The role of termites and mulch in the rehabilitation of crusted Sahelian soils

Promotoren: Dr. Ir. L. Stroosnijder
hoogleraar in de Erosie en de Bodem- en Waterconservering

Dr. L. Brussaard
hoogleraar in de Bodembiologie

Abdoulaye Mando

The role of termites and mulch in the rehabilitation of crusted Sahelian soils

Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
Dr. C.M. Karssen
in het openbaar te verdedigen
op woensdag 23 april 1997
des namiddags vier uur in de aula
van de Landbouwuniversiteit te Wageningen.

Thesis Wageningen Agricultural University

ISBN 90-5485-700-5

This study was financially supported by the Wageningen Agricultural University

Cover design: Ernst van Cleef

Propositions

1 Crusted soils cannot be rehabilitated effectively unless infiltration is increased.
This thesis

2 Under the semi-arid conditions of the Sahel, soil fauna is a key element without which the improvement of agricultural production through the management of organic material cannot be achieved.
This thesis.

3 The manipulation of termite-mediated processes should be taken into account in the management of soil to enhance soil quality in agroecosystems of the semi-arid Sahelian zone.
This thesis

4 The physical effect of mulch without termites is of less importance than the effect of termites induced by mulching for the rehabilitation of crusted Sahelian soil.
This thesis

5 Termite-induced change of soil structure favours serveral soil properties such as hydraulic conductivity and infiltration, but not the soil's capacity to store water.
This thesis

6 In the semi-arid regions, the state of the soil surface is the most important factor governing the field soil water balance.
Casenave, A. and Valentin, C., 1989. Les états de surface de la zone Saheliélienne. Influence sur l'infiltration. Edition de l'ORSTOM. Paris.
This thesis

7 Termites are key ecosystem engineers in semi-arid ecosystems.
This thesis
Black, H.I.J. and Okwakol, M.J.N., 1997. Agricultural intensification, soil biodiversity and agroecosystem function in the tropics: the role of termites. Applied Soil Ecology (in press).

8 If there was ever a time in history that we should consider all possible alternatives to solve agricultural problems in the Sahel, then that time is now.

9 It is a mistake to think that a participatory approach in rural development is sufficient for economic development in the Sahel.

10 Whoever could make two ears of corn .... to grow upon a spot of ground where only one grew before, would deserve better of mankind,...than the whole race of politicians put together.
Jonathan Swift, a voyage to Brobdingnag.

11 Aid should contribute to kill aid.

12 The Antenne should not be closed in 1998.

Abdoulaye Mando
'The role of termites and mulch in the rehabilitation of crusted Sahelian soils'.
Wageningen, 23 April, 1997

Abstract

Land degradation is a major agricultural problem in the Sahel. During recent decades Sahelian soils have gone through serious and various forms of degradation, the most spectacular one being the extension of completely bare and crusted soils. This thesis focuses on the contribution of termite activity triggered by the use of various types of mulch to the rehabilitation of crusted soils in the Sahelo-Soudanian zone of northern Burkina Faso.

Mulch, when placed on a crusted and bare soil, can trigger termite activity within a few months. Termite activity results in a change in soil structure. Many burrows are opened through the sealed surface of the soil due to the burrowing activity of the termites. Throughout the soil profile, macropores with irregular shapes and with different diameter sizes are created. The aggregation of the soil by termites through their building systems is also observed. As a result of changes in soil structure, other soil physical properties are also improved. Soil resistance to cone penetration is reduced from a critical to a suitable level for vegetation growth. Bulk density is decreased and soil hydraulic conductivity is greatly increased. Water infiltration and drainage are also greatly improved. The combination of the increase of porosity and infiltration and the cover effect of mulch results in an increase of soil water availability in the soil profile during the growing season.

Termite activity enhances decomposition of the mulch and hence nutrient release in the soil. The quantity of this nutrient release depends on chemical quality of the mulch.

The change of soil characteristics due to termite activity was enough to create conditions necessary for natural vegetation development and crop production on previously degraded bare soils.

Acknowledgements

This thesis results from a cooperation between the University of Ouagadougou and the Wageningen Agricultural University. I gratefully acknowledge the organisational and material support received from the research project "Natural resource management in the Sahel", jointly undertaken by both universities. I would like to express my gratitude to the project team (Wim van Driel, Maja Slingerland, Jan Willem Nibbering, Joop Begemann and Teunis van Rheenen) whose cooperation and scientific interest made this study possible. Marie-Louise is particularly thanked for being available at any time I needed her help.

I would like to thank WAU for granting me the sandwich fellowship that allowed me to stay in Wageningen during 12 months for the preparation of my research and the write-up of the thesis. I am particularly indebted to my professors Leo Stroosnijder and Lijbert Brussaard who showed great interest in the research and have taken a lot of time to supervise it. Without their guidance during the field work and the write-up, this thesis would never have materialized. Many thanks also to their families who did their best to make my stay in Holland enjoyable. I would like to thank all staff members of the department of Irrigation and Soil and Water Conservation of Wageningen Agricultural University, particularly Fred de Klerk, Max Rietkerk, Dirk Meindertsma, Jan de Graaff, Emiel van Loon, Wim Spaan, Leo Eppink and Jacquelijn Ringersma and the secretaries for their assistance. The families of Jan de Graaff and Jan Joost Kessler are sincerely thanked for their efforts to make my stay in Holland enjoyable. I am very obliged to dr. Rienk Miedema who committed himself to introduce me to soil micromorphology and to supervise the part of my work dealing with this specialism. Also, I would like to thank Dick Schoonderbeek from the Winand Staring Centre for giving me a hand during the quantitative study of the micromorphological samples.

I am obliged to Dr. Tom Wood and Dr. Helaina Black for their warm welcome at the Natural Resources Institute, Kent, UK., and for all their assistance I have got during my stay. Sincere thanks also to Dr. Helaina Black for identifying the termite species. Joost Brouwer and Christiaan Kooyman are acknowledged for fruitful comments they made on the original proposal of the research and during my visit to Niamey. Dr. Prosper Zombré from the University of Ouagadougou (IDR) is warmly thanked for his help in the soil mapping.

During my enjoyable time in Bourzanga, accomplishing the often tiring but lovely field work, many people have been of great help to me. I would like to thank Nana Damien, Pakodé Issa, Imola Ferro, Sidibe Moussa, Nikiema Laurant and Baba Keita. I am grateful to Roger Kaboré, my roommate at the Antenne for everything. I owe a lot to the local farmers of Bourzanga who gave me a piece of land for the research. They have also given me a hand on several occasions. I am obliged to the local administrative authority of Bourzanga who have provided free housing for myself and the students who have participated in the field work. The local representatives of the Ministry of the Environment and the AFVP (French volunteers for development) are acknowledged for the multiple and various services they have offered me.

Finally I wish to thank my wife Rachel for her patience when coping with a husband who is not only often out, but also always busy with termites and land degradation even when he is in.

Table of contents

Chapter 1

Introduction

Soil degradation

Environmental degradation is proceeding at an unprecedented rate in many tropical regions, especially in the semi-arid Sahelian zone, jeopardizing the potential of the agricultural system to meet the food, fuel and clothing needs of the ever increasing population. In this zone, the combined effect of soil organic matter depletion, primary production decrease due to mismanagement of the fragile ecosystem and the harsh climatic conditions has resulted in the extension of crusted soils (Stein et al., 1988; Stroosnijder, 1992). These soils are characterised by very low infiltration capacity, nutrients imbalance, reduced biodiversity and therefore zero to very low primary production. The most common response to this phenomenon has been land abandonment. Some of the consequences are: (1) the decrease of the per capita availability of arable land which has reached a critical threshold in many southern Saharan countries (World Bank, 1989); the decrease of the per capita food production and subsequently the decline of human welfare and (2) the occurrence of a social crisis due to the ever increasing shortage of land.

In such circumstances, the Sahelian countries have no choice but to undertake land rehabilitation. For economic and environmental reasons, modern techniques such as the use of fertilizers and heavy machines are not suitable for land rehabilitation in the Sahel. Therefore, attention focuses on alternative solutions. The aim of the work reported in this thesis was to evaluate to which extent termite activity, when it is triggered on crusted soil can improve soil properties and functions (i.e primary production and environmental buffering).

Termites as part of the soil system

Termites, animals of the order Isoptera are polymorphic social insects which live in nests (termitaria) of their own construction (Lee and Wood, 1971). On the basis of their food sources functional groups can be defined. Three main groups are known; (1) Plant material feeders: live, fresh dead and dead material in various stages of decomposition and soil rich in organic matter (Wood, 1996), (2) humivorous termites feeding on humus and (3) fungal feeders. Cases of cannibalism are also found (Lee and Wood, 1971). Readers are referred to Lee and Wood (1971), Wood (1996) and Black and Okwakol (1997) for more details on food sources of termites.

On the basis of nesting behaviour two main groups are found: soil nesting termite species including mound building species and subterranean species (having subterranean nests), and non-soil nesting species (such as arboreal nesting species in Amazonia, Martius, 1994).

Termites are the most important soil fauna in the arid tropics (Lee and Wood, 1971; Lobry de Bruyn and Conacher, 1990 and Bachelier, 1978), intensely interacting with the soil. Both the biotic and abiotic state of the soil affect the termite population and activity. Soil water content is a key element affecting termite activity as termites are very susceptible to desiccation because of their soft cuticle with poor water retaining properties (Moore, 1969). Termites need a lot of water to produce the saliva for mixing their building materials.

The quality and availability of food and thus the vegetation type in the environment determine the composition and the size of a termite community. Soil textural composition and other soil physical conditions are important factors for termite activity. Bachelier (1978) stated that termites disappear from an environment with less than 10 % clay content. According to Boyer (1975) all soil nesting termites prefer soils with a (clay+silt)/sand ratio superior to 10. Within this group, humivorous species prefer soils with the lowest clay content. Cracking clay soils are not suitable to termites as the seasonal cracking prevents termites from building stable structures (nests and galleries). The exact influence of soil type on the geographical distribution of termites species is not well known and future research should pay closer attention to this aspect.

A relatively high and constant temperature during the major part of the year is essential for termite survival. Pomory (1977) has found a minimum temperature for termites in Africa of 9°C . In Texas, USA, Bodine and Ueckert (1975) have found the same minimum temperature for termites.

The construction of nests, gallery systems or sheetings from soil or from a mixture of soil and other material within the soil horizons or on the soil surface affect the physical and chemical status of both the material used for the construction and the surrounding soil from which the materials were taken. In fact, structure, structure stability, porosity and chemical status of the soil are to a large extent altered by termite activity (Greaves, 1962; Lee and Wood, 1971; Maldagué, 1964; Lobry de Bruyn and Conacher, 1990; Elkins et al., 1986; Mando, 1991; Lee and Foster, 1991 and Humphreys, 1994).

Termites and soil physical properties

The influence of termites on soil physical properties is dynamic, involving bioturbation and biochemical action, (Black and Okwakol, 1997). A lot of work has been carried out on the effect of mound building termites on soil aggregates and other soil physical properties (Miedema and van Vuure, 1977; Boyer, 1975; Eschenbrenner, 1986; Lee and Wood, 1971; Lobry de Bruyn and Conacher, 1990). Their behaviour in selecting, transporting, and manipulating soil particles and cementing them together with saliva brings some immediate changes in soil structure and properties (Wood, 1996). Although mound building termites have the most obvious effect on the soil, the activity of subterranean nesting termites can be equally or even more important to natural ecosystems and agrosystems (Bodine and Ueckert, 1975; Ferrar, 1982; Nutting et al., 1993). In this thesis, the main focus will be on the effect of subterranean termites on soil physical properties as little attention has been paid to their possible positive role in soil management. It is known that the vast three-dimensional network of subterranean galleries and epigeal runways associated with foraging and nest construction affect pore space (Maldagué, 1964; Arshad, 1982; Kooyman and Onck, 1987; Mando, 1991) and the infiltration of water into the soil (Elkins et al., 1986). Whitford, (1991) investigated the effect of subterranean termites in Chihuahuan desert rangelands in New Mexico. On plots where termites had been eliminated, soil bulk density was 1.99 g cm^{-3}, soil porosity was 25%, infiltration rate was 51 mm h^{-1} and runoff volume after 45 mm of heavy rainfall (124 mm h^{-1}) was 38 mm. On the termite plots, the soil bulk density was 1.70 g cm^{-3} , soil porosity was 36%, infiltration rate was 88 mm h^{-1} and runoff volume after 45 mm of heavy rainfall was 18 mm. No example of such experiments in the Sahel is known although termites are the major soil fauna component of the region.

The implications for smallholder farmers of the termites' mediating role in regulating soil quality is quoted in the literature (Logan, 1992; Lal, 1987, Veeresh and Belavadi, 1986) but an experimental approach to ascertain the relevance of the effect of termites on soil porosity and water infiltration and its significance for soil management is not explored so far. These aspects therefore form an important part of this thesis.

Termites and vegetation development

Ratcliffe et al. (1952) noted that in a semi-arid area termite galleries extend to considerable depths below the surface, sometimes penetrating an underlying mass of limestone. They found that plant roots frequently followed the courses of old soil-packed galleries. Robinson (1958) studied the development of roots of coffee plants in infilled termite galleries in Kenya. He concluded that where axial roots penetrate termite tunnels there was a high degree of fine root proliferation. Arshad (1982) measured higher plant species diversity and biomass production associated with termite foraging territories as compared to the surroundings. In the Chihuahan (New Mexico) desert, the mediating role of termites in nutrient cycling and water availability is reflected in primary production and plant community structure (Moorhead and Reynolds, 1991, Whitford, 1991). Elkins et al. (1986) found a decline of vegetation diversity and biomass production from plots where termites were eliminated. The problem with many of these findings is that causes and effects are often not well separated. The use of termite activity as a soil management strategy for vegetation establishment is rarely quoted in literature. Therefore this thesis will deal with this aspect emphasising the use of termites as biological tools for land rehabilitation.

Study area

The study area is situated in northern Burkina Faso (West Africa), about 4° west and 13° north. All the work in this thesis was conducted in Bourzanga which is a village located in the province of Bam (Figure 1.1).

Climate and vegetation

The area has a Sahelo Soudanean climate according to the classification of Unesco (1977). Rainfall amount in the area is irregular, ranging from 400 mm to 700 mm per year. Rainfall occurs in four months (June to September). The rainfall is unimodal and is governed by two specific winds. The harmattan brings dry and dusty air from the Sahara regions (north) and is accountable for the dry period. The second specific wind is the monsoon which brings

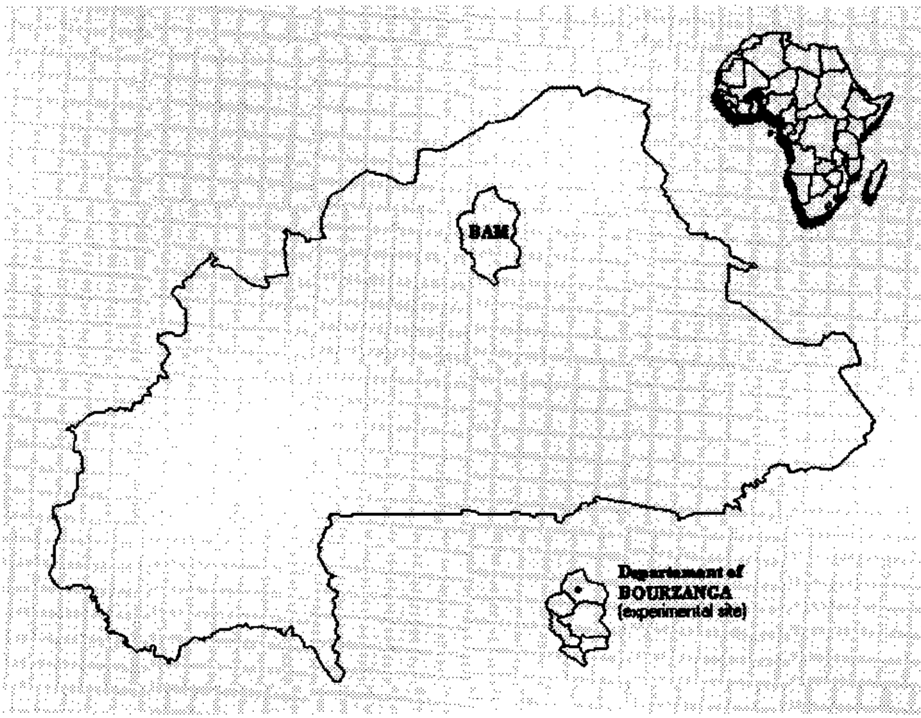

Figure 1.1: *Location of the experimental site*

humid air from the atlantic ocean (south-west) and is accountable for the rainy season. The line along which the above two winds meet is called the Inter Tropical Front (ITF). The area south of the ITF is wet and the one north of it is dry. The ITF reaches the experimental site going north by the end of May and passes it again going south by October.

