetable relish while fresh; they were also boiled and dried for preservation for use in dry season when green vegetables were scarce. The fresh green pods were also boiled and eaten as snacks. Groundnuts and pigeon peas were roasted, salted and eaten also as a snack and in some instances pounded into flour and used to season leaf vegetables. Farmers also used legumes such as pigeon peas, soybean and mucuna as animal feed. Male farmers in particular stated that some legumes were fed to animals in order to boost milk production.

In terms of soil fertility potential of legume crops, farmers perceived that mucuna was the best for soil fertility improvement based on the leafy biomass yield they had in 2002/2003 season and 11.2% opted for growing mucuna for that reason. This was also reflected in the high rating mucuna had on contribution of legumes to soil fertility (Table 4).

Table 4. Farmer rating of soil improving legume technology traits[1]

Treatment	Weeding labour requirement	Seed availability	Contribution to food security	Contribution to cash sales	Contribution to soil fertility
Maize control	3.1	3.3	2.2	2.3	1.5
Maize + pigeon peas[2]	2.5	1.9	3.6	2.8	2.7
Maize + Mucuna[3]	3.5	2.5	2.4	2.3	3.6
Maize + Bambara[2]	2.2	2.8	2.9	2.4	2.1
Maize + Cowpeas[2]	2.1	3.1	3.4	3.1	2.8
Maize + Soybeans[3]	2.3	2.9	3.1	2.3	2.6
Maize + Tephrosia[2]	2.8	1.5	2.0	1.9	1.8
Maize + Sunhemp[3]	2.6	1.9	2.0	1.7	2.4
Maize + Grahamiana[3]	2.6	1.7	2.5	1.7	2.6
LSD	0.4	0.5	0.4	0.6	0.5

[1] Rating: 1 = very low; 2 = low; 3 = high; 4 = very high
[2] Maize-legume intercrops (recommendation)
[3] Maize-legume rotation (recommendation)

Farmer perceptions on the use of Inorganic fertilizer

These technologies were mostly targeted for areas growing hybrid maize and high value crops to pay for the cost of the chemical fertilizers. While farmers perceived numerous benefits of using the inorganic fertilizers compared to the organic sources of fertilizers such as quick yield response (meeting food security needs), easy to apply and easy to access as most of the fertilizer is sold in many rural markets, the high cost of inorganic fertilizers and the introduction of the structural adjustment program have forced government and non-governmental institutions to explore alternative and economically feasible means of soil fertility improvement (Kanyama Phiri *et al*., 1998). In Malawi, such efforts include the development of area-specific recommendations for soil fertility improvement which include the evaluation of economic rates of fertilizer application. Most of the farmers involved in the survey expressed concern over the high cost of the chemical fertilizers in the country which is currently selling at MK 3,200.00 per 50 kg bag (approximately 32 US Dollar per 50 kg bag of Urea).

Farmer perceptions on the use animal and compost manure

Farmers with livestock (especially in the Northern Region of Malawi) use farmyard manure to increase soil fertility. The main advantages of this practice according to the farmers were that the effects were seen immediately they applied the manure. Other farmers also stated that manure making that used locally available materials, were cheaper than the inorganic fertilizers. Most of the farmers have the knowledge associated with their preparation. However, the major drawback was that quantities of farmyard manure were generally low and variable. This is due to livestock ownership, particularly cattle, being very low amongst the farmers (about 15% of the sampled households had livestock). In some parts of the country farmers composted household refuse near to the homestead which is used to fertilize vegetable gardens. Here again the constraint is the availability of the manure in required quantities as well as labour and transportation materials of the manure from point of production to the farms.

Conclusions and Lessons learnt

Soil fertility is a major determinant of increased crop yields in Malawi. The use of organic matter technologies offers practical solutions to sustainable soil fertility management in Malawi so long as crop residues and green manures are returned to the soil. The results of this study have indicated that farmer involvement in developing new technologies is crucial in increasing demand for more soil fertility technologies given the perceived benefits and requirements. Farmers have knowledge about the various technology options and their contribution to soil fertility and food security. However, adoption and production of these technologies in Malawi is still low. Farmers indicated a lack of seed, lack of markets particularly for farmers who produced surplus legume crops, poor soils, livestock damage and lack of labour as the factors limiting adoption of these practices. There is also a need to study each farmers socio-economic situation and promote only what is feasible considering the labour, household income, land holding sizes and soil type owned by the different farming households.

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Suitable approach for sustainable soil fertility management in Sahelian zone of Niger, West Africa

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Keywords: indigenous knowledge, soil fertility management, weeding, Niger, West Africa

Abstract

*Soil fertility management is a critical factor in the production of rain-fed millet (**Pennisetum glaucum** (L) R.Br.) in the Sahel of West Africa. Due to the low and often erratic rainfall distribution and the predominance of highly weathered sandy soils, yield stability of crops is often compromised. Despite trial applications of new approaches and strategies, farmers have maintained their traditional ways of farming. It is of utmost importance to find ways of promoting new developments that are suitable and adaptable to traditional farmers. One essential aspect is to focus on indigenous knowledge to understand the farmer so as to come up with possible solutions to the issue of suitable agricultural development. This paper presents a case study on the role of indigenous knowledge in the Sahelian zone of Niger, West Africa. A field survey and interview were conducted in the Fakara, Dantiandou District of Tillaberi prefecture, Western Niger. A two-year field experiment was carried out simultaneously on farmers' fields in the study area in order to evaluate farmer practices. A split-plot design experiment was conducted with the main factor being fertilization and sub factor weeding. In general, soil fertility management in the study area is undertaken through the application of transported farmyard manure, corralling by pastoralist and fallow. Fallow, which has less accessibility due to its distance from a village and without a relationship to pastoralist, was dominant as it occupied more than 60% of the entire farm area. A fallow period of between 2-4 years tends to be widely adopted. However, this is insufficient to completely restore the fertility of the soil before the next cropping period. Weeding improved production of millet under fallow condition. However, soil exploitation was aggravated by the increase in total biomass production. Sustainable ways to compensate nutrient lost will be discussed in this paper based on the information from the respondents.*

Introduction

Soil fertility problems remain a high priority for agricultural development in Africa and the role of scientific information is important to improve the situation. However, in most cases, a scientific point of view can only partially reflect the farmers' point of view in terms of agricultural development. The complexity of farmers' society creates a gap between the scientist and the farmer. This gap should be bridged in order to facilitate mutual understanding on the problems to be tackled.

In the past years, many studies on soil fertility management have been undertaken in Niger (e.g. Bationo et al. 1998; Ly et al. 2000; Yamoah et al. 1998). Several technologies derived from these studies were disseminated to farmers' field. Unfortunately, the adoption rate of the disseminated technologies was rather low (Abdoulaye, T. *et al*. 2000). Therefore, developing a suitable technology to improve soil fertility management on farmers' fields is still one of the most important issues to raise agricultural production (ICRISAT 2002). Suitable technologies can only be widely adopted if the importance of farmers' issues is taken into account.

Indigenous knowledge (IK) is receiving considerable attention in recent years in terms of social and agricultural development (UNCED 1992; Ishida et al. 1998). However, most of the information about IK is oral patrimony from generation to generation (Roman et al. 1992). Though obtaining the information behind the reasoning of traditional people in natural resource management is of utmost interest to identify appropriate technologies, there exists a prejudice that IK is against development (Morin-Labatut & Akhtar 1992).

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The objective of this study was to have better understanding of existing IK in terms of soil fertility management in Sahel zone of West Africa. The IK is empirical oral patrimony from generation to generation and therefore it should be processed in a scientific manner and evaluated quantitatively to identify the most useful information for agricultural development. It is also necessary to look at farmers' practice in crop production to evaluate local practice and to identify the possible scenarios to make outputs adaptable and sustainable at farmers' level.

Materials and methods

Site description

The survey was conducted in three villages of the Fakara region, Dantiandou District of Tillaberi prefecture, Western Niger (60-90 km Northeast of Niamey) in West Africa: Banizounbou (145 households), Tchigo Tegui (135 households), and Kodey (100 households). Principal tribes of this area are Zarma, the agriculturalist who engage in rain fed cereal production such as millet (*Pennisetum typhoides*) and cowpea (*Vigna unguiculata*), and Fulani, the pastoralist who engage in livestock production. The prevailing soil type in the Fakara is a Psammentic Paleustalfs, which has a high sand fraction and typical characteristics of an infertile soil. The rainfall pattern of this area is mono modal starting from June till September. Total amount of rainfall is about 500 mm peaking in August.

Gathering indigenous knowledge (IK) in terms of fertility management of agricultural land

A questionnaire was prepared in order to identify the way farmers recognize the agricultural land in the study area. Two steps were taken for gathering the information on land management. The first step was to obtain IK from representative informants and the second step was to confirm recognition as well as perception of this information through different generation and different villages. The prepared questionnaire was developed with the help of an agent who has been working in the area for 11 years in different projects and can speak local languages such as Zarma and Foulfoulde (the language of Fulani). To verify the information obtained in step one, 120 farmers (40 per village) from different generations and locations were interviewed. Three villages, Banizoumbou, Tchigo Tegui and Kodey were targeted and 10 farmers of each age category: 21-30 yr, 31-40 yr, 41-50 yr and >50 yr, were interviewed. In addition to the farmers' view on agricultural land, the Fulani were also interviewed by the same agent to determine their relationship with the Zarma. A total of 92 Fulani households from Fakara were interviewed. All information gathered through the survey was written in French notation.

Quantitative evaluation on farmers' practice for crop production

In order to obtain IK through farmers' practice on millet production, a two-year field experiment was carried out from 2003 to 2004 in Gourou Yena, Fakara region. The experiment was a 2 factorial split-plot with three replications. The main factor was fertilization and weeding frequency was the sub factor. In conventional practice, farmers weed twice during the cropping season, but in most cases don't apply fertilizer. However, the need for fertilization is increasing due to increased food demand. Through our experiment, we attempted to understand the farmers' perspective of conventional practice for millet production and determine a rational way to improve this production system through fertilization. The treatments used in this experiment were a combination of weeding with fertilization: inorganic fertilizer (IF) + twice of weeding (2W), IF+1W, IF+0W, inorganic fertilizer with cow manure application through local practice (IM) +2W, IM+1W, IM+0W. Treatments with no fertilizer application (NF) were also established, and treatments were NF+2W, NF+1W and NF+0W. In this experiment, NF+2W was the control and NF+0W was the absolute control. DAP (Di-ammonium phosphate) was used as the source of IF with the dosage of 20 kg/ha (Bationo, A. *et al* 2000) by hill application. The cow manure was obtained through the corralling system where the livestock are restrained in the field during night. The manure was applied at 6 t DM/ha (William, T.O. *et al.* 1995).

Results

Farmers' knowledge on soil classification and land management

The results obtained from the survey to gather IK of soil fertility and agricultural land management showed that the farmers classified the soils in the study area by color and texture. The farmers' recognized Labu tchirey, a soil with a reddish sandy texture, as the dominant soil type in this area. This soil was classified as Psammentic Haplustalfs or Psammentic Paleustalfs, and has a high sand content (92~96%) and poor chemical characteristics.

Two types of agricultural land in study area were classified dependent on the presence of fertility management practice. Farms that had some form of fertility management were either intensively or extensively managed. Intensively managed land was classified as "Birgui-farey" (which means land with fertility) and had three different sub-classifications based on the organic amendment used. "Birgi-nougou" was land managed by transported farmyard manure, "Gah-zeno" is by corralling and "Farey-djibo" is by crop residues. Of these three different sources of organic amendment, Farey-djibo was the least practical due to high demand for crop residue for livestock feeding, substitute for fire wood, construction, etc. Therefore Birgui nougou and Gah zeno were generally the most common practice for intensively managed land. The extensively managed land is called "Farey", meaning land restored by using a fallow system. This classification also had different sub-classifications depending on how many years cultivation there had been since the fallow period. The sub-classifications were "Farey-zeno", "Sakara", "Lali banda", "Koiri koiri", "Koiri zeno", meaning respectively, fallow land, or the 1st year, 2nd year, 3rd year or 4th year of cultivation since the fallow. The farms without management were considered as degraded land due to the continuous cultivation diminishing their agricultural potential. There were three levels of degraded land, and Labu Farga was considered the most degraded.

Geographical distribution of agricultural land based on classification of land management practice

The results showed that 66% of the fertility management of the surveyed area was achieved by fallowing, 18% using corralled manure and 16% using farmyard manure. These proportions are indicative of the harsh environment and the low availability of organic matter that can be used for soil fertility management. This highlights the importance of trying to mitigate this situation to improve the livelihood in Sahel. The survey also revealed that the fallowed agricultural land was in a critical situation as fallow periods were being shortened. The land in the study area was usually managed using 6 years cultivation and 3 years fallow. This practice is likely to accelerate soil-land degradation, as a previous study (Hayashi 2005) showed that land fallowed for 2 years was less fertile than that receiving 4 years of fallow, and even 4 years of fallow was less fertile than Sakara (land fallowed for more than 4 years). This indicates that soil fertility can not be restored sufficiently when the fallow cycle is shortened to 2 to 4 years and the resulting chronic decline in fertility leaves the soil completely degraded. This needs to be considered when trying to aim for better conservation technology in fallow system.

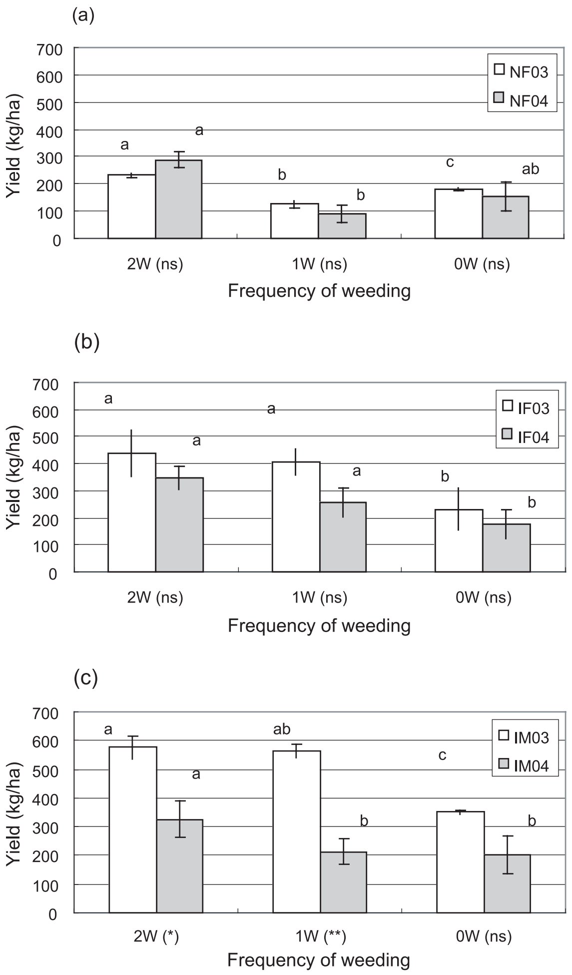
From a geographical perspective, the management systems mentioned above were variously distributed in distance from the residential areas. Transporting manure produced from household waste or farmyard manure generally occurred when the farmer's residence was less than 1 km away. The fallow system was used in areas more than 2 km away from the residential area, while the corralling system was intermediate being distributed in a range of 1 km to 2 km. This distribution was due to socio-economic factors encountered in the study area. Fallow systems which were managed extensively can not be enhanced by the other systems due to constraints such as difficulties for transporting manure by the farmer, or water scarcity for livestock for the pastoralist. Also, the corralling system can not be managed too close to the farmers' residence, because of conflict between farmer and pastoralist. Normally the pastoralist manages the corralling system at a distance from the farmers' residence as livestock can cause damage to the farmer's possessions, or die from eating non edible materials like plastic bags or cloth. These geographical constraints limit the type of organic material that can be applied to agricultural land, and also determines who takes charge of the agricultural land in these different systems.

Evaluation of productivity through conventional agricultural system

Although the extensively managed fallow system was the dominant form of agricultural land management, farmers still considered weeding as an indispensable input in order to secure crop production to supply the household food demand. On average, crops were weeded twice, however, some crop lands were not weeded at all during the season due to insufficient labour supply caused by economic and social constraints.

Other agricultural inputs such as inorganic fertilizer are not commonly used due to the infrastructure problems in the rural areas of Sahel (Abdoulaye, T. *et al.* 2000). However, using a combination of inorganic fertilizer with organic materials like livestock manure to enhance the millet production on these low fertile sandy soils shows promise. The field experiments carried out in this study illustrate the change in millet production over 2 years under different fertilizer management systems (Figure 2-A, B and C).

When no fertilizer was applied, weeding twice (NF2W) resulted in a better yield than with one



Bars of the same color followed by same letter (a, b or c) do not differ significantly, P = 0.05, *,**; Significant difference at 5%, 1% ns; no significance

Figure 1. Millet yields (kg ha^{-1}) for different treatments. 2W, 1W and 0W represent frequency of weeding. Graph (A) is for non fertility treatment (NF), (B) is for fertility application through DAP (IF), and (C) is for DAP with livestock excrements (IM)

(NF1W) or no weeding (NF0W) (Figure 2-a). The yield for second year at NF2W was improved as the weeding was carried out just after the rain and harvest index increased from 0.19 to 0.31. In contrast, the first year of IF and IM treatments resulted in better yields at each frequency of weeding than was obtained from NF2W. It is notable that in the first year, the treatments receiving only one weeding in both the IF and IM management systems yielded as high as those receiving two. However, by the second year, the yield of IF and IM decreased and the yields were only as high as that obtained from NW2W in the second year. There were significant differences in yield between the first and second year in the IM2W and IM1W treatments and these treatments yielded considerably higher than the corresponding IF treatments. However, by the second year the yields for the IM treatments were similar to the IF treatments, indicating that the livestock excrements was only effective for the first year. Overall, the mean harvest index of IM was better at each weeding frequency than that for IF and NF suggesting that the application of livestock excrements can enhance seed production of millet.

Discussion

The information about IK obtained by this study demonstrated that soil and agricultural land management was diverse even in extensively managed fields. This allows the farmers to use their finite resources efficiently to make their production sustainable. According to the results, 34% of agricultural land in study area was for organic matter application through corralling or recycling of domestic waste or farmyard manure, and 66% was extensively managed using a fallow system. The high proportion of fallow management is understandable as farmers in this study area usually owned 36 ha of agricultural land per household (non published data), thus making a large portion of this land at a great distance from the allocation of finite resources. However, another input such as labour required for weeding was allocated evenly for all management systems, although it was hard hand labour using a local hoe. Normally farmers aimed to weed twice during the cropping season, but this frequency declined depending on individual constraints for the various households. The results obtained in the field experiment demonstrate the impact of weeding even when there is no fertilizer input, as yields obtained in the both the first and second years declined as the frequency of weeding decreased. Despite the intensive hand labour necessary for weeding, the yield from the fallow system remained quite low, and may still not be sufficient to motivate the farmer to expend the effort required to improve management practices for increased agricultural production. However, it was notable that in the first year, a single weeding resulted in yields comparable to that obtained with double weeding and the yield was still compromised in the second year by single weeding with fertilizer application.

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Farmers' approaches on rehabilitations of degraded soils in the Northeast of Thailand

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Abstract

Soil degradation in the Northeast of Thailand is extremely severe due to both low current commodity prices and general poverty of small farmers that does not allow appropriate inputs for those production systems. Fortunately, some farmer innovators have developed soil rehabilitation technologies for farmers that utilize sandy soils in their production systems. The essence of the technology is based on experiences and observations on the ability of natural habitats to recover after land clearings. The observations have led to attempts by farmers to transform agricultural field into an integrated farming system and agroforestry that reduce soil disturbances with some small organic amendments. The success of this approach is evident since plant ecosystems have emerged that has enabled other higher fertility requiring crops to be grown in an integrated manner with low external inputs. These practices are evident in a diverse array of ecosystems of the Northeast of Thailand on more than 50 farmer fields. As a result productivity and the appearance of previously degraded sandy soils have been reversed to similar levels of the former pristine soil fertility. From soil sampling of those farmer fields and their analysis indicate that most of soil fertility parameters are replenished to a similar level under forest covers. After 5-7 years of agroforestry, soil organic matter could be found as high as 5-7% in the 0-5 cm, or 1% in the 0-10 cm soil depth with crumb structure and evidences of various soil faunal activities. In most cases of integrated farming systems and agroforestry, soil organic matter has increased to at least 0.5%. Cation exchange capacity was also increased in relation to soil organic matter. With the increases in cation exchange capacity, all cations were high, and in most cases higher than fertility status in forest soils. The increases could be attributed to both natural and man-made influences.

Introduction

Soil and land degradation have to a significant degree been driven from different socio-economic pressures that operate at both the macro and micro scales (Matsuo, 2002; Panichapong, 1988). Through this process there have been losses of biodiversity, forest lands and finally agriculture production systems that have not adopted appropriate conserving practices (Figure 1) (Noble et al., 2004b). Various attempts for reversing degradation from different organizations and development agencies have been done with limited successes, due to application of single approaches for systematic issues and constraints (Noble et al., 2004a, Webb, 2003). Chemical fertilizer applications is one example where there is limited improvement in soil fertility, but with improve crop production in most cases (Ragland and Boonpuckdee, 1987). Most practices have eventually resulted in greater soil degradation in most production systems. This degradation has caused losses not only in natural resources but also affected negatively the livelihood and ability of poor farmers to achieve self sufficiency and enhance their incomes (Noble et al., 2001).

Figure 1. Degraded soils showing signs of surface wash associated with inappropriate management

The dominant strategies to reversing degradation have focused addressing a single issue by importing and recycling external sources without conservation. Some of these practices have resulted in short-term on site advantages, but they may produce degradation off site due to continuous export (Noble et al., 2000). As such the effects of the technologies were only short-term for crop and soil productivity improvement.

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The objectives of the current study are as follows:

1. To survey the successful cases of soil rehabilitation using indigenous technical knowledge.
2. To document rehabilitation changes associated with the implementation of indigenous technical knowledge on soil properties.
3. To evaluate potential extension of indigenous technical knowledge within and external to Local Wisdom Networks

Methodology

1. Planning meeting with Local Wisdom Networks and preliminary survey
2. site selection and planning for sample collection for laboratory analysis using modified paired sites comparison techniques (Noble et al. 2000) but only using composite top soil samples.
3. site history collection
4. data compilation and analysis

Preliminary field surveys

Information on soil rehabilitation has been collected from farmer networks and Local Wisdom Networks, during both meetings and general field surveys. It was found that most of the rehabilitation has been associated with organic amendment and tree planting. An example has been drawn from the case of Mr. Kammee Mungkun of Nakhon Ratchasima (Figure 2).

Figure 2. Mr. Kammee Mungkun on his farm where he has adopted significant tree planting

He has collected most of available organic materials available from both around his farm and his home site for improvement of his paddy field. Moreover, he also gradually planted numbers of trees on paddy buns within his farm for more than 10 years. As a result productivity of his land has been greatly improved with less and less necessity of soil amendment. Besides, he has observed that trees have different growth rates and degree of soil rehabilitation. In this respect he has observed that larger leaves can cover the soil and rehabilitate the soil ecosystems faster than smaller species due to soil cover.

In the case of Mr. Chantee Pratumpa a Local Wisdom Member of Nakhon Ratchasima (Figure 3), started his garden plot on dugout materials from his farm ponds. He has found that at minimum inputs of small dose cattle manure in vegetable plots and gradual successions of trees, the soil could be improved to similar color of surface forest soil. Mr. Chiang Thaidee of Surin Province has improved his garden with coconut coir and other products of coconut. He also found that the soils could be improved in both there appearances and productivity (Figure 4).

Figure 3. Mr. Chantee Pratumpa Local Wisdom Member of Nakhon Ratchasima

For Mr. Phai Soisraklang the Local Wisdom Networks leader of Burirum, he has used various kinds of plant materials for soil improvement and found that most of natural plants growing on his land could be used as green manures for vegetable plot improvement (Figure 5). The materials include weedy species, shrubs and tree branches. The practice could be used for rehabilitation of degraded lands.

For Mr. Boontem Chaila, a Local Wisdom Network member of Khon Kaen, has developed an integrated farming systems on his former upper paddy

Figure 4. Garden plots of Mr. Chiang Thaidee at Surin

Figure 5. Mr. Phai Soisraklang at his experiment on his farm

over the past 14 years (Figure 6). The results indicated that soil fertility has been physically improved both by soil structure and color of surface soils to 20 cm, comparing to similar paired sites.

For Mr. Kamdueang Pasi learning centre, has constructed the platforms for tree planting using subsoils as landfill (Figure 7). After 7 years, soil under Acacia mangium has been greatly improved as shown in the right picture below. The surface soil has changed from pale brown to a black color. When the situation was compared with tree plantation on degraded soil,

Figure 6. Mr. Boontem Chaila plots built from landfill materials from his farm ponds 14 years ago

Figure 7. The plot of 7 years under agroforestry on degraded soil (top) and landfill (bottom), the bottom picture tends to compare landfill and under agroforestry (carried by Mr. Kamdueang's hands)

the depth of soils is found to be 4 inches for the same period of 7 years.

For Mr. Suthinan Prachayaprut's network centre, there are a number of tree and crop systems that have been assessed and implemented (Figure 8). There are improvements of soils compared to the attributes of the degraded soils after more than 20 years. Eucalyptus plantations have demonstrated improvement of soils in most of the systems. Soils are black and fertile, at least from the soil surface to 10 cm.