Mean daily temperature varies from 20 to 30°C with great diurnal changes (Bunasol, 1995).

The vegetation is of the Sahelo Soudanian type. Perennial grasses are rare in the area, only *Andropogon gayanus* is found in the valleys and on the borders of the arable plots. The annual herb species are dominated by *Schoenefeldia gracilis*, *Aristida adscencionis* and *Zornia glochidiata*. Shrubs of Combrataceae and Minosaceae (mainly *Acacia* spp) families dominate the woody component of the vegetation. The most common species are: *Combretum micranthum, Combretum glutinosum, Sclerocarya birrea, Acacia nilotica* and *Acacia seyal*. Due to human pressure (fire, overgrazing and continuous cultivation) bare spots are spreading in the area.

Geology, geomorphology and soils

The underlying rocks in the area belong to a precambrian basement complex consisting of crystalline rocks (porphyroid granite and biotite granite) and associated metamorphic rocks, mainly of schistic character (Hottin and Ouédraogo, 1975).

The area lies 350 m above sea level and the landscape can be characterized by a catena with the following positions: crest, upper slope, middle slope, lower slope and valley bottom. Regosols dominate the crests and the upper slopes while at the middle and lower slopes Lixisols and Cambisols are found (Bunasol, 1995). The soils are chemically poor and have clay with low activity (Bunasol,1995).

Termites in the area

Termites are the most important soil fauna component of the area. Ouédraogo (1990) has found species of the following genera: *Macrotermes, Odontotermes* and *Cubitermes*. In the experimental site, three species were identified: *Odontotermes smeathmani* (Fuller) *Microtermes lepidus* (Sjöst) and *Macrotermes bellicosus* (Sjöst) (H.I.J., Black, pers.comm.).

Outline of the thesis

The main aim of this study was to monitor the dynamics of crusted-soil physical properties, its water balance and its vegetation after triggering termite activity through the application of mulch. Figure 1.2 presents the split-plot design of the experimental field. Details are given in Chapters 4, 5 and 6. It consisted of three blocks, two main treatments [Termite (T) plots and Non Termite plots (NT)], four subtreatments (Straw mulch, Wood mulch, Composite mulch and Bare at rates of 3, 6, 4 and 0 Mg ha $^{-1}$ respectively). The main plots were 50 m * 50 m and located 50 m apart.

Two additional studies were also carried out: (1) Assessing the effect of termites on infiltration in order to understand how termites affect infiltration of consecutive rainfall events into termite-modified soil; (2) Establishing the effect of termites and the chemical composition of the applied mulch on nutrient uptake and crop performance.

The results of quantitative and qualitative micromorphological investigations of termite burrows and termite-made aggregates are presented in Chapter 2. Chapter 3 contains an analysis of termite-mediated change of infiltration into crusted soil. The effect of consecutive showers on infiltration parameters is discussed. Chapter 4 deals with the effect of termites and mulch on soil physical properties and Chapter 5 deals with the effect of mulch and termites on the water balance of initially crusted soil. Chapters 6 and 7 present the response of the natural vegetation and the response of cow pea to the triggering of termite activity through mulch. Finally, findings from chapters 2 to 7 are synthesized in Chapter 8 and the consequences for future research and soil management are discussed.

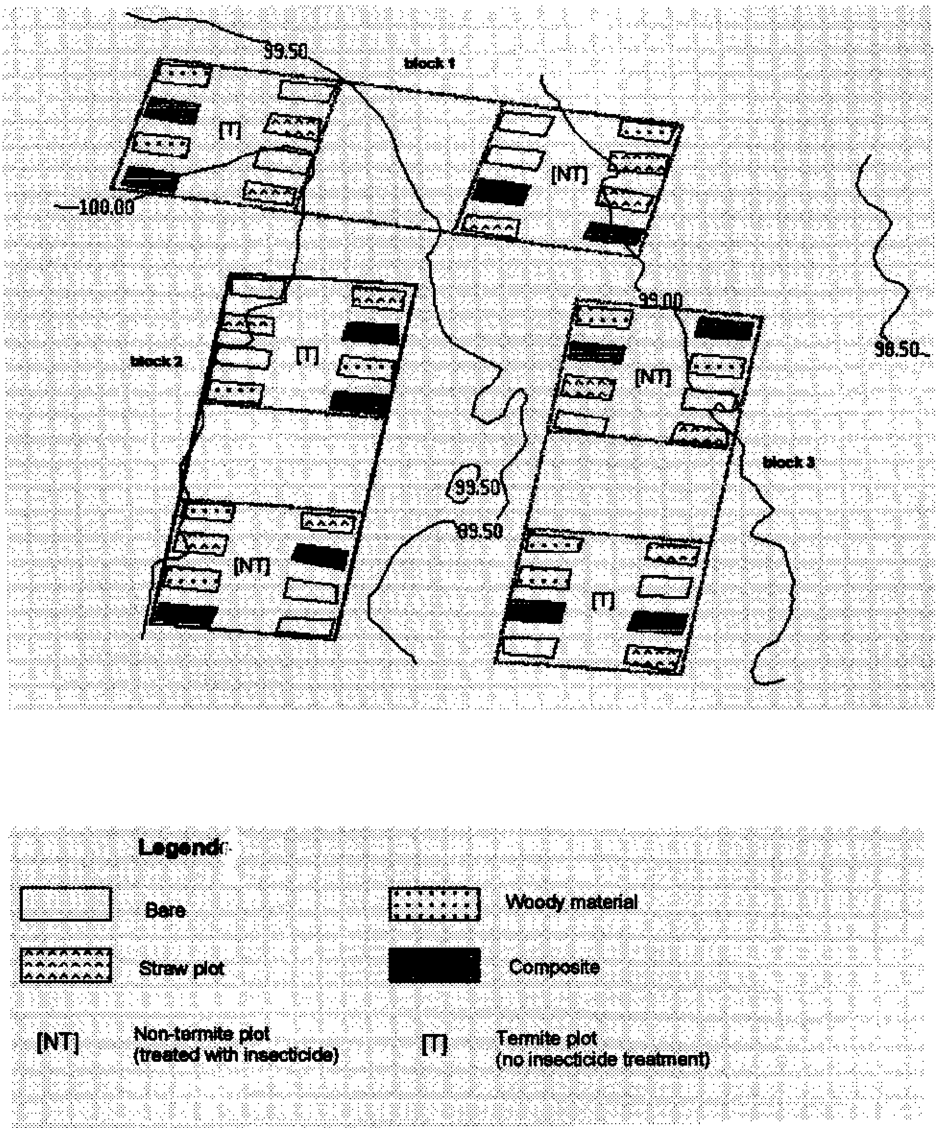

Figure 1.2: *Experimental design*

References

Arshad, A.M., 1982. Influence of the termites *Macrotermes michaelseni* (Sjöst) on soil fertility in semi arid savannah ecosystems. Agro-Ecosystems, 8:47-58.

Bachelier, G., 1978. La faune du sol, son action. Editions de l' ORSTOM, Paris, 391 pp.

Black, H.I.J. and Okwakol, M.J.N., 1997. Agricultural intensification, soil biodiversity and agroecosystem function in the tropics: the role of termites. Applied Soil Ecology (in press).

Bodine, M.C. and Ueckert D.N., 1975. Effect of desert termites on herbage and litter in a short green ecosystem in West Texas. Journal of Range Management, 28:250-264.

Boyer, P., 1975. Les différents aspects de l'action des *Bellicositermes* sur les sols tropicaux. Annales des Sciences Naturelles, 17:447-504.

Bunasol, 1995. Etude morpho-pédologique de la province du Bam (échelle 1/500.000). Rapport Technique n°97, Vol 1, 155 pp+annexes.

Elkins, N.Z., Sobol, G.V., Ward, T.J. and Whitford, W.G., 1986. The influence of subterranean termites on the hydrological characteristics of a Chihuahuan desert ecosystem. Oecologia, 68:521-528.

Eschenbrenner, V., 1986. Contribution des termites à la micro-aggrégation des sols tropicaux. Cahier OROSTOM, série pédologie, XXII: 397-408.

Ferrar, F., 1982. Termites of a South African savannah IV. Subterranean populations, mass determinations and biomass estimations. Oecologia, 52:147-151.

Greaves, T., 1962. Studies of the foraging galleries and the invasion of living trees by *Coptotermes acinaciformis* and *C. brunneus* (Isoptera). Australian Journal of Zoology, 10:630-651.

Hottin, G. and Ouédraogo, O.F., 1975. Carte géologique de la Haute Volta. Echelle 1/1 000 000. BUMIGEB, Ouagadougou, 86pp.

Humphreys, G.S., 1994. Bioturbation, biofabrics and biomantle: an example from the Sydney Basin. In: A.J. Ringrose-Voase and G.S Humphreys (Editors), Soil Micromorphology: Studies in Management and Genesis. Developments in Soil Science, 22:421-436.

Kooyman, C. and Onck, R.F.M., 1987. The interactions between termite activity, agricultural practices and soil characteristics in Kisii district, Kenya. Wageningen Agricultural University Papers, 87:1-120.

Lal, R., 1987. Tropical Ecology and Physical Edaphology. Wiley & Sons. New York, 230 pp.

Lee, K.E. and Foster, R.C., 1991. Soil fauna and soil structure. Australian Journal of Soil Research, 6:745-775.

Lee, K.E. and Wood, T.G., 1971. Termites and Soils. Academic Press, London and New York. 251 pp.

Lobry de Bruyn, L.A. and Conacher, A.J., 1990. The role of termites and ants in soil modification: a review. Australian Journal of Soil Research, 28:55-93.

Logan, J.W.M., 1992. Termites (Isoptera)- a pest or resource for small farmers in Africa. Tropical Science, 32: 71-79.

Maldagué, M.E., 1964. Importance des populations de termites dans les sols équatoriaux. Trans. 8th Int. Congress Soil Science, Bucharest, 3:743-751.

Mando, A., 1991. Impact de l'activité des termites sur la dégradation de la biomasse végétale et quelques propriétés physiques des sols dégradés: Etude menée a Zanamogo (Burkina Faso). Mémoire de fin d'études, Université de Ouagadougou, ISN/IDR, Ouagadougou, 76 pp.

Martius, C., 1994. Diversity and ecology of termites in Amazonian forests. Pedobiologia, 38:407-428.

Miedema, R. and van Vuure, W., 1977. The morphological, physical and chemical properties of two mounds of *Macrotermes bellicosus* (Smeathman) compared with surrounding soils in Sierra Leone. Journal of Soil Science, 28:112-124.

Moore, B.P., 1969. Biochemical Studies. In: K. Kirshma and F.M., Weesner (Editors). Biology of Termites, Volume, 1. Academic Press, New York, London, pp. 407-432.

Moorhead, D.L. and Reynolds, J.F., 1991. A general model of litter decomposition in the northern desert. Ecological Modelling 56:197-219.

Nutting, W.L., Haverty, M.I. and La Fage, P., 1987. Physical and chemical alteration of soil by two subterranean termite species in Sonoran desert grassland. Journal of Arid Environments, 12:233-239.

Ouédraogo, P., 1990. Contribution à l'inventaire des termites au Burkina Faso et étude de méthodes de contrôle des termites. Mémoire de fin d'études, Université de Ouagadougou, ISN/IDR. Ouagadougou. 80 pp.

Pomory, D.E., 1977. The distribution and abundance of large termite mounds in Uganda. Journal of Applied Ecology, 14: 465-476.

Ratcliffe, F.N., Gay, F.J. and Greaves, T., 1952. Australian termites, CSIRO. Melbourne. 215 pp.

Robinson, J.B.D., 1958. Some chemical characteristics of termite soil in Kenya coffee fields. Journal of Soil Science, 9: 58-65.

Stein, J.L., Day, J.C., Papendick, R.I., Meyer, R.E. and Bertrand, A.R., 1988. Improving and sustaining productivity in dryland regions of Developing Countries. In B.A. Stewart (editor), Advances in Soil Science, 8:79-122.

Stroosnijder, L., 1992. Desertification in Sahelian Africa. The Courier, 133:36-39. EEC, Brussels, Belgium.

Unesco, 1977. Carte de la répartition mondiale des régions arides. Notes techniques du MAB, n^0 7, Unesco, Paris. 93 pp.

Veeresh, G.K., and Belavadi, V.V., 1986. Influence of termite foraging on the fertility status of the soil. Journal of Soil Biology and Ecology, 6:53-66.

Whitford, W.G., 1991. Subterranean termites and long-term productivity of desert rangelands. Sociobiology, 19:235-243.

Wood, T.G., 1996. The agricultural importance of termites in the tropics. Agricultural Zoology Reviews, 7:117-150.

World Bank, 1989. Sub-Saharan Africa: from crisis to sustainable growth: a long-term perspective study. Washington D.C., USA. 300 pp.

Chapter 2

Termite-induced change in soil structure after mulching degraded (crusted) soil in the Sahel

Mando, A. and R. Miedema, 1997. Termite-induced change in soil structure after mulching degraded (crusted) soil in the Sahel. Applied Soil Ecology (in press).

Abstract

A morphological approach was used to study the influence of termite activity on crusted soil. The structure of the top layer (0 - 10 cm) of these soils is degraded (no functional voids and no aggregates). Composite mulch (woody material + straw) was applied at the rate of 4 Mg ha^{-1} to trigger the activity of termites. Termite-induced features in soil structure were described and quantified by means of field observations, observation with polarizing microscope and computerized image analysis using Quantimet 970.

The termite activity after the application of the mulch resulted in a change from a compact grain structure (original structure) to a chamber and channel structure. The channels and chambers accounted for over 60% of the macroporosity in the 0-10 cm layer. Unmulched plots (i.e bare plots) mostly had packing voids, very few macropores, no voids with equivalent circle diameter (ECD) greater than 2 mm and one-third the number of voids with ECD > 100 μm compared with the plots with termite activity in the 0-10 cm layer. In the mulched plots the sealed surface was perforated by termites, resulting in many visible open voids. These plots were covered by sheetings that consisted of fine soil material transported to the soil surface and linked up by termites.

In the deeper layers, termite-induced change of soil structure after mulching was difficult to confirm since both on mulched and bare plots there are many termite-mediated features from previous termite activity. These features are numerous voids, open or infilled, generally with crumbs. The latter are the only type of aggregate found in these soils, suggesting that termites play an important role in soil aggregation in such environments.

This study provides information about the influence of termites in the improvement of a sealed/crusted topsoil structure. It shows that soil surface management such as mulching which enhances termite activity is an option to consider when improving degraded soil structure.

Key words: termites, mulch, soil structure, macropores, aggregates, rehabilitation.

Introduction

In the Sahel, the combined effects of climatic conditions, continuous cultivation, overgrazing and trampling by cattle have resulted in the spread of bare soils with a degraded structure and a sealed surface which impedes water infiltration and root growth. Such soils constitute a great threat to the Sahelian agricultural system and should therefore be rehabilitated if the agricultural system is to be sustained. However, their rehabilitation cannot be achieved unless conditions are created for the restoration of voids open to the surface, to facilitate the movement of water and air and the growth of plant roots into the soil profile (Anderson, 1988, Edwards et al., 1990). In the Sahel tillage is often used to create voids to allow water to infiltrate into sealed soils, but this practice has been proved to create unstable voids (Kooistra et al., 1988) and thus has no lasting effect on infiltration (Stroosnijder and Hoogmoed, 1984).