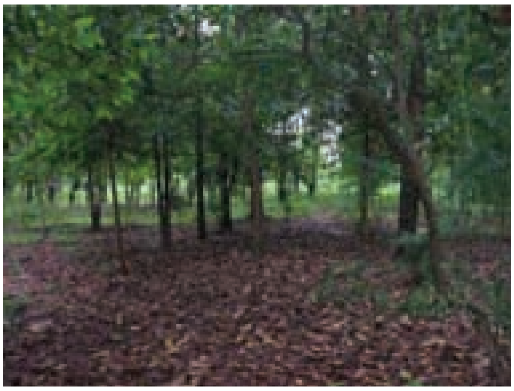

Figure 8. Agroforestry systems of Mr. Suthinan's learning centre (left) and soil improvement techniques for vegetable production

Results of soil sample analysis

Soil analysis for supporting the observations that were made has been undertaken for selected sites according to suggestions of the Local Wisdom Network members. This assessment involved a paired site approach. The results are as followed:

Table 1. Changes of soil properties of Mr. Boontem Chaila network

Name	Depth (cm)	Plots	Soil properties													
			pH		EC (ms/cm)	%		CEC (cmol/kg)	(meg/100 g soil)					ECEC (cmol/kg)	mg kg^{-1}	
			water	$CaCl_2$		O.C.	O.M.		K	Ca	Mg	Na	Al+H		ext. P	NH4-N
Boontem	0-10	Control	6.01	5.49	0.05	0.83	1.44	2.84	0.28	2.31	0.76	0.04	–	3.39	64	5.00
		Improvement	6.78	6.39	0.21	1.66	2.87	7.96	0.55	6.34	1.67	0.03	–	8.59	103	35.00
	20-30	Control	5.33	4.77	0.02	0.41	0.71	2.61	0.15	1.62	0.84	0.05	–	2.67	73	2.10
		Improvement	6.55	6.18	0.07	0.59	1.02	5.70	0.41	3.75	1.55	0.05	–	5.76	79	6.90
	50-70	Control	5.54	4.65	0.02	0.29	0.50	2.03	0.13	1.34	0.51	0.08	–	2.06	29	1.30
		Improvement	6.18	5.59	0.03	0.46	0.80	3.86	0.23	2.84	0.77	0.08	–	3.91	30	3.00

Table 2. Changes of soil properties in farms of Mr. Tas Krayom network

Name	Depth (cm)	Plots	Soil properties											
			pH		EC (ms/cm)	%		CEC (cmol/kg)	(meg/100 g soil)					ECEC (cmol/kg)
			water	$CaCl_2$		O.C.	O.M.		K	Ca	Mg	Na	Al+H	
Tas	0-15	Improvement	6.70	6.60	0.26	1.44	2.47	8.74	0.40	13.8	1.93	0.35	0.20	16.64
	0-15	Improvement	6.30	5.40	0.19	0.42	0.72	5.28	0.23	6.24	1.00	0.34	0.50	8.31
	0-15	Control	8.10	6.70	0.31	0.41	0.71	0.24	0.53	3.06	4.44	2.47	0.60	11.10

Table 3. Changes of soil properties in farms of Mr. Phong Katepiboon network

Names	Depth (cm)	Plots	Soil properties											
			pH		EC (ms/cm)	%		CEC (cmol/kg)	(meg/100 g soil)					ECEC (cmol/kg)
			water	$CaCl_2$		O.C.	O.M.		K	Ca	Mg	Na	Al+H	
Phong	0-15	Improvement	6.01	5.93	0.15	0.20	0.34	17.16	0.69	2.83	12.65	3.24	–	19.42
Apichart	0-15	Improvement	7.51	7.25	0.31	0.43	0.74	18.84	1.72	1.28	20.51	1.47	–	24.99
Tongsa	0-15	Improvement	6.33	6.22	0.17	0.14	0.24	15.97	1.91	2.47	7.19	3.40	0.20	15.17
	0-15	Control	6.49	6.36	0.41	0.41	0.71	9.83	1.89	2.75	6.24	3.16	–	14.04

Table 4. Changes of soil properties in farms of Mr. Tongbai Tonlo network

Names	Depth (cm)	Plots	Soil properties											
			pH		EC (ms/cm)	%		CEC (cmol/kg)	(meg/100 g soil)					ECEC (cmol/kg)
			water	$CaCl_2$		O.C.	O.M.		K	Ca	Mg	Na	Al+H	
Tongbai	0-15	Control	7.30	6.60	0.47	1.15	1.99	3.55	0.94	21.78	2.42	0.39	0.40	25.93
	0-15	Improvement	7.00	6.50	0.31	0.17	0.28	1.53	0.20	1.40	0.28	0.26	0.20	2.34
Kawin	0-15	Control	7.20	6.80	0.40	0.33	0.56	2.32	0.38	2.82	0.49	0.18	0.40	4.28
	0-15	Improvement	7.40	7.20	0.39	0.05	0.09	2.01	0.14	2.30	0.27	0.23	0.20	3.14
Sawat	0-15	Control	6.80	6.30	0.49	1.57	2.70	18.13	1.30	21.37	4.08	0.59	0.40	27.74
	0-15	Improvement	5.90	5.20	0.33	0.27	0.46	17.74	0.84	20.73	3.37	1.12	0.60	26.66
Chamnong	0-15	Control	5.90	5.20	0.30	0.60	1.03	3.47	0.19	2.84	0.46	0.38	0.40	4.28
	0-15	Improvement	7.20	7.00	0.40	0.16	0.28	2.41	0.54	5.29	1.11	0.31	0.60	7.85
Utis	0-15	Control	5.60	5.30	0.50	1.09	1.88	4.16	0.25	3.45	0.49	1.35	0.60	6.14
	0-15	Improvement	5.60	5.00	0.28	0.51	0.88	3.13	0.44	1.85	0.39	0.43	0.80	3.91

Table 5. Changes of soil properties in farms of Mr. Yu Sunthornthai network

Names	Depth (cm)	Plots	Soil properties											
			pH		EC (ms/cm)	%		CEC (cmol/kg)	(meg/100 g soil)					ECEC (cmol/kg)
			water	$CaCl_2$		O.C.	O.M.		K	Ca	Mg	Na	Al+H	
Kaitisak	0-15	Control	6.90	6.10	0.17	0.94	1.62	8.93	0.18	0.55	9.13	0.49	0.20	10.55
	0-15	Improvement	7.10	6.50	0.21	1.28	2.21	7.53	0.22	0.36	22.70	0.87	0.40	24.52
Weerawat	0-15	Control	6.90	6.50	0.17	0.26	0.45	3.16	0.36	0.75	2.45	0.17	0.40	4.12
	0-15	Improvement	7.00	6.50	0.34	3.60	6.21	13.30	1.20	0.59	20.30	5.12	1.00	28.17
Suntanee	0-15	Control	7.70	6.90	0.37	0.26	0.45	6.43	0.26	2.20	5.50	0.46	0.20	8.62
	0-15	Improvement	7.20	6.70	0.25	2.50	4.31	8.38	0.85	0.42	17.60	3.20	0.80	22.89
Somboon	0-15	Control	7.00	6.50	0.15	0.61	1.05	3.61	0.64	0.46	2.17	0.35	0.60	4.22
	0-15	Improvement	6.60	6.40	0.18	0.26	0.45	4.59	0.52	0.38	3.41	0.69	0.20	5.19
Pradab	0-15	Control	6.50	5.50	0.10	0.18	0.31	1.81	0.24	0.46	0.20	0.04	1.00	1.94
	0-15	Improvement	6.40	6.10	0.21	1.18	2.04	5.62	0.53	0.42	6.77	0.83	0.20	8.75
Praderm	0-15	Control	6.70	6.40	0.16	0.53	0.91	4.19	0.31	0.34	2.79	0.47	0.20	4.10
	0-15	Improvement	6.80	6.60	0.25	1.56	2.69	7.38	0.67	0.34	15.90	0.97	0.60	18.54
Supan	0-15	Control	8.80	7.90	0.40	0.11	0.19	5.98	0.25	2.99	10.70	0.07	0.40	14.39
	0-15	Improvement	7.10	6.80	0.14	0.29	0.50	2.20	0.25	0.49	1.45	0.24	0.40	2.84
Sorn	0-15	Control	6.10	4.20	0.07	0.76	1.04	4.54	0.23	0.44	1.89	0.19	4.60	7.36
	0-15	Improvement	6.50	5.50	0.18	0.24	0.41	5.97	0.31	0.44	4.37	0.47	0.20	5.80
Somniam	0-15	Control	6.60	5.70	0.14	0.54	0.94	3.90	0.64	0.65	3.88	0.66	0.20	6.03
	0-15	Improvement	6.90	6.00	0.26	1.55	2.68	6.71	1.29	0.60	7.94	1.11	0.40	11.34

Table 6. Changes of soil properties in farms of Mr. Sanan Parisawong network

Name	Depth (cm)	Plots	Soil properties											
			pH		EC (ms/cm)	%		CEC (cmol/kg)	(meg/100 g soil)					ECEC (cmol/kg)
			water	$CaCl_2$		O.C.	O.M.		K	Ca	Mg	Na	Al+H	
Sanan	0-15	Control	6.30	5.60	0.20	2.20	3.80	20.80	1.40	30.40	11.30	3.00	0.20	46.20
	0-15	Improvement	6.50	5.70	0.30	1.40	2.40	44.50	1.20	30.50	10.10	3.30	0.20	45.20

Table 7. Changes of soil properties in farms of Mr. Chiang Thaidee network

Names	Depth (cm)	Plots	Soil properties											
			pH		EC (ms/cm)	%		CEC (cmol/kg)	(meg/100 g soil)					ECEC (cmol/kg)
			water	$CaCl_2$		O.C.	O.M.		K	Ca	Mg	Na	Al+H	
Chaing	0-15	Control	6.30	5.50	0.12	0.17	0.29	2.50	0.65	0.84	1.51	0.17	0.60	3.78
	0-15	Improvement	6.70	5.90	0.20	0.84	1.45	4.23	0.47	0.69	11.60	0.69	0.40	13.82
	0-15	Improvement	6.90	6.10	0.26	2.27	3.91	9.20	0.98	0.59	22.80	1.95	0.60	26.90
Chaluay	0-15	Improvement	5.60	4.90	0.30	0.47	0.81	2.79	0.18	2.56	0.31	0.30	0.60	3.93
Dan	0-15	Improvement	7.20	6.80	0.43	0.20	0.35	5.64	0.45	9.22	0.83	0.79	0.40	11.69
	0-15	Control	5.70	4.70	0.27	0.28	0.49	1.80	0.41	0.80	0.16	0.30	0.60	2.26

Table 8. Changes of soil properties in farms of Mr. Chalee network

Names	Depth (cm)	Plots	Soil properties											
			pH		EC (ms/cm)	%		CEC (cmol/kg)	(meg/100 g soil)					ECEC (cmol/kg)
			water	$CaCl_2$		O.C.	O.M.		K	Ca	Mg	Na	Al+H	
Supee	0-15	Improvement	4.60	4.10	0.35	2.28	3.94	8.87	0.52	5.00	1.10	0.32	2.20	9.14
Pannya	0-15	Control	5.30	4.50	0.27	0.72	1.25	5.07	0.42	2.76	1.21	0.42	1.20	6.02
	0-15	Improvement	4.60	3.90	0.33	0.27	0.46	5.52	0.43	1.41	0.93	0.30	4.00	7.06
Manee	0-15	Improvement	6.40	6.10	0.19	1.31	2.26	3.53	0.33	0.51	5.54	1.01	0.40	7.78
	0-15	Control	6.70	5.80	0.11	0.67	1.15	2.98	0.73	0.48	1.73	0.74	0.60	4.27
	0-15	Improvement	5.00	3.70	0.04	1.37	2.36	13.25	0.67	6.75	1.07	0.81	4.30	13.60
Nikom	0-15	Improvement	6.40	6.10	0.19	1.31	2.26	3.53	0.33	0.51	5.54	1.01	0.40	7.78
	0-15	Control	6.70	5.80	0.11	0.67	1.15	2.98	0.73	0.48	1.73	0.74	0.60	4.27
Weerachai	0-15	Improvement	6.10	4.20	0.11	0.14	0.24	5.55	0.42	0.86	0.55	0.61	1.60	4.03
	0-15	Control	6.00	4.70	0.14	0.87	1.50	3.10	0.38	1.06	0.64	0.30	0.61	2.98
Chalee	0-15	Improvement	5.70	4.30	0.10	0.40	0.68	4.33	0.24	1.05	0.34	0.38	1.80	3.81
	0-15	Control	6.00	4.80	0.13	0.85	1.46	3.18	0.46	1.38	0.59	0.34	0.60	3.36
Boonmee	0-15	Improvement	5.50	4.30	0.12	0.48	0.84	4.19	0.24	1.07	0.36	0.31	2.00	3.98
	0-15	Control	6.30	5.00	0.14	0.32	0.55	3.65	0.46	0.63	0.19	0.57	0.60	2.45

Discussion

From the land use history of each paired plots for improvement comparisons, most of them have been gradually transformed from natural forests to monocrop production systems. Primary production systems were upland rice and upland crops. Thereafter, when lands were sufficiently cleared there was a move towards lowland rice production. The practices of such production systems were cultivation without or with little soil cover. These practices have become the norm for hard working farmers. As such soils are vulnerable to sunlight and direct raindrop impact. Moreover, when there is infiltration of rainwater into the soil, this often results in leaching losses of soluble cations from the soil due to low ability of these soils in retaining these nutrients in an exchangeable form. These leaching losses are a degradation process that is common to sandy soils in semi-arid to humid environments. Often there is the perception that if farmers leave their lands under tree/vegetation cover other than cropping, that these farmers are easy-going or even lazy farmers.

In many cases, farm pond construction has transformed land and soil ecosystems for both on site and off site. The off site effects includes filling up the land with dugout materials from farm pond preparation. In some cases the dugout materials could be problematic due to lateritic materials or can have some physical limitations that could even exacerbate the effects of soil degradation.

From the primary evaluation of rehabilitation potentials, it was found that physical appearances has been greatly improved after a period of 3-5 years under trees or integration farming systems. Dark black color developed after 5-7 years. Actual rehabilitation was observed with the growth and forming of root mats in the surface soils. Rehabilitation potential from an example of using Eupatorium odoratum for 2 years also shows good soil physical appearances.

Most of the agricultural systems that the farmer network expressed as good practices for soil rehabilitation are integrated farming systems that comprised of diversified crop and plant production systems. Despite general low inputs during the production processes, there is general rehabilitation evidence in the soil systems. The essence of the practices seems to be derived from less or undisturbed natural environment and soil habitats. Only from the second year after the implementation of these integrated management systems was it found that both soil fertility and productivity have been reversed towards rehabilitation trends. Another indigenous practice on soil productivity rehabilitation is the utilization of soil materials from termite mounds and dredged lake sediment. Even though the quality could be low, it has been compensated by being a low cost management improvement strategy. Farmers usually compared amount of nutrients in the sediment to fertilizer bags and found that it could be more beneficial to use lake sediment than chemical fertilizers for the similar cost and productivity. Conclusion of the surveys and observation suggested that rehabilitation processes were primarily from top layers and gradually extending down the profile with times. Primary signs of improvement included soil color and later soil structure. For the productivity, there were improvements of growths of plants that are requiring good soils.

From soil sampling and analysis, suggested that most of the farmer observations are confirmed by laboratory results. Clear increases in soil fertility and productivity were clearly demonstrated after 5-7 years after most of the practices, despite observations revealed earlier productivity rehabilitation in the 2nd year and soil rehabilitation appearances in the 3rd year. The minimal disturbance of soil ecosystems seemed to be the key factor leading to natural soil and ecosystem rehabilitation and rehabilitation processes could be observed within 2-3 years for degraded soils and 3-5 years for land-filled subsoil.

Organic matter in top (0-10 cm) soil is generally higher than the nearby paired site regardless of period from the initiation of the improvement phase. However, with longer periods of the improvement phases from 5 years onwards, increases in organic matter in the top soils were at least double that at the start, from less than 1% to 2, 3, 5 or even 6% in some cases. Clear evidence of reversing soil degradation with respect to increased soil organic matter are presented in Figure 9.

Soil pHs in improved systems were generally higher than the control paired sites (Figure 10). The improvements were found when the paired site show low pH ranges of 4-5. However, when the paired site

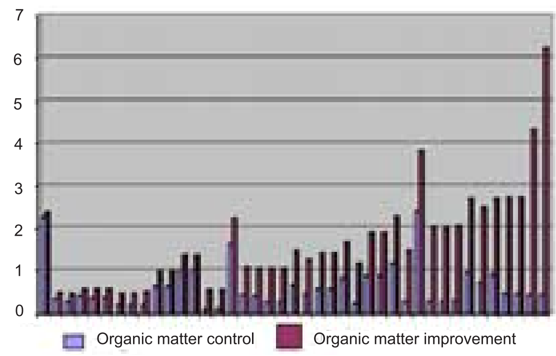

Figure 9. Summary of organic matter improvement varying periods under integrated farming systems and agroforestry

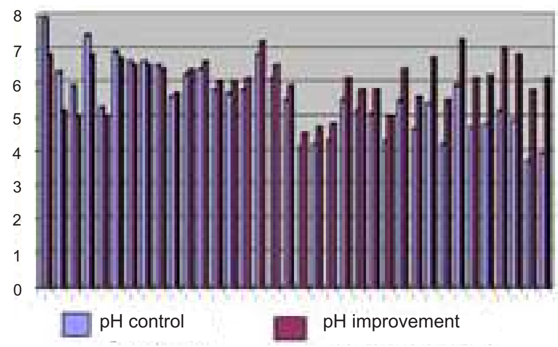

Figure 10. Summary of soil pH (0.01 M $CaCl_2$) improvement after periods of integration farming systems and agroforestry

pHs were relatively high, there were no changes or even decreases in soil pH as shown in Figure 10. Most of EC values of the soils were not considered to be within the problematic ranges for salinity, as such the increases of EC could be more beneficial to the soil fertility and soil productivity (Figure 11). There were mostly increases in EC over the control paired sites as shown in Figure 11. Cation exchange capacities of the soils were slightly improved in most cases. The biggest increase was found with long term improvement as shown in Figure 12. The small changes could be associated with transformation of organic materials from plant debris and litter that were not directly associated with the increases of organic matter in the soils. Effective CEC is the indicator of nutrient accumulation in the soil profile. It was found that the accumulation was increasingly higher with times as shown in Figure 13.

When the data is compared to the baseline northeast forest soil data, it is suggested that the rehabilitation potential of the farmer practices are very close to forest improvement potentials, especially when the soil and land were managed in similar ways to natural forest systems. The potential rehabilitations are even faster with degraded soils than the landfill

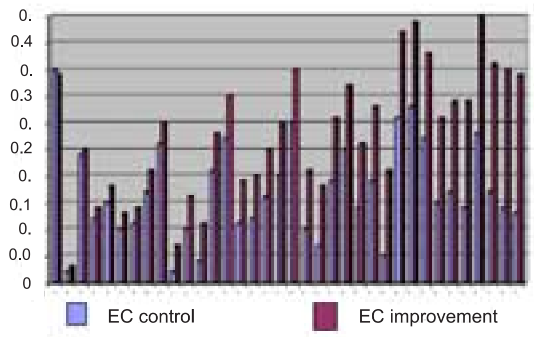

Figure 11. Summary of EC (ms/cm) improvement after periods of integration farming systems and agroforestry

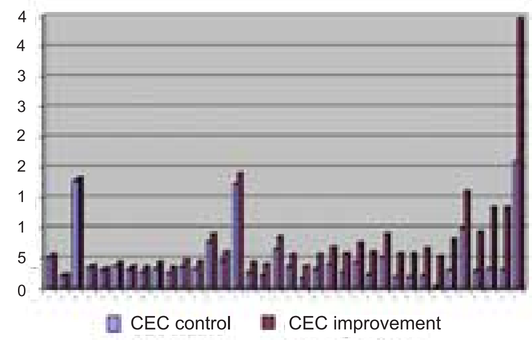

Figure 12. Summary of CEC (cmoles/kg) improvement after periods of integration farming systems and agro-forestry

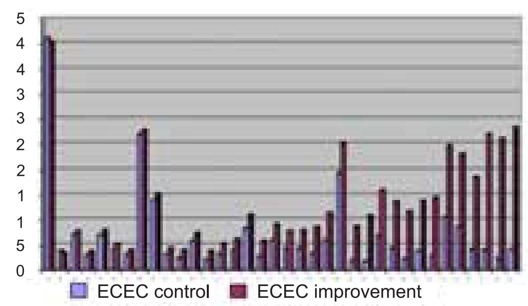

Figure 13. Summary of ECEC (cmoles/kg) improvement after periods of integration farming systems and agro-forestry

systems. The most likely rehabilitation processes could be the tree effects on the natural soil and forest ecosystems.

Summary

The results of the study indicated that changes in productivities were clearly observed by land owners long before the observed changes in soil properties. The observed changes in soil productivity by land owners were even over the effects of conventional chemical fertilizer application. In most cases, farmers have confirmed through memory that the productivity has improved. The changes of soil properties were clearly visibly observed on the soil surface and from topsoil to depths. Organic matter was found increased with associated EC and CEC, and finally ECEC which are indicators of nutrient accumulations.

Therefore it could be concluded that indigenous improvement systems could be used to rehabilitate degraded soils. Successes have derived from less disturbed ecosystems with minimal inputs. Results of this study could be used for both actual practices for reversing soil degradation and policy making for low input management of sandy soils. The essences of the practices are less disturbed and reduced application of toxic materials to the soil and environment. This would allow natural soil processes to revive the soil systems and resulting in holistic soil improvement as shown in this study.

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Poster Session 1

"Global extent of tropical sandy soils and their pedogenesis"

Spatial heterogeneity in sandy soils of the Sahel region in West Africa: implications for desertification processes

Shinjo, H.[1]*; K. Ikazaki*[1]*; U. Tanaka*[2] *and T. Kosaki*[2]

Keywords: desertification, geostatistics, NDVI, satellite image, spatial heterogeneity

Abstract

The large inter-annual fluctuation in precipitation and the spatial heterogeneity in soil inherent fertility often make it difficult to assess desertification temporally over a given period. To overcome this difficulty, we examined the possibility of spatial heterogeneity as an index of desertification. Our hypothesis is that spatial heterogeneity of soil and vegetation will reach a maximum at the middle of desertification processes, while soil and vegetation would in general have a homogeneous character at its beginning and end. In ancient sand dunes in Northern Burkina Faso receiving about 400 mm of annual rainfall, our field survey consisted of 50 m transect survey at 9 sites and 450 m transect survey at a single site to identify plant species at the regular intervals. Soil samples were taken at the 450 m transect survey. Six satellite imageries of Landsat-TM from 1986 to 2002 and one satellite imagery of ASTER in 2003 at the end of rainy seasons were also used. The 50 m transect survey revealed that maximum diversity of plant species was found at the medium level of plant biomass, validating the hypothesis at the plant species level. The 450 m transect survey validated the hypothesis at the plant coverage level indicating that maximum heterogeneity of plant coverage was found at its medium level. The positive correlation between plant coverage and sand content suggested that plant growth would be reduced once the sandy surface soil was eroded and hard loamy subsurface soil with low water permeability was exposed on the surface. Thus, in this region, the soils with the sandy surface layer could be regarded as productive. Analysis of the satellite imagery indicated that the hypothesis could be correct spatially although no place had experienced the whole process of the hypothesis from 1986 to 2002. Further validation in extended space and time would be necessary.

Introduction

Desertification, the land degradation in arid, semi-arid, and dry subhumid areas (UNEP 1997), is one of the challenging issues for mankind due to its serious impact on human welfare and environment. Desertification risk assessment would help control desertification and achieve sustainable land use. The remotely sensed data such as aerial photos and satellite images have been employed for this purpose since archival data enable us to obtain land information in the past and assess temporal change in land characteristics (UNEP 1997; Mouat et al. 1997). However, the large inter-annual fluctuation in precipitation and the spatial heterogeneity in soil inherent fertility often make it difficult to assess desertification temporally over a given period. One of the measures proposed to overcome this difficulty is indexing spatial heterogeneity. Schlesinger et al. (1990, 1996) found that soil moisture and nutrient status and subsequently vegetative conditions had become spatially heterogeneous as desertification proceeded and proposed “the island of fertility” theory. On the other hand, our field observation in the Sahel region of Northern Burkina Faso suggested that spatial heterogeneity of vegetation decreased as land surface become bare. Thus, we integrated Schlesinger’s theory with the observation to hypothesize that spatial heterogeneity of soil and vegetation will reach a maximum at the middle of desertification processes, while soil and vegetation would in general have a homogeneous character at its beginning and end (Figure 1). Following above-mentioned finding of Schlesinger’s, Tucker et al. (1991), Milich and Weiss (2000), and Seixas (2000) employed coefficients of variance (CV) of normalized difference vegetation index (NDVI) of satellite images for desertification assessment. However, since spatial resolution in the first two studies was as coarse as 7.6 km and the last study did not relate NDVI with ground truth data, the

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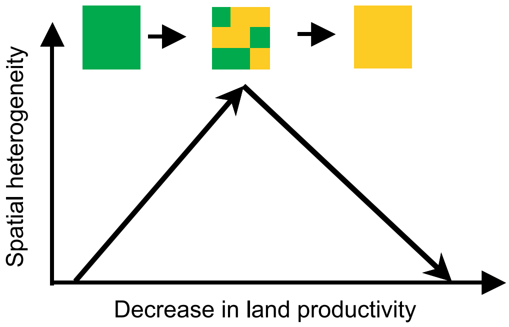

Figure 1. Hypothetical diagram of desertification process

assessment at the finer scale with the validation of NDVI by ground truth data would be necessary for the purpose of sustainable land use at a village scale. Thus, the objectives of our study are to understand the actual status of spatial heterogeneity in sandy soils of the Sahel region in West Africa and examine the possibility of spatial heterogeneity as the index of desertification processes.

Materials and methods

The study area is located in Takabangou Village, Oudalan Province, Burkina Faso receiving about 400 mm of annual rainfall (Figure 2). In this area, millet fields and fallow land occupy strips of ancient sand dunes extending from east to west, while the area between the ancient sand dunes is less covered with sand and used as rangeland. Dominant native plant species were *Aristida mutabilis*, *Cenchrus biflorus*, *Schoenefeldia gracilis* and *Eragrostis tremula*.

Our field survey consisted of 50 m transect surveys at 9 sites in October 2002 and 450 m transect survey at one site in October 2003 (Figure 2). At each site for the 50 m transect survey, plant species were identified at intervals of 50 cm in the 50 m transect and aboveground plant biomass in 1 m^2 was measured at 3 points in the transect. Shannon-Weaver's diversity index, H', was calculated at each site by

$$H' = -\sum P_i \times \log_e P_i \quad (1)$$

where P_i is the frequency of plant species i in the 50 m transect.

At the site of the 450 m transect survey, three 450 m rows were set 30 m apart from each other (Figure 3). After plant species were identified at intervals of 1 m in the rows, bare rate was calculated every 30 m along the rows as the percentage of the frequency of plant absence. Soil samples from the depth of 0-5 cm were also taken every 30 m, air dried and analysed for soil texture.

Six satellite scenes of Landsat-TM in 1986, 1992, 1999, 2000, 2001 and 2002 and one scene of ASTER in 2003 were used. All scenes were captured

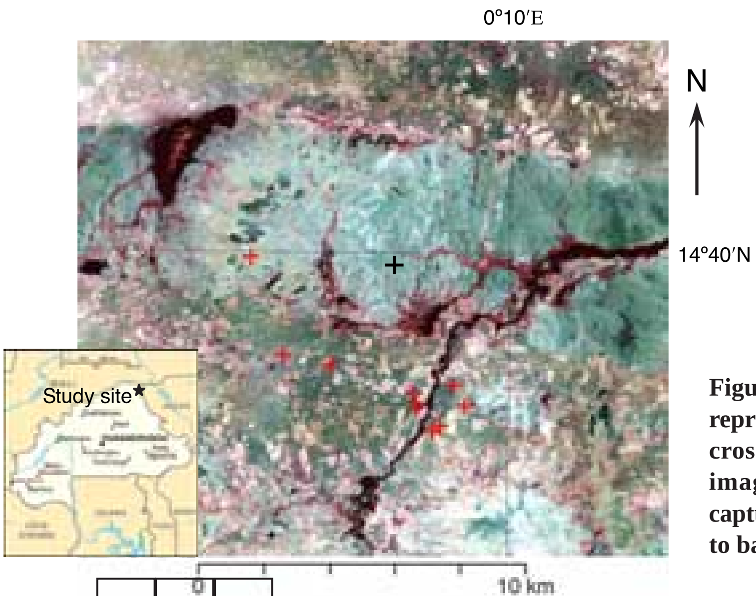

Figure 2. Location of the study site. Red crosses represent the 50 m transect survey sites and the black cross the 450 m transect survey site. Background image is a false color composite of Landsat TM captured on Oct. 14, 2002 by assigning digital number to band 4, 3 and 2 to R, G and B respectively

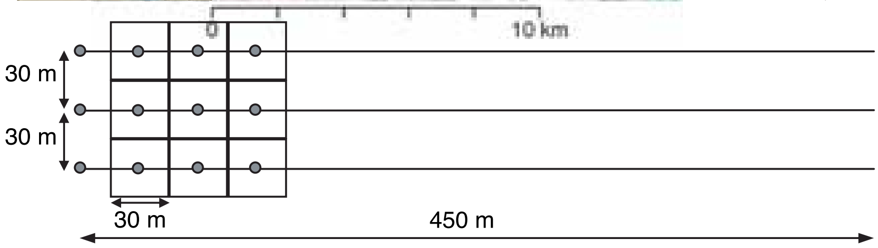

Figure 3. Design for 450 m transect survey. Three 450 m rows were set 30 m apart from each other. Dots show soil sampling points. Squares show units for calculation of bare rate. Bare rates in nine units shown in the figure are complied to calculate their mean value and coefficient of variance

at the end of rainy seasons. After geometrical correction with ground control points and conversion to absolute radiance, temporal variation caused by path radiance was corrected by subtracting a minimum pixel value in each scene from each pixel value. With the corrected pixel values, NDVI was calculated for each scene by

$$\mathrm{NDVI} = (\text{band } 4 - \text{band } 3) / (\text{band } 4 + \text{band } 3) \quad (2)$$

Since inter-annual variation in NDVI values of each pixel due to climatic variation such as variation in amount and distribution of rainfall make it difficult to estimate the long term trend, the NDVI values were standardized using the following:

$$\text{Standardized NDVI} = (\mathrm{NDVI} - \mathrm{NDVI}_{mode}) / \mathrm{NDVI}_{std} \quad (3)$$

where NDVI_{mode} is mode value of NDVI in each scene, and NDVI_{std} is standard deviation of NDVI in each scene (Koizumi et al. 2003).

Results and discussion

Since the 50 m transect survey revealed that maximum diversity of plant species was found at the medium level of plant biomass (Figure 4), it is implied that land characteristics were heterogeneous to realize many plant species at the medium level of land productivity. Thus, the hypothesis was validated at the plant species level.

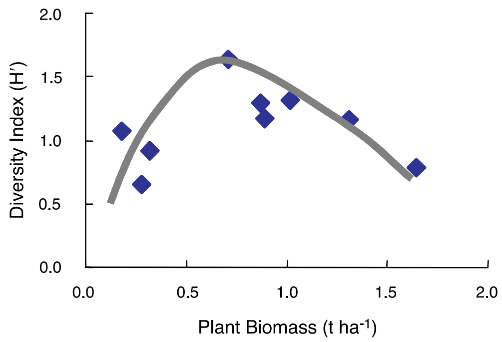

Figure 4. Relationship between diversity index and plant biomass at the 50 m transect survey sites

The 450 m transect survey resulted in a negative correlation between the bare rate and sand content, implying that plant growth would be reduced once the sandy surface soil was eroded and hard loamy subsurface soil with low water permeability was exposed on the surface (Figure 5). Thus, in this region, soils with a sandy surface layer could be regarded as

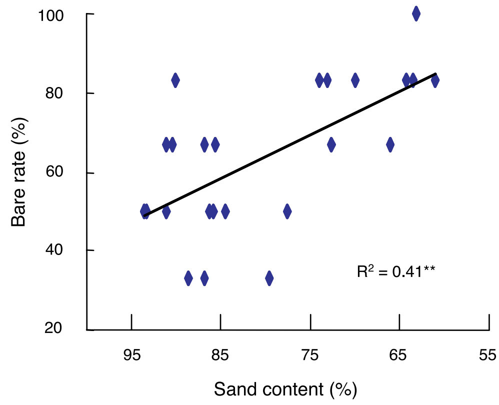

Figure 5. Relationship between bare rate and sand content at the 450 m transect survey site

productive. The bare rate calculated every 30 m in the 450 m transect survey was compiled for 9 neighbouring units to obtain mean values and coefficients of variance (CV) of bare rates (Figure 3). As shown in Figure 6, a negative correlation between CV and mean value of the bare rate indicated that plant coverage at its medium level of bare rates was spatially rather heterogeneous as expected by the hypothesis. However, since no high plant coverage with the less than 40% of mean bare rates was found at the site, the hypothesis could be only validated at the plant coverage level. In addition, it is of note that the desertification process at the site had already passed the one Schlesinger described.

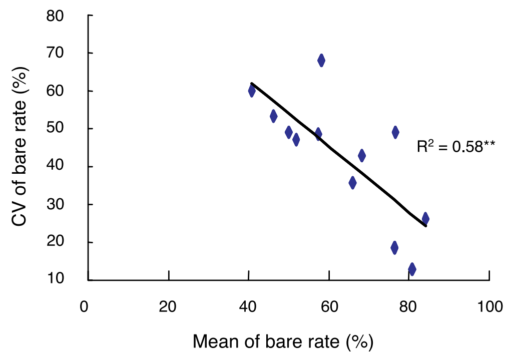

Figure 6. Relationship between mean values and coefficients of variance (CV) of bare rate in 3 × 3 unit at the 450 m transect survey site

Before Landsat-TM data was employed to compensate the insufficient field data set for validating the hypothesis, two conditions were examined. The first was the correlation of NDVI derived from satellite images with ground truth data and the other was whether the spatial resolution of satellite data was fine enough to evaluate the spatial heterogeneity of ground truth data. Figure 7 proves that ground truth data of bare rates can be estimated by NDVI. To examine the

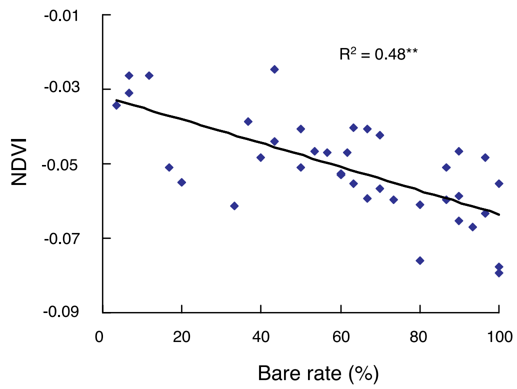

Figure 7. Relationship between bare rate and normalized difference vegetation index (NDVI) in October 2003 at the 450 m transect survey site

second condition, a geostatistical analysis was performed. Assigning 1 to the points without plants and 0 to the points with plants in the rows of the 450 transect survey, the semivariance was calculated as follows:

$$\gamma(h) = \frac{1}{2N(h)} \sum (Z(x) - Z(x+h))^2 \qquad (4)$$

where γ(h) is semivariance at lag h, N(h) is number of the observation pairs which were apart from each other by the lag h, Z(x) is observation at point x, and Z(x + h) is observation at point (x + h). Figure 8 shows that the semivariance reached its maximum at the lag of 67 m to which the spatial dependence was limited (Webster and Oliver 2001). Thus, it is suggested that average size of vegetative patches was 67 m and the spatial resolution of 30 m for Landsat-TM data was adequate enough to distinguish vegetative patches.

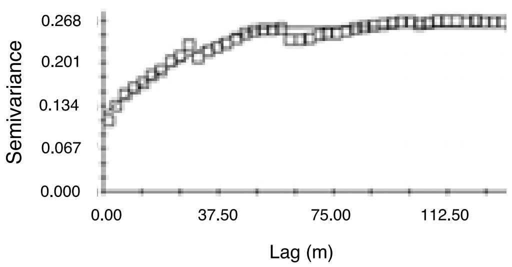

Figure 8. Semivariogram of plant absence at the 450 m transect survey site

Now that the two conditions were met by NDVI of Landsat-TM data, the hypothesis was examined by the time series of standardized NDVI. For this purpose, 11 points in the study area were selected that were observed to have the largest temporal variation in NDVI, covered the whole range of NDVI found in the study area, and scattered over the whole study area.

Figure 9 shows that the maximum CV of NDVI was found at the moderate level of mean NDVI, suggesting that the hypothesis could be correct spatially. However, since no point had experienced the whole process of the hypothesis from 1986 to 2002, it seemed that the drastic desertification had not taken place in the study area during the period examined and that vegetative coverage were rather controlled by inherent land productivity. Further validation in extended space and time would be necessary.

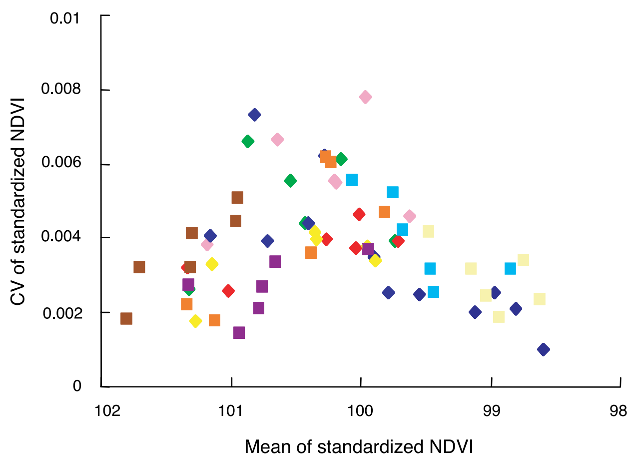

Figure 9. Relationship between mean values and coefficient of variance of standardized NDVI at the selected 11 points in the study area. Symbols with the same color and shape represent values at one point from 1986 to 2002

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The potential productivity of sandy soil for sugarcane in some regions of Thailand associated with micromorphological observation

Sindhusen, P.[1]*; H. Pichainarong and K. Marlairodsiri*

Abstract

Six sandy soils from different regions of Thailand namely, central region, the east-coast and the northeast that are used for sugarcane production were selected to study micromorphological characteristics. Results from micromorphological analysis indicate that there is a link between yield of sugarcane and microstructure. The highest productivity of sugarcane (69 t/ha) was observed on the Kamphaeng Saen series in the central region which has a ratio of 60:40 for coarse/fine(c/f) particles, that is particles that are bigger and smaller than 10 μm respectively. The c/f related distribution pattern is close porphyric. The microstructure shows evidence of vughy structure, and the total pore space is about 20% at a depth of 20-40 cm. The lowest production yield (53 t/ha) was observed at Huai Thalang variant in the northeast which has c/f ratio of 88:12. The c/f related distribution pattern is gefuric mixed with chitonic. The microstructure showed bridged grain structure mixed with pellicular grain structure, voids are predominantly simple packing voids, and the total pore space is approximately 10% at a depth of 20-30 cm. The greater abundance of macropores (or vughs) for rooting, may account for the increased yields observed.

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Poster Session 2

"Socio-economic imperatives"

Protection ratio, an economic indicator for assessing locations for strategic dike reinforcement for erosion management in rainfed paddy-upland sandy soil mini-watersheds

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Abstract

Farmers in Northeast Thailand manage mini-watershed ecosystems in which each farmer has rainfed paddies in valley bottoms and upland fields in sandy soils on sloping valley sides. Farmers grow glutinous rice in the paddies for home consumption and sugarcane and cassava in the uplands as cash crops. We chose one village, Nong Saeng, Khon Kaen Province, to develop a participatory research process to identify management needs and test rapid solutions. This resulted in an economic indicator, the protection ratio, for assessing locations for strategic dike reinforcement.

The process consisted of four steps: 1) farmer selection of mini-watershed transect locations for needs assessment; 2) presentation of technical options for solution of needs; 3) farmer selection of an option to adapt; 4) selection of test sites. Farmers proposed using magnesium oxide (MgO) for dike reinforcement at strategic breakage locations. Locations were chosen based on a dike breakage survey and a watershed model. Four sites were located between upland fields and the central paddy area.

The protection ratio calculated as area of paddy protected in rai (0.16 ha)/10 m^2 *reinforced dike was developed as an indicator of economic benefits. Economic costs were based on tractor rental to repair dikes annually and materials and labour costs of MgO reinforcement in the first year. Economic benefits were based on observed yields in protected and non-protected areas and projections over three rainfall scenarios. At site A with a protection ratio of 0.7 (2.1 rai protected by 31.1 m*^{2} *reinforced dike), net benefit of Bht 1,118 was realized only under the most favourable scenario of 1 dry year and 2 normal years. At site C with a protection ratio of 5.4 (9.7 rai protected by 17.9 m*^{2} *dike), positive economic benefit of Bht 5,468 was estimated over one dry, one wet, and one normal year.*

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Poster Session 3

"Chemical properties and their effect on productivity"

Assessment of salinity hazard by electromagnetism induction method in flooded sandy paddy soils

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J. Wiengwongnam[4] *and C. Hammecker*[1]

Keywords: Salinity, Electromagnetic Induction, Sandy soils, Rice field, Northeast Thailand

Abstract

Salinity is a major constraint for rainfed rice production in Northeast Thailand sandy lowlands. Salinity surveys are currently performed using Electromagnetic Induction method (EMI) that is associated with soil conductivity measurements. Previous survey methods have consisted of performing EMI measurements during the dry season with the assumption that capillarity rise was the main cause of salt excess in the top layers of the growing rice. Hydrodynamic studies have demonstrated that in some cases the main process of salt enrichment of the top layer consists of the ascent of salt water from the aquifer during the rice cycle. An adaptation of EMI measuring device was realized in order to allow the surveys to be performed during the flooded period. Measurements in horizontal and vertical dipole configuration were performed in an area of contrasted salinity, comparing the obtained values with the conductivity of soil and water mixtures of the top layer. Measurements during rice flooding period indicated better relationship between salt contents and vertical dipole measurements than those performed during the dry season. Salinity in the top layers in the two different stages was identified with two different processes of spatial distribution: on the one hand, capillarity rise during the drying period, and on the other hand the circulation of saline solutions during the flooded periods. Therefore, EMI measurements during flooded periods should be recommended in salt-affected sandy paddy soils as more accurate and representative of conditions that influence plant performance.

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Cation exchange capacity of sandy salt-affected paddy soils by ammonium acetate, cobalt-hexamine and compulsive method

Promkutkaew, A.[1]*; O. Grunberger*[1]*; S. Bhuthorndharaj*[2] *and A.D. Noble*[3]

Keywords: Cation Exchange Capacity determination methods, sandy and salt-affected soils, paddy fields

Abstract

Sandy soils of Northeast Thailand have for long been identified as problematic soils. Acidity, salinity, low organic matter contents and low cation exchangeable capacity (CEC) have been established as the main soil constraints to rice production on these sandy soils. CEC values are dependent on clay content, soil organic matter content and soil pH. In the context of sandy salt-affected soils, precise and accurate determinations of low CEC values are often considered problematic and a large number of methods are available to measure this attribute. The objective of the study was to compare the values obtained on a set of 6 samples using different methods of CEC determination in the context of salt-affected sandy paddy soils. Ammonium acetate method at pH 7 and cobalt-hexamine at soil pH methods with or without alcohol pretreatment were compared with compulsive method, with $CaCl_2$ at the same pH. In sandy soil paddy profiles with a low clay content and CEC values measured with compulsive methods, less to 2.67 $cmol_c\ kg^{-1}$ determinations with ammonium acetate and cobalti-hexamine methods presented linear relationships with the compulsive method results in $cmol_c\ kg^{-1}{}_{(of\ soil)}$ $CEC_{cobalt} = CEC_{compulsive} * 0.45 + 1.84$, $R^2 = 0.93$) and ($CEC_{ammonium} = CEC_{compulsive} * 0.37 + 1.91$, $R^2 = 0.87$). The same type of relationships were established performing previous alcohol treatment in order to remove salts although with lower significance (respectively $R^2 = 0.56$ and $R^2 = 0.80$). These results indicate that using ammonium acetate or cobalt-hexamine methods, in salt-affected sandy soils with a CEC lower 2.67 $cmol_c\ kg^{-1}$ will lead to overestimation of CEC when compared to compulsive method. This overestimation was found to be independent of pH values and salt-effect.

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Mineralogical and chemical properties of low activity kaolin-rich, light-textured soils in Thailand

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Keywords: Light-textured soil, kaolin, CEC, specific surface area

Abstract

Highly weathered light-textured soils with low chemical activity are common in Thailand and provide significant management constraints. Representative topsoils and subsoils of Kohong, Klong Thom, Sadao, Tasae, Yasothon, Thai Muang, Chalong, and Hang Chat series have been investigated by X-ray diffraction (XRD), transmission electron microscopy (TEM) and chemical analyses. Clay-sized particles in the soils range from 76 to 207 g kg^{-1} (median 139 g kg^{-1}). These soils are acid (pH in water 4.0-4.8), having very low to low organic matter contents (2.4-23.4 g kg^{-1}), low cation exchange capacity (0.6-4.5 cmol$_c$ kg^{-1}), and very small to small values of specific surface area (SSA) (2-11 m^2 g^{-1}). Kaolin group clay minerals are the major constituents (>70% content) of the clay fraction, with minor amounts of inhibited vermiculite, illite, quartz, and anatase. Goethite is present in most of the soils with hematite in Sadao series (Typic Kandiudults). These soil kaolins exhibit a wide range of crystal sizes ranging between 0.06 to 0.83 µm, and most of the crystals are very small, euhedral, hexagonal platy. They contribute most of the CEC of these soils.

The Fe_d concentrations in these soils (4-12 g kg^{-1}) are much higher than Fe_o concentrations (0.2-1.6 g kg^{-1}) with the values of Fe_o/Fe_d ranging from 0.05 to 0.23 (median 0.12) indicating that most of the free iron oxides are crystalline which is consistent with XRD measurements. Amounts of Al_d and Al_o are about equal with median values of 0.7 and 0.4 g kg^{-1}, respectively. These oxide constituents are important for the retention of anionic plant nutrients.

CEC provides a measure of cation retention as does SSA and both properties have linear positive significant relationships with clay content (r = 0.58, 0.93), Al_d (r = 0.79, 0.75), Al_o (r = 0.81, 0.62), and Fe_o (r = 0.69, 0.68).

We consider that the small amounts of clay-sized materials in these soils play a vital role in plant nutrient retention and the soils should be managed conservatively to protect these materials.

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Phosphate desorption by sandy soils of Northeast Thailand

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Keywords: Light-textured soil, P-sorption isotherms, P desorption

Abstract

Sandy soils which are very common in Northeast Thailand have the capacity to adsorb different amounts of phosphate. This study was undertaken to determine the amount of adsorbed phosphate released from five sandy soils from the region. Adsorption was first carried out by shaking samples of each soil for 30 minutes, twice daily for 6 day, with 0.01 M $CaCl_2$ solution containing phosphate in a concentration range from 1 to 32 mg P L^{-1}. Desorption isotherms were determined in a similar manner by re-shaking the wet samples and their adsorbed phosphate with calcium chloride solution using a soil:solution ratio of 1:10. Measurements suggest that phosphate sorption for all soils were almost irreversible. The adsorption and desorption isotherms of all soils conformed to the Langmuir equation. The adsorption maximum value was used to determine the phosphate saturation. Desorption of adsorbed phosphate increased with increasing saturation percentage. Average desorbability at low saturation (<20%) and high saturation (>80%) was 0.5 and 12% respectively. Dithionite – citrate – bicarbonate and oxalate extractable iron were the major phosphate adsorbents in the study.

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Clays concentrate nutrient reserves in a toposequence of sandy soils in Northeast Thailand

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Keywords: Sandy soils, clay mineralogy, proton-consumption, clay dissolution

Abstract

Poorly fertile sandy soils are widespread in Northeast Thailand. This represents a serious threat to local farmers and constrains economic development in the region. Here, we evaluate the fertility of these soils. We studied the physico-chemical and mineralogical properties of five pedons along a transect located at 25 km Southwest of Khon Kaen, respectively under forest (F), sugarcane (SC) and in paddy fields (PF1, PF2, PF3). All soils have a very low organic matter content (<1%). They differ in weathering stage and mineral reserve. The well drained soils under the F and SC are more weathered than the poorly drained PF profiles. Kaolinite is the major phyllosilicate in F and SC, whereas smectite is the dominant clay mineral in PFs. In the toposequence, the total content of major alkaline and alkaline-earth cations (TRB), i.e. mineral reserve, is confined to the clay fraction (<2 µm). From PFs to SC and F, it decreases with decreasing CEC and total Mg content, as well as with the disappearance of smectite and the appearance of 1:1-2:1 mixed layered clay minerals. In addition, KCl-extractable Al becomes the major cation on the effective CEC in the well drained soil profiles. We propose that clay minerals act here as key proton-consumers. As such, smectite dissolution is supported by a high content of exchangeable Mg relatively to Ca, and by the XRD detection of 1:1-2:1 interstratified clays. Such clay minerals represent, indeed, an intermediate stage in the processes of smectite dissolution and kaolinite formation in low silica and freely drained soil environments. The conservation of the clay exchanger must be a key objective in the management and use of these poor sandy soils. In addition, ***in situ*** *soil monitoring is required to further assess the dissolution of 2:1 clay minerals and the proposed corresponding Mg-depletion.*

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The potential of Quartzipsamments for sugarcane growing in Southeast Coast, Thailand

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Keywords: Sugarcane production, light textured soils, chemical and physical properties, suitability assessment

Abstract

A study on the potential of Quartzipsamments to support the growing of sugarcane on the Southeast Coast, Thailand was undertaken on four representative soil areas. The methodology used in this study included pedon analysis of soils in the selected areas, laboratory analyses of their physico-chemical properties, mineralogy, micromorphological characteristics and assessment of their properties related to sugarcane crop requirements.

Results of the study revealed that these soils are Quartzipsamments deposited on the coastal plain. They are deep soils developed mainly on local alluvium and wash deposits derived from granite. Their micromorphological characteristics show subangular to subrounded quartz grains as the major fabric component. Their texture ranges from sand to loamy sand and their bulk density ranges from moderately low to high (1.40-1.82 Mg m^{-3}). Chemical analysis of soils indicates that they have a strong acid to neutral reaction (pH 5.1-6.8). They have very low to low organic matter contents (0.2-9.4 g kg^{-1}), very low total nitrogen (0.01-0.03 g kg^{-1}), very low to high available phosphorus (1-95 mg kg^{-1}) and very low to low available potassium (1.5-46.8 mg kg^{-1}). The soils have very low to medium cation exchange capacity (2-11 $cmol_c$ kg^{-1}). Their base saturation percentage varies widely from 4-77%. Their electrical conductivity ranges from 0.1-1.9 dS m^{-1} indicating no salt-effect.

Fertility assessment results indicate that most of these sugarcane-growing soils have low fertility except for a single area where the soil has a moderate fertility status. Their potential based on suitability assessment indicates that most of them are moderately suited but one profile is not suited for sugarcane growing because of its sandy texture and strongly acid condition. A recommended approach to increase their potential for sugarcane growing includes an emphasis on soil organic matter conservation and a more intensive soil-fertilizer management. A continuing effort on soil-fertilizer management is clearly needed to maintain effectiveness in sugarcane growing on these soils.

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Influence of fertilizer inputs on soil solution chemistry in eucalypt plantations established on Brazilian sandy soils

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Keywords: ***Eucalyptus*, biogeochemical cycles, soil solution, chemistry, nitrate, aluminum, fertilization, Brazil**

Abstract

The present paper is part of a comprehensive approach currently developed in Brazil to study biogeochemical cycles at the ecosystem level in ***Eucalyptus grandis*** *plantations. It aims at assessing changes occurring in water chemical composition throughout their transfer in the soil, during the first year after planting. A lysimetry was installed in a 5-year-old* ***E. saligna*** *stand. Lysimeters were strategically positioned within a compartment of* ***E. saligna*** *prior to the clear felling of the stand that would allow the assessment of a fertilization experiment planned on the same site for the next rotation. About 180 zero-tension lysimeters were installed in the upper soil layers and 136 ceramic cups were setup horizontally down to a 3 m depth and connected to an automatic vacuum pump. After the harvest of the* ***E. saligna*** *stand, a fertilization experiment of* ***E. grandis*** *improved seedlings was initiated using a complete randomized block design, with 6 blocks and 5 treatments. The objective was to compare the influence of different amounts of ammonium sulphate and sewage sludge fertilizations on biogeochemical cycling. At the end of the rotation, nutrient concentrations in soil solutions were low whatever the depth and the lysimeter type. After clear felling, soil solution ionic balances were dominated by* NO_3^- *and* Al^{3+}*, whose concentrations increased substantially. No obvious change in concentrations was observed for all other elements. A proton unbalance, resulting from the interruption of* NO_3^- *uptake by plants after harvesting, might be responsible for the aluminium accumulation in soil solutions. After planting, fertilizer inputs were responsible for increasing concentrations of all elements applied until 1 m deep. Twelve months after planting* ***E. grandis****, the chemistry of soil solutions at 3 m deep had not developed. The monitoring of soil solution chemistry is going on in order to quantify the effects of these different fertilizations on deep drainage nutrient losses.*

Introduction

Fast growing *Eucalyptus* plantations cover approximately 3 millions hectares in Brazil. This sector is of great economical importance since the *Eucalyptus*-plantation production supplies the Brazilian cellulose and paper industry as well as the metallurgy industry through the production of vegetal charcoal. Due to several decades of research, the productivity of these plantations now ranges from 30 to 50 kg ha^{-1} year^{-1} according to soil characteristics and water availability (Gonçalves et al., 2004).