The stimulation of soil fauna, especially termites, in the semi-arid and arid zones is an option to improve soil structure (Mando et al., 1996). Termites can affect the soil by their burrowing and excavation in search of food, or the construction of living spaces or storage chambers in the soil or above the ground. The active transport of soil particles and their deposition on the soil surface or in voids can significantly affect soil structure (Lee and Foster, 1991). Many authors have pointed out the effects of termite activity on soil fertility. Elkins et al. (1986) have reported a decrease of soil infiltration capacity after termites had been eradicated from the Chihuahuan desert ecosystem. Mando (1997) has shown that the stimulation of termite activity on crusted soil improves its physical properties and its water balance and has related that situation to termite burrowing activity. However, few data exist on the nature of the subterranean termite-induced soil structure and pedofeatures, as most available data are on the pedofeatures of mound-building species (Miedema and Van Vuure, 1977, Wielemaker,1984, Miedema et al., 1994; Eschenbrenner, 1986). Furthermore, very little has been done to make use of termite-mediated processes in land management.

This paper describes a micromorphological study of the effect of subterranean termite burrowing and building activity in the improvement of degraded soil structure. The aim was to describe termite-induced soil microstructure and pedofeatures in order to establish and evaluate the extent of termite-induced change of the structure of crusted soil after mulching.

Methods

Site Description

The investigation was conducted in northern Burkina Faso, West Africa (about 4° West, 13° North). The climate is Sahelian Sudanian according to Unesco (1977). Rainfall is unimodal and occurs for 4 months (from June to September). Temporal and spatial irregularity is one of the major characteristics of rainfall distribution in this area. Annual rainfall is ranging from 400 mm to 700 mm.

The vegetation is of the steppe type according to Unesco's (1973) classification, with large bare areas. The life form for the grasses is dominated by annual therophytes; perennial grasses are rare (Mando, 1991). The woody component is dominated by shrubs. The most important families are Mimosaceae and Combretaceae. The common termite genera are *Microtermes, Macrotermes* and *Odontotermes*. The most common soil types in the area are Lixisols and Cambisols (Bunasol, 1995).

The experiment from which data are reported was laid out on a Ferric Lixisol according to FAO-Unesco (1994). It has a pH (H_2O) of about 4.1 at 5 cm depth and of 6.1 at 110 cm depth. CEC ($CaCl_2$ extraction) is 6 meq per 100 g at 5 cm depth and 12.4 meq per 100 g at 120 cm depth. The textural class is sandy loam (20% clay, 43% silt and 37% sand). The average bulk density is 1.5 g cm^{-3} at 5 cm depth and is 1.7 g cm^{-3} below 70 cm depth. Soil organic matter content is 0.51% at 5 cm depth but decreases to 0.17% at 120 cm depth.

A mulch of straw + woody material applied at the rate of 4 Mg ha^{-1} was used to trigger termite activity on the bare sealed soil. The proportion of the mulch was 1/3 straw and 2/3 wood and both wood and straw were collected from a surrounding silvopastoral area. Six mulched plots and six bare plots were used for the experiment, each plots measuring 15 m * 8 m in size. The mulch was applied in June 1993. In October 1995 the termite population was assessed on the mulched plots using the method described by Anderson and Ingram (1989). Five soil cores of 20*20*20 cm were taken from each plot and all termites in the cores were hand-sorted and counted. Termite species were identified, but termites were not counted per species or genus.

On the mulched plots termites had made macropores which were open at the soil surface. Soil transported to the surface by termites (sheetings) was measured at 10 sampling points on each plot two weeks after a rain event. Each sampling point consisted of 1 m^2 in which all the sheetings (termite-made pedofeatures) were collected and weighed and all open macropores were counted.

Vertical soil micromorphological samples of 7 * 7 * 7 cm of soil were taken at 0-7 cm, 30-37 cm and 100-107 cm depths in October 1995 from two mulched plots and two bare plots and then were impregnated according to Fitzpatrick (1970). Three vertical thin sections of 25 μm thickness were prepared from the samples of each depth. The thin sections were examined with a polarizing microscope and described qualitatively according to Bullock et al. (1985).

Macroporosity was studied quantitatively using an epidiascope with transmitted light, equipped with a scanner and a macrolens. The porosity photograms were analyzed with a Quantimet 970. The resolution of the pixel was 110 μm. Two types of data were collected, field data and feature-specific data (Jenkinson, 1992). Field data were collected to be able to ascertain the volume fraction of macropores or other features of the thin sections. Feature-specific data provided detailed information on individual features such as size, number, size class distribution and shape. Only the collected data on area, Equivalent Circle Diameter (ECD) and the number of features are considered in this paper. The feature-specific data can help to relate the voids to their origin. To ascertain the direct contribution of termites to the soil macroporosity and pedofeatures, enlarged pictures (*1.9) were made from the thin sections. These pictures were used to draw termite-made features (voids and infillings) on overheads. Termite-made voids were recognized either by their mammillated (dendroid) shape or by coatings which are characterized by bridged grains. Termite-made infillings were recognized by the presence of bridged microaggregates. The drawings were then scanned and analyzed by the Quantimet 970 to determine the characteristics of the features (numbers, area).

Results

Termite-made macropores and fabrics (sheetings) on the topsoil (field observations)

The subterranean Macrotermitinae species *Odontotermes smeathmani* (Fuller) and *Microtermes lepidus* (Sjöst) were found in the plots in total of 2150 m^{-2} $\pm$ 1120 termites.

On all mulched plots, termite activity could be seen from the presence of open macropores covered by sheetings constructed by termites for protection. The macropores can be up to 1 cm in diameter and this size indicated that they are voids made by *Odontotermes smeathmani* (Fuller) according to Kooyman and Onck (1987), *Microtermes* voids are less than 2 mm in diameter. The sheetings have bridged grain structures. The material used to build these structures probably originated from the surrounding soil matrix and hence its b-fabric did not contrast with the surrounding groundmass. Mulched (woody material + straw) plots had both a great number of macropores (86 ± 20) and a great amount of sheetings (10.7 ± 3.9 Mg ha^{-1}). Bare plots showed no traces of termite-made features in the topsoil. Within two weeks the termites dug out over 10 Mg ha^{-1} from the soil and reworked it into sheetings. We know this because two weeks lapsed between the last rainfall event which washed away the previous sheetings and the day on which the data were collected.

Microstructure and pedofeatures and their interpretation

The 0 - 10 cm soil layer on termite-infected plots has a very weakly developed soil structure. Very few crumbs with mean diameters of less than 250 μm are found locally. These crumbs are either loose infillings or are clustered near channels. These crumbs consist of bridged microaggregates with interaggregate voids; they are probably termite pedofeatures (sheetings). The soil at that depth has a chamber and channel microstructure (Fig. 2.1a). The channels, oriented parallel or perpendicular to the soil surface, are interconnected and also connected with chambers. In some cases they fuse and form a very large channel (Fig. 2.1b). Most of the channels have a mean diameter up to 5 mm but a few larger ones also occur. There are fewer chambers than channels. Most of the channels are empty and mammillated (Fig. 2.2a). Very few of them are loosely infilled by a mixture of crumbs and coarse mineral grains; most are not coated but a few are partially coated by bridged microaggregates. Passive infillings (not induced by soil fauna) are also found (Fig. 2.1a). Such infillings have the same structure and b-fabric (birefringence fabric) as the surrounding groundmass. The b-fabric indicates the arrangement and orientation of the fine fraction of the soil (basically the clay fraction). From the absence of compressed walls surrounding the voids it can be concluded that these voids do not impede water flowing through them from diffusing into surrounding soil matrix. Few infillings and chambers coated with bridged grains are found.

At 30 cm depth the same microstructure persists, but more chambers than channels and less packing voids were found at that depth than in the upper layer. The connection of the channels and chambers is clearer and most of the chambers are either fine clay-coated or bridged grains material coated. The latter are termite fabrics (Fig. 2.2b) and may be up to 70 μm thick. The bridged grains coatings suggest that the voids are stable and the typical clay coatings are clear evidence of the movement of the clay in that layer, as well as of a preferential flow of water through these voids. The clay movement is characteristic of Lixisols. Many chambers are loosely infilled with termite-made crumbs (Fig. 2.2c). The crumbs and the bridged grain coatings at that depth have a more contrasting b-fabric than is the case in the top layer, because the building material is a mixture of clay, silt and organic material.

The same microstructure and pedofeatures that exist at 30 cm were found at 100 cm depth. There are fewer chambers than channels and both are dominantly empty. The packing voids are less important than in the upper layers because of the increase in clay content in that layer.

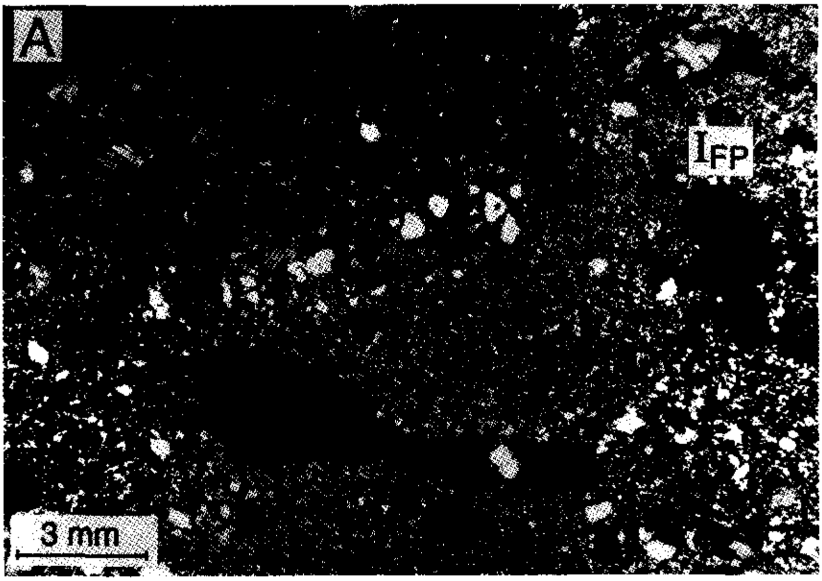

Figure 2.1a: *Cross polarized image of chambers and channels microstructure on the 0-10 cm layers of mulched plot. Ifp: passive infilling having the same microstructure and the same b-fabric as the surrounding groudmass.*

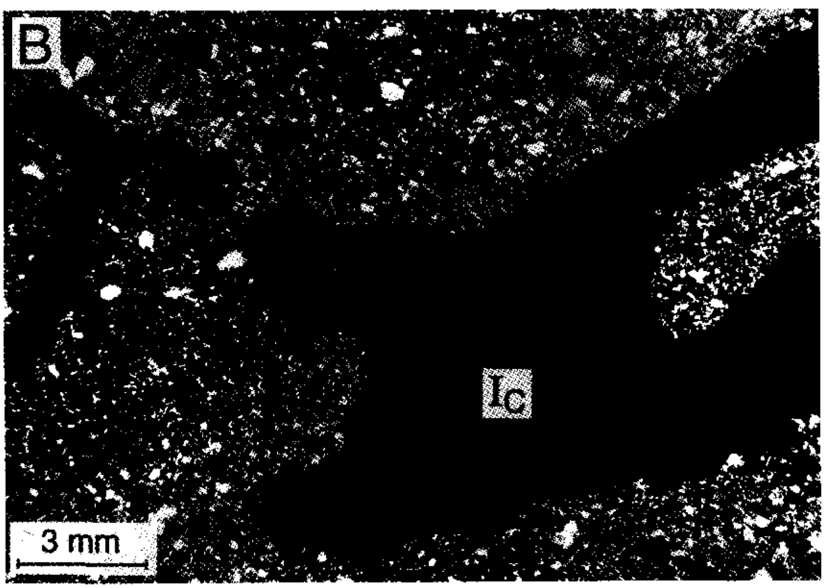

Figure 2.1b: *Cross polarized image of channel microstructure in the 0-10 cm layer of mulched plot. Note the interconnection of channels in the middle of the image (Ic).*

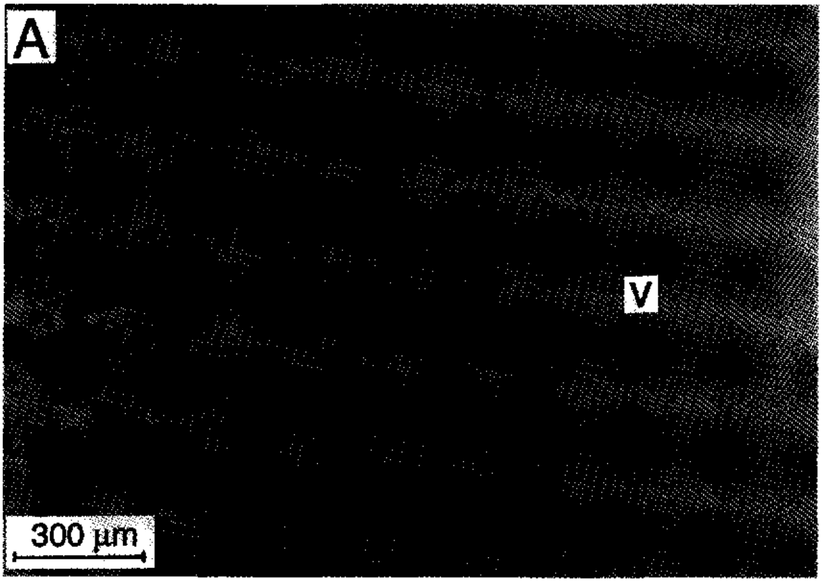

Figure 2.2a: *Full polarized image of a mammillated shape of termite-made void at 30 cm, v: void.*

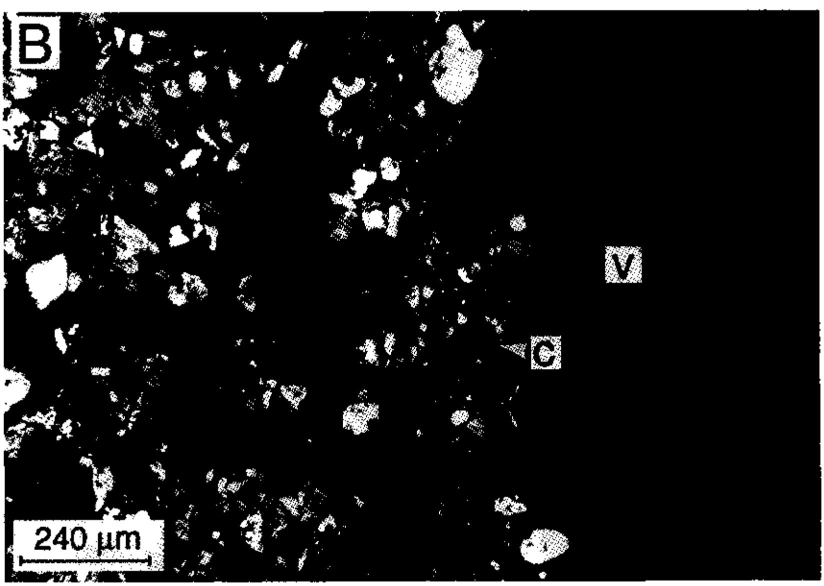

Figure 2.2b: *Cross polarized image of termite made void coated with bridged grain material coatings at 30 cm depth. V: void, C: bridged grain coatings.*

In summary, soil profiles in termite plots have many voids, apparently creating good drainage conditions. At depths of 10 cm and 100 cm in these soils some large channels occurred without any special protection, like the chambers coated by bridged microaggregates found at 30 cm. This suggests that the layer at about 30 cm is where the dominant species lives and has storage chambers while the upper layer only contains passages for food collection, and that the lower layer contains more passages for collecting fine material and also voids for living in.