The ecological impact of *Eucalyptus* plantations has been widely discussed around the world (Cossalter and Pye-Smith, 2003). In particular, water consumption by eucalypt stands has been extensively investigated. But few studies have ever assessed the influence of silviculture on superficial water chemistry. Such studies are nonetheless necessary to identify and foster practices minimizing the silvicultural impact on the water table chemistry of afforested catchments.

A comprehensive approach is currently being conducted at the University of São Paulo to study the

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biogeochemical cycles of nutrients in *Eucalyptus grandis* plantations. This project is developed at the ecosystem level in an experimental stand representative of large areas of plantations in Brazil. The overall aim of the study is to assess the consequences of silviculture, and more particular of different fertilizer inputs, on water quality and long-term soil fertility by measuring water and nutrient fluxes throughout the ecosystem. The present paper focuses on changes occurring in soil solution chemical composition during the first year after planting.

Materials and methods

Site characteristics

The study was conducted at the ESALQ/USP experimental station of Itatinga (23º02′S, 48º38′W). The annual mean precipitation is 1,300 mm and the annual mean temperature is 20ºC. Figure 1 shows the time course of rainfall and temperature over the sampling period. The selected site is representative of the typical relief of the São Paulo Western Plateau. The maximum altitude of the area is 863 m. The slopes are flat to undulating (3%) in the experimental stand. The lithology is composed of sands, Marilia formation, Bauru group. The soils are “Latossolos Vermelho-Amarelo” according to Brazilian classification. Soil analysis showed that sand content was >75%, whatever the soil layer, down to >6 m.

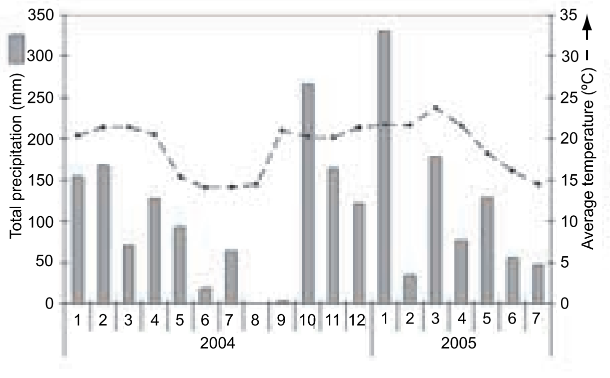

Figure 1. Time course of average temperature (ºC) and total precipitation (mm) at the experimental site

The Itatinga experimental station has been covered for 60 years with *Eucalyptus saligna* plantations. These stands were first planted in 1945 on pasture and have been managed in short rotation coppices for fire wood production since then. The experimental design was implemented in 2003 in a 6 ha coppice harvested in 1997, and planted in 1998 with *Eucalyptus saligna*. Tree spacing was 3 m × 2 m and only a NPK (10:20:10) starter fertilization of 300 kg ha^{-1} was applied.

Methodology

A lysimetric design was installed at the beginning of 2003 in the 5-year-old *E. saligna*. Lysimeters were positioned appropriately for a fertilization experiment planned on the same site for the next rotation, after the harvest. A 3 months period was left for soil stabilization, and then nutrient fluxes were monitored over a 9 month period prior to the harvesting of the stand (from July 2003 to February 2004). In February 2004, the stand was clear felled and the stumps killed using glyphosate. Improved *E. grandis* seedlings were planted on the same planting rows at half-distance between the stamps, without any soil preparation. The previous stocking density was maintained (2 m × 3 m spacing).

A nitrogen fertilization experiment was then initiated using a complete randomized block design, with 6 blocks, 5 treatments and 100 trees per plot. The fertilization treatments imposed were those classically used by Brazilian companies on these soil types: all mineral fertilizers but N (T1) (Control), all mineral fertilizers (T3), and sewage sludge fertilization (T_5). Nutrient fluxes were measured in these three treatments (T_1, T_3, T_5) in blocks 1, 2 and 3. Blocks 4, 5 and 6 were installed to sample trees at various ages without disturbing the lysimetry design (Table 1). T_2 and T_4 treatments were installed to help establish a response curve to N inputs. The fertilizations applied in each treatment are presented in Table 1.

The soil solution sampling equipment was installed in blocks 1, 2 and 3 of treatments T_1, T_3, T_5 according to a systematic constant scheme. Throughfall solutions were collected from 12 funnels systematically located beneath the trees in each one of the 9 experimental plots. In each plot, 3 sets of 9 narrow zero-tension lysimeters (40 × 2.5 cm) were installed beneath the forest floor, and zero-tension plate lysimeters (50 x 40 cm) were introduced at 15, 50 and 100 cm deep (5 at each depth) from pits backfilled after installation with the horizons in their natural arrangement. The litter and soil solutions were collected in polyethylene containers situated downhill in closed pits. Moreover, 4 replicates of tension lysimeters were installed horizontally at the depths of 15 cm, 50 cm, 1 m, and 3 m in each plot. They were connected to a vacuum pump and automatically maintained at a constant suction of -70 kPa. Ceramic-cup solutions were collected in glass bottles. All lysimeters were set up representatively near and between the trees to take into account spatial variability. In each plot, lysimeters of same type and depth were connected to one collector in order to

Table 1. Experimental treatments and fertilization strategies imposed

	Nitrogenous fertilization			Other fertilizers
	Amount	Fertilizer type	Application type	
		Control		
T1	0		4 equal partsat planting	■ Triple superphosphate (75 kg ha^{-1} P_2O_5)
T2	40 kg ha^{-1}	Ammonium sulfate	6 months	■ KCl (30 kg ha^{-1})
T3	120 kg ha^{-1} (commercial fertilization)		12 months	■ Trace elements (45 kg ha^{-1} FTE BR12) ■ Boron (45 kg ha^{-1} Borogran)
T4	360 kg ha^{-1}		18 months	■ Dolomitic limestone (2 t ha^{-1})
T5	350 kg ha^{-1} N_{total}	10 t ha^{-1} sewage sludge (Barueri, SP)	2 equal parts at planting at 8 months	■ KCl (30 kg ha^{-1} K_2O)

reduce the number of chemical analyses. Chemical analyses of solutions collected by each ceramic cup separately were performed in a few blocks and depths in order to estimate the spatial variability (data not presented). Rainfall solutions were collected in a 1 ha opened area, next to the experimental plots.

Solutions were collected each week from July 2003 to June 2005. A composite sample for each type of collectorwas prepared every 4 weeks. The solutions were filtered (0.45 µm) and the pH was measured. SO_4^{2-}, NO_3^-, NH_4^+, Cl^-, $H_2PO_4^-$, $K^{+,}$ Ca^{2+}, Mg^{2+}, Na^+ were analysed by chromatography (Dionex). Al, Fe, Si and dissolved organic carbon (DOC) were determined by ICP and Shimadzu equipment for each depth, treatment and collector type on a three-block composite sample.

Soil solution ionic balances were computed considering the species: SO_4^{2-}, NO_3^-, NH_4^+, Cl^-, H_2PO_4, K^+, Ca^{2+}, Mg^{2+}, Na^+, H^+. NO_2 and Fe concentrations were very low so that they were neglected in the calculations. As the pH of soil solutions were between 4 and 5 until 1 m deep, aluminium was considered as Al^{3+} in this first preliminary approach.

The whole study will help to relate the soil solution characteristics to the dynamics of biomass and nutrient accumulation in the stands, as well as of nutrient returns to the soil with litter fall and forest floor decomposition.

Results and discussion

Nutrient concentrations in soil solutions were low (<100 μmol_c L^{-1}) over the 9 months of monitoring at the end of stand rotation, whatever the depth and the type of lysimeter (Laclau et al., 2004). A similar behaviour was observed in other tropical forest plantations. This confirms the species ability to prevent deep drainage nutrient losses as soon as the root system is completely developed (Lilienfein et al., 2000; Laclau et al., 2003a).

Clear felling sharply increased nitrate concentrations in surface (0-50 cm) soil layer solutions, and this, without any fertilizer application (Figure 2). This pattern suggests that the sudden interruption of N uptake by plants resulting from herbicide application, combined with the production of mineral N by the mineralization of soil organic matter and forest residues, led to an accumulation of mineral N in these soil layers.

Soil solution ionic balances were dominated by NO_3^- and Al^{3+}, and the concentrations of other elements were little influenced by clear felling during the first months (data not shown). The accumulation of NO_3^- in soil solutions was thus linked with the release of Al^{3+} in soil solutions. The hypothesis formulated to explain such behaviour was that the interruption of NO_3^- uptake by plants leaded to a proton unbalance which might be responsible for the accumulation of aluminium in soil solutions. Indeed, after clear felling, the protons released during the nitrification were no more removed from soil solutions by plant anion uptake and thus, accumulated in the soil solution (Van Breemen et al., 1984). The H^+ may then have desorbed the Al^{3+} on the ion-exchange sites and solid phase dissolution, leading to an increase of aluminium concentrations in soil solutions. As an increase of Si concentration in soil solutions was also observed after clear cutting, some mineral weathering may also have occurred under H^+ influence, releasing mineral Si and Al in soil solutions.

After the planting, fertilizer inputs were responsible for an increase in surface layer concentrations in all elements applied (K^+, Cl^-, NH_4^+, SO_4^{2-}, Ca^{2+}, Mg^{2+}). It resulted in increasing sums of cations and anions as well as the predominance of the elements brought by fertilization in the ionic balance, as for NH_4, Mg and Ca regarding cations (Figure 3). The sum of cations was then very high (>7,000 μmol_c L^{-1}) but declined with depth and time until reaching more common values at 3 m deep. At this depth, the sum of cations was approximately 200 μmol_c L^{-1}, that

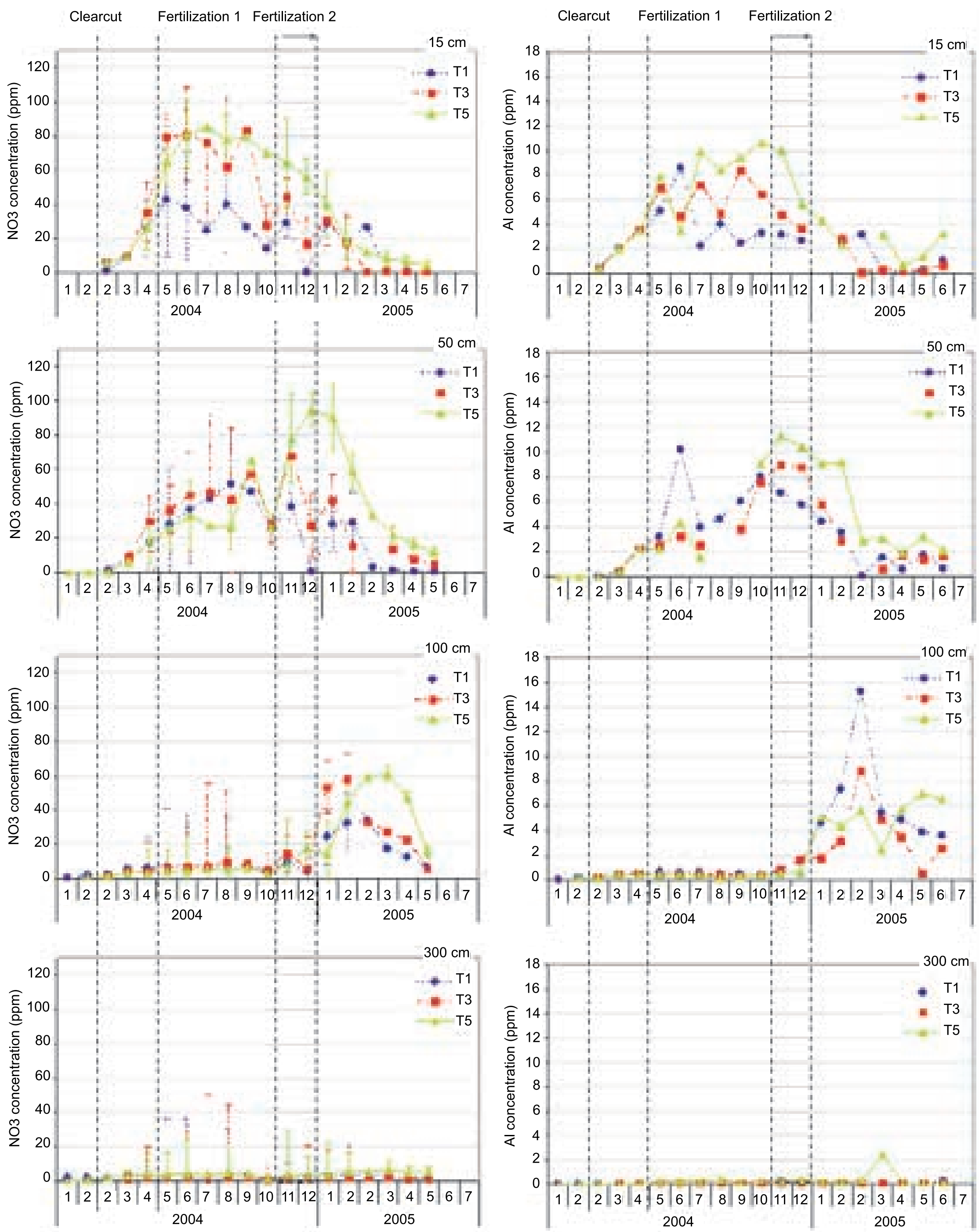

Figure 2. Time course of nitrate and aluminium concentrations (mg L^{-1}) at different soil depths according to the fertilization applied. T_1: 0 N; T_3: 30 kg N ha^{-1} at age 0, 6, and 12 months; T_5: 5 t ha^{-1} of sludge waste (180 kg N ha^{-1}) applied at age 0 and 8 months. Vertical bars represents standard deviations when n ≥3

is, of the same order of magnitude of total cationic concentrations observed before clear felling and confirms previous observations under *Eucalyptus* plantations in the Congo (Laclau et al., 2003a). These values confirm the nutrient poorness of these sandy soils. In comparison, total cationic charges reported in solutions collected in undisturbed *Eucalyptus* native forests in Australia were about 1,000 $\mu mol_c L^{-1}$ (Adams and Attiwill, 1991; Attiwill et al., 1996) as in most studies in temperate forest ecosystems (e.g. Beier and Hansen, 1992; De Vries et al., 1995; Cortez, 1996; Marques and Ranger, 1997).

In the case of aluminium and nitrates, this enrichment was cumulated in treatments T_3 and T_5 to the first accumulation mentioned above (resulting from herbicide application). During the winter 2004, nitrate concentrations reached 80 mg L^{-1} in the top soil (15 cm

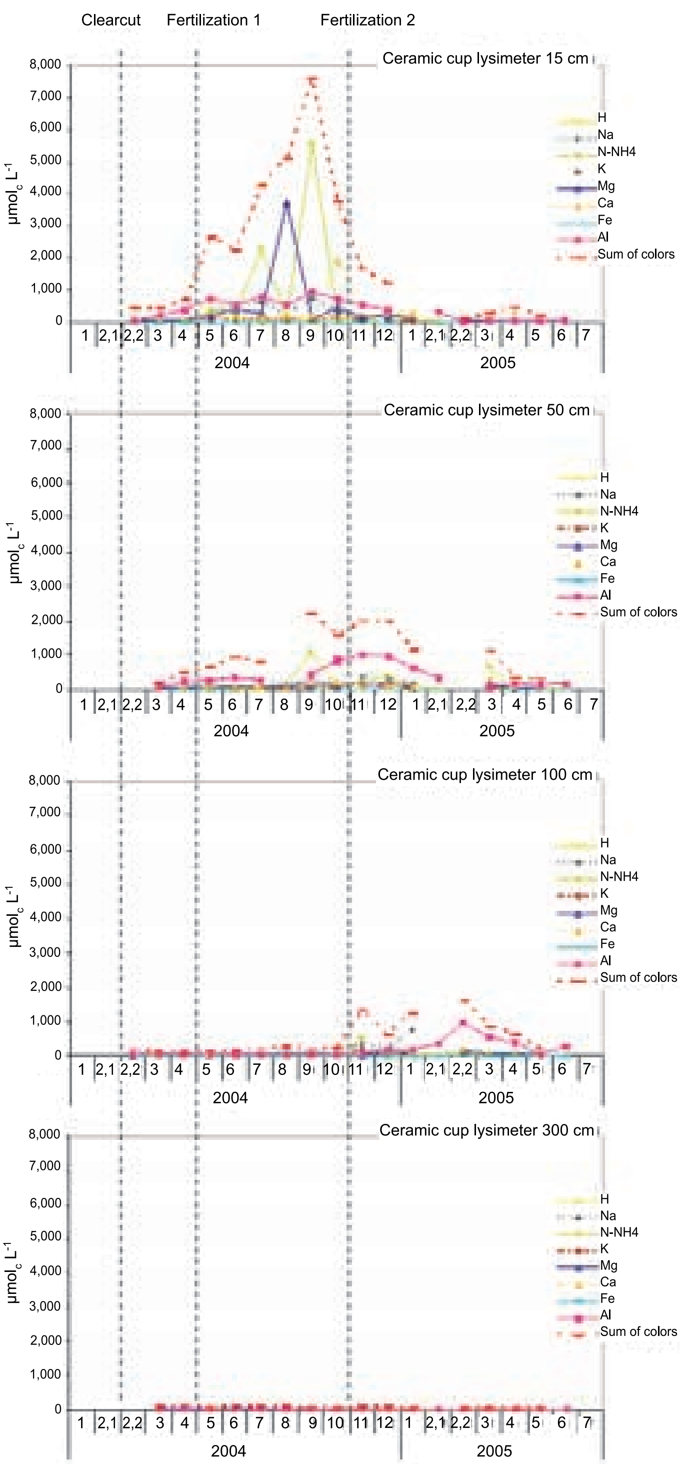

Figure 3. Time course of cations ($\mu mol_c\ L^{-1}$) at different soil depths in treatment 3.Valency attributed to each cation: H^+, Na^+, N-NH4$^+$, K^+, Mg^{2+}, Ca^{2+}, Fe^{3+}, Al^{3+}

deep, solutions sampled by ceramic-cup lysimeters). After September 2004, the rainfall events led to a decrease in nitrate concentrations at 15 cm deep. Nitrates were then leached to deeper soil layers, as well as uptaken by tree roots to support the growth. The nitrate concentration peaked at 50 cm deep from September 2004 to February 2005, where it reached 95 mg L^{-1} in T_5. It reached the depth of 100 cm from January to May 2005 where it ranged up to 60 mg L^{-1} in T_3 and T_5 (Figure 2). Fifteen months after clear felling the *E. saligna* stand and twelve months after planting *E. grandis*, the soil solution chemistry of deeper layers (300 cm deep) had not been modified. Soil moisture sensors (TDR) installed in the experiment showed that preferential drainage were not the dominant transfer process in this sandy soil, which was consistent with the time course of NO_3^- concentrations at 3 m deep.

Moreover, soil solution concentrations can be compared to nutrient uptake by the trees. At 1 year of age, the total dry biomass (above and below-ground) of the stands were 9,380, 12,430 and 10,920 kg ha^{-1} in treatments T_1, T_3 and T_5, respectively (Laclau et al., 2005). The amount of nutrients taken up from the soil during the first year of growth ranged from 70 to 104 kg N ha^{-1}, 4 to 9 kg P ha^{-1}, 31 to 46 kg K ha^{-1}, 31 to 45 kg Ca ha^{-1}, 10 to 17 kg Mg ha^{-1}, according to treatment. A sharp increase in Leaf Area Index (LAI) was observed during the first rainy season (LAI ranged from 0.4 to 0.7 at age 6 months and from 2.0 to 2.7 at age 1 year). During the second year of growth, the tree uptake should considerably increase: at the end of the first year of growth, the root system had already reached 3 m deep, and during the second year of growth stand nutrient requirements will be maximal (Laclau et al., 2003b). Moreover, evapo-transpiration is expected to increase in this stand until canopy closure at age 2 years. The drainage flux should then considerably decrease until 3 m deep during the second year of growth. Beyond 3 m deep, soil moisture sensors (TDR) installed in this experiment will make it possible to quantify the drainage fluxes and therefore the losses of nutrients. These losses are expected to be low since during the first year of growth the soil solution enrichment had not reach 3 m yet, and since as seen before, the nutrient uptake by the trees is expected to increase significantly during the second year of growth.

Conclusion

The biogeochemical cycling study in progress in this Brazilian eucalypt plantation showed a clear influence of clear felling on nitrate and aluminium. Despite high rainfall amounts, one year after planting, they had not reached the depth of 3 m yet. This pattern, as well as TDR sensors installed in the experiment, suggests that preferential drainage was negligible in this sandy soil. The monitoring of soil solution chemistry will go on during the second year of growth.

This study is expected to assess whether the fast development of eucalypt root system and the high nutrient requirements of the early growth make it possible to avoid large nutrient losses by deep drainage, despite the relatively high amounts of fertilizers applied.

Acknowledgements

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Greenhouse gases production and emission from saline sandy paddy fields in Khon Kaen, Thailand

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Keywords: Methane and CO_2 emissions, paddy rice, saline sandy soils

Abstract

In recent years, atmospheric composition of greenhouse gases has been changing rapidly. Since methane (CH_4) is continuing to increase its concentration faster than other greenhouse gases such as carbon dioxide (CO_2) and nitrous oxide (N_2O), methane attracts attention internationally as an important greenhouse gas. The paddy field occupies one of major sources of the methane. In this r esearch, production potential of the greenhouse gases in tropical saline sandy paddy soil was investigated and the influences of fertilization and methods of crop establishment on these gases fluxes were also examined in tropical saline sandy paddy fields. The soil samples were collected from three paddy fields (Ban Kota, Ban Don Do, Ban Kham Pia) in Khon Kaen, Thailand and used inr laboratory incubation experiments to measure CH_4 and CO_2 product potential, mineral N, soluble organic carbon and ferrous iron changes during the incubation. Mor eover, we measured greenhouse gas fluxes by the closed-chamber method in Ban Kota paddy field. Methane production varied widely among soils, but similar trends were observed with CO_2 production, although not as other parameters. Methane and CO_2 emissions were higher from broadcasted rice crops when compare with transplanted plots but no obvious difference was found between organic and chemical fertilization treatments.

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Poster Session 4

“Physical properties of tropical sandy soils”

Water infiltration in saline sandy soils

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Keyword: Salinity, sodicity, hydraulic conductivity, infiltration, sandy soils, Northeast Thailand

Abstract

In Northeast Thailand 80% of the population is dependent on agriculture, growing mainly rainfed rice in the lowlands, predominantly for household consumption. This region faces water scarcity, inherently low fertility soils, soil compaction and more recently, soil salinity. Over the last decade salinisation problems have increased severely, leading to important yield losses and land abandonment. Despite water resources being limited, their management is one of the most important tools for the farmers to combat salinity, as water flow governs the salt transfer from the saline water table towards the surface. In order to quantify and to model the possibilities offered by water management as precisely as possible, it is necessary to determine flow characteristics of soil within the profile.

Water flow in soil is chiefly governed by hydraulic conductivity which is usually considered as an intrinsic soil property. However in saline soils, the clay fraction can either become dispersed or flocculated depending on the solution composition. Consequently the quality of the solution (Electrical Conductivity and Sodium Adsorption Ratio) affects soil structure, hence hydraulic conductivity of soil and general water flow through a soil profile. In order to quantify this phenomenon in situ hydraulic conductivity measurements have been performed using a disk infiltrometer. Considering field conditions, infiltration measurements have been performed with both, distilled and saline water in order to simulate the behaviour of rain water and groundwater. The results showed clearly that the hydraulic conductivity was significantly lower with distilled water when compared with saline water. Despite having low clay content (approximately 4%) these sandy soils were very responsive to sodicity. Basing on these soil properties, a model of the water flow and saline patches development is proposed.

Introduction

In the Northeast of Thailand, the lowlands are mainly dedicated to sticky (glutinous) rice production for home consumption. However these paddy soils are seriously affected by salinisation and during the last few decades the phenomenon has increased with the rise in saline water tables. After deforestation in the recharge area, groundwater rise effectively mobilizes halite deposits of the Mahasarakham formation, which eventual reach the soil surface. However salinity does not affect soils uniformly, as it appears in discrete patches of 5 to 10 m of diameter. Water flow in soils chiefly controls the salinisation process and it is therefore crucial to understand the water dynamics in these soils, if rehabilitation or management is to be achieved.

In addition to the osmotic stress that salinisation imposes on the crop, sodicity may also modify soil structure. As soil structure chiefly governs the water flow, hydraulic conductivity is consequently affected. The influence of mixed salt solutions percolation on the soil hydraulic conductivity has been studied previously by several authors (Abu-Sharar et al., 1987; Curtin et al., 1994; Amézketa and Aragües, 1995; Abu-Sharar and Salameh, 1995) and empirical models have been established (Mc Neal, 1968; Suarez et al., 1984). These studies assert that elevated exchangeable sodium levels at low concentrations cause dispersion and swelling of the clay minerals and consequently a reduction in hydraulic conductivity of the soil. The development of this phenomenon in the presence of sodium invariably indicates that there is a threshold level for these changes to occur, especially for high Sodium Adsorption Ratio levels. However, most studies have in general been conducted in the laboratory on repacked disturbed soil columns. The results obtained with these experiments are representative of the behaviour of the clay and cannot

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be assumed to be indicative of the behaviour of transport properties under field conditions.

The objective of this study was to measure hydraulic conductivity of soils with different salt solution concentrations in order to evaluate water flow; whether it is natural rain water or saline water originating from the water table, and to asses the influence of organic matter management on soil hydrodynamic properties.