In the profiles of bare plots, at 0-10 cm depth, the soil shows a compact grain microstructure with primary coatings and a locally more dense grain microstructure (fig. 2.2d). No aggregates are found in this layer. The voids at the top of the thin section are mostly packing voids. In the bottom of the thin section, channel infillingsand chambers infillings are found in one of the replicates. These voids are infilled by single coarse grains, some of which are coated with fine clay. These are a clear indication of the role of water in the infilling process.

At depths of 30 cm and 100 cm, termite-made channels and chambers and microstructure look like those in the mulched plots at the same depths. Termite pedofeatures like crumbs and termite-mediated infillings and coatings are also abundant in these layers. In these layers voids coated with fine clay are also found (Fig. 2.3), indicating a clay illuviation (argillic horizon, characteristic of Lixisols).

The pedofeatures and structure of bare plots at depths of 30 cm and 100 cm are a clear indication of previous termite activity, whereas features like chambers and channels in the topsoil and in the first 10 cm of the soil have been completely destroyed by the degrading processes acting on the soil. The very thin coatings of silt on the grain in the infillings at that depth found in the micromorphological analysis suggest that sediment yield in water flow may be responsible for the pores being filled up. The consequences of the degrading processes are the destruction of the soil voids and the sealing of the soil surface, creating serious problems of water and air flow and root growth.

Profiles with present termite activity differ basically from those without present termite activity in having large voids (interconnected channels and chambers) in the 0-10 cm layer.

Macropores in the soil profile

The results of the macroporosity measurements on vertical thin sections of two layers are presented in Tables 2.1a and 2.1b. The volume area of the macropores (ECD > 0. 1 mm) decreased with depth on mulched plots but increased with depth on bare plots. In the 0 - 7 cm layer of bare plots, macropore volume area and number were only about a fifth of those on mulched plots. There were no voids larger than 3 mm in the 0 -7 cm layer of bare soil but these voids accounted for more than 60 % of the macroporosity in termite plots and over 38% of soil total porosity calculated from bulk density (Table 2.2). In termite plots, voids with ECD greater than 0.1 mm account for 59% of the total porosity, but this type of voids accounts for only 15% of the total porosity calculated from soil bulk density data in bare plots. At 30-37 cm depth, the bare plots had a greater volume fraction of macropores but the termite plots had a greater area of voids with an ECD larger than 0.1 mm.

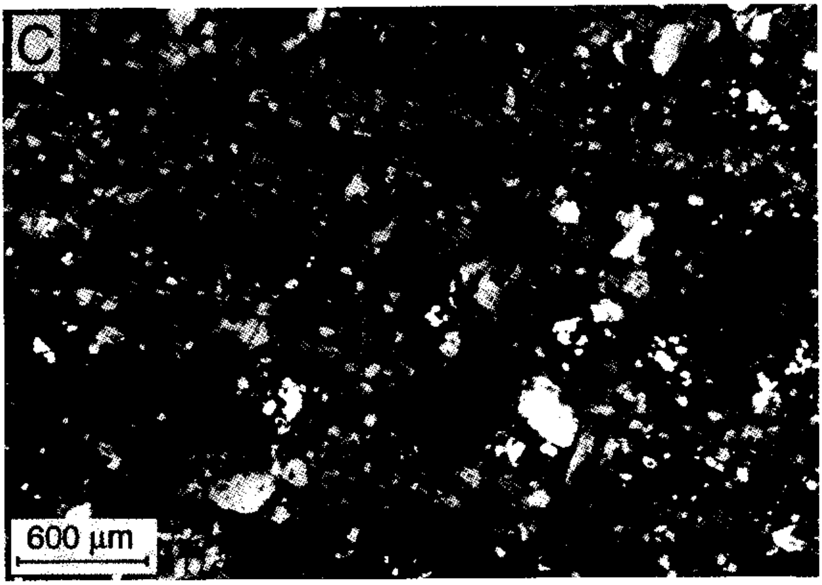

Figure 2.2c: *Cross polarized image of a channel infilling (termite made pedofeature) at 30 cm depth. Note that the infilling is bridged by crumbs.*

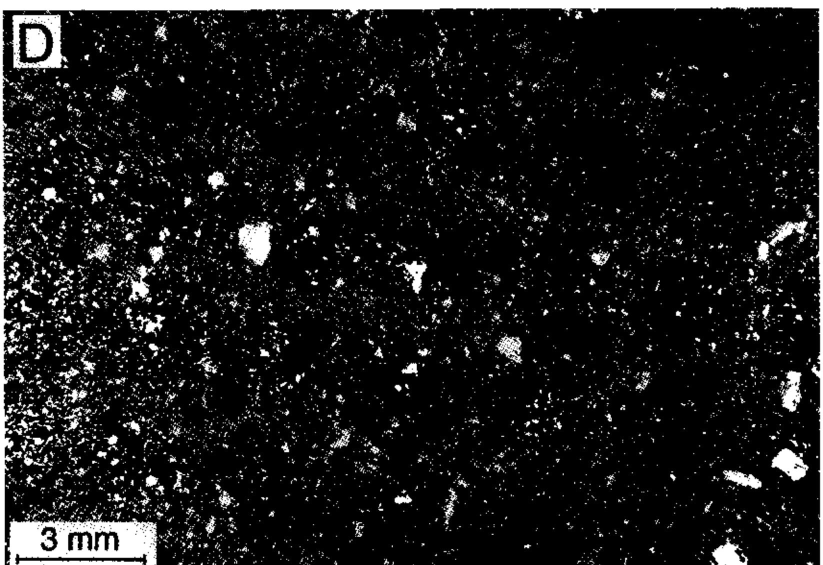

Figure 2.2d: *Cross polarized image of a compact grain microstructure in the 0-10 cm layers of bare plot.*

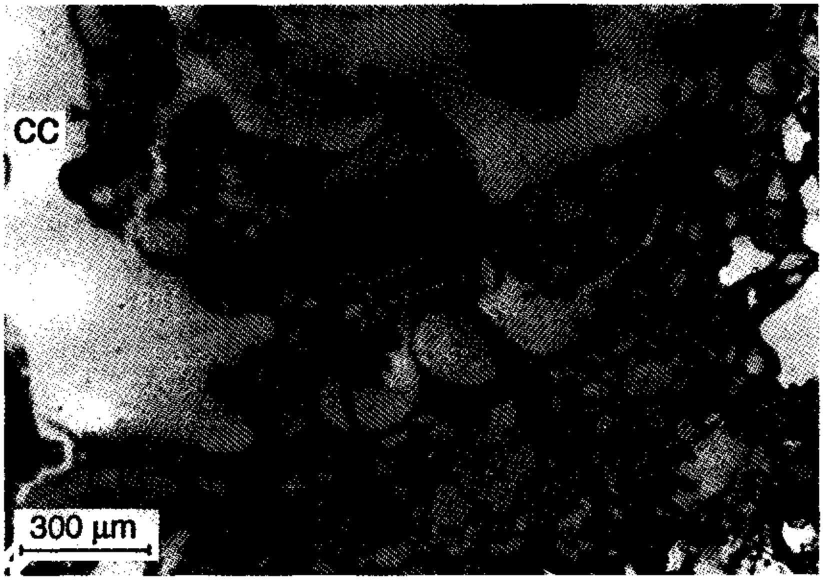

Figure 2.3: *Full polarized image of a clay typic coating at 30 cm depth. cc: clay coatings.*

ECD (mm)	T	NT
> 0. 1	24.4 ± 4.6	5.5 ± 1.1
> 3	16.1 ± 9.6	0 ± 0.0
3 - 1	3.2 ± 1.3	1.3 ± 0.0
1 - 0.5	2.0 ± 1.2	1.4 ± 0.0
0.5- 0.1	3.0 ± 0.1	2.7 ± 0.0

Table 2.1a: *Percentage of macropore area (at least 0.1 mm in ECD) in vertical thin sections of termite and non termite plots at 0- 7 cm depth expressed as % of the area of the thin section. Results are mean ± standard deviation (n = 3); ECD: equivalent circle diameter, NT: non termite plots (bare). T: termite plots (mulched).*

ECD (mm)	T	NT
> 0.1	5.77 ± 1.3	10.2 ± 2.2
> 3	2.46 ± 1.8	3.5 ± 1.4
3 - 1	1.54 ± 1.1	2.1 ± 0.5
1 - 0.5	0.7 ± 0.5	1.9 ± 0.4
0.5 - 0.1	0.9 ± 0.7	2.0 ± 1.5

Table 2.1b: *Percentage of macropore area (at least 0.1 mm in ECD) in vertical thin sections of termite and non termite plots at 30-37 cm depth expressed as % of the area of the thin section. Results are mean ± standard deviation (n= 3); NT: non termite plots (bare). T: termite plots (mulched).*

The analysis of the pictures indicated that termite-induced voids in the 0-7 cm layer accounted for almost 50 % of voids with ECD >0.1 mm and voids having a ECD greater than 3 mm. Termite-made voids have a greater volume area fraction and ECD in the 0-7 cm layer compared with the 30-37 cm layer but are fewer in number (Table 2.3). Other termite features like loose infillings became important in layers deeper than 10 cm, and there was no difference between plots with present termite activity (mulched) and plots with no current termite activity (Table 2.3).

Discussion

One finding of the research is that sealed/crusted soils have a very weakly developed soil structure in the 0 - 7 cm layer only but that below this depth the structure is rather well developed, with many open voids and with micromorphological evidence that these voids are a medium that permits water flow (clay coatings and infilled voids). This is not only consistent with Casenave and Valentin (1989) but also explains their findings that in the arid and semi-arid Sahelian zone the properties of the soil surface are the most important factors controlling the hydrological behaviour of the soils. This also indicates that processes of degradation by water are largely confined to the soil surface and first 10 cm. Therefore soil management in the semi-arid regions should be focused on the maintenance of the topsoil and surface structure.

The voids in the layer deeper than 10 cm in the plots without actual termite activity display many termite-induced features, e.g., bridged microaggregate coatings and bridged grains infillings presumably remaining from former termite activity. This confirms that in the semi-arid ecosystem termites are one of the most important biological agents reworking the soils (Lobry de Bruyn and Conacher, 1990; Bachelier, 1978; Humphreys, 1994). Our results indicate that under the conditions studied, soil structure degradation is the consequence of the eradication of soil fauna that once were continuously opening new voids and thus were counteracting the degrading processes destroying the voids.

		0 - 7 cm		30 -37 cm	
	ECD (mm)	%P (>0.1 mm)	%P	% P (>0.1 mm)	%P
T	> 3	59	38.6	21.5	n.a
	3 - 1	18	7.7	38.5	n.a
	1 - 0.5	9.3	4.6	17.5	n.a
	0.5- 0.1	13.6	7.1	27.5	n.a
	> 0.1	100	59.1	100	n.a
NT	> 3	0	0	36	n.a
	3 - 1	24.3	3.6	20.7	n.a
	1 - 0.5	25.6	3.8	20.7	n.a
	0.5- 0.1	50	7.2	29	n.a
	> 0.1	100	14.9	100	n.a

Table 2.2: *Percentage of voids per ECD (Equivalent Circle Diameter) expressed as % of the area of voids with ECD > 100 µm (%P> 0.1 mm) and as % of total porosity (P) calculated from bulk density data. n.a: data not available; NT: non termite plots (bare). T: termite plots (mulched).*

Our work also shows that soil management techniques that enhance termite activity, such as mulching are an alternative to techniques such as soil tillage for the rehabilitation of degraded soil structure. Within a short time subterranean termites create a soil structure with many voids open to the soil surface and a loose topsoil. The voids which result from the collection and removal of fine material for building and nesting are critical to soil functions (plant production, water partition, environmental buffer...) as they allow water and air flow. The features constructed for protection on the soil surface (sheetings) contribute to create some loose layers on the topsoil. It has been found (Basppa and Rajagopal, 1991, Mando, in prep.) that termite-made sheetings contain more nutrients than the underlying soil. The increase in soil porosity through termite activity is mostly achieved via the fraction of macrovoids and consequently leads to the reduction of the proportion of smaller pores, and thus to a change in the pore size distribution. This is a clear indication that termite-induced change of soil structure may favour soil parameters such as hydraulic conductivity, infiltration, but not necessarily the soil's capacity to store water, especially at high pressure. The presence of the termite-induced voids in deeper layers suggests that termite activity enhances water recharge in deep layers, and this confirms and explains the results of Mando (1997) who measured better drainage in termite plots compared with non-termite plots.

Another finding from our research is that in the Sahelian conditions, in which soils have low organic matter content and low active clay content, termites are a major factor controlling soil aggregation because of their building activity. Termite-worked material is more stable than the surrounding ground mass because of the saliva the termites add when building their structures (Kooyman and Onck,1987; Eschenbrenner,1986). Kooyman and Onck (1987) estimated that termite pedofeatures account for 20 % of the area of soil matrix. In our case the proportion of termite pedofeatures was smaller, probably because of the instability of our sandy soils (Miedema et al., 1994).

Conclusion

The triggering of termite activity on crusted soil leads to a change in the soil structure through three processes giving rise to three features:

- The transport of material to the soil surface to construct sheetings for protection while searching for food.

- The excavation of irregularly-shaped voids open to the air (chambers and channels). These voids are in some cases clay coated or bridged microaggregates coated.

- The aggregation of the soil, particularly below 10 cm, through the construction of bridged grains coatings and crumbs that form the void infillings.

All three features have a critical influence on soil properties. The first process contributes to loosen the soil and this enables the soil to resist the degrading processes acting on the soil, such as water erosion and waterlogging. Therefore in such circumstances, land management in low input farming system should take into account and exploit termite activity to enhance soil productivity. Management that is detrimental to soil fauna should be minimized, to let the soil work for us (Elliott and Coleman, 1988).

		Depth (cm)	% thin section area	ECD (mm)	nv
Voids	T	0-7	11.8 ± 2.7	1.1-12	11 ± 3
		30- 37	3.44 ± 1.6	1.2 - 4.1	14 ± 3
	NT	0-7	0.0 ± 0.0	n.a	0 ± 0
		30- 37	3.6 ± 0.4	1.1 - 9.2	12 ± 2
Infillings	T	0-7	1.2 ± 1.2	1.3 - 13.2	2 ± 0
		30- 37	17.5 ± 3.5	1.01 - 18.5	8 ± 5
	NT	0-7	0.0 ± 0.0	n.a	0 ± 0
		30- 37	15.5 ± 2.5	0.8 - 9.2	14 ± 3

Table 2.3: *Termite-made voids and infillings in mulched termite plots and bare plots [results are mean ± standard deviation (n = 3)] nv: number of voids, ECD: Equivalent Circle Diameter (results are smallest and biggest ECD), NT: non termite plots (bare). T: termite plots (mulched).*

Acknowledgements

We wish to thank Dr. A.G. Jongmans for technical assistance, D. Schoonderbeek for his help with the Quantimet, Dr. H.I.J. Black for the identification of termites and Professors L. Brussaard and L. Stroosnijder for their valuable comments on the manuscript.

References

Anderson, J.M., 1988. Invertebrate mediated transport processes in soil. Agric. Ecosyst. Environ., 24: 4-19.

Anderson, J.M. and Ingram, J.S., 1989. Tropical Soil Biology and Fertility: a Handbook of Methods. CAB international, 171 pp.

Bachelier, G. 1978. La faune du sol, son action. Editions de l' ORSTOM, Paris, 391 pp.

Basppa, H. and Rajagopal, D., 1991. Physico-chemical properties of termite-modified soils due to foraging on dung in comparison with the surrounding soil. Sociobiology, 16: 175-185.

Bullock, P., Fedoroff, N., Jongerius, A., Stoops, G., Tursina, T. and Babel, U., 1985. Handbook for Soil thin Section Description. Albrighton, Waine, 152 pp.

Bunasol, 1995. Etude morpho-pédologique de la province du Bam (échelle 1/500.000). Rapport Technique n^0 97, Vol. 1, 155 pp+annexes.

Casenave, A. and Valentin, C., 1989. Les états de surface de la zone Sahélienne. Influence sur l'infiltration. Editions de l'ORSTOM, Paris, France, 230 pp.

Edwards, W.M., Shipitalo, M.J., Owens L.B. and Norton, L.D., 1990. Effects of *Lumbricus terrestris* L. on hydrology of continuous no-till corn fields. Geoderma, 46:73-84.

Elkins, N.Z., Sobol, G.V., Ward, T.J. and Whitford, W.G., 1986. The influence of subterranean termites on the hydrological characteristics of a Chihuahuan desert ecosystem. Oecologia, 68: 521-528.

Elliott, E.T. and Coleman, D.C., 1988 . Let the soil work for us. Ecol. Bull., 39: 23-32.

Eschenbrenner, V., 1986. Contribution des termites à la micro-aggrégation des sols tropicaux. Cahier ORSTOM, serie Pédologie, XXII, 397-408.

FAO-Unesco, 1994. Soil map of the world. Revised legend with corrections. Technical paper n^0 20, ISRIC, Wageningen, 139 pp

Fitzpatrick, E. A., 1970. A technique for the preparation of large thin sections of soil and unconsolidated materials. In D.A. Osmond and P. Bullock (eds), Micromorphological techniques and applications. Technical Monograph 2, Rothamsted Experimental Station, Harpenden, Herts, Uk, 3-13.

Humphreys, G.S., 1994. Bioturbation, biofabrics and biomantle: an example from the Sydney Basin. In: A.J. Ringrose-Voase and G.S Humphreys (Editors), Soil Micromorphology: Studies in Management and Genesis. Developments in Soil Science, 22: 421-436.

Jenkinson, G., 1992. An introduction to the operation and capabilities of image analysis systems. Tech. Rep., Cambridge Instruments, Cambridge.

Kooistra, M.J., Juo, A.S. and Schoonderbeek, D., 1988. Soil degradation in cultivated Alfisols under different management systems in Southern Nigeria. In: L.A. Douglas (Editor), Soil Micromorphology: A Basic and Applied Science. Developments in Soil Science, 19: 61-68.

Kooyman, C. and Onck, R.F.M., 1987. The interactions between termite activity, agricultural practices and soil characteristics in Kisii district, Kenya. Wageningen Agricultural University Papers 87-3: 1-120.

Lee, K.E. and Foster, R.C., 1991. Soil fauna and soil structure. Australian Journal of Soil Research, 6:745-775.

Lobry de Bruyn, L.A. and Conacher, A.J., 1990. The role of termites and ants in soil modification: a review. Australian Journal of Soil Research, 28: 55-93.

Mando, A., 1991. Impact de l'activité des termites sur la dégradation de la biomasse végétale et quelques propriétés physiques des sols dégradés: Etude menée a Zanamogo (Burkina Faso). Mémoire de fin d'études, Université de Ouagadougou, ISN/IDR, 76 pp.

Mando A., 1997. The effect of termite and mulch on the water balance of Sahelian crusted-soils. Soil Technology (accepted for publication).

Mando, A., Stroosnijder, L. and Brussaard L., 1996. Effect of termite and mulch on infiltration into crusted soil in the Sahel. Geoderma, 74: 107-113.

Miedema, R. and Van Vuure, W., 1977. The morphological, physical and chemical properties of two mounds of *Macrotermes bellicosus* (Smeathman) compared with surrounding soils in Sierra Leone. J. Soil Sci., 28: 112-124.

Miedema, R., Brouwer J., Geiger S.C. and Vandenbeldt, R.J., 1994. Variability in the growth of *Faidherbia albida* near Niamey, Niger, Africa: micromorphological aspects of termite activity. In: A.J. Ringrose-Voase and G.S Humphreys (Editors), Soil Micromorphology: Studies in Management and Genesis. Developments in Soil Science, 22: 411-419.

Stroosnijder, L. and Hoogmoed, W.G., 1984. Crust formation on sandy soils in the Sahel, II: Tillage and its effects on the water balance. Soil and Tillage Research, 4:321-337.

Unesco, 1973. International classification and mapping of vegetation. Ecological Conservation n⁰ 6, Unesco, Paris, 93 pp.

Unesco, 1977. Carte de la répartition des régions arides. Notes Techniques du MAB, n⁰ 7, Unesco, Paris, 77 pp.

Wielemaker, W.G., 1984. Soil formation by termites. A study in the Kisii area, Kenya. Doctoral thesis, Agricultural University Wageningen, 132 pp.

Chapter 3

Effects of Termites on Infiltration into Crusted Soil

Mando, A., L. Stroosnijder and L. Brussaard, 1996. Effects of Termites on Infiltration into Crusted Soil. Geoderma, 74:107-113

Abstract

In northern Burkina Faso (West Africa), a study was undertaken to explore the possibilities of restoring the infiltration capacity of crusted soils through the stimulation of termite activity. Treatments consisted of the application of a mulch of a mixture of wood and straw without insecticides (resulting in 'termite plots') and the application of the same mulch and an insecticide (Dursban with chloropyrifos as the active ingredient) to prevent termite activity (resulting in 'non-termite plots'). Three rainfall simulations of 60 minutes duration with an intensity of 50 mm/h at an interval of 24 hours between the first and the second and 72 hours between the second and third simulation were applied, to study the effect of consecutive showers on termite-modified soil characteristics. Cumulative infiltration amounts, final infiltration rates, soil water content and porosity were larger and bulk density was smaller on termite plots as compared to non-termite plots. This suggests that termites may be an important agent in soil-crust control and in the improvement of soil physical properties in Sahelian ecosystems.

Introduction

Termites are the most important soil fauna in the Warm Seasonally-Dry Tropics (Lobry de Bruyn and Conacher, 1990). Much work has been done on termite biology and their ecological role in ecosystems. It shows that termites may have a great impact on soil properties and soil genesis. The dense network of their galleries improves soil porosity and aeration (Lee and Foster, 1991; Mando, 1991), infiltration and water storage and, consequently, increases soil primary productivity (Elkins et al., 1986). Termites also play a key role in nutrient recycling (Basppa and Rajagopal, 1991) and modify soil chemical characteristics by mixing soil from different layers (Mando, 1991). Brouwer et al. (1993) found that termites contribute considerably to soil microvariability in the Sahelian zone. Mulching and branching soils is an indigenous method to attract termites (Chase and Boudouresque, 1987). The infiltration rate of such mulched and branched areas with intense termite and worm activity increases considerably (Casenave and Valentin, 1992). This is due to the combined effect of soil cover (by mulch and branches) and termite activity. No measurements are known of infiltration in termite and non-termite plots without the simultaneous effect of the mulch that attracted the termites. Here, we examine the potential role of termites in tackling soil physical degradation (especially soil crusting), which is one of the major agricultural problems in the Warm Seasonally-Dry Tropics.

Materials and methods

The study was conducted on bare, crusted soil located in the northern part of Burkina Faso (Bourzanga, Bam Province, 4^0 West, 13^0 North). The soil consists of sandy loam in the top layer, but is rich in clay in deeper layers (Ferric Lixisol according to FAO-classification). This region has a Soudano-Sahelian climate. The average annual rainfall is 470 mm. The wet period lasts four months from June to September. The vegetation is sparse. Woody species are dominated by shrubs. The most important species belong to the genus *Acacia* and the Combretaceae family. Grasses are dominated by *Schoenefeldia gracilis* and *Arista adscensionis*. Perennial grasses are rare.

In November 1993 four blocks were laid out on bare crusted soil (classified as 'Erosion Crust' according to Casenave and Valentin, 1989), each block consisting of one plot, on which a mulch mixture of straw of *Pennisetum pediculatum* and wood of *Pterocarpus lucens* was applied to attract termites (resulting in 'termite plots'), and another plot, on which the same mulch was applied to create similar mulch conditions, but which was treated with an insecticide (Dursban with chloropyrifos as the active ingredient) every two weeks at the rate of 400 g active ingredient per hectare, to prevent termite activity and resulting in 'non-termite plots'. Termite activity was checked every two weeks. By May 1994 all plots on which no insecticide was applied, had been invaded by termites. There were no termites in the non-termite plots. Mulch layers were then removed manually from the plots and the following measurements were conducted: (i) the number of macropores made by termites (easily recognized since they are covered with a characteristic sheeting and their mean diameter is larger than 3 mm) as an estimate of the foraging activity of the termites, (ii) bulk density and porosity of undisturbed 100 cm^3 samples of the topsoil (0-5 cm), (iii) amount and rate of infiltration following rainfall simulation with an ORSTOM type rainfall simulator (Casenave, 1982) and (iv) gravimetric water content in disturbed samples and porosity in undisturbed samples after three rainfall simulations. We conducted three simulations of 60 minutes duration on each plot (i.e. 4 replications) with an intensity of 50 mm/h. The second simulation was conducted 24 hours after the first and the third was conducted 72 hours after the second. Between simulations plots were not covered, except when it began to rain naturally. Less than 30 mm of natural rain fell during the experiment. Infiltration measurements were carried out on 1 m^2 squares enclosed by metal frames. Runoff from the plot was caught in a box and was then pumped into a collecting tank in which the volume of the water was recorded manually. During rain simulations we recorded the elapsed time between the beginning of the simulation and the onset of ponding. We called this ponding time (PT). We also noted the elapsed time between the onset and the end of the runoff and called this runoff time (RT). Runoff was recorded every five minutes. The difference between rainfall intensity and runoff intensity provided the cumulative infiltration and the infiltration rate. Hence, surface depressional storage was treated as infiltration, and not as runoff, in the calculations. Since it was assumed that the crust that had been broken due to the activities of the termites will be restored by the impact of the rain, the infiltration rates could not be fitted with the physically well-defined Philip equation which is only valid for rigid soils. Instead, we used an empirical equation proposed by Morin and Benyamini (1977) which allows for crust formation during the rainfall/infiltration process:

$$I_t = (I_0 - I_f) e^{-\alpha CR} + I_f \qquad \text{(Eq.1)}$$

where: I_t = infiltration rate (mm h^{-1}), I_0 = initial infiltration rate (mm h^{-1}), I_f = final infiltration rate (mm h^{-1}), α = coefficient (mm^{-1}), CR = cumulative rain since the beginning of the rainfall (mm) with CR = P*t where t = time since the beginning of the rain (hour), P = rainfall intensity (mm h^{-1}) .

The Student Newman-Keuls' test for multiple comparisons (Miller, 1981) was used for all relations to assess significant differences at the 0.01 level.

Results

Termite activity in the plots

Before the experiment no termite-made open tunnels were found on the plots. Seven months later, there were still no termite-made open tunnels in the non-termite plots. But an average of 88 (SD=5) open tunnels were counted per square metre in termite plots. All observed termites belonged to the genus *Odontotermes* which are subterranean termites.

Ponding and runoff time

Although ponding times were consistently higher in the termite plots, the differences with the non-termite plots were statistically not significant (Table 1). Ponding time on the termite plots recorded during the third rainfall was found to be higher than ponding time on the non-termite plots during the first rainfall. On the non-termite plots, ponding time increased slightly from the first rainfall to the third rainfall. On the termite plots, however, ponding time during the second rainfall was shorter than it was during the first rainfall, but ponding time during the third rainfall turned out to be longer again than ponding time during the second rainfall. Apparently, the soil is better able to recover physically between rainfall events due to the previous activity of the termites on termite plots than on non-termite plots.

Treatment	PT (min)	RT (min)	I_c (mm)
Termite plots 1st rain	8' 15'' a	52' 25'' a	12.9 a
Termite plots 2nd rain	6' 20'' a	50' 12'' ab	11.89 a
Termite plots 3rd rain	7' 35'' a	46' 32'' ab	9.2 ab
Non-termite plots 1st rain	4' 13'' a	49' 7'' ab	5.28 b
Non-termite plots 2nd rain	5' 13'' a	45' 57'' b	5.28 b
Non-termite plots 3rd rain	5' 13'' a	45' 20'' b	4.51 b

Table 3.1. *Ponding time (PT), runoff time (RT) and cumulative infiltration (Ic) after 30 minutes of simulated rain. Treatments having the same letter(s) are not significantly different.*

Runoff time was greater in termite plots than in non-termite plots and decreased slightly with consecutive rainfall simulation.

Infiltration

Cumulative infiltration after 30 minutes of rainfall in the termite plots was higher than in the non-termite plots (Table 3.1). In the termite plots infiltration decreased with the number of rain simulations. However, even during the third simulation cumulative infiltration in the termite plots was still higher than the infiltration during the first simulation in the non-termite plots.

Measured infiltration rates fitted well with the exponential model of Morin and Benyamini (1977). For all treatments r^2 was 0.99 (Table 3.2). The infiltration rate declined with cumulative rainfall amount. The decline was faster and went deeper for the non-termite plots than for the termite plots (Figure 3.1). This is confirmed by the fact that α, which is a coeffiscient that describes the decline of the infiltration with the increasing amount of rainfall, was statistically greater in termite plots than in non-termite plots.

Ponding time was longer for the termite plots, but shortened with subsequent rainfalls (Figure 3.2). Final infiltration rates (I_f) and intial infiltration rate I_0 were not statistically larger in termite plots than in non-termite plots but I_f was slightly higher on termite plots than non-termite plots for each run. In all plots, especially the termite plots, I_f after the second and third rainfall was smaller, although not statistically significantly, than after the first rainfall. Due to the higher infiltration in termite plots soils were wetted till greater depths. This can be seen (Table 3.3) from measurements of the volumetric soil moisture content (by neutron scattering) at 60 cm depth at the end of the simulation runs.

Treatments	α (mm^{-1})	I_0 ($mm\ h^{-1}$)	I_f ($mm\ h^{-1}$)	r^2
Termite plots 1st rain	0.05 a	71.3 a	7.1 a	0.99
Termite plots 2nd rain	0.08 b	71.7 a	5.6 a	0.99
Termite plots 3rd rain	0.08 b	73.5 a	6.6 a	0.99
Non-termite plots 1st rain	0.10 c	73.3 a	5.8 a	0.99
Non-termite plots 2nd rain	0.10 c	74.1. a	4.7 a	0.99
Non-termite plots 3rd rain	0.10 c	73.4 a	5.2a	0.99

Table 3.2. *Average infiltration parameters. For meaning of symbols see Equation 1.*

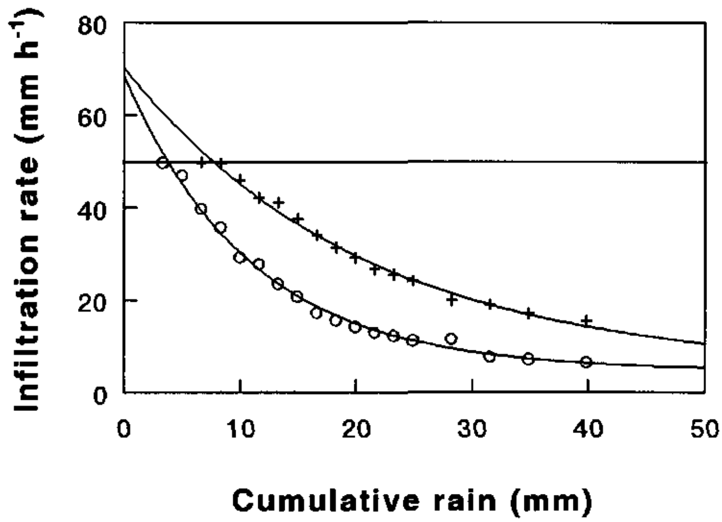

Figure 3.1. *Average (3 runs) infiltration rate (mm h^{-1}) in simulated rainfall plots (4 reps) as a function of cumulative rain (mm): + = termite plots and o = non-termite plots. Curves are fits with a 3-parameter exponential equation.*

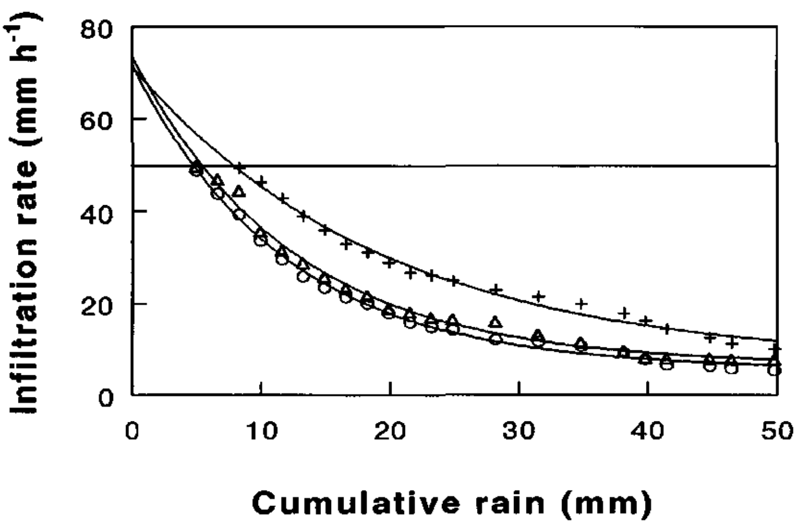

Figure 3.2 *Average infiltration rate (mm h^{-1}) in termite plots (4 reps) for three runs of simulated rainfall: + = first run, o = second run and Δ = third run. Curves are fits with a 3-parameter exponential equation.*

Soil physical properties

In all termite plots we found large macropores made by termites but after the rainfall simulations the macropores were no longer visible. Porosity of the top 0-5 cm soil layer in the termite plots was greater than in the non-termite plots. The difference was about 7% (Table 3.3). Bulk density of the same top soil was therefore higher in the non-termite plots. Despite the decrease of porosity with successive showers, the lowest value of soil porosity in the termite plots, i.e., the porosity after the third rainfall, was still higher than the porosity in the non-termite plots. Here, soil porosity remained constant before and after the rain.