Material and methods

Experimental design

Infiltration properties were measured *in situ* with a disk infiltrometer (Figure 1) in order to evaluate the saturated hydraulic conductivity of the soil under undisturbed conditions and with solutions being representative of field conditions. These properties were measured with both deionized water, and a NaCl brine at the same concentration as the groundwater (250 meq/l) in two contiguous plots, inside and outside saline patches. The two plots have different managements: in the first one L25 the farmer follows carefully the water level during the cropping season

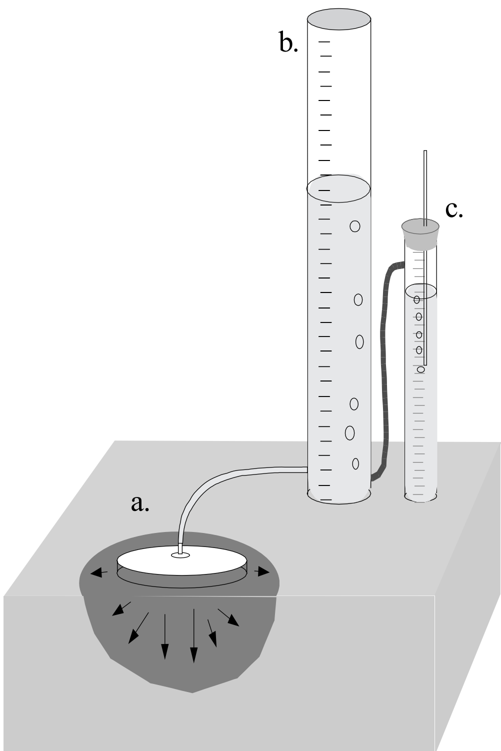

Figure 1. Schematic of a disk infiltrometer showing a. the actual disk on the soil surface allowing for 3D water flow, b. the water (or brine) reservoir and, c. the Mariotte device controlling the suction imposed at the soil surface

and introduces organic matter amendments, especially on the saline patches, whereas in the second one L14, the farmer only puts very little effort in the management of the field. This is a commonly observed where yields of rice have declined significantly and farmers are not willing to invest the effort to try to remediate their fields.

Saturated hydraulic conductivity was calculated with the multipotential method (Perroux and White, 1988; Smettem and Clothier, 1989). Three infiltration measurements were undertaken in each situation at two suction values and for each type of solution. These measurements were undertaken at different depths down the soil profile.

Model

Water Infiltration into soil is usually well described by the Philip equation (1957):

$$I = S\sqrt{t} + A\,t \qquad (1)$$

where S is the sorptivity, resulting from the flow due to capillary pressure head in dry soil, and *A* the constant infiltration rate parameter, depending on the gravity flow. As infiltration from a disc is unconfined and water flow is 3-dimensional, the hydraulic conductivity is calculated with the constant infiltration rate *A* according to Woodings’ equation (1968):

$$A_0 = K_0 + \frac{4 \cdot \phi_0}{\pi \cdot r} \qquad (2)$$

$$\phi_0 = \int_{hi}^{h0} K(h) \cdot dh \qquad (3)$$

where r is the disc radius, A_0 is the constant infiltration rate, K_0 the hydraulic conductivity, and ϕ_0, the matrix flux potential for applied infiltration suction h_0, h_i is the initial pressure head of the soil. Assuming an exponential relation for conductivity with pressure head (Gardner, 1958): $K(h) = K_s \cdot \exp(\alpha \cdot h)$, the matrix flux potential derives into a simple relation, $\phi_0 = K_s \cdot \exp(\alpha \cdot h_0)/\alpha$ where Ks is the saturated hydraulic conductivity and α the exponential slope. Equation (1) becomes:

$$A_0 = K_s \cdot \exp(\alpha \cdot h_0) \cdot \left(1 + \frac{4}{\alpha \cdot \pi \cdot r}\right) \qquad (4)$$

When performed for two pressure heads (h_0 and h_1), the exponential slope is calculated: $\alpha = \mathrm{In}\,(A_1/A_0)/(h_1 - h_0)$ and introduced into equation (4) to calculate the saturated hydraulic conductivity Ks.

In order to determine easily and graphically, the infiltration parameters *S* and *A* from the infiltration data, Philip's equation can be rewritten as follows:

$$I/\sqrt{t} = S + A\sqrt{t} \quad (5)$$

When representing these results graphically as I/√t versus √t diagram, the infiltration appears as a straight line defined by a slope *A* and an ordinate to origin *S*.

Location and soils

The study was established in Northeast Thailand, near Pra Yuhn, Khon Kaen region (16º27.8′N, 102º6.9′E). Saline patches in the rice fields were identified and delimited by EM38 measurements. The infiltration experiment was performed during the dry season in March 2005. The soil represents a quaternary aeolian deposits (Lesturgez, 2005), with a fine sandy loam texture, but with a low clay content. However, within the profile the clay content increases from 3% near the surface to 10% at 50-60 cm. Similarly the bulk soil density varied from 1.46 10^3 kg m^{-3} in the most surface layers to 1.92 10^3 kg m^{-3} at 50 cm. This dense layer seems to be continuous except in discrete points under the saline patches where it has not been found. Wider exploration in the area with penetrometer, confirmed this observation.

Results and interpretation

The infiltration measurements were performed during the dry season (March 2005) at different depths. A typical set of infiltration curves is presented in Figure 2, where distilled and saline water have been used to generate the data. It demonstrates clearly that in saline patches, infiltration with a saline solution is in accordance with Philip's equation and is represented by a straight line according to equation (5). Contrasting this, for distilled water the Philip's model does not entirely describe the infiltration kinetics, as curvilinear relation was observed (Figure 2). Based on the fact that as the distilled water enters the soil, a dilute salt solution is progressively formed that induces clay dispersion. The consequence is a reduction of hydraulic conductivity depending on the concentration of the infiltrating solution. Previous laboratory experiments on undisturbed soil monoliths (Rivallan, 2004) showed a linear positive relationship between solution concentration and saturated hydraulic conductivity, indicating that infiltration rate decreases with time when distilled water or rain water enters the soil. However, in order to calculate a saturated hydraulic conductivity, we used the tangent to the infiltration curve for an arbitrarily chosen amount of infiltrated water, equivalent for each experiment, as depicted in Figure 2.

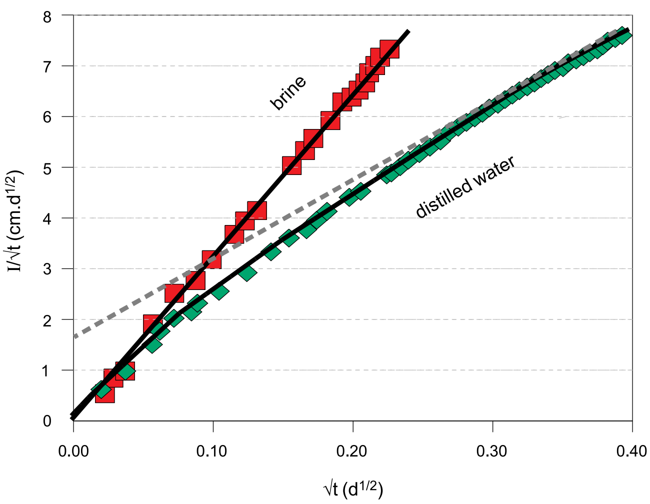

Figure 2. Example of infiltration curves in a I/√t vs √t diagram in a saline patch. Squares infiltration with brine; diamonds infiltration with distilled water. Dotted grey line: tangent for calculating parameter *S* and *A*

As expected, when brine was used for infiltration measurement, the saturated hydraulic conductivity was systematically higher than distilled water (Figure 3). This clearly illustrates the clay dispersion phenomenon under saline soil conditions when diluted with fresh water is applied that leads to the partial blockage of the pores. The measurements performed with brine can be considered as representing the intrinsic Ks values for this soil, as the conditions are fulfilled for clays to be flocculated, and hence optimal for water flow. However, these saturated hydraulic conductivity values are very low for sandy soils as the maximum values are less than 5 cm d^{-1} whereas for sandy soils Ks is usually found 500 to 700 cm d^{-1} (Carsel and Parrish, 1988).

In each of the assessments irrespective of management and within or outside a saline patch, hydraulic conductivity varies with depth in the soil profile. Inside the saline patches, in both plots, the maximum saturated hydraulic conductivity was observed in the surface layers (6 cm), where the salt concentration is highest. This probably illustrates changes in soil structure when salt crystallizes in the pores. Outside saline patches, Ks in the topsoil is 3 times higher in L25 (4.2 cm d^{-1}) than in L14 (1.4 cm d^{-1}). This difference is most probably due to the soil management, as L14 does not receive routine applications of organic matter unlike L25. On the other hand, an important decrease of Ks at a depth of 17 cm represents typically the plough layer. Hydraulic conductivity of the deepest soil layer (56 cm) is not influenced in the case of plot L14 whether measurements are taken inside or outside the saline

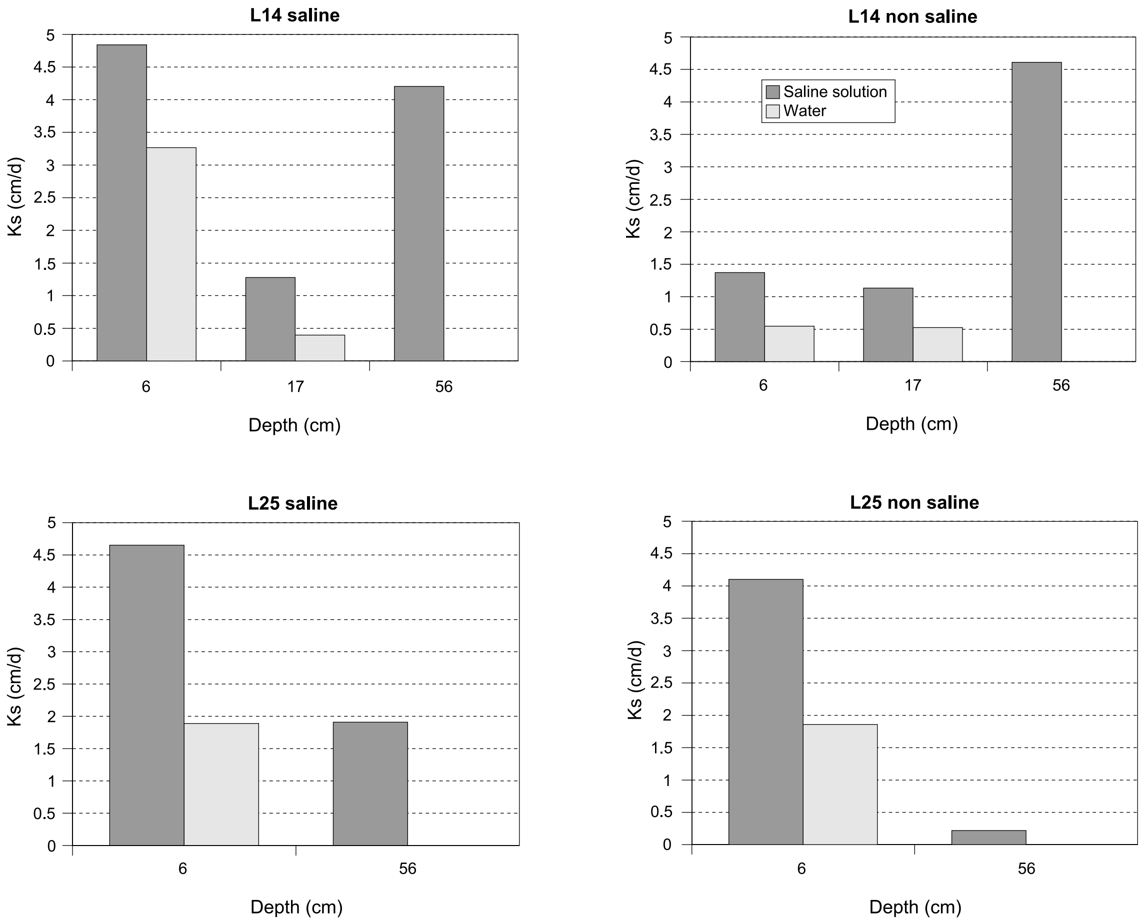

Figure 3. Saturated hydraulic conductivity inside (saline) and outside (non saline) the saline patches in both plots L14 and L25, measured with saline solution (dark grey) and distilled water (light grey)

patch (Figure 3). In contrast, in the case of L25 there is a drastic decrease in Ks between inside and outside the patch at 56 cm depth. The presence of the dense layer described previously is clearly illustrated here in L25, where it fades inside the saline plot. However this difference is not marked as distinctly in L14.

In both plots L14 and L25, the saturated hydraulic conductivity is higher inside the saline patch than outside, whether distilled water or brine is used for infiltration (Figure 3). As infiltration occurs with a limited amount of water (approximately 2 liters), the soils solution in the upper part of the profile does not get diluted sufficiently to reach the optimal dispersion concentration. However one can expect that during the cropping season the dispersion concentration is reached and that Ks declines significantly.

Basing on these first results, one can propose a functional model of water flow and solute transport in these sandy saline soils. As infiltration of fresh water tends to be limited in the saline patches, possibilities of leaching the salts downwards during the cropping season are therefore limited. On the other hand, capillary rise of saline water from the water table towards the soil surface is favoured at the end of the cropping season as Ks increases due to the presence of highly concentrated saline solutions. Consequently, if the plots are not flushed regularly during the cropping season, superficial salinity levels will increase and widespread naturally.

Conclusion

Saturated hydraulic conductivity was measured *in situ* with a disk infiltrometer inside and outside saline patches in two contiguous plots with different management. From this simple experiment several conclusions can be drawn about the i) intrinsic parameters of soils, ii) the techniques used to measure them and iii) the dynamics of water and salt in these soils. The intrinsic saturated hydraulic conductivity measured was very low compared to the values usually observed for sandy soils. The presence of silt is presumably contributing to these observed responses. However this feature ensures the possibility of ponding and consequently favours rice cropping. It has been shown that saturated hydraulic conductivity is dependant on the quality of the infiltrating solution, because distilled water tends to disperse the clays and block infiltration pathways. Hence under saline conditions it is important to measure hydraulic conductivity with solutions that have similar solute compositions to those found naturally. Moreover these results demonstrate that in highly managed plots the infiltration properties are higher than in the low management plot, highlighting the importance of organic amendments. Despite no actual numerical modelling being performed, it can be assumed that if no surface flushing of salts is undertaken during the cropping season, the degree and extent of salinity will increase. Nevertheless the complete water flow and salt transport has to be simulated numerically with a model, taking into account the development of saturated hydraulic conductivity with solution composition and concentration, which still has to be designed.

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Wind processes improve water infiltration in Sahelian sandy rangeland

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Keywords: Wind erosion, water erosion, Burkina Faso, penetrometer, Sahel

Abstract

Sandy microdunes often provide a privileged habitat for primary production of Sahelian agro-ecosystems. In degraded areas, they can also be potential starting points for the regeneration of eroded surfaces. The aim of this study was to understand the role of sandy covers in the retention of rain and runoff waters along overgrazed Sahelian hillslopes. It focuses on the interactions between wind and water processes.

Water can be of benefit in the development of vegetation if it is able (i) to infiltrate through crusted soil surfaces; (ii) reach a sufficient depth not to be evaporated rapidly; and (iii) to be accessible to the root system. In the present study, the wetting-front depth (WFD) was a relevant indicator that permitted to assess whether the three above criteria were satisfied. Investigations were conducted within three plots with different sizes (14,000, 376 and 36 m^2) and grids of observations (4 m, 0.5 m and 0.- m respectively). The largest one was a micro-catchment patched with sandy aeolian deposits. The others were distinct microdunes with a typical asymmetric shape. A cone penetrometer was used to estimate WFD and survey, its spatial variability. Soil surface conditions (micro-relief, plant cover, crusted areas) were also recorded.

At the catchment scale, WFD values ranged between nil and 1 meter. The deepest infiltration occurred within sandy deposits with an herbaceous cover of more than 50% (surface of the drying type) and along gullies filled with coarse sands (surface of the runoff type). Minimum WFD values were observed on bare crusted surfaces with gentle slope (surface of the erosion type). At the microdune scale, the most important depths of penetration were observed through bare windward surfaces with steep slopes. This unexpected result is attributed to wind deflation and splash erosion hampering the development of impervious crust.

Introduction

Dryland ecosystems develop strategies to adapt and resist adverse conditions such as drought. Naturally contracted vegetation patterns such as tiger bush is a well-known example of such strategies (Valentin *et al*., 1999). Dotted bush is another example that can frequently be found in the Sahelian zone of Burkina Faso (Leprun, 1999). Dotted bush is generally associated with sandy grassy microdunes. The genesis, development and evolution of these microdunes result from an array of factors including wind and water processes. These aeolian landforms are considered as “islets of fertility” (Thiombiano, 2000) where biomass production (Grouzis, 1991) and water infiltration (Ribolzi *et al*., 2003) are significantly higher than in other parts of the landscape. They support a primary production which is essential as a stable food supply for cattle, and are also potential initial points for the regeneration of degraded Sahelian environments.

One of the most limiting factors for natural vegetation growth within microdunes is access to water by plant root systems. It is well known that infiltration capability of Sahelian soils mainly depends on their surface features (Casenave and Valentin, 1992). The aim of this paper is to provide a better understanding of water infiltration and percolation through microdune soils. We focus on the influence of soil surface and subsurface characteristics on the spatial variability of infiltration. Water can be beneficial to the development of vegetation if it is able (i) to infiltrate through soil surfaces; (ii) to reach a sufficient depth not to be evaporated rapidly; and (iii) to be accessible to the root system. The wetting-front depth (WFD) proved

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a relevant indicator of the three above mentioned criteria. Our investigations were conducted at several spatial scales along an overgrazed hillslope in the Sahelian zone of Burkina Faso.

Material and methods

Study area

The study area is located in Northern Burkina Faso, some 13 km from Dori (UTM30, WGS84, 809,847 m East, 155,093 m North). The climate is of the Sahelian type, with a single rainy season which lasts from June to September. The average annual rainfall recorded in Dori is 512 mm. The dominant wind is the dry dust-laden Harmattan wind that blows from the northeast during the dry season and blows from the southwest during the wet season. Mean annual potential evapotranspiration, calculated by the Penman method, is about 2,396 mm. Most of the soils are solonetz soils (haplic Solonetz in the FAO terminology) developed from calco-alkaline granitic rocks.

Observations were conducted within three experimental plots of different sizes. The largest one (14,000 m^2) was a small catchment (BV1) composed of five main soil surface types (Figure 1a) according to the classification by Casenave and Valentin (1992): (1) bare erosion surfaces (ERO) accounted for 33.6% of the total catchment area, (2) pavement surfaces (G), which were also bare, covered 0.4% of the catchment area, (3) sedimentation surfaces (SED) covered the bottom of ponds and depressions, accounted for 1.2% of the catchment area, (4) runoff type surfaces (RUN) which mainly consisted of laminated materials of various textures deposited within rills represented 4.2% of the catchment area, and (5) the drying type surfaces (DRY), covered the leeward area of sandy microdunes represented 59.9% of the catchment area. Microdune soils accounted for 69% of the total catchment area; they supported vegetation with an herbaceous cover density exceeding 50% for about 2/3 of the total area at the high of the rainy season.

We also selected two microdunes (MD1 and MD2) for detailed investigations. MD1 and MD2 had respectively a medium (376 m^2) and a small (36 m^2) surface area. DRY was by far the dominant surface type for these plots. The soil below DRY surface was composed of two main horizons. The upper horizon (5-7 cm thick) comprised a deposit of sand with numerous macropores formed by plant roots and soil fauna. This top layer corresponded to the sand thickness affected by cattle trampling. The total porosity of this horizon ranged between 39 and 47%, with a proportion of non-functional vesicles varying from place to place. The horizon below had a laminated structure alternating between continuous sandy and plasmic layers. This second horizon laid over a massive silty-sandy impervious horizon.

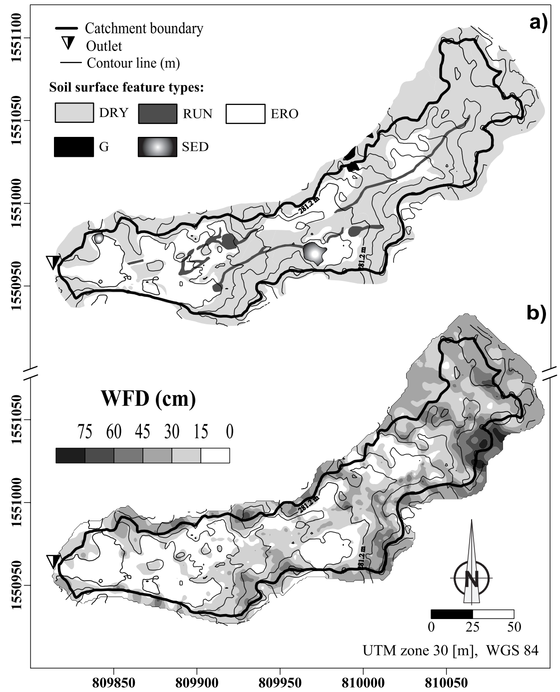

Figure 1. Maps of the largest plot (BV1 catchment) showing a) the relief and the main soil surface features, and b) the wetting-front depth (WFD) at the height of the 1999 rainy season, one day after the 16 August 1999 rainfall event (Rainfall depth = 39 mm). Surface of the drying type (DRY); Surface of the runoff type (RUN); Surface of the erosion type (ERO); Surface of the pavement type (G); Surface of the sedimentation type (SED)

Topography and soil characteristics

Topography measurements were accurately conducted on each experimental plot using an optical level. For BV1, the digital elevation model and slope gradient were estimated using a set of 1 m grid measurements covering the entire catchment (i.e. 5,890 points). For MD1, micro-relief was determined according to a 0.5 m grid (i.e. 1,484 points). For MD2, topography measurements were made every 0.1 m following an E-W transect across the microdune. We estimated surface conditions visually using the method of Casenave and Valentin (1992). Four soil pits within an adjacent microdune allowed us to estimate root density profiles within the sandy aeolian deposit.

Wetting-front depth

A soil cone penetrometer was used to estimate the wetting-front depth (WFD) within the three experimental plots. The penetrometer was made up of a steel 30-deg circular cone ($ø_{base}$ = 20 mm) fastened to one end of a metallic graduated stick (ø = 15 mm, length = 1.1 m). These dimensions satisfy the standards of the American Society of Agricultural Engineers. The steel cone was inserted manually. WFD was accurate within ±1 cm of the measured value. WFD measurements within BV1 were conducted during the climax of the 1999 rainy season, one day after a rainfall event (16 August, 39 mm). Measurements covered the entire surface of the catchment and were made according to a 4-m grid (i.e. 1959 points). In MD1, WFD determinations were also conducted in 1999, but following a different rainfall event (12 July, 76 mm), which was the first and the most important event of the rainy season (rainfall depth = 39 mm). As for BV1, measurements covered the entire plot, but with finer grid of 0.5 m (i.e. 755 points). For MD2, data were performed 2 days after another rainfall event (24 June 2002, 20 mm), every 0.2 m along a representative E-W transect of 17.2 m long.

Results and discussion

Influence of soil surface type at the catchment scale

WFD within BV1 ranged between nil and 0.87 m (Figure 1b). The mean value was 0.23 m with a standard deviation of 0.17 m. This result reveals the extreme variability of infiltration within this small catchment. The zones of deeper infiltration coincide with surfaces of the drying and runoff types. In contrast, infiltration through bare crusted surfaces (ERO, G) was very limited or even nil. Figure 2 shows the median, first and third quartiles, maximum and minimum values of WFD within the main soil surface types (DRY, ERO, RUN, G and SED). The infiltration depth ranking was DRY>>RUN>ERO≈G≈SED. The difference between DRY and RUN was highly significant (threshold of significance: α = 0.050, Mann-Whitney unilateral test, P <0.0001) and significant between RUN and ERO (P = 0.0003). No significant difference was found between ERO and G (P = 0.108) and between G and SED (P = 0.091). Compared to DRY surface with lower vegetation cover, the surfaces with a vegetation cover of more than 50% had a significantly higher WFD values (P <0.0001).

Our results at the catchment scale clearly showed that sandy aeolian deposits had by far the highest WFD, and demonstrated the positive effect of

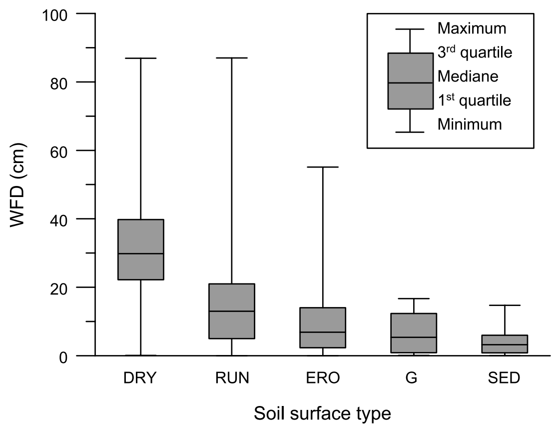

Figure 2. Box-Whiskers plot of wetting-front depths (WFD) measured within the main soil surface features (drying-type: DRY; runoff-type: RUN; erosion-type: ERO; pavement-type: G; sedimentation type: SED) of the largest plot (BV1) at the high of the 1999 rainy season, one day after the 16 August rainfall event (Rainfall depth = 39 mm)

the herbaceous cover density on water penetration depth. Microdune soils allowed a rapid and sufficiently deep infiltration so that the water did not evaporate rapidly (Karambiri, 2003) and was therefore accessible to plant roots. These results are not surprising for semi-arid areas. They confirm the influence of soil crusting (e.g. Hoogmoed *et al*., 1984) and vegetation on water infiltration in soils. It was also observed that pathways of runoff (RUN surfaces) were privileged zones where the WFD could be relatively high, particularly when concentrated runoff dissected pervious sandy aeolian deposits. This is consistent with the findings of Peugeot *et al*. (1997) who assumed significant stream bed infiltration in order to balance the hydrological budget of a small Sahelian catchment in Southwestern Niger.

Influence of subsurface conditions at the microdune scale

MD1 and MD2 had similar morphological and surface features. Figure 3 shows some bio-physical characteristics and WFD along MD2. Three ERO sub-units were identified within the bare windward area. Starting at the eastern end of the microdune, the first unit was covered by a continuous erosion crust with slopes ranging between 5 to 20 degrees. The second unit, also bare, was characterised by a fragmented surface resulting from wind erosion, with a degree of fragmentation increasing with slope angle and elevation (i.e. crumbling down of the laminated structure of plasmic and sandy layers). The third unit, also exposed under the direct influence of the wind action, was located on the upper ridge of the microdune. It was a narrow fringe of grass stubble

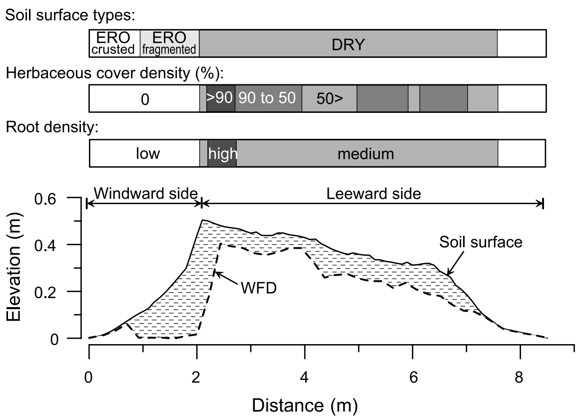

Figure 3. Soil surface types (erosion-type: ERO; drying-type: DRY), herbaceous cover and root densities, relief and wetting-depth front (WDF) across the small microdune (MD2) measured two days after the 24 June 2002 rainfall event (Rainfall depth = 20 mm)

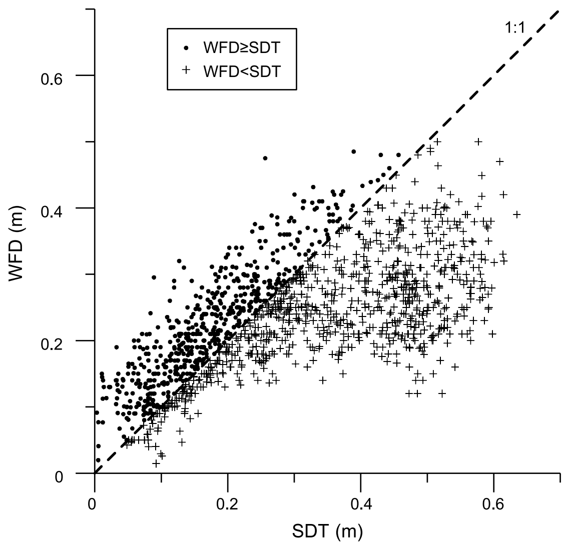

Figure 4. Wetting-front depth (WFD) measurements as a function of sandy deposit thickness (SDT) within the medium-size microdune (MD1) one day after the 12 July 1999 rainfall event (Rainfall depth = 76 mm)

(dead roots exposed at the base) dating back to the previous year. Three major soil surface units were also observed on the leeward side. The first one was a narrow sand-accumulation unit (about 50 cm wide) colonized by *Bracharia villosa*, with a cover density exceeding 90% at the high of the rainy season (Figure 3). The second soil unit was a DRY surface with a more scattered herbaceous cover. The third leeward unit was similar to the first windward one. It was bare and covered with an erosion crust. The density of live roots along the DRY surface was moderate and almost homogeneous near the soil surface (0-10 cm). In contrast, higher live root densities were found within the deeper horizons (10-40 cm) of the sand-accumulation unit colonized by *Bracharia villosa*.

In the most eastern unit (crusted ERO surface) of MD2, WFD was close to the soil surface (Figure 3). The two following windward units (steep fragmented ERO surfaces), WFD increased sharply and reached the silty-sand layer below the microdune. There, drainage was limited by this impervious layer. In the leeward side, WFD values remained high below the sand-accumulation unit with *Bracharia villosa*. Beyond this unit (i.e. drying type surfaces), WFD showed a wavy-like pattern and did not reached the impervious layer. In the last unit at the western end of the transect, the WFD was very close to the soil surface.

As for BV1 and MD2, the WFD of MD1 appeared extremely variable (Figrue 4). The minimum and the maximum values observed were 0.0 and 0.50 m respectively. The mean value was 0.22 m with a standard deviation of 0.11 m. This variability could be related to the sand deposit thickness (SDT). Figure 4 shows the WFD measurements as a function of SDT. Two situations can be distinguished. The first situation, when WFD≥SDT, WFD and SDT were very well correlated ($r = 0.91$) and data were fitted with a linear regression ($R^2 = 0.82$). In the second situation, when WFD < SDT, the correlation coefficient between the two parameters remained high but lower than previously ($r = 0.70$). Data could not be fitted satisfactorily with a linear regression ($R^2 = 0.49$) due to the dispersion of WFD values within the areas with high SDT. To explain the dispersion of WFT for the highest SDT, we compared windward and leeward WFD values with SDT ≥0.3 m. This assessment led to the conclusion that the steep windward areas located in the eastern part of the plot had higher WFD values compared to the leeward areas (threshold of significance: $\alpha = 0.050$, Mann-Whitney unilateral test, $P < 0.0001$).

Our measurements clearly showed that the impervious horizon below the microdune controlled and limited vertical drainage. When WFD<SDT (the wetting front still did not reach the impervious horizon), our results showed an increasing dispersion of WFD with the increase of SDT (Figure 4). This wetting front dispersion might be the consequence of preferential flows resulting from heterogeneous surface or subsurface characteristics. At the soil surface level, we observed local variability: discontinuous vegetation cover characterised by micromounds of annual plants alternating with patches of bare, crusted surfaces (drying type) or of loose sand, trampled by livestock.

Uneven wetting front might also be the consequence of heterogeneous subsurface conditions due to the presence of: (i) coarse sand lenses (Boll *et al*., 1996); (ii) non-functional vesicular porosity near the surface; (iii) macroporosity caused by ant and termites activity (Léonard and Rajot, 2001); (iv) vertical shrinkage cracks. Textural interfaces are also known to force water to flow laterally (Ribolzi *et al*., 2003).

Why was wetting-front deeper within steep windward zones?

In the West African Sahel, convective rainstorms are often preceded by strong windstorms (Visser *et al*., 2004). During these windstorms, the steep windward side of microdunes is exposed to wind deflation: sand grains transported by wind hit the soil surface, a process through which they weaken or even fragment water-related erosion crusts (e.g. Neuman *et al*., 2005), hence improving soil water infiltrability at the onset of the rainfall event which often follows the sandstorm. During rainfall, the crumbled materials generated by wind deflation (residues of plasmic microlayer and free grains of sands) are easily removed by raindrop impacts (i.e. splash erosion). The destroyed erosion crust forms progressively again during the following rainfall event. We hypothesise that this crust reconstitution process is slower on steeper micro-slopes. Such a tendency (i.e. more infiltration on steeper slopes) was already described in tropical environments on steep loamy soils (Janeau *et al*., 2003).

Most of the time in the Sahel, rainfall is accompanied with a strong northeastern wind, which diverts raindrops from their vertical trajectory, so that windward sides of microdunes receive more rainwater per unit area and are more subjected to splash. Splash preferentially translocates soil particles downhill, which prevents the development of crusts and maintain a good water infiltrability. The previous hypothesis is still valid in the case of raindrops with a vertical trajectory. In this case, the trend for increased infiltration with slope gradient is ascribed to weaker crusting on steeper slopes: raindrops would hit the soil at a more acute angle, and thus with less vertical kinetic energy per unit area (Poesen, 1986). Lateral shearing forces due to raindrop impact might increase with slope radient, and lead to the detachment of soil particles, hampering soil crusting.

Conclusion

Wetting-front depth measurements using a simple cone penetrometer allowed us to better understand infiltration and water storage capability in Sahelian rangelands. Our main results can be summarized according to five main points:

1. At the catchment scale, the wetting-front depth ranged from nil to 1 m. The deepest infiltration occurred within sandy aeolian deposits (drying type surface) with an herbaceous cover of more than 50%.
2. Pathways of concentrated runoff (rills) favoured water infiltration, especially when they dissected the surface of pervious sandy soils.
3. At the microdune scale, the most important penetration depths were observed in bare windward surfaces with steep slopes. This unexpected result is attributed to the combined effect of wind deflation and splash erosion which prevent the development of impervious crusts.
4. Wavy-shape water fronts observed under leeward slopes were related to soil surface characteristics; e.g. the wetting-front depth was deeper along the ridge of assymetric microdunes where sand-accumulation units colonized by *Bracharia villosa* developed.
5. Internal heterogeneities of sandy soil layers limited infiltration and/or forced the water to flow laterally: e.g. the wetting-front depth in the thinnest part of microdunes was controlled by the impervious layer below the sand deposit.

Acknowledgment

The present work was supported by the Département des Ressources Vivantes of the Institut de Recherche pour le Développement (IRD). We acknowledge with gratitude INERA (Institut National de l'Environnement et de Recherche Agricole, Burkina Faso) for providing access to the site.

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Hardpan formation of some coarse-textured upland soils in Thailand

Anusontpornperm, S.[1]*; S. Nortcliff* [2] *and I. Kheoruenromne*[1]

Keywords: Hardpan development, tillage, root penetration, cassava yield

Abstract

This study on hardpan formation of some coarse-textured upland soils in Thailand was focussed on soils with the upper part of their profile containing more than 700 g kg^{-1} *sand. Objectives were to illustrate characteristics of hardpan induced by tillage practice, relationships among properties involved and impacts on agricultural uses. Ten selected soils were all Typic Paleustults. They were collected from Northeast Thailand, and were under a cassava production at the time of sampling. Pedon analysis and laboratory analyses on their properties were carried out based on standard methods. They were deep soils derived from sedimentary rocks, having an argillic horizon in subsoils. The hardpan was found directly below plough layer of all soils, approximately at a depth between 20 and 35 cm from the soil surface. Within these layers, high values of bulk density were observed with a range from 1.60 to 1.79 g cm*$^{-3}$ *while hydraulic conductivity values varied between 0.04 and 1.66 cm hr*$^{-1}$*. These layers also have lower total porosity percentage (31.70-39.62%) than others from the same profile. Field consistency data when dry shows that they are predominantly slightly hard to hard. These are indicative of consolidation induced by repeated tractor traffic running across the field during land preparation. This excess traffic is responsible for a reduction of infiltration rate, and subsequent increase in runoff and water erosion. Furthermore, impervious layer also restricts root penetration into deeper subsoil where the growing crop may take advantage of stored nutrients and moisture, especially in years when rainfall is insufficient for normal crop growth and development. In association with the low fertility status and low available water holding capacity of these soils, the formation of hardpan may further lower or restrict the yield of cassava. In addition, soil degradation caused by erosion will become even more prevent under these soil conditions.*

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The effect of salinity on sandy soils physical characteristics and rice root system development: a case study from Northeast Thailand

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Keywords: Sandy soils, saline patches, root development, soil porosity

Abstract

During the last several decades, saline patches have appeared in paddy fields located on sandy soils of Northeast Thailand this being due to capillary rise of underground saline water associated with elevated watertables. This soil salinisation decreases rice production and is a major threat for future agricultural production as these saline patches can spread making paddy fields highly saline. Under extreme saline conditions these saline patches are colonized by halophytes. Since the physical characteristics of sandy soils do not seem to be affected by salinity, research has focused predominantly on changes in chemical characteristics associated with soil degradation. The objective of this study is to determine whether i) salt concentration of the saline patches induces physical degradation in sandy soils and 2) if farmer strategies associated with organic matter spreading improves soil characteristics and root development of rice. In a severely affected area, we selected two neighbouring farm holds that had contrasting organic matter (OM) management strategies implemented during the last decade: OM was never used (OM°), differed from the farmer who routinely applied to saline patches (OM^+). In each of the farmers holding, 4 fields were selected, each field containing one saline patch. In each plot, 3 areas were identified and were the focus of the study: P the middle of the saline patch where rice is unable to grow (bare soil), S at the edge of the saline patch where rice development is restricted and C, the surrounding area not affected by salinity where rice development and yield are considered as adequate. Saline patches have significantly reduced porosity (0-20cm). Reduced porosity is correlated with a drastic reduction in root development both frequency and depth of proliferation. Farmers’ strategies associated with OM spreading increased soil porosity and improved root development regardless of any chemical improvement in the soil. Consequently, physical degradation cannot be neglected to characterize saline patches and rehabilitation techniques need to address both chemical and physical issues. The reason for poor plant development within saline patches is still unclear and requires further research. The study demonstrated that despite their low amount of clay, sandy soils are far from ‘inert’ under saline conditions.

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Poster Session 5

"The role of organic matter and biological activity"

Mineralization of organic amendments in a sandy soil of Central Vietnam

Backer, C.D.[1]*; Q.H. Pham*[2]*; N.C. Chiang*[1] *and* ***J.E. Dufey***[1]

Keywords: Soil organic matter management, manures, tropics, sandy soils

Abstract

Farming systems in sandy areas of the tropics require special attention to the management of organic matter. According to a recent survey within the Vietnam-Belgium joint project, a great diversity of organic materials is used by farmers in the coastal sandy zone of Central Vietnam. Research is currently being conducted to evaluate the fertilization capacity of various organic amendments. The poster presents the first results on the mineral-N evolution through the incubation of an acid sandy soil from the Thua Thien Hue Province, amended with 4 types of organic matter: buffalo manure (BM), pig manure (PM), chicken manure (CM), and ash + urine (AU). Along with NH_4^+ *and* NO_3^- *measurements, pH, electrical conductivity (EC), and redox potential (Eh) were monitored during incubation. Two laboratory experiments were undertaken according to the incubation method recommended by Keeney (1982) under anaerobic conditions at 37ºC; the first experiment was conducted with 30 g organic amendment per kg of soil for 0, 2, 5, 10, and 20 days as incubation times; the second was carried out with 20 and 40 g organic matter per kg of soil during one week.*

Initially, significant amounts of NO_3^- *are found with PM and CM, whereas AU released only* NH_4^+*. Limited amounts of inorganic N were released by BM. During the first week of incubation, there was a rapid, but temporary, drop of Eh, and increase of pH, EC and* NH_4^+ *concentration in the soil solution.* NO_3^- *disappeared quickly for PM and CM. Only slight variations of these parameters were observed after 10 days, which justified the short incubation period to screen organic matter amendments for their N fertilization capacity, notwithstanding their long term contribution to the soil organic pool. Total inorganic N release was in the order CM > AU > PM ≈ BM.*

It is worth noting that organic amendments increased soil alkalinity, or soil acid neutralization capacity (release of bicarbonate anions), which can be roughly inferred by pH increase at similar Eh and CO_2 *pressure values. For a soil amended with 3% organic matter, the pH values after 20 days were approximately 8 for CM and AU, about 6.5 for PM and BM, compared to 5 for the control soil.*

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Patterns of soil organic carbon and nitrogen in grazed and un-grazed exclosures of semi-arid rangelands in South Africa

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Keywords: Overgrazing, soil organic matter, exclosures

Abstract

Approximately 66% of the total rangeland surface has become degraded in South Africa. Overall synthesis derived from participatory research has shown that communal rangeland management characterized by overgrazing and overstocking is unsustainable and will lead to irreversible rangeland degradation. However, there is scant quantitative information on the influence of soil factors on rangeland degradation in some of these areas. In this study, we examined the effects of livestock grazing and exclusion on soil organic carbon and nitrogen (nitrate and ammonium) at three communal sites (Austrey 1, Eska/Neuhan and Tseoge). Soil samples were collected at 30 cm depth in April 2004 from open grazed plots and 5 year exclosures. Anova and Tukey HSD ($p < 0.05$) were used to test significant differences. Only organic carbon was significantly different across sites ($p = 0.049$), averaging 0.18 mg kg^{-1}. Overall no significant difference was recorded at the sites for organic carbon ($p = 0.37$), NO_3^- ($p = 0.66$), and NH_4^+ ($p = 0.90$) between grazed and un-grazed plots. Patterns of soil variables differed across sites. At Eska/Neuhan and Tseoge sites, organic carbon increased with grazing, while it decreased at Austrey 1. Nitrate increased at Austrey 1 and Tseoge whereas it decreased at Eska/Neuhan. Results from this study showed that grazing-induced rangeland degradation is site-specific and might be related to some other factors.

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Selection of bacteria from soil samples for liquid biofertilizer production

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Abstract

Twelve isolates of bacteria which could produce cellulase, protease and lipase, were screened from already identified bacteria from several locations including; soil surrounding a food waste dumping area in Bangkok; soil around a hot spring area from Sankampang, Chiang Mai, Thailand; decomposed vegetables and compost from The Royal Project, Chitralada Palace. The selected bacteria were identified as 5 isolates of ***Bacillus cereus,*** *1 isolate of* ***Bacillus subtilis,*** *4 isolates of* ***Bacillus coagulans,*** *1 isolate of* ***Serratia marcescens*** *and 1 isolate of* ***Pseudomonas aeruginosa.*** *When the enzyme activities were detected, the bacterial isolates with the highest activities of each enzyme were selected for the experimental production of liquid biofertilizer from solid waste. The result from the antagonistic test revealed that these bacteria could be grown together without inhibiting each other and were suitable for biofertilizer production. The solid wastes were then sampled from home food waste and synthetic waste composed of the leftovers from vegetables, animals and used oil in the ratio of 1:1:1 by weight. The liquid biofertilizer consisted of 6 pots as follows: Pot 1 – home food waste; Pot 2 – home food waste with 12 isolates of bacteria; Pot 3 – synthetic waste; Pot 4 – synthetic waste with 12 isolates of bacteria; Pot 5 – autoclaved synthetic waste; and Pot 6 – autoclaved synthetic waste with 12 isolates of bacteria. After 30 days of composting, the properties of the product were determined and were as follows: temperature = 28ºC, pH = 7.5-8.5, moisture content = 80%; C/N ratio = 8.00-16.80 and nutritional values N, P, K; 1.40, 1.20, 1.23 gm% respectively. From these results the nutritional values obtained from the liquid biofertilizers were higher than that obtained from fish waste and some other types of biofertilizers. In addition, the rate of decomposition was more complete. Therefore, the bacteria from this study were appropriate for the decomposition of the waste and hence useful for the production of the liquid biofertilizers.*

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Management of subsoil hard pans in tropical sodic sandy soil

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Keywords: Sodic soils, hardpan formation, ploughing, gypsum, coir

Abstract

The deflocculation of soil particles and organic matter in sodic sandy soils leads to the formation of subsoil hardpans. The presence of a hardpan at a depth of 30 cm from the soil surface limits the cultivation of deep rooted crops by hindering root penetration, movement of water and plant nutrients. A field experiment was conducted using annual moringa ***(Moringa oleifera*** *Lam.) as test crop. Management strategies involving integrated effect of ameliorating measures viz., mechanical (tillage methods-chisel ploughing), chemical (application of gypsum as per the Gypsum Requirement of soil) and organic ameliorants (composted coir waste, raw coir waste and FYM) were assessed. The influence of subsoil hard pan in tropical sandy soils on root penetration, root volume, hydraulic conductivity, soil bulk density and soil moisture retention characteristics were studied. The results revealed that hydraulic conductivity, soil moisture content, root volume and root penetration ratio were increased due to the integrated use of chisel ploughing, composted coir waste and gypsum. Chisel ploughing and organic amendments incorporation reduced the soil bulk density.*

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Nitrogen dynamics under different farmer practices in sandy salt-affected paddy fields in Northeast of Thailand

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Keywords: N dynamic, Organic Matter incorporation, salt-affected sandy soils, Rice fields, Northeast Thailand

Abstract

Soil salinity hazard along with nitrogen mineralization has been identified as the main limiting factors for rice production in Northeast paddy fields. Management activities in rice systems, such as fertilization and Organic Matter (OM) incorporation, affect losses of N through denitrification activity. The aim of the study was to quantify the effects of different farmer practices and level of salinity on the Nitrogen dynamic in soil solution. Two neighbouring fields with different farmer practices were selected. One field was managed with the incorporation of OM and supplied with fertilizers while the other had no amendment at all. Soil solution sampling was performed each week in 2004, at three depths (10, 25 and 45 cm) over a 3 month period under flooded conditions. In each field, sampling was performed in two profiles with distinct salinity levels. Samples were analyzed for NH_4-N and NO_3-N. Results indicated that accumulation of mineral N during cropping period demonstrated the capacity to supply sufficient N to produce reasonable rice yields. Evidences of the influence of OM incorporation, fertilizer application and anaerobic soil conditions were found on the dynamics and distribution patterns of NH_4-N in the soil solution. OM management resulted in sufficient NH_4-N supply for rice in the root zone and enhanced nitrification-denitrification processes. Salinity influenced the rate of mineralization, nitrification-denitrification processes, leading to potential NO_3-N contamination of groundwater, especially under extreme salinity conditions. With no OM incorporation, nitrification-denitrification was depleted due to lack of carbon source for microbial activity. It should be noted that further research is needed to confirm under controlled conditions, the influence of high salt contents on nitrogen dynamics.

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Poster Session 6

“The management of these agro-ecosystems”

Sandy soil improvement using organic matter and mineral fertilizers on the yield and quality of papaya

Ta-Oun, M.[1]*; S. Panchaban*[1]*; S. Pruangka* [2] *and P. Therajindakajorn*[1]

Keywords: Sand soils, manures, mineral fertilizers, papaya fruit quality

Abstract

In an effort to improve the chemical and physical properties of a sandy soil from Northeast Thailand, a study was undertaken where varying rates of manure and mineral fertilizers were applied to growing papaya. The experiment was a fully randomized factorial design with 3 replications. Rates of manure, mineral fertilizer containing primary, secondary and trace elements and complete fertilizer were varied at rates of low, medium and high. It was found that secondary elements had more effect on the growth of papaya than trace elements. A complete fertilizer mixture is essential for increased yield. The highest rates of material concentration gave the highest yield of Kag nual variety than manure, primary elements, secondary elements and trace elements by the average of 3.89, 2.23, 3.62, 2.13 and 0.53 kg rai^{-1} *respectively. The high rates of manure gave higher Vitamin C and sweetness both in row and ripen fruits which the values were closed to primary element fertilizer and complete fertilizer with the average range of 47-51 mg-ascorbic acid per 100 g fresh weight and 8.36-8.99% Brix which improved the papaya fruits quality resulting in more crunchy fruit with a better taste.*

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Effect of various amendments on yield and quality of papaya grown on sandy soils

Ta-Oun, M.[1]*; S. Panchaban*[1]*; S. Pruangka*[2] *and P. Therajindakajorn*[1]

Keywords: Mineral fertilizers, manures, pumice, fruit quality, sandy soils

Abstract

To study sandy soil amendment material together with 13-13-21 mineral fertilizer for better stand and growth of Kag nual papaya variety, the experiment design was a factorial completely randomized blocks design with 3 replications. Five kinds of soil amendment material namely 1) manure 2) dolomite 3) phosphate rock 4) pumice and 5) pumice sulfate were applied at three rates. Results indicate that basal application of manure gave higher yield than dolomite, phosphate rock, pumice and pumice sulfate with average fresh fruit of 3.74, 2.16, 3.05, 1.78 and 1.49 t/rai respectively. Basal applications of manure at 3, 6 and 12 kg/hole gave the average fruit weight of 3.71, 3.71 and 3.81 t/rai respectively. The medium rate of dolomite, phosphate rock, pumice and pumice sulfate gave better results than lowest and highest rates with the average of 2.86, 3.05, 2.00 and 2.00 t/rai respectively. The application of dolomite and basal manure application tended to increase Vitamin C, sweetness, and electrical conductivity of raw fruits when compared to phosphate rock, pumice and pumice sulfate. This resulted in more crunchy and better tasting fruit.

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Vietnam-Belgium project for improving food crop productivity on the sandy soils of the coastal zone in Central Vietnam

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Keywords: Integrated farming systems project, sandy soils, soilcarbon management

Abstract

Central Vietnam is composed of two contrasting topographic areas parallel to the coastline: mountains in the West and lowlands in the East where most of the population is concentrated. Sandy soils are largely dominant in the cultivated area in this narrow strip along the sea. Typical constraints of these soils are chemical infertility and acidity, excessive drainage capacity, low organic matter content, associated with particular climate limitations: heavy rain, floods and droughts during certain periods. Environmental conditions also favour pests and diseases. An integrated research approach is foreseen to improve yield and quality of crops and achieve sustainable development of farming systems including socio-economic aspects. To meet these objectives, knowing the natural limitations of sandy soils, the project is focused on the carbon cycle in the whole farming system (soil-plant-animal) aiming at the better placing a great value on organic matter than is currently the case. This includes not only existing organic sources within the farms (crop residues, animal faeces) but also possible exogenous sources such as aquatic plants from pounds and more especially from the great lagoon of Thua Thien Hue Province which encompasses some 22,000 ha. The research for optimal management of organic matter includes earthworms composting, a technique already tested in South Vietnam by partners of the project. Biotic constraints, i.e. pests and diseases, are also evaluated in order to suggest integrated control of pathogens and insects in the framework of global farming systems and the environment.

Socio-economic studies are conducted in parallel in all research activities in order to estimate expected improvement of households’ income from some reorientation of farming practices. In the first step of the project, a detailed survey was carried out among 145 households in villages from the 4 districts of the coastal area of the Thua Thien Hue Province. Existing practices and the socio-economic situation are evaluated and selected pilot farmers are involved in the research of optimal practices. Soil samples (300) and organic matter samples (95) were collected during this survey. The partners of the project (2004-2008) include the Hue University of Agriculture and Forestry, the National Institute for Soils and Fertilizers in Vietnam, the Faculty of Agricultural Sciences of Gembloux, and the Catholic University of Louvain in Belgium.

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Salinity control by farmers practices in sandy soil

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Keywords: sandy soil, farmers practice, salinity, rice production, water ploughing, land levelling

Abstract

Northeast Thailand is an area where the population (near 20 million) is dependent on white rice production, for their livelihood. Rice is produced on low fertility sandy soils using traditional techniques within the context of significant socio-economic constraints. Rice production is generally low due to several constraints that are not entirely due to the farmer. The development of salinity is one of the environmental constraint that farmers face. Salinity often becomes evident as salt patches that appear as crusts during the dry season. In field studies it has been shown that a combination of flooding, puddling and drainage reduced the level of salinity by 50% (initial electrical conductivity >4 mS cm^{-1}*). With this decline in salinity rice is able to grow adequately in these patches. However, this positive effect is only temporary. Field measurements indicated that, salt plumes due to the positive pressure head of the saline groundwater forced saline waters to the surface. The saline patches were located on slight elevations within the field, suggesting that they become points of salt concentration associated with capillary rise as the paddy dries out. Through land levelling these high points would be eliminated and reduce the risk of salt concentrations. In addition, levelling the field surface would during flooding result in a more uniform depth of water above the saline patches. Levelling cannot stop the upward movement of saline water under pressure but it can alleviate the secondary salinisation due to surface evaporation when the soil dries out. This simple and easily adopted practice represents an effective method of managing salinity associated with groundwater rise in these lowland rice production systems.*

Introduction

According to recent estimations, 6.5% of the earth’s surface is affected by problems of salinisation (Cheverry et al., 1998). This is also the case, in Northeast Thailand on soils that are of low fertility. In this region, approximately 17% of soils are affected by salinity (Arunin, 1984) and a further 108,000 km^2, which is more than twice the size of Switzerland are potentially at risk from the same phenomenon. In Northeast Thailand, the main cause of the extent of salinisation is believed to be upland deforestation leading to a rise of the saline water table (Williamson et al., 1989). In some cases the salinisation causes saline patches to form, which can reach a diameter of 25 meters.