Discussion

Placing mulch on a bare and crusted soil in a semi-arid environment led to the colonization of the soil by termites which were quickly able to change the physical characteristics of the top soil. The crust was destroyed by the galleries dug by the termites in the soil. Three types of burrows were observed. The first type were subsurface burrows that result from the construction of sheetings. The second type were channels used by the termites when leaving their nests. The third type were burrows that result from the construction of the nests. The first two types accounted for the increase in porosity of the top 5 cm of soil and for the average of 88 open tunnels per m^2. The second and third type of burrows extended to a depth of up to 1 m. Type 1 burrows are transient, but as long as termites are present they are continuously renewed and, therefore, contributed considerably to the increased infiltration into the soil. Burrows of type 2 and 3 presumably are very persistent (still recognizable in soil that has been left by termites), although no data seem to be available on their average longevity.

Termites also modified the micro-roughness of the soil surface that helped to delay the onset of ponding. The network of galleries which termites build up in the soil allowed the infiltration process to continue even after the soil surface had become saturated. Greater infiltration rates and longer ponding times lead to more infiltration and less runoff. This increases water availability in the soil. During the process, however, raindrop impact causing splash erosion starts filling the galleries. Galleries are not completely filled up, but the openings of the galleries get covered. This causes a reduction of surface roughness, a shortening of ponding time, a reduction of porosity and a decline in infiltration rate. The results suggest that the longer the time between two showers, the greater the capacity of the soil for water infiltration remains. This points out the role of initial soil moisture content in the infiltration process. The wetter the soil the more destructive raindrop impact is in covering the openings of galleries. The destructive force of raindrop impact on unprotected soil also follows from a comparison of our data with those of Casenave and Valentin (1992). These authors measured higher final infiltration rates (25-40 mm hr^{-1}) under the combined effect of mulch and termites than the final infiltration rates we found. Their data were similar to our data at a cumulative rainfall of 30 mm after the beginning of the rainfall. In our experiment, the soil transported to the surface by termites, was removed with the mulch. The difference can be due to the protective effect of mulch that prevents the fast formation of a

	Water content at 60 cm depth (vol. %)	Porosity before rain (%)	Porosity after rain (%)
Non-termite plots	6.1 a	37 a	37 a
Termite plots	10.9 b	44 b	43 b

Table 3.3: *Effects of termites and consecutive showers on soil physical characteristics. Treatments having the same letter are not significantly different at the 0.01 level.*

new crust. Termite-modified soil infiltration curves fitted well with the Morin and Benyamini (1977) infiltration model.

Conclusion

Termites are an important factor to be considered in soil management systems for land rehabilitation in semi-arid tropical areas where water infiltration on degraded crusted soil is a problem. Mechanical methods like soil tillage have been reported to be unsustainable to control crusting because a few rainfalls are enough to build up a new crust (Stroosnijder and Hoogmoed, 1984). The present study indicates that termites can be regarded as a useful biological agent to control soil crust formation and to correct soil physical problems in the Sahel.

References

Basppa, H. and Rajagopal, D., 1991. Physico-chemical properties of termite-modified soils due to foraging on dung in comparison with the surrounding soil. Sociobiology 16: 175-185.

Brouwer, J., C. Stephen and Rick, J.V., 1993. Variability in the growth of *Acacia albida*: The termites connection? in Vandenbelt, R.J. and C. Renard (editors), Proceedings of the regional *Acacia albida* Workshop, Niamey, Niger, pp 117-121.

Casenave, A., 1982. Le mini-simulateur de pluie: condition d'utilisation et principes de l'interprétation des mesures. Cah. ORSTOM, série hydrologie 4:207-227

Casenave, A. and Valentin, C., 1989. Les états de surface de la zone Sahélienne. Influence sur l'infiltration. Editions de l'ORSTOM, Paris, France. 230p.

Casenave, A. and Valentin, C., 1992. A runoff capability classification system based on surface features criteria in semi-arid areas of West Africa. Journal of Hydrology, 130: 231-249.

Chase, R. and Boudouresque, E. 1987. Methods to stimulate plant regrowth on bare, Sahelian forest soils in the region of Niamey, Niger. Agriculture, Ecosystems and Environment, 18: 211-221.

Elkins, N.Z., Sobol, G.V., Ward, T.J. and Whitford, W.G., 1986. The influence of subterranean termites on the hydrological characteristics of a Chihuahuan desert ecosystem. Oecologia 68: 521-528.

Lee, K.E. and Foster, R.C., 1991. Soil fauna and soil structure. Australian Journal of Soil Research, 6:745-775.

Lobry de Bruyn, L.A. and Conacher, A.J., 1990. The role of termites and ants in soil modification: a review. Australian Journal of Soil Research, 28: 55-93.

Mando, A., 1991. Impact de l'activité des termites sur la dégradation de la biomasse végétale et quelques propriétés physiques des sols dégradés: Etude menée a Zanamogo (Burkina Faso). Mémoire de fin d'études, Université de Ouagadougou, ISN/IDR, 76p.

Miller, R.G., 1981. Simultaneous statistical inference. 2nd ed. Springer, New York etc., 299p.

Morin, J., and Benyamini, Y., 1977. Rainfall infiltration into bare soils. Water Resources Research, 13:184-192.

Stroosnijder, L. and Hoogmoed, W.G., 1984. Crust formation on sandy soils in the Sahel. II: Tillage and its effects on the water balance. Soil and Tillage Research, 4:321-337.

Chapter 4

Effect of termites and mulch on the physical rehabilitation of structurally-crusted soils in the Sahel.

Mando, A., 1997. Effect of termites and mulch on the physical rehabilitation of structurally-crusted soils in the Sahel. Land Degradation and Development (in press).

Abstract

The effectiveness of mulch and termite activity in the rehabilitation of the physical properties of crusted soil was studied in northern Burkina Faso (Province de Bam). A split plot design was used with three replications each being on one soil type. The soil types were Ferric Lixisol, Haplic Lixisol and Chromic Cambisol. The main factor was termite activity, and to this end dieldrin (0.50 kg a.i ha^{-1}) was used to create plots without termite activity next to plots with termite activity. The subplots consisted of *Pennisetum pedicellatum* mulch, wood *Pterocarpus lucens* mulch and composite (wood + straw) mulch, applied at rates of three, six and four t ha^{-1}, respectively.

Two years after establishing the experiment, the combined effect of termites and mulch on the change in soil physical properties was measured. The parameters used for this assessment were porosity, saturated hydraulic conductivity and soil resistance to cone penetration. Soil water content was also measured. Termite activity was found to increase soil porosity and soil saturated hydraulic conductivity, to improve soil water status and to reduce soil bulk density and soil resistance to cone penetration. The only difference between bare plots and mulched plots without termites was in water content. This indicates that the mechanism whereby mulch improves the physical properties of crusted soil is mainly based on soil biological processes and to a limited extent on protecting soil against weather impact.

Key words: rehabilitation, termites, mulch, physical properties, structural crusts.

Introduction

Physical degradation of the soil is a major problem in the Sahelian region (Kaboré, 1994). After analyzing the processes involved, Pieri (1989) and Lal et al.(1989) concluded that the worst step in soil degradation is the collapse of the soil structure, i.e the deterioration of the soil physical properties. Once this stage has been reached, soil recovery is no longer possible without deliberate human intervention to create the conditions necessary. For these reasons, people in the Sahel have developed a range of physical and biological methods to control degradation and rehabilitate degraded soils, with mulching to improve soil properties being one of the most widespread (Wades and Sanchez, 1983). Adams (1966) considers that mulch is effective in improving soil physical properties because its many tiny barriers obstruct runoff and thus increase infiltration. However other researchers have emphasized that it is the accumulation of wind and/or water transported sediment on mulched soil that is responsible for improving soil conditions (Toutain and Wespelaere, 1977). Mando et al. (in press) have shown that in the Sahel mulch often attracts termites whose channels provide stable macropores for water flow. However, there are few data on the effectiveness of these channels in improving the physical properties of crusted soil. According to Tian et al. (1993) and Chase and Bourdouresque (1987), mulch affects soil water content partly by lowering soil daily maximum temperature and reducing evaporation. Although various aspects of the mulch effect on soil have been documented, there is little information to establish to what extent each aspect of mulching is effective in improving soil physical properties. Yet this information is critical when designing suitable mulch technology to deal with a specific physical problem. This study therefore aimed to evaluate the change in the physical properties of structurally-crusted soils resulting from mulch application and termite activity.

Methods

Site Description

The investigation was conducted on a 4 ha fenced area near Bourzanga in northern Burkina Faso, West Africa (about 4° W, 13° N). The climate is Sahelian Sudanian according to UNESCO (1977). Rainfall is monomodal and typically occurs for 4 months from June to September. Its distribution is irregular in time and space, and the current trend is for annual means to decrease (see Table 4.1).

The vegetation is of the steppe type according to UNESCO's (1973) classification, with large bare areas. The life form of the grasses is dominantly annual therophytes, and perennial grasses are rare (Mando, 1991). The woody component is dominated by shrubs, the most important families being *Mimosaceae* and *Combretaceae*. The common termite genera are *Microtermes, Macrotermes* and *Odontotermes*.

Lixisols and Cambisols are the commonest soil types in the area (BUNSOL, 1995). The soil types on the experimental site are:

- Chromic Cambisol with a pH between 5 and 8 from 5 cm to 120 cm depth, CEC < 17 cmol (+) kg^{-1} from 0 cm to 120 cm depth. The textural classes according to the USDA system are sandy-clay-loam in the top 5 cm (sand: 49%, silt 29% and 21% clay) and clay below 70 cm depth (20% sand 35% silt and 45% clay,). Bulk density is 1600 kg m^{-3} at 0-5 cm layer and 1700 kg m^{-3} at 120 cm depth. Soil organic matter content is 0.6% between 0 cm and 20 cm depth and 0.2% at 120 cm depth.

- Ferric Lixisol with a pH of about 4.1 at 5 cm and of 6.1 at 110 cm depth. CEC is 6 cmol(+) kg^{-1} at 5 cm depth and 12.4 cmol (+) kg^{-1} at 120 cm depth. The textural class is

Period	mean rainfall (mm)
1964 to 1973	572
1974 to 1983	547
1984 to 1993	456

Table 4.1: *Mean annual rainfall in Bourzanga from 1964 to 1993.*

sandy loam (37% of sand, 43% silt and 20% clay). Bulk density is 1500 kg m^{-3} at 5 cm depth and 1700 kg m^{-3} at depths below 70 cm. Soil organic matter content is 0.51% at 5 cm depth but decreases to 0.17% at 120 cm depth.

- Haplic Lixisol with pH < 5, CEC < 9 cmol (+) kg^{-1} and sandy loam textural class (53% sand, 25% silt and 21% clay). Average bulk density is 1400 kg m^{-3} at 5 cm depth and 1600 kg m^{-3} at 120 cm depth. Soil organic matter content is 0.3% at 5 cm depth and 0.17% below 100 cm depth.

Annual runoff is very high: 60-80% of annual rainfall on Cambisols and 50-90% on Lixisols because of the degraded status of these soils. Soil crusting is the major problem, but soils also suffer from nutrient deficits.

Experimental design

A split plot design was used, with three blocks, one on each soil type. The main treatment was the use of an insecticide to obtain termite infested plots [T] and non termite plots [NT]. We used dieldrin at a rate of 0.50 kg a.i ha^{-1} spread on [NT] plots just before the experiment began. Dieldrin is an organochlorine whose common name is HEOD. It is a persistent and non-systemic insecticide of high contact and stomach activity to most insects (Charles, 1979). Dieldrin was used after Dursban EC (at the rate of 0.40 kg a.i ha^{-1}) had failed to keep termites away from [NT] plots.

The main plots were 50 * 50 m and were 50 m apart. The subplots were two groups of four subplots, each measuring 15 m * 8 m and 8 m apart. The two groups of subplots in each main plot were 15 m apart. Mulch treatments were randomly applied in these plots. These were straw of *Pennisetum pedicellatum* [S] applied at 3 t ha^{-1}, woody material of *Pterocarpus lucens* [W] applied at 6 t ha^{-1} and composite [C] (woody material and straw) treatments applied at 4 t ha^{-1}. In addition there was a control with no mulch, called bare [B] (Figure 1.2).

Field and laboratory work

In October 1994 (just at the end of the 1994 rainy season), two undisturbed soil samples of 100 cm^3 were taken from the 0-5 cm layer in each subplot to determine soil bulk density. They were oven dried at 105° C for 24 hours to obtain their dry weight, from which soil bulk density was determined.
Soil porosity was calculated using the following formula.

$$\text{Porosity } (\%) = 1 - d_b/d_e * 100 \qquad [1]$$

where d_b is dry bulk density and d_e is soil particle density, which was considered to equal 2600 kg m^{-3}.

Saturated hydraulic conductivity (K_{sat}) was determined from the same undisturbed soil samples using the constant head method (Klute, 1986).

An Eikelkamp penetrometer of 60° cone angle and 100 mm^2 surface was used to study soil resistance to cone penetration down to 100 cm in October 1994. Four measurements were performed on each subplot except those in the [NT] plots. The measurements could not be performed in the [NT] plots because the resistance to cone penetration of the top-soil exceeded the capacity of the penetrometer (10 MPa). Therefore, for the data analysis we assumed that the resistance to cone penetration was 10 MPa in the [NT] plots. In the graphs, they are shown to be above 10 MPa.

Soil water content was measured using a neutron probe along the soil profile from 20 cm to 120 cm depth every week in 1994 and 1995. The measurements were performed between June and October in 1994 but between July and October in 1995 because the rains started late in that year. Four replicated measurements were performed per depth in each subplot.

Analysis of Variance (ANOVA) was used to establish the differences between treatments, but the statistical analysis of the water content data was carried out per soil type using ANOVA of a completely randomized design. Data from the wetting period (the period at the beginning of the rainy season) and the wet period (the period when the rainfall exceeds potential evaporation and the soil profile is already wet) were used. The Newman Keuls test was used for the comparison of all means (Miller, 1981).