Salinisation of soil is of increasing importance to national stakeholders concerned with the conservation of their agricultural land (Kohyama K. and Subhasaram, 1993). A decrease in rice production yield due to the occurrence of these regional saline patches could have serious affects on this area’s ability to satisfy the rising food demands of its increasing population (Fukui, 1991. Kono, 1991). In addition, rice cropping forms an intricate part of Northeast Thai culture, well established and important in a socio-cultural and economic aspectsl (Formoso et al., 1977), for which a decreasing yield would have serious consequences. The majority of the local population produce glutinous rice intended for their own consumption. When the area is large enough, jasmine rice is also produced for commercial consumption (Berio, 2005). Pluvial monoculture of rice crops is the main source of agricultural income in this area.

The problems of salinisation have been studied for many years in this region of Thailand (Arunin, 1984; Mitsuchi et al., 1986; Yuvaniyama A. 2001). However, there are still unanswered questions on the dynamics of these saline patches, especially during the

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rainy season and the possibility of the farmer’s practices controlling their development. With this objective, ways of controlling the effects of these saline patches were studied, and in particular, the tillage practices used in preparing the soil, that includes levelling in the presence of standing water within the field. This practice has already been used in other contexts and on other soils, notably in Senegal (Hammecker and Maeght, 1999). It was then necessary to evaluate the duration of the effects of the resulting desalinisation on the next season’s crops when the soil would be submerged. Topographic readings and measures by penetrometer were made in order to better explain the processes of soil evolution.

Materials and methods

Study area

The experiments were conducted on plots in Pra Yuhn, near Khon Kaen, Northeast Thailand (16º21′12.744″ North and 102º36′29.8″ East). The region’s soils are very sandy (Mitsuchi et al., 1986; Yuvaniyami 2001) and also poor in nutritive elements (Ragland and Boonpuckake, 1988). The soil has a sandy loam texture (Grunberger, 2002), less than 10% clay content and low levels of organic matter (Table 1).

These utisols of the Roi Et series have low cation exchange capacity, less than 5 $cmol_c\ kg^{-1}$ of soil (Table 1). In the saline patches the exchangeable complex has a higher sodium content compared to outside the patch. The region has a tropical, Savannah climate with rainfall of 1,200 mm that fall pre-dominantly from May to October. Evaporation is higher than precipitation, except in the height of the rainy season from July to September (Bolomey, 2002). Soil is regularly saturated by solutions of NaCl as the water table rises and conductivity has an average value of 20 dS m^{-1} and pH of 5.82. The water table is near the soil surface at the end of the rainy season and draws down by two metres in the dry season.

The soil was cultivated using traditional implements whilst maintaining a sufficient water level so that the entire field surface was covered. The soil surface was levelled and once completed, the excess surface water was drained from the field.

Three sampling exsercises were undertaken using a grid made up of squares each measuring 2 m^2 that covered the whole plot. The quantity of reference points gathered has enabled the results to be presented in map form. It has also been possible to describe the form of the saline patches seen at soil surface in a spatial context. The topsoil (0-20 cm) of soil were removed in a tube and then mixed. EC of the soil extract (1:5) was measured on each sample. Two hundred samples were collected over the three sampling dates. The first phase took place before working the soil, the second, just after drainage of surface water following cultivation and levelling. The third phase took place after rice was harvested. The first two phases of sampling will show the effect of desalinisation by cultivation of the soil under a shallow water layer and the third phase will give information as to the persistence of this desalinisation.

The levelling of the topsoil was made easier by using topographic references (with a precision of 1 cm) on the same grid system as the maps of salinity. Seven other maps were made of the topographic surface on other plots with saline patches in order to provide more information. Resistance measures were made using a hand penetrometer (Eijkelkamp), on several plots of the same area inside and outside the saline patches and at profiles from 0-80 cm. Each layer was tested five times for each profile 5 by 5 cm.

Results

The initial map of salinity, made on the plot prior to cultivation of the soil clearly showed the presence of saline patches covering 20% of the area (Figure 1).

Maximum EC values exceeded 4 ds m^{-1} at many points in the saline patch. The second map, made after the soil was worked resulted in a significant decline in EC with maximum values not exceeding more than 2 dS m^{-1}. This was attributed to the diluting effect of

Table 1. Selected soil chemical and physical properties in and external to a salt patch

Depth (cm)	Interior of the salted spots						External of the salted spots					
	Sand %	Silt %	Clay %	CEC $cmol_c\ kg^{-1}$	pH H_2O	C %	Sand %	Silt %	Clay %	CEC $cmol_c\ kg^{-1}$	pH 1:5	C %
0-9	66	28	6	1.4	7.0	0.4	55	40	4	2.0	4.4	0.4
15-20	60	34	6	1.5	6.7	0.1	63	31	6	2.0	5.7	0.1
25-35	63	31	6	1.5	6.4	0.0	60	34	5	2.4	5.9	0.0
45-55	48	29	14	4.7	7.5	0.0	44	42	15	2.5	5.6	0.0

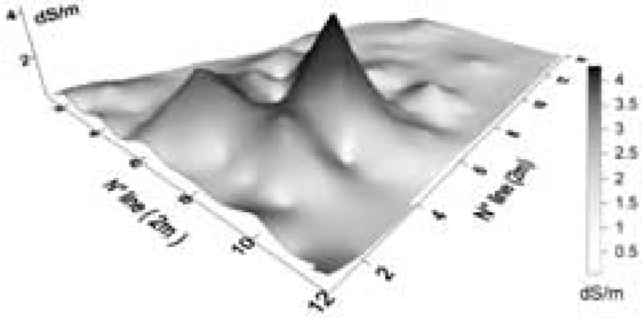

Figure 1. Map of electrical conductivity (EC) prior to land preparation

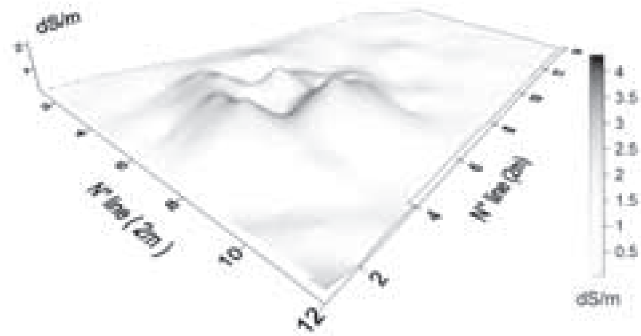

Figure 2. Distribution of saline patches after cultivation, puddling and subsequent draining of the field prior to rice establishment

the standing water and the subsequent draining of the field (Figure 2).

The third map, made after the harvest of the rice crop clearly shows that the salinity has started to rise during the growing season reaching values of 2.6 dS m^{-1} (Figure 3).

These readings show that it has not been possible to maintain the positive effect of desalinisation during the four months of crop cycle where the soil surface is submerged under a surface layer of water that is maintained due to the presence of bunds. The rising saline water table increased salinity in the centre of the saline patch to a depth of 20 cm from soil surface, the depth from which the soil samples were collected.

The topographic map reveals that the saline patches are found on slight elevations within the field of around 5 cm compared to surrounding soil surface (Figure 4).

The results of the control readings for the topography of 8 other plots confirm that for this area, 100% of the highest salinity occurs on elevated soil (Figure 5).

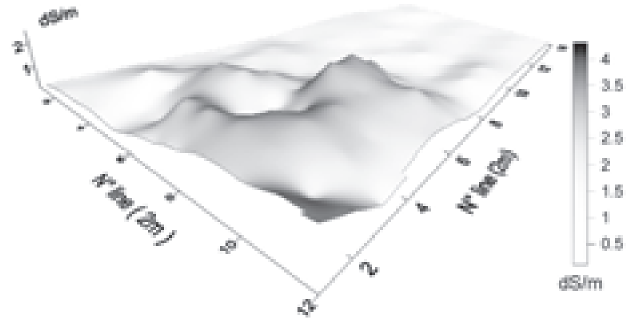

Figure 3. Electrical conductivity measurements conducted at the time of the rice harvest

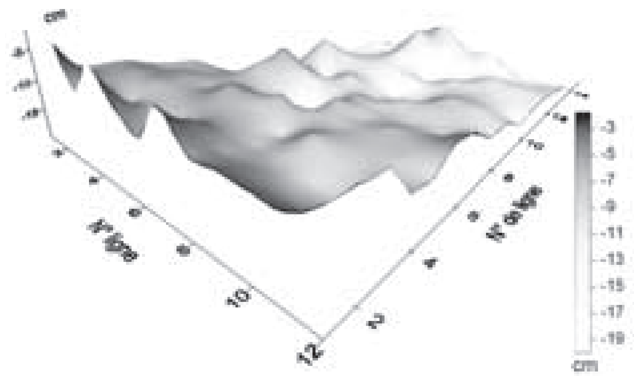

Figure 4. Topographic map of height differences within a field indicating the non-uniform levelling achieved

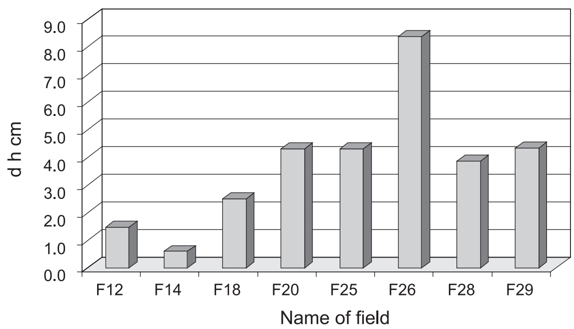

Figure 5. Differences between the average height of saline patches when compared to non-saline areas in each of 8 fields sampled

The soils in the study plot typically show a layer of compact, resistant soil between -40 and -70 cm from surface. However, resistance measurements by penetration at the centre of the saline patches have shown that this resistant layer is absent (Figure 6). These results show an important difference in layer structure between the soil profile inside and outside the patch. This raises many questions as to the role of this compact layer and suggests the need for further research to understand the reasons for this modification in the profile which normally appears to be homogenous.

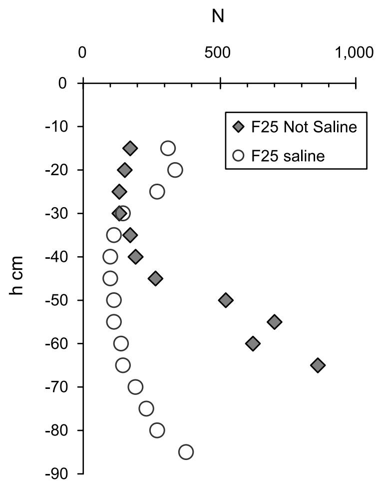

Figure 6. Penetrometer resistance measurements on soil profile inside and outside saline patch

Conclusion

This study has shown that it is possible to temporarily reduce the salinity associated with saline patches using simple farming techniques to work the soil. This desalinisation is altered by the rise of the saline water table towards the soil surface during the period of submersion. Salinity was however, found to be lower to that measured at the beginning of the field’s crop cycle. This technique therefore enables at least temporarily more favourable growing conditions by reducing salinity by 50% in the elevated centre of the patch. This reduction even though temporary, also helps to prevent an eventual build up of salinity over the seasons.

The levelling out of the soil to reduce topographic differences between the elevated saline patch, and the rest of the field also has beneficial effects. The surface water could be maintained more evenly over the field’s entire surface, helping to dilute salinity from the rising saline water table during submersion. The levelling of the sureface also helped to slow down the eventual formation of a drawing-up action on the higher parts of saline patches, sticking out from the surface during the dry season.

These simple methods of working the soil whilst submerged, levelling the surface and then draining off of the excess standing water can improve soil conditions for rice production. Easily implemented by farmers, these techniques are valuable in the control of soil salinity.

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Land degradation assessment in drylands: are there management solutions?

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Keywords: Land degradation, assessment tools

Abstract

The project on land degradation assessment in drylands (LADA) is the official tool of the UNCCD and the GEF to develop a standard assessment methodology. LADA generates up-to-date ecological, social, and economic and technical information, including a combination of traditional knowledge and modern science, to guide integrated and cross-sectoral planning and management in drylands. LADA is developing tools and methods to assess and quantify the nature, extent, severity and impacts of land degradation, watersheds and river basins, carbon storage and biological diversity at a range of spatial and temporal scales. It is also building the national, regional and international capacity to analyse, design, plan and implement interventions to mitigate land degradation and establish sustainable land use and management practices.

LADA is to assess the regional and global baseline condition of land degradation with the view to highlighting the areas at greatest risk (hot spots). These assessments are supplemented by detailed local assessments that focus on root cause analysis of land degradation and on local (traditional and adapted) technologies for the mitigation of land degradation. Areas where land degradation is well controlled are included in the analysis.

LADA develops, with country participation, a framework for land degradation assessment at global and national levels through a consensus building process for which the long-term purpose is to identify socio-economic environmental benefits accruing from addressing land degradation in drylands in terms of conservation of biodiversity and international waters, and sequestration of carbon.

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Phosphorus index for tropical sandy rice field and pineapple fields

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Keywords: Phosphorus index, pineapples, sandy soils

Abstract

Sandy soils are typically infertile and required significant amounts of fertilizer to maintain their productivity. Both chemical fertilizer and organic fertilizer such as manures or composts not only provide important nutrients to the growing plant but are also subject to fixation by the soils, surface runoff and leaching into the groundwater. Phosphorus is one of the major factors influencing the development of algal and microorganism bloom in water bodies. Phosphorus concentrations in the soil, the rate and method of phosphorus application, soil erosion and water runoff are used as factors in the calculation of a phosphorus index (PI). Paddy sandy soil from Surin Province that typically represented a lowland area and a sandy soil from an upland pineapple production system from Prajuab-kirikan Province were used in this study. PI values calculated were 16.5 and 10 respectively. These values are rather low and indicate that these soils have a low potential in losing phosphorus. PI is an easily procedure to estimate phosphorus lost and surface wastewater risk assessment. Factors that influence PI and the methods of reducing PI were discussed.

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The potential of Quartzipsamments for sugarcane growing in Southeast Coast, Thailand

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Keywords: Sugarcane production, light textured soils, chemical and physical properties, suitability assessment

Abstract

A study on the potential of Quartzipsamments to support the growing of sugarcane on the Southeast Coast, Thailand was undertaken on four representative soil areas. The methodology used in this study included pedon analysis of soils in the selected areas, laboratory analyses of their physico-chemical properties, mineralogy, micromorphological characteristics and assessment of their properties related to sugarcane crop requirements.

Results of the study revealed that these soils are Quartzipsamments deposited on the coastal plain. They are deep soils developed mainly on local alluvium and wash deposits derived from granite. Their micromorphological characteristics show subangular to subrounded quartz grains as the major fabric component. Their texture ranges from sand to loamy sand and their bulk density ranges from moderately low to high (1.40-1.82 Mg m^{-3}). Chemical analysis of soils indicates that they have a strong acid to neutral reaction (pH 5.1-6.8). They have very low to low organic matter contents (0.2-9.4 g kg^{-1}), very low total nitrogen (0.01-0.03 g kg^{-1}), very low to high available phosphorus (1-95 mg kg^{-1}) and very low to low available potassium (1.5-46.8 mg kg^{-1}). The soils have very low to medium cation exchange capacity (2-11 $cmol_c$ kg^{-1}). Their base saturation percentage varies widely from 4-77%. Their electrical conductivity ranges from 0.1-1.9 dS m^{-1} indicating no salt effect.

Fertility assessment results indicate that most of these sugarcane-growing soils have low fertility except for a single area where the soil has a moderate fertility status. Their potential based on suitability assessment indicates that most of them are moderately suited but one profile is not suited for sugarcane growing because of its sandy texture and strongly acid condition. A recommended approach to increase their potential for sugarcane growing includes an emphasis on soil organic matter conservation and a more intensive soil-fertilizer management. A continuing effort on soil-fertilizer management is clearly needed to maintain effectiveness in sugarcane growing on these soils.

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Properties of coarse-textured Alfisols under cassava in Thailand

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Keywords: Alfisols, chemical characteristics, kaolin, cassava production

Abstract

Two Haplustalfs and one Paleustalf under cassava in Khon Kean Province, Thailand were selected for this study with the objective of assessing the relationship between spatial difference of soils, their use suitability and environment. These soils developed on washed deposits over local alluvium derived from clastic sedimentary rocks. Methods of the study included morphological analysis of soils in the field, laboratory chemical and mineralogical analyses of soil samples according to standard methods.

Results from the study revealed that all soils are deep and well developed with Ap-E-Bt-2C profile type. Their textures range from loamy sand to sandy loam. Dominant chemical characteristics include acidic condition (pH 4.6-6.9), low plant nutrient status and low organic matter content (0.63-3.73 g kg^{-1}), low extractable bases (0.05-2.14, 0.03-1.94 and 0.02-0.28 cmol kg^{-1} for Ca, Mg and K) and low cation exchange capacity (0.10-5.81 cmol kg^{-1}). Kaolin is the major constituent in the clay fraction with quartz dominating the silt and sand fractions. These two minerals reflect the low fertility status of these soils. As evidence of pits on quartz sand grains would indicate strong chemical weathering conditions. Concentrations of heavy metals (Cr, Co, Ni, Cu, As, Pb) illustrate little variation within all soil profiles. However, most of these element concentrations are not high enough to pose environmental hazard. For economic crop production, cassava is the most suitable crop for these soils. A recommended approach to increase the potential of these soils for other crops, include a more intensive soil-fertilizer management along with soil and root zone moisture conservation practices.

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Effect of land use management on groundwater and soil salinization in Northeast Thailand

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Abstract

Distribution of secondary salinization in Northeast Thailand is mainly caused by man-made. This paper deals with the effect of land use management in recharge area on saline groundwater to reduce soil salinization in discharge area.

There is about 2.8 million ha of saline soils or 17% of the total area of Northeast Thailand. The soils are classified as severe, moderate and slight saline areas of 240,000, 590,000 and 2,020,000 ha, respectively, and another estimated 3,140,000 ha of recharge area. Rock salt of the Mahasarakham Formation beneath the soil is the cause of soil and water salinization in the region. Human mismanagement affects water imbalance that causes secondary salinization through deforestation, salt making, reservoir construction and improper water management. Reforestation of neems (Azadirachta indica) and eucalyptus (Eucalyptus camaldulensis) is recommended for planting in recharge areas to decrease saline groundwater in discharge area. But it is difficult to follow because mainly present land use of the recharge area has already been changed to cassava plantation.

Effect of eucalyptus plantation and management in cassava plantation on saline groundwater level has been carried out at Nakhon Ratchasima Province in 2005. The results show obvious confirmation to be one of the recommendations for management in recharge area to reduce salinizaton in discharge area.

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Characteristic and management of tin mine tailings in Thailand

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Abstract

Soil characteristics of tin mine tailings are generally of low fertility and have unfavourable physical conditions for supporting plant growth resulting this being due to disturbance during the tin mining operation. Management of the tailings for further use may be dependent upon ownership of the tailings land. Attempts to utilize the tailings for agricultural use through experiments and trials have been undertaken by the Office of Research and Development for land management among others. This includes the planting of forest tree species, growing of agricultural crops, improvement of the soil by several methods to elevate the fertility status and create more favourable conditions for plant growth. Successful methods consist of chemical fertilizer either used directly or by mixing with manure and other materials that are likely to improve the physical properties of tailings and ameliorate toxic conditions. There is still no large-scale application of the research findings due to the difficulties in initial improvement of the topographic condition of the tailings and the economic situation of the owner.

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The improved presences of Halophilic bacteria in sandy saline soils with the application of chemical fertilizer, bioextract and molasses

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Keyword: Halophilic bacteria, saline soil, bioextract, chemical fertilizer, molasses

Abstract

The influence of Halophilic bacteria in enhancing saline soil was assessed after the application of chemical fertilizer, bioextract and molasses. Saline soils were sampled from the area of an old salt farm, Baan Nongwang, Kantarawichai District, Mahasarakham Province, Thailand. Soil textural composition was classified as a sandy loam with 79% sand. The sampled soils were transferred to pots without disturbing soil structure, simultaneously, chemical fertilizer, bioextract or molasses was added. The analysis included physical and chemical properties of the improved saline soils after 0, 14, 28 and 42 days of the additions.

The results revealed that the soils initial electrical conductivity (EC) was 7.13 mS/cm which was considered as moderately saline and limited plant growth. The number of Halophilic bacteria prior to the improvement was 7.346 Log CFU/g soil. After the addition of bioextract or molasses, there was a significant decline in EC, this being greatest on soils that had been treated with bioextract where the EC decreased to 4.44 mS/cm, followed by the soil improved with molasses; the EC reduced to 4.73 mS/cm. In addition, Halophilic bacteria populations were found to decline in those soils that had been treated with bioextract to a value of 6.753 Log CFU/g soil and for molasses treated soil to 6.667 Log CFU/g soil. Soil organic matter increased through the addition of either bioextract or molasses. Contrasting this, saline soil improved with a chemical fertilizer, the number of Halophilic bacteria increased at the highest (7.575 Log CFU/g soil) compared to those improved with bioextract or molass. Optimal salinity and pH introduced suitable conditions for Halophilic bacteria where the chemical fertilizer was applied to saline soil. To improve sandy saline soils, the addition of bioextract or molasses is recommended as these treatments reduce the EC of soils and enhance the populations of Halophilic bacteria compared to those of chemical fertilizer application.

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Saline soil improvement with biofertilizer for the growing kale (*Brassica Albonglabra*)

Kurukodt, J.[1]

Keywords: Sandy soil, biofertiliser, kale, saline soil improvement

Abstract

Sandy saline soil occupied large areas of Northeastern Thailand and is considered as one of the most significant soil degradational and environmental problems facing the region. Associated with this problem is decline soil fertility. In the current study improving the soil fertility through the use of biofertilizer was assessed. Biofertilizer was applied at the following rates; 0, 5:1, 5:3 and 5:5 (soil: biofertilizer). The soil collected from the Chiang Yun District, Mahasarakham Province, Thailand was highly saline with and EC of 9.86 dS/m and was used in the pot experiment. Soil properties including major nutrients; N, P and K, EC, pH were determined prior to and at the termination of the pot experiments. The growth of Kale was determined 45 days after establishment. The application of biofertilizer at the ratio of 5:5 showed optimal soil improvement with a reduction in soil EC to 1.59 dS/m and incremental increases in N, P and K. Highest Kale growth and production were also observed at this rate. The role of Biofertilizer in the rehabilitation of sandy saline soils was demonstrated.

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Organic agricultural systems for cassava crops in soil group 40

Junrungreung, S.[1]*; S. Chinon*[1]*; T. Rattanakaew*[1] *and S. Saelim*[1]

Keywords: Green manures, sandy soils, cassava

Abstract

A study was carried out on Soil Goup 40 during 2003-2005 at Amphoe Jombung Ratchaburi Province where the soil is classified as a sandy loam with a low inherent fertility. The design of the trial comprised of a completely randomized block design with 10 treatments with 3 replications which were as follows; control, conventional method, the combination of using of ***Canavalia sp*** *as green manure and mulching with* ***Vigna sp*** ***Crotolaria sp*** *as green manure, mulching with* ***Vigna sp*** *and* ***Canavalia sp*** *as green manure and mulching with* ***Vigna sp.*** *The another 4 treatments were* ***Canavalia sp*** *and* ***Crotolaria sp*** *as green manures and mulching with* ***Vigna sp*** *incorporated with liquid fertilizer,* ***Crotolaria sp*** *and* ***Vigna sp*** *as green manure mulching with* ***Canavalia sp*** *incorporated with liquid fertilizer. There was a tendency for those treatments comprising of green manure incorporate with mulching and liquid fertilizer having greater height, yield and starch of cassava than those treatments receiving just the green manure incorporated with mulching or conventional method. The height, yield and starch of cassava in these treatments were in the range 22.78-30.23 ton/ha, 127.2-141.3 cm and 12.2-14.9% respectively. Moreover, it was found that the combination of* ***Crotolaria sp****. incorporated with* ***Canavalia sp*** *and liquid fertilizer resulted in the highest, yields and starch. An assessment of the economic return on investments indicated that the combination of* ***Crotolaria sp.*** *incorporated with* ***Canavina sp*** *and liquid fertilizer gave the greatest net profit.*

[1] Institute of Research and Development for Soil Biotechnology, Land Development Department Ministry of Agriculture and Cooperatives, Bangkok 10900, Thailand.

Poster Session 7

"Successes and failures: Stakeholders and development agencies perspectives in enhancing the livelihoods of communities on light textured sandy soil"

Reclamation of deteriorated land in Khao Hin Sorn Royal Development Study Center

Swuttanakoon, S.[1]*; K. Tiwatri*[1] *and B. Patanakanok*[1]

Keywords: Rehabilitation sandy soils, agroforestry

Abstract

Forty years ago the area of the Khao Hin Sorn Royal Development Study Center was covered by fertile forest. Due to deforestation for cultivation of corn and cassava without soil improvement, the land became infertile and erosion-prone area.

The Khao Hin Sorn Royal Development Study Center was established under the initiative of H.M. the King in 1979, at Khao Hin Sorn sub-district, Phanom Sarakarm District, Chachoengsao Province. The objective is to develop farmers' land by means of water resources development, forest rehabilitation and application of production techniques in agriculture and animal husbandry, where farmers and extension workers could visit, observe demonstrations and obtain some knowledge on agriculture to apply in their real life. Agroforestry was conducted as a systematic framework for cooperation in development work among the various government agencies on an area of 340 hectares. Over the past 25 years, natural resources have been reclaimed. The area has improved significantly and serves as a successful demonstration model to conduct development activities to improve the well-being of people in surrounding areas. According to field surveys of the area and cross checked by Quick Bird satellite image (taken in November 2004), it can be conclude that the percentage of forest area, field crops, orchard, horticulture, pasture and paddy field, infrastructure and water resources are 46.26, 20.27, 3.26, 0.45, 0.07, 18.73 and 10.97 of the area respectively.

[1] Khao Hin Sorn Development Study Center, Land Development Department, Chachengsao, Thailand.