Results

Mulch triggered termite activity on [T] plots with TC having the greatest termite activity (termite number and termite- made macropores) and TS and TW being a distinctive group. For details see Mando, et al., 1994.

Soil bulk density/porosity

Soil porosity was statistically significantly greater on [T] plots than [NT] plots ($P=0.02$). Bulk density was therefore lower on [T] plots. The average difference in porosity between the two treatments was about 3 %. There was no statistically significant difference between mulch treatments and there was no interaction of Termites and Mulch treatments (see Table 4.2). Soil type (block effect) did not interact significantly with treatments to affect soil porosity.

Saturated hydraulic conductivity

The saturated hydraulic conductivity was more than five times greater in [T] plots than in [NT] plots (see Table 4.2). The K_{sat} of some soil samples from the [T] plots could not be measured in the laboratory because of high bypass flow. The mulch type was found to have a statistically significant effect on saturated hydraulic conductivity, with Composite mulch plots having the greatest effect followed by Straw and Woody material. The interaction of Termite and Mulch type revealed that [NT] mulched plots did not differ statistically from each other and formed a distinctive group with bare plots. The descending order of K_{sat} values in [T] plots was Composite, Woody material and Straw. Soil did not interact significantly with the treatments to affect K_{sat}.

	Porosity (%)		Ksat (10^{-5} m s^{-1})	
TC	41.48 a		3.56 a	
TW	41.10 a		1.06 a	
TS	42.03 a		0.47 a	
B	36.10 a		0.14 b	
NTC	38.50 a		0.34 b	
NTS	36.58 a		0.23 b	
NTW	39.60 a		0.15 b	
	df	P	df	P
Bl	2	0.60	2	0.40
T	1	0.02	1	0.05
M	3	0.50	3	<0.01
T*m	5	0.18	5	<0.01

Table 4.2: *Effect of termites and mulch on soil porosity and saturated hydraulic conductivity. TS = termite straw, TC = termite composite, TW = termite woody material, B = bare, NTC = non termite composite, NTS = non termite straw, NTW = non termite woody material. T = termite, M = mulch. P = probability of treatment having the same effects, df = degree of freedom, Bl = block*

Cone penetration resistance

The topsoil (0-10 cm) in [NT] plots and Bare plots had resistance to cone penetration that exceeded the capacity of the penetrometer (10 MPa). Soil resistance to cone penetration was statistically smaller in [T] plots than in [NT] plots ($P < 0.05$). Mulch and Termite interaction significantly affected soil resistance to cone penetration ($P < 0.01$ for the case of each depth), with TC (Termite+composite mulch) having the lowest value, followed by TS (Termite+Straw mulch) and TW (Termite+woody material mulch), which formed a distinctive group. This pattern was observed throughout the profile in Termite plots. [NT] mulched plots formed a distinctive group with Bare plots for the topsoil (0-10 cm). In [T] plots the resistance to cone penetration decreased until a depth of 30 cm and then increased with depth (see Figure 4.1).

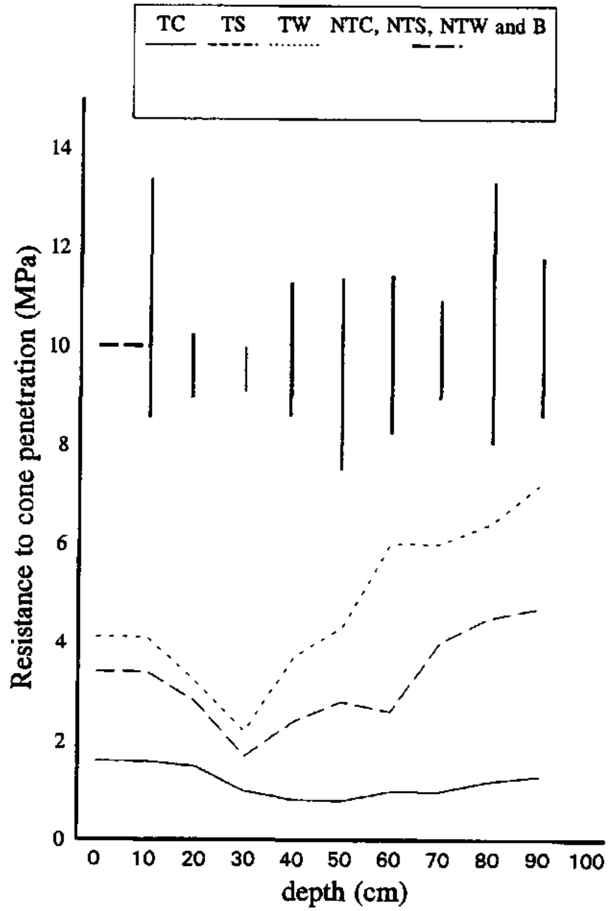

Fig. 4.1: *Effect of termites and mulch on soil resistance to cone penetration. Error bars represent LSD (0.05). TC, TS, TW respectively represent Termite composite, Termite Straw, Termite Woody material and B, NTC, NTS, NTW respectively represent Non termite Composite, Non termite Straw, Non termite Woody material and were set at the upper limit of the measurement in the topsoil: 10 MPa.*

Distribution of water in the soil profile

The treatment had similar effects on water distribution in all soil types and in all periods. As an example the data from the Chromic Cambisol are presented below.

Wetting period

In 1994 (Figure 4.2a) all [NT] plots had a mean volumetric water content less than 13% at all depths but all [T] plots had a water content above 13 % throughout the soil profile, except for TW which had a lower water content in the 0 - 50 cm layer. In the 20 to 50 cm layer, only TC and TS were wetter than [NT] and Bare plots in 1994 but they were not statistically different from NTC and NTS. In the same year, the mean water content in layers deeper than 50 cm was higher in all [T] plots than in [NT] plots. Bare plots had the lowest water content although they formed a distinctive group with [NT] plots.

In 1995 (Figure 4.2b), all [NT] plots and Bare plots formed a distinctive and cohesive group at all depths, except at 120 cm where Bare plots had a clearly lower water content. All [T] plots were homogeneous except at 20 cm depth where TC was statistically different from the distinctive group of TS and TW. Throughout the soil profile, TC had the greatest water content, followed by TS and TW, but the latter were closer to each other than they were in 1994, when TS was clearly wetter than TW during the same period.

Wet period

In the wet periods of both years, the mean values for the water content were higher in all [T] plots than in [NT] plots throughout the soil profile. In 1994 (Figure 4.3a) TS had the greatest mean water content followed by TC and TW whose water content were close to those of [NT] plots, but in 1995 (Figure 4.3b) TC was wetter than TS which was drier than TW from 20 cm to 70 cm. All [NT] plots had statistically the same water content.

Discussion

The results show that termite activity in mulched plots of crusted soil increases the porosity and saturated hydraulic conductivity of the soil compared with bare plots and with mulched [NT] plots. Termites create macropores and loosen the soil by burrowing and therefore reduce soil bulk density and increase soil porosity. This agrees with earlier findings of Mando and Miedema (press) from another experiment conducted at the same site in which greater porosity was measured on [T] plots compared with [NT] plots. In the previous experiment, the average difference in soil porosity between the [T] plots and [NT] plots was about 7%. The difference of porosity values between the two treatments was smaller in the present study (3 %) because the samples for ascertaining porosity were taken at the end of the rainy season. Even though the rainfall during the season filled the pores made by termites before the rainy season the porosity was still greater in [T] plots than in [NT] plots.

Macropores made by termites enhance the internal flow of water in the soil and account for the higher K_{sat} on termite plots. They may sometimes create conditions for an important preferential flow. Mando et al. (in preparation) found that many termite-made voids were coated with fine clay, which is evidence that these voids conduct water flow.

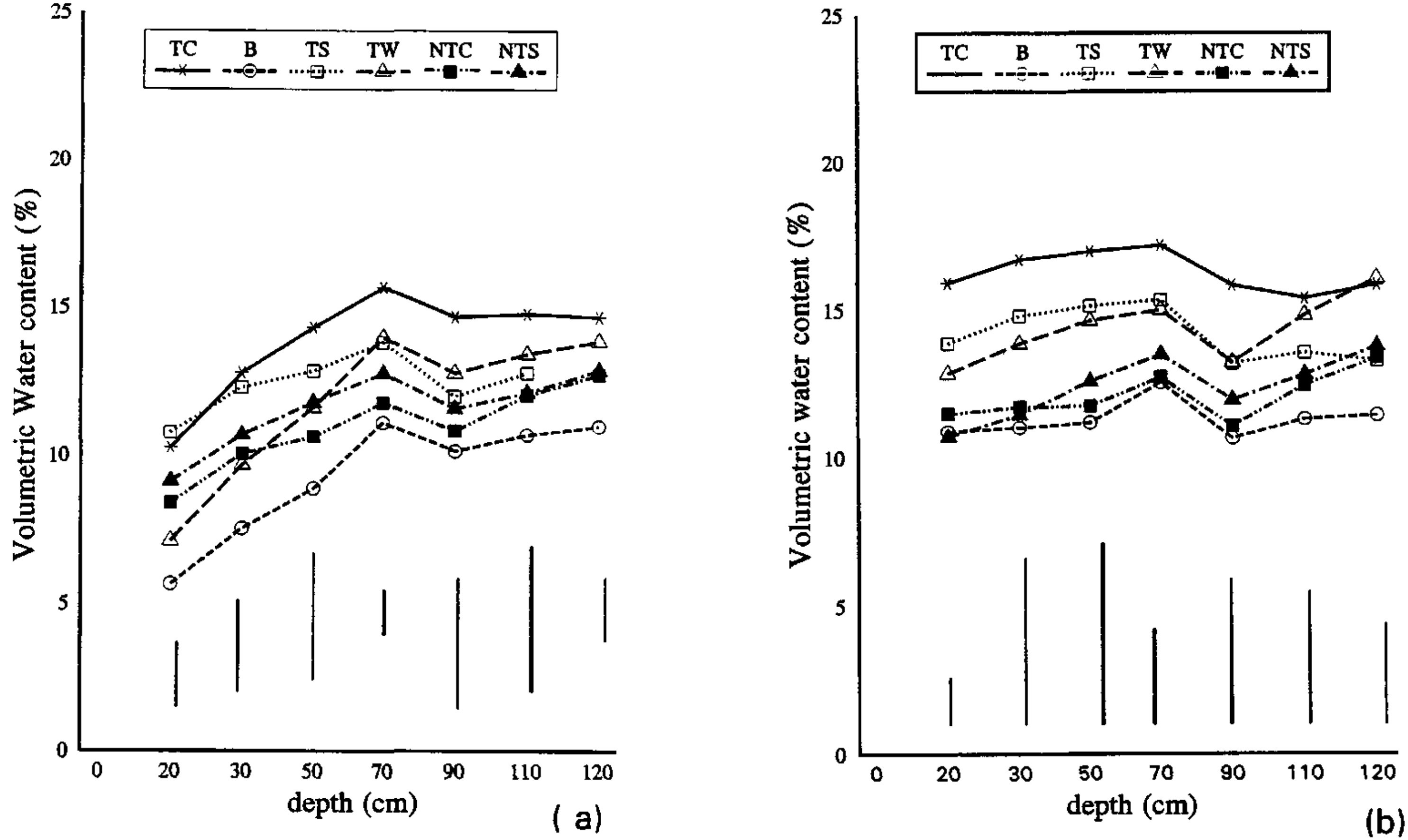

Figure 4.2: *Effect of termites and mulch on soil water distribution in the Chromic Cambisol in the wetting period: June 1994 (a) and June 1995 (b). Error bars represent LSD (0.05). Legend is the same as Figure 4.1 .*

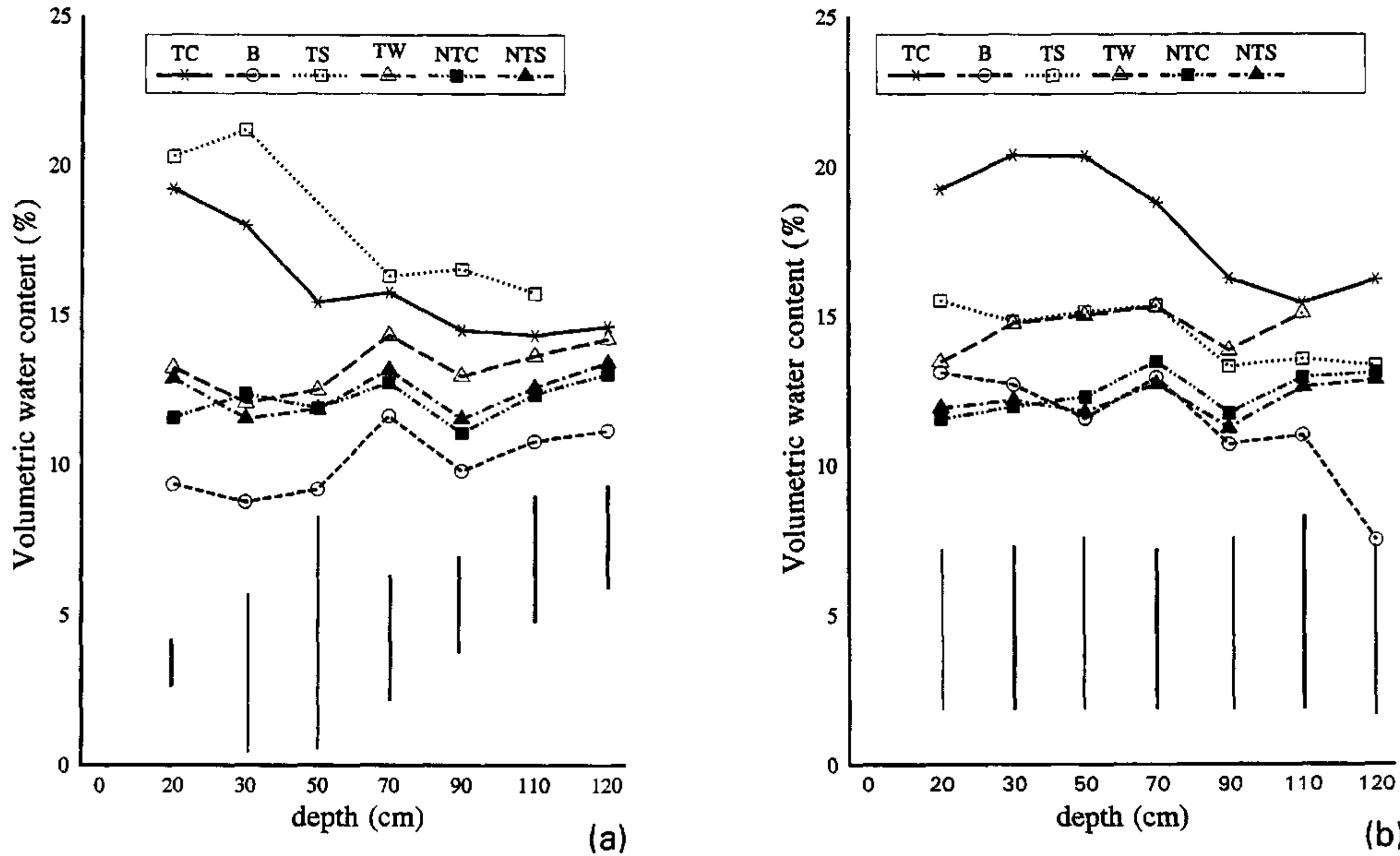

Figure 4.3: *Effect of termites and mulch on soil water distribution in the Chromic Cambisol in the wet period (August 1994 (a) and August 1995 (b). Errors bars represent LSD (0.05).*

The combined effect of a decrease in bulk density and an increase in porosity resulted in the decrease of soil resistance to cone penetration. The crusted status of the [NT] and Bare plots was responsible for the greater soil resistance to cone penetration. Crust is known to be more resistant to cone penetration than the subsoil (Mullins and Ley, 1995). The values of soil resistance to cone penetration on [NT] and Bare plots greatly exceeded the critical limit to root elongation. In fact, Greacen et al. (1969) ranged critical values for root growth between 0.8 and 5 MPa, depending on the crop. The consequences of termite activity in our experiment were therefore that the soil resistance of soil in the rooting zone was reduced to values below the critical level. Thus termite activity alleviates the constraint to vegetation development posed by this resistant layer. Mando (unpublished data) found a negative correlation between plant biomass and the soil's resistance to cone penetration. The mechanism of the reduction of the soil's resistance to cone penetration is the combined effect of destruction of the crust by termite burrowing and the removal of soil by termites which loosens the soil and leads to an increase in soil water content.