Conference programme

Monday, 28 November 2005

Room: Royal Orchid 1

07:30 – 09:00 Registration

09:00 – 10:00 Welcome addresses by:
- Khon Kaen Governor,
- Director General of Land Development Department (LDD, Thailand)
- Representative from Institut de Recherche pour le Développement (IRD, ex-ORSTOM, France)
- Representative from International Water Management Institute (IWMI)
- Representative from Food and Agriculture Organization (FAO) of the United Nations

10:00 – 10:15 Chairman of the Organizing Committee report

10:15 – 10:30 Presiding inaugural address

10:30 – 11:00 **Coffee / Tea**

11:00 – 11:30 Strategic management for poverty alleviation of people inhabited problem soil areas by Dr. *Santhad Rojanasoonthon (Director of the Research Section, The Royal Project Foundation)*

11:30 – 12:00 Poor soils make poor people and poor people make the soil worse by Dr. *Alfred E. Hartemink (Deputy Secretary General, the International Union of Soil Sciences)*

12:00 – 13:00 **Lunch**

Room: Royal Orchid 1

Session 1. Global extent of tropical sandy soils and their pedogenesis

Chairman: Pisoot Vijarnsorn
Rapporteur:

13:00 – 13:40 Sandy soils of Asia: a new frontier for agricultural development?
Eswaran, H.*; T. Vearasilp; P. Reich and F. Beinroth*

13:40 – 14:00 Analysis of spatial distribution patterns of soil properties and their determining factors on a sloped sandy cropland in Northeast Thailand.
Funakawa, S.*; Yanai, J.; Hayashi, Y.; Hayashi, T.; Noichana, C.; Panitkasate, T.; Katawatin, R. and Nawata, E.*

14:00 – 14:20 Sandy soils of Cambodia.
Seng, V.*; Bell, R.W.; White, P.F.; Schoknecht, N.; Hin, S. and Vance, W.*

14:20 – 14:40 Soil characteristics and crop suitability of sandy soils in Hainan, China.
Zhao Yu-Guo*; Zhang Gan-Lin and Gong Zi-Tong*

14:40 – 15:00 Sandy soils in Southern and Eastern Africa: Extent, properties and management.
Hartemink, A.E.*; J. Huting and K. Giller*

15:00 – 15:20 **Coffee / Tea**

15:20 – 15:40 Coastal sandy soils and constraints for crops in Binh Thuan Province, Southern Central Vietnam.
Nguyen Cong Vinh

Session 2. Socio-economic imperatives

	Chairman: Pisoot Vijarnsorn **Rapporteur:**
16:20 – 16:40	Challenges for farmer-researcher partnerships for sandy soils in Northeast Thailand. ***Caldwell, J.S.****; S. Sukchan and C. Ogura*
16:40 – 17:00	Farming systems in the sandy area of the Thua Thien Hue Province, central Vietnam. Survey of socio-economic situation and constraints identified by farmers. ***Pham Khanh Tu****; Hoang Thi Thai Hoa; Hoang Nghia Duyet; Le Dinh Huong; Nguyen Dang Hao; Nguyen Thi Dung; Nguyen Minh Hieu; Le Duc Ngoan; Pham Quang Ha; Lebailly, Ph.; Francis, F.; Haubruge, E.; Bragard, C.L. and Dufey J.E.*

Room: Royal Orchid 2

Session 3. Chemical properties and their effect on productivity

	Chairman: Narong Chinabut **Rapporteur:**
13:00 – 13:40	Managing sandy soils in Northeast Thailand. ***Wada, H.***
13:40 – 14:00	Changes in soil chemical properties under two contrasting plantation systems on the Zululand coastal plain, South Africa. ***Noble, A.D.****; Berthelsen, S. and Mather, J.*
14:00 – 14:20	Clay mineral dissolution following intensive cultivation in a tropical sandy soil. ***Dur, J.C.****; Wiriyakitnateekul, W.; Lesturgez, G.; Pernes, M.; Elsass, F.; Hartmann, C. and Tessier, D.*
14:20 – 14:40	Hydrotalcite: leaching-retarded fertilizers for sandy soils. ***Gillman, G.P.***
14:40 – 15:00	Assessment of salinity hazard by Time Domain Reflectometry in flooded sandy paddy soils. ***Grunberger, O.****; Maeght, J.L.; Montoroi, J.P.; Rattana-Anupap, S.; Wiengwongnam, J. and Hammecker, C.*
15:00 – 15:20	**Coffee / Tea**
15:20 – 15:40	Effects of land use changes on soil chemical properties of sandy soils from tropical Hainan, China. ***Wu, W.****; Mingzhi Chen and Bo Sun*
15:40 – 16:00	Improvement of the saline sandy soil in Northeast Thailand using polyvinyl alcohol (PVA). ***Dejbhimon, K.*** *and Wada, H.*
16:00 – 16:20	Impact of agricultural practices on the biogeochemical functioning of sandy salt-affected paddy soils in Northeastern Thailand. ***Quantin C.****; Grunberger O.; Suvannang N. and Bourdon E.*
16:20 – 16:40	Remediation of soil acidification by form of nitrogen fertilizer on grass swards of Australia and Thailand. ***Armour, J.D.****; S. Berthelsen; S. Ruaysoongnern; P.W. Moody and A.D. Noble*
16:40 – 17:00	Influence of afforestation with eucalypts in Congolese savannas on long-term nutrient availability in the soils. ***Laclau, J.-P.****; Deleporte, P.; Bouillet, J.-P. and Ranger, J.*
17:00 – 18:00	**Poster session**
19:00 – 21:00	**Meet and greet**

Tuesday, 29 November 2005

Room: Royal Orchid 1

Session 4. Physical properties of tropical sandy soils

Chairman: Andrew Noble
Rapporteur:

08:00 – 08:40 Physical properties of tropical sandy soils: A large range of behaviours.
Bruand, A.*; Hartmann, C. and Lesturgez, G.*

08:40 – 09:00 Compaction processes in a tilled sandy soil.
Lesturgez, G.*; Hartmann, C.; Tessier, D. and Poss, R.*

09:00 – 09:20 Physical reorganization of sand due to the motion of a solid intruder.
Kolb, E.*; Clément, E.; Douady, S. and Courrech du Pont, S.*

09:20 – 09:40 Wind and water erosions of non cultivated sandy soils in the Sahel: a case study in Northern Burkina Faso, Africa.
Rajot, J.L.*; Ribolzi, O.; Planchon, O. and Karambiri, H.*

09:40 – 10:00 Surface crusts of semi-arid sandy soils: types, functions and management.
Valentin, C.

10:00 – 10:20 **Coffee / Tea**

10:20 – 10:40 An estimation of water retention properties in sandy soils of Southern Brazil.
Bortoluzzi, E.C.; Rheinheimer, D. and ***Tessier, D.***

10:40 – 11:00 Hydraulics of rill initiation on a low-slope sandy soil.
Tatard, L., ***Planchon, O.****; Nord, G., Favis-Mortlock, D.; Wainwright, J.; Silvera, N.; Ribolzi, O. and Esteves M.*

11:00 – 11:20 The co-composting of waste bentonites from the processing of vegetable oil and its impact on selected soil properties of a light textured sand.
Soda, W.*; Noble, A.D.; Suzuki, S.; Simmons, R.; Sindhusen, L. and Bhuthorndharaj, S.*

11:20 – 11:40 Short-term effects of agricultural practices on the soil structure and hydrodynamic in a deep tilled hardened sandy-silty volcanic-ash soil *(cangahua)* in Ecuador.
Podwojewski, P. *and Jean Louis Janeau*

11:40 – 13:20 **Lunch**

Room: Royal Orchid 1

Session 5. The role of organic matter and biological activity

Chairman: Alfred Harteminck
Rapporteur:

13:20 – 14:00 Organic matter and biofunctioning in tropical sandy soils and implications for its management.
Blanchart, E.*; Albrecht, A.; Bernoux, M.; Brauman, A.; Chotte, JL.; Feller, C.; Ganry, F.; Hien, E.; Manlay, R.; Masse, D.; Sall, S. and Villenave, C.*

14:00 – 14:20 On-farm assessment of long term effects of organic matter management on soil characteristics of paddy fields threatened by salinity in Northeast Thailand.
Clermont-Dauphin, C.*; C. Hartmann; J.L. Maeght; E. Beriaux and C. Sagnansupyakorn*

14:20 – 14:40	Nitrogen mineralization capacity of coastal sandy soils of the Thua Thien Hue Province, Central Vietnam. ***Hoang Thi Thai Hoa****; Thai Thi Huyen; Tran Thi Tam; Hoang Van Cong; Do Dinh Thuc; Chiang, Cl.N. and Dufey, J.E.*
14:40 – 15:00	Effects of salinity-tolerance cyanobacterium *Nostoc* sp. on soil characteristics and plant growth. ***Inubushi, K.****; Morita, S.; Miyamoto, K.; Obana, S.; Tulaphitak, D., Tulaphitak, T. and Saenjan, P.*
15:00 – 15:20	Dry matter production and digestibility of *Centrosema pubescens* and *Pueraria phaseoloides* with rock phosphate fertilization and mycorrhizae inoculation in latosolic soil. ***Lukiwati, D.R.***
15:20 – 15:40	**Coffee / Tea**
15:40 – 16:00	Short-term dynamics of soil organic matter and microbial biomass after simulated rainfall on tropical sandy soils. ***Sugihara, S.****; Shinya Funakawa; Hitoshi Shinjo and Takashi Kosaki*
16:00 – 16:20	Eucalypt litter quality and sandy soils: addressing two cumulative effects on topsoil organic-matter and soil faunal activity in African plantations. ***Bernhard-Reversat, F.****; Mboukou-Kimbatsa, I. and Loumeto, J.J.*
16:20 – 16:40	Effect of fallowing on carbon sequestration in a humid tropical sandy soil (Mangodara, Burkina Faso). ***Nacro H.B.****; Masse D. and Abbadie L.*
16:40 – 17:00	Soil organic matter loss and fertility degradation under different agricultural land uses in sandy soils of Northeast Thailand and the use of organic materials of different qualities as a possible restoration measure. ***Vityakon, P.***

Room: Royal Orchid 2

Session 6. The management of these agro-ecosystems

Chairman: Pirmpoon Keerati-Kasikorn
Rapporteur:

08:00 – 08:40	The management of the agro-ecosystems associated with sandy soils. ***Bell, R.W.*** *and Seng, V.*
08:40 – 09:00	Long-term topsoil changes under pearl millet production in the Sahel. ***Anneke de Rouw***
09:00 – 09:20	Subsurface leaky pipe irrigation with vertical option as a suitable irrigation method for light soils. ***Golabi, M.*** *and Akoondali, A.M.*
09:20 – 09:40	The optimal size of farm ponds in Northeast Thailand with respect to farming style and multiple uses of water and under various biophysical and socio-economic conditions. ***Penning de Vries, F.W.T.****; Ruaysoongnern, S. and Wong Bhumiwatana, S.*
09:40 – 10:00	Role of bio-resources in improving the fertility of coastal sandy soils for sustainable groundnut production. ***Singaravel, R.****; Prasath,V. and Elayaraja, D.*
10:00 – 10:20	**Coffee / Tea**

10:20 – 10:40	Performance of rice in lowland soils amended with humified sludge and organic manures. ***Ofori, J.****; Masunaga, T. and Wakatsuki, T.*
10:40 – 11:00	Paddy use and status of water resources in a first order watershed in a sandy soil area of Northeast Thailand. ***Ogura C.****; Sukchan, S.; Suzuki K. and Caldwell J.S.*
11:00 – 11:20	Overview of sandy soils management in Vietnam. ***Ha, P.Q.****; B.H. Hien; H.T.T. Hoa; P.K. Tu; H.T. Ninh; B.T.P. Loan; V.D. Quynh and J.E. Dufey*
11:20 – 11:40	Carbon mineralization in coastal sandy tracts under semi dry rice production. ***Kaleeswari, R.K.****; R. Kalpana and P. Devasenapathy*
11:40 – 13:20	**Lunch**

Room: Royal Orchid 2

Session 6. The management of these agro-ecosystems (continued)

Chairman: Christian Valentin
Rapporteur:

13:20 – 14:00	A decision support framework for the sustainable management of sandy soils. ***Moody P.W.****; Vinh N.C.; Cong P.T. and Legrand J.*
14:00 – 14:20	Managing organic inputs for enhancing biological and physico-chemical soil health in the West African savannas. ***Vanlauwe, B.***
14:20 – 14:40	Re-evaluation of fertility status of sandy soil in Northeast Thailand with reference to soil-plant nutrient budgets. ***Yanai, J.****; Nakata, S.; Funakawa, S.; Nawata, E; Tulaphitak, T.; Katawatin, R. and Kosaki, T.*
14:40 – 15:00	Addition of clay based soil ameliorants to light textured soils to reduce nutrient loss and increase crop productivity. ***Berthelsen, S.****; Noble, A.D.; Ruaysoongnern, S.; Webb, M.; Huan, H. and Yi, J.*
15:00 – 15:20	Effect of organic and inorganic fertilizers on yield and quality of ruzi grass (*brachiaria ruziziensis*) grown on saline sandy soils of the Northeast, Thailand. ***Panchaban, S.****; Ta-Oun, M.and Sanunmuang, S.*
15:20 – 15:40	**Coffee / Tea**
15:40 – 16:00	Positive impact of traditional rice cropping on geochemical qualities of saline sandy soil in Northeast Thailand. ***Maeght, J.L.****; Hammecker, C.; Quantin, C.; Grunberger, O.; Nopmanee, S.; Bourdon, E. and Poss, R.*
16:00 – 16:20	Significance of soil management practices on degradation and/or conservation of upland sandy soils in semi-arid West Africa ***Tanaka, U.***
16:20 – 16:40	Management solution for improving soil organic matter for crop productivity and environmental quality in the tropical island of Guam ***Golabi, M.H.****; P. Denney and C. Iyekar*
16:40 – 18:00	**Poster session**

Wednesday, 30 November 2005

Mid-symposium field trip

09:00 – 09:45	Depart the Sofitel Racha Orchid Hotel to Ban Nong Saeng District Amphoe Muang
09:45 – 11:00	Stop 1: Sandy soil profiles under different land use that include virgin upland forest, cultivated sugarcane, lowland paddy and barren upland areas showing significant erosion. JIRCAS and LLD host the site.
11:00 – 11:20	Travel to Khon Kaen Industrial and Community Education College Amphoe Chonabot
11:20 – 14:00	Stop 2: Enjoy traditional Isaan style food and relax in the traditional sala. An exhibition of silk and cotton products will be on display and for sale.
14:00 – 14:30	Travel to Stop 3
14:30 – 16:00	Stop 3: The salinization and management of salt-affected soil of Northeast Thailand will be presented by LDD and IRD. The effect of long-term eucalyptus plantation on recharge areas will be demonstrated.
16:00 – 16:45	Depart for the Sofitel Racha Orchid Hotel

Symposium dinner

19:00 – 22:00

Thursday, 1 December 2005

Room: Royal Orchid 1

Session 7. ***Successes and failures: Stakeholders and development agencies perspectives in enhancing the livelihoods of communities on light textured sandy soils***

	Chairman: Daniel Tessier **Rapporteur:**
08:30 – 09:00	The “Dr Soils” Programme of the Land Development Department, Thailand. ***Chinabut, N.***
09:00 – 09:20	Crop and soil management under integrated farming systems in Northeast Thailand: an individual farmers experience. ***Polthanee, A.***
09:20 – 09:40	Sustainable intensification of crop-livestock systems on sandy soils of Latin America: trade-offs between production and conservation. ***Ayarza, M.****; Raucher, F.; Vilela, L.; Amezquita, E.; Barrios, E.; Rao, I. and Rondon, M.*
09:40 – 10:00	Technologies for sustainable management of sandy Sahelian soils. ***Bationo, A.****; Waswa, B.; Ouattara, B.; Kihara, J. and Vanlauwe, B.*
10:00 – 10:20	**Coffee / Tea**

10:20 – 10:40 Farmer perceptions, choice and adoption of soil management technologies in maize-based farming systems of Malawi.
Kabuli, A.M. *and Phiri, Mar*

10:40 – 11:00 Suitable approach for sustainable soil fertility management in Sahelian zone of Niger, West Africa.
Hayashi, K.*; Matsunaga, R. and Aboudlaye, T.*

11:00 – 11:20 Farmers' approaches on rehabilitation of degraded soils in the Northeast of Thailand.
Ruaysoongnern, S.

11:20 – 12:00 *Panel discussion*

12:00 – 13:30 **Lunch**

Session 8. Issues and priorities for the future sustainable utilization of light textured and sandy soils in the tropics

Chairman: Hari Eswaran
Rapporteur:

13:30 – 15.30 *Open forum discussion*

15:30 – 15:50 **Coffee / Tea**

15:50 – 17:30 *Closing Session*

Poster presentation

Session 1. Global extent of tropical sandy soils and their pedogenesis

Spatial heterogeneity in sandy soils of the Sahel region in West Africa: implications for desertification processes.
***Shinjo, H.**; Ikazaki, K.; Tanaka, U. and Kosaki, T.*

The potential productivity of sandy soil for sugarcane in some regions of Thailand associated with micromorphological observations.
***Sindhusen, P.**; H. Pichainarong and K. Marlairodsiri*

Session 2. Socio-economic imperatives

Protection ratio, an economic indicator for assessing locations for strategic dike reinforcement for erosion management in rainfed paddy-upland sandy soil mini-watersheds
***Caldwell, J.S.**; Sukchan, S; Ogura, C.; On-ok, W. and Prabpan, M.*

Session 3. Chemical properties and their effect on productivity

Assessment of salinity hazard by electromagnetism induction method in flooded sandy paddy soils
***Grunberger, O.**; Maeght, J.L; Montoroi, J.P; Enet, Y; Rattana-Anupap, S.; Wiengwongnam, J. and Hammecker, C.*

Cation exchange capacity of sandy salt-affected paddy soils by ammonium acetate, cobalt-hexamine and compulsive method
***Promkutkaew, A.**; Grunberger, O.; Bhuthorndharaj, S. and Noble, A.D.*

Mineralogical and chemical properties of low activity kaolin-rich, light-textured soils in Thailand
***Wiriyakitnateekul, W.**; Suddhiprakarn, A.; Kheuruenromne, I. and Gilkes, R.J.*

Phosphate desorption by sandy soil of Northeast Thailand
*Srikhun, W.; and **Keerati-Kasikorn, P.***

Clays concentrate nutrient reserves in a toposequence of sandy soils in Northeast Thailand
*Caignet, I.; Iserentant, A.; Wiriyakitnateekul, W.; Suksan, S.; Maeght, J.L.; Hartmann, C. and **Delvaux, B.***

The potential of Quartzipsamments for sugarcane growing in Southeast Coast, Thailand
***Tawornpruek, S.**; Suddhiprakarn, A. and Kheoruenromne, I.*

Influence of fertilizer inputs on soil solution chemistry in eucalypt plantations established on Brazilian sandy soils
***Maquere, V.**; Laclau, J.-P.; Gonçalves, J.L.M.; Piccolo, M.C.; Krushe, A.V.; Rosias, M.F.G. and Ranger, J.*

Greenhouse gases production and emission from saline sandy paddy fields in Khon Kaen, Thailand
*Murakami, M.; Amkha S.; **Inubushi, K.**; Yagi, K.; Tulaphitak, D.; Tulaphitak, T. and Saenjan, P.*

Session 4. Physical properties of tropical sandy soils

Water infiltration in saline sandy soils
***Hammecker, C.**; R. Razzouk; J-L Maeght and O. Grunberger*

Wind processes improve water infiltration in Sahelian sandy rangeland
***Ribolzi, O.**; Hermida, M.; Delhoume, J.P.; Karambiri, H. and Thiombiano, L.*

Hardpan formation of som coarse-textured upland soils in Thailand
Anusontpornperm, S.*; Nortcliff, S. and Kheoruenromne I.*

The effect of salinity on sandy soils physical characteristics and rice root system development: a case study from Northeast Thailand
Hartmann, C.*; Hao, H.; Maeght, J.L.; Noble, A.D.; Yuvaniyama, A. and Polthanee, A.*

Session 5. The role of organic matter and biological activity

Mineralizaton of organic amendments in a sandy soil of Central Vietnam
De Backer C.; Pham Quang Ha; Chiang N.C. and ***Dufey J.E.***

Patterns of soil organic carbon and nitrogen in grazed and un-grazed exclosures of semi-arid rangelands in South Africa
Moussa A.S.*; Van Rensburg L.; Kellner K. and Bationo A.*

Selection of bacteria from soil samples for liquid biofertilizer production
Piamtongkam, R.; Yongvanich, T. and ***Chulalaksananukul, W.***

Management of subsoil hard pans in tropical sodic sandy soil
Kaleeswari, R.K.*; R. Kalpana and P. Devasenapathy*

Nitrogen dynamics under different farmer practices in sandy salt-affected paddy fields in Northeast of Thailand
Suvannang, N.*; Quantin, C.; Grunberger, O.; Maegh, J.L. and Chutchitt, S.*

Session 6. The management of these agro-ecosystems

Sandy soil improvement using organic matter and mineral fertilizers on the yield and quality of Papaya
Mongkon Ta-Oun*; Santibhab Panchaban; Suttipong Pruangka and Patcharee Therajindakajorn*

Effect of various amendments on yield and quality of papaya grown on sandy soils
Mongkon Ta-Oun*; Santibhab Panchaban; Suttipong Pruangka and Patcharee Therajindakajorn*

Vietnam-Belgium project for improving food crop productivity on the sandy soils of the coastal zone in Central Vietnam
Pham Khanh Tu; Pham Quang Ha; Tran Van Minh; Bui Huy Hien; Lebailly, Ph.; Haubruge, E.; Maraite, H.; Bragard, C.; Delvaux, B.; Chiang, N.Cl. and ***Dufey, J.E.***

Salinity control by farmers practices in sandy soil
Maeght, J.L.*; Grunberger, O. Hammecker, C.; Sukchan Somsak; Hartmann, C. and Wiriyakinateekul W.*

Land degradation assessment in drylands: are there management solutions?
Niino, Y.

Phosphorus index for tropical sandy rice field and pineapple fields
Sukreeyapongse, O.*; Charanworapan, C.; Pongkanjana, A. and Kanjanathanaset, K.*

The potential of Quartzipsamments for sugarcane growing in Southeast Coast, Thailand
Tawornpruek, S.*; Suddhiprakarn, A. and Kheoruenromne, I.*

Properties of coarse-textured Alfisols under cassava in Thailand
Thanachit, S.*; Suddhiprakarn, A.; Kheoruenromne, I. and Gilkes, R.J.*

Effect of land use management on groundwater and soil salinization in Northeast Thailand
Yuvaniyama, A.*; Lertsirivorakul, R. and Sriboonruang, V.*

Characteristic and management of tin mine tailings in Thailand
Srithongchim, S. *and Tepsuporngul, A.*

The improved presences of halophilic bacteria in sandy saline soils with the application of chemical fertilizer, bioextract and molasses
Choruk, K.

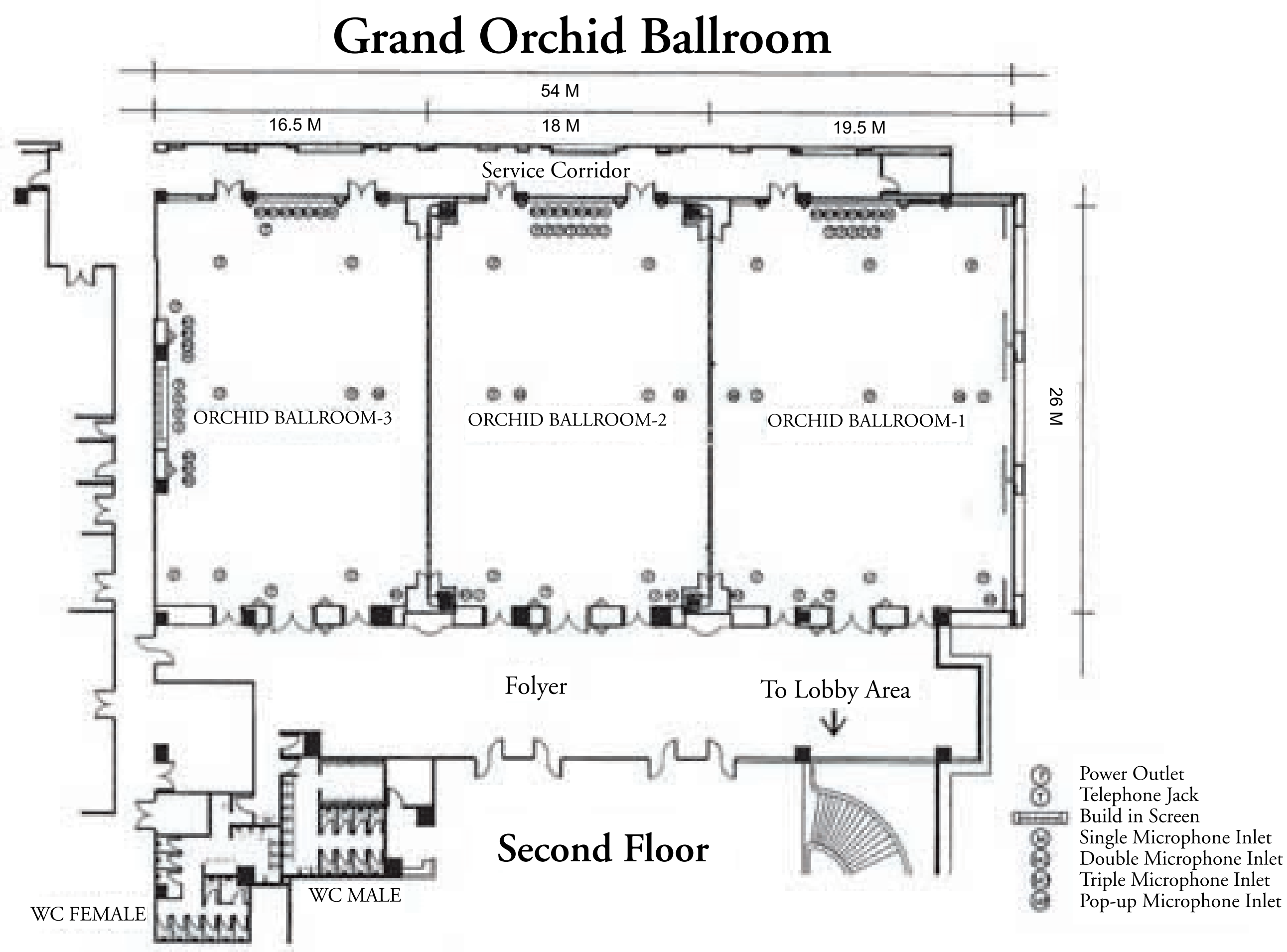
Saline soil improvement with biofertilizer for the growing kale (*brassica albonglabra*).
Kurukodt, K.

Organic agricultural systems for cassava crops in soil group 40
Junrungreung, S.*; S. Chinon; T. Rattanakaew and S. Saelim*

Session 7. Successes and failures: Stakeholders and development agencies perspectives in enhancing the livelihoods of communities on light textured sandy soil

Reclamation of deteriorated land in Khao Hin Sorn Royal Development Study Center
Swuttanakoon, S.*; Tiwatri, K. and Patanakanok, B.*

Conference Rooms



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