The decrease in resistance to cone penetration in the 10 cm to 30 cm layer may be explained by the field history. Before being abandoned because of excessive crust formation, the field had been used for farming of sorghum (Ranson and Lafaye pers. comm.) and this layer below the crust represents the old tilled layer.

Macropores on [T] plots are important not only to enable rainfall to infiltrate the soil but also to capture overland flow. On mulched plots this capture is enhanced by the many tiny barriers of the mulch that delay runoff. All these factors enhanced the water distribution in the soil profile in [T] plots. Furthermore these plots accumulate more water because of the open macropores. Their greater hydraulic conductivity allows a better distribution of water along the profile, and water recharges more deeply in [T] plots than in [NT] plots. The reason that in dry periods, [T] plots may be drier at 20 cm depth than in [NT] plots is the greater extraction of water by the vegetation, which is more developed on [T] (Mando et al., in prep.).

Mulch without termites did not affect the intrinsic characteristics of the soil but did affect soil water distribution particularly during periods of drought. The reason that in such periods the mulched [NT] plots, especially those mulched with straw, sometimes had a greater water content than [T] plots is that the mulch was more effective on [NT] plots than [T] plots, because it has not been removed by termites.

Conclusion

This study has demonstrated that intrinsic soil properties like porosity/dry bulk density and K_{sat} on structurally crusted soil after mulch application are determined by termite activity in the Sahelian semi-arid zone. The consequences of the termite activity are improved soil water status and a reduced soil resistance to cone penetration which are critical to plant production. Therefore in agroecosystems with low external input, the manipulation of termite-mediated processes should be taken into account in the management of soils to enhance soil quality. Furthermore, in such circumstances any agronomic measures detrimental to this termite activity should be minimized.

Acknowledgements

Thanks are due to Prof. L. Stroosnijder and Prof. L. Brussaard for the interesting discussions during the field work and for useful comments on the manuscript.

References

Adams, J.E., 1966. Influence of mulches on runoff, erosion and soil moisture depletion. Proceedings of the Soil Science Society of America, 30:110-114.

BUNASOL, 1995. Etude Morpho-pédologique de la province du Bam (échelle 1/50.000),(Rapport Technique n⁰ 97, vol.1). BUNASOL, Ouagadougou.

Chase, R. and Boudouresque, E., 1987. Methods to stimulate plant regrowth on bare, Sahelian forest soils in the region of Niamey, Niger, Agriculture, Ecosystems and Environment, 18:211-221.

Charles, R.W., 1979. The pesticide manual: a world compendium (6th edn.). British Protection Council, London, 295 pp.

Greacen, E. L., Barley, K. P. and Farrell, D.A., 1969. The mechanism of root growth in soils with particular reference to the implication of root distribution. pp. 256-268 in W.J. Whittington, (ed.). Root growth, Butterworths, London.

Kaboré, V., 1994. Amélioration de la production végétale des sols dégradés (zippéllés) du Burkina Faso par la technique des poquets (Zai). Thèse de doctorat. EPFL, Lausanne.

Klute, A. (ed.) 1986. Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods (2nd edn.). American Society of Agronomy, Madison, Wisconsin.

Lal, R. and F.J., Hall, G.F. and Miller, F.P., 1989. Soil degradation: Basic processes. Land Degradation & Rehabilitation, 1:51- 69.

Mando, A., 1991. Impact de l'activité des termites sur la dégradation de la biomasse végétale et quelques propriétes physiques des sols dégradés: Etude menée à Zanamogo (Burkina Faso). Mémoire de fin d'études, Université de Ouagadougou, ISN/IDR.

Mando, A., Van Driel, W.F. and Zombré, N.P., 1994. Le rôle des termites dans la restauration des sols ferrugineux tropicaux encroutés au Sahel. Contribution au 1er colloque international de l'AOCASS: Gestion durable des sols et de l'environnement en Afrique tropicale.

Mando, A., Stroosnijder, L. and Brussaard, L., 1996. Effects of termites on infiltration in crusted soil. Geoderma, 74:107-113.

Mando, A. and Miedema, R. (in press). Termite-induced change in soil structure after mulching degraded (crushed) soil in the Shel. Applied soil Ecology (in press).

Miller, R.G., 1981. Simultaneous statistical inference (2nd edn). Springer Verlag, New York.

Mullins, C.E. and Ley, G.J., 1995. Mechanisms and characterization of hardsetting in soil. Pp. 157 -170 in H.B. So, G.D. Smith, and R.J. Loch (eds.). Sealing, Crusting and Hardsetting Soils: Productivity and Conservation. Australian Society of Soil Science, Brisbane.

Pieri, C., 1989. Fertilité des terres de savanes. Bilan de trente années de recherche et de développement agricole au sud du Sahara. Ministère de la coopération/CRAD, Paris.

Tian, G., Kang, B.T and Brussaard, L., 1993. Mulching effect of plant residues with chemically contrasting compositions on maize growth and nutrient accumulation. Plant and Soil, 153:179-187.

Toutain, B. and Wespelaere, G., 1977. Pâturages de l'ORD du Sahel et de la zone de délestage au nord-est de Fada N'Gourma (Haute Volta) (Tome I: Les pâturages naturels et leur mise en valeur). Institut d'Elevage et de Médecine Vétérinaire des Pays Tropicaux, Paris.

Unesco, 1977. Carte de la répartition des régions arides (Note techniques du MAB, n° 7). Unesco, Paris.

Unesco 1973. International classification and mapping of vegetation. Ecological Conservation n° 6, Unesco, Paris.

Wades, W.K. and Sanchez, P.A. 1983. Mulching and green manure application for continuous crop production in the Amazon Basin. Agronomy Journal, 75:3

Chapter 5

The impact of termites and mulch on the water balance of crusted Sahelian soil

Mando, A., 1997. The impact of termites and mulch on the water balance of crusted Sahelian soil. Soil Technology (in press).

Abstract

The effects of termite activity and four mulch types on the water balance of crusted soil were studied on two soils (a Lixisol and a Cambisol) in northern Burkina Faso. A split plot design with three replications was used, with Termite and Non Termite as main factor and Mulch treatments as second factor with three variables consisting of *Pennisetum pedicellatum* mulch (Straw), woody material of *Pterocarpus lucens* mulch (Woody material) and Composite mulch (straw + woody material) applied at rates of 3, 6 and 4 t ha^{-1} respectively. Dieldrin kept termites away from the non termite plots during the experiment. Water balance terms were assessed during three rainy seasons (1993, 1994 and 1995).

Termite activity resulted in a statistically significant increase of water infiltration, soil water storage and drainage. In 1993 the mean values for soil storage were higher (but not statistically significant) on mulched plots than on bare plots. During 1994 and 1995 the three mulch treatments formed a distinctive group that differed from bare treatments. Mulch treatment did not affect evapotranspiration and drainage in the two dry/normal years (1993 and 1995). Termite activity in mulch resulted in a statistically significant improvement in the humidification and water conservation of the crusted soil. Mulch without termites did not have a statistically significant effect on the water status of structurally crusted soil. This suggests that termite activity is a key element in the effectiveness of the mulching technique on crusted soil in the Sahel.

Key words: termites, mulch, crusted soil, infiltration, water storage, drainage, evapotranspiration.

Introduction

Lack of adequate water supply is the principal constraint to crop production in arid and semiarid tropical regions (Lal, 1991). This is not due to water shortage in these regions, as their annual rainfall varies from about 400 mm to over 1000 mm (Monteith, 1991), but is mainly the result of water loss from runoff and evaporation. The degree of water loss is worsened by degraded and crusted soil, which particularly increases the loss by runoff. These soils are now becoming a major agricultural problem in the Sahel (Kaboré, 1994) and they must be rehabilitated if sustainable agriculture is to be achieved in this region. Degraded and crusted soils are often unproductive because of nutrient imbalance but mostly because of water shortage. These soils cannot be rehabilitated unless the conditions necessary to reduce runoff from them are created.

For environmental and economic reasons in the Sahel, the most appropriate approaches to increase the soil water infiltration and storage capacity are those based on renewable, available and affordable resources. One such approach is to use termite-mediated processes to improve the soil water balance. Termites are not only among the most important soil fauna of the tropics (Lobry de Bruyn and Conacher, 1990); they are also known to play an important role in some soil processes such as decomposition (Wood, 1976) and soil structure formation (Mando, 1991, Wielemaker, 1984). However, so far little use has been made of termite-mediated processes in land management, especially in soil rehabilitation. It seems possible that termite activity on crusted soil can be triggered by mulch and that termite-mediated processes can improve the infiltration of water into the soil and the soil water storage and drainage capacity, thereby reducing runoff. The present study therefore explores the possibilities of using termite activity and mulch to rehabilitate crusted soil in the Sahel by reducing water loss from runoff and evaporation.

Methods

Site Description

The investigation was conducted on a 4 ha fenced area near Bourzanga in northern Burkina Faso, West Africa (about 4° West, 13° North). The climate is Sahelian Sudanian according to Unesco (1977). Rainfall is monomodal and occurs for 4 months from June to September. Its distribution is irregular in time and space, and the current trend is for annual means to decrease (Table 5.1).

The vegetation is of the steppe type according to Unesco's (1973) classification, with large bare areas. The life form of the grasses is dominantly annual therophyte, and perennial grasses are rare (Mando, 1991). The woody component is dominated by shrubs. The most important families are *Mimosaceae* and *Combretaceae*. The common termite genera are *Microtermes, Macrotermes* and *Odontotermes*.

Lixisols and Cambisols are the commonest soil types in the area (Bunasol, 1995). The soil types on the experimental site are:

- Chromic Cambisol with a pH between 5 and 8 from 5 cm to 120 cm depth, CEC < 17 meq 100 g-1 from 0 cm to 120 cm depth. The textural classes according to the USDA system are sandy clay loam in the top 5 cm (49% sand, 29% silt and 21% clay) and clay below 70 cm depth (45% clay, 20% sand and 35% silt). Average bulk density is 1.6 g cm^{-3} at 0-5 cm layer and 1.7 g cm^{-3} at 120 cm depth. Soil organic matter content is 0.6% between 0 cm and 20 cm depth and 0.2% at 120 cm depth.

Period	mean rainfall
1964 to 1973	572 mm
1974 to 1983	547 mm
1984 to 1993	456 mm

Table 5.1: *Mean annual rainfall in Bourzanga from 1964 to 1993.*

- Ferric Lixisol with a pH of about 4.1 at 5 cm and of 6.1 at 110 cm depth. CEC is 6 meq 100 g^{-1} at 5 cm depth and 12.4 meq 100 g^{-1} at 120 cm depth. The textural class is sandy loam (37% of sand, 43% silt and 20% clay). The average bulk density is 1.5 g cm^{-3} at 5 cm depth and 1.7 g cm^{-3} at depths below 70 cm. Soil organic matter content is 0.51% at 5 cm depth but decreases to 0.17% at 120 cm depth.

- Haplic Lixisol with pH < 5, CEC < 9 meq 100 g^{-1} and sandy loam textural class (53% sand, 25% silt and 21% clay). Average bulk density is 1.4 g cm^{-3} at 5 cm depth and 1.6 g cm^{-3} at 120 cm depth. Soil organic matter content is 0.3% at 5 cm depth and 0.17% below 100 cm depth.

Annual runoff is very high: 60-80% of annual rainfall on Cambisols and 50-90% on Lixisols because of the degraded status of these soils. Soil crusting is the major problem, but soils also suffer from nutrient deficits.

Experimental design

A split plot design was used, with three blocks, one on each soil type. The main treatment was the use of an insecticide to obtain termite infested plots [T] and non termite plots [NT]. We used dieldrin at a rate of 500 g a.i ha^{-1} spread on [NT] plots just before the experiment began. Dieldrin is an organochlorine whose common name is HEOD. It is a persistent and non systemic insecticide of high contact and stomach activity to most insects (Charles, 1979). Dieldrin was used after Dursban EC (at the rate of 400 g a.i ha^{-1}) had failed to keep termites away from [NT] plots.

The main plots were 50 * 50 m and were 50 m apart. The subplots were two groups of four subplots, each measuring 15 m * 8 m and 8 m apart. The two groups of subplots in each main plots were 15 m apart (Figure 1.2). Mulch treatments were randomly applied in these subplots. These were straw of *Pennisetum pedicellatum* [S] applied at 3 t ha^{-1}, woody material of *Pterocarpus lucens* [W] applied at 6 t ha^{-1} and composite [C] (woody material and straw) treatments applied at 4 t ha^{-1}. In addition there was a control with no mulch called bare [B]. Different rates of mulch were used, to achieve the same degree of cover of organic mulch on the subplots.

The experimental site was established in June 1993 and was fenced to exclude large herbivores. Data were collected every year from 1993 until November 1995.

Field data

We used the most common water balance model given as:

$$ET = I - \Delta S - D \quad [1]$$

and

$$I = P - R \quad [2]$$

Where ET is evapotranspiration, I is infiltration (surface storage is considered as infiltration), ΔS is change in soil water storage, D is deep drainage, P is precipitation and R is runoff. P, R and the soil water content were measured and ET, D and I were derived from [1] and [2]. S was calculated using the soil water content data and [6]. All the variables were expressed in mm.

Precipitation

An automatic rain gauge and a simple rain gauge installed at 1 m above the soil surface were used to record rainfall characteristics. The former allowed us to record rainfall amount, intensity and duration. The latter was used to check the automatic rain gauge's operation.

Runoff

Runoff data were collected on each subplot (treatment) from 1 m^2 squares enclosed by metal frames (1.25 m * 0.80 m). Runoff from the enclosed frame was caught in a 60 litres barrel buried in the soil. After each rainfall event, the collected runoff water was pumped out and measured. The difference between rainfall and runoff is considered to be infiltration, assuming that any water remaining on the soil surface eventually infiltrates.

Water storage

The soil water content from which the soil water storage was calculated was assessed using a neutron probe. For the calibration, we compared neutron count rates with volumetric water content data obtained by the conventional oven-drying method (samples dried at 105 °C during 24 hours). A linear relationship between count ratio and volumetric water content per layer can be drawn: $\%WC = a*R0/RS + b$ where %WC, R0, RS, a,b are volumetric water content, neutron count in soil, neutron count in a standard medium and constants respectively. R0/RS is the Count Ratio (CR).

The following equations were obtained using more than forty pairs (count ratio, water content) per depth layer.

0-50 cm $\%WC = -3.45 + 16.31\ CR$ ($r^2 = 0.92$) [3]

50-70 cm $\%WC = -6.41 + 18.00\ CR$ ($r^2 = 0.93$) [4]

>70 cm $\%WC = -12.57 + 21.58\ CR$ ($r^2 = 0.92$) [5]

Water storage (S) in the soil profile was calculated from the following formula:

$S = \Sigma\ WC(z)$ [6]

where WC(z) is the volumetric water content at depth z. Water content in the 0-10 cm layer was assumed to be equal to the water content in the layer 10 cm - 20 cm for the calculation of (S).

In all subplots, two access tubes were installed until 120 cm, except in a few places where it was impossible to bore deeper than 100 cm because of very hard layers. Data were collected every three days during the wet period and every week during the dry periods, at depths of 20, 30, 50, 70, 90, 110 and 120 cm.

Drainage (D) and Evapotranspiration (ET)

We used the I and S data and the equation [1] to calculate D + ET.

$I\text{-}\Delta S = ET + D$ [7]

For the separation of (I-ΔS) over the terms ET and D we used the following reasoning based on the magnitude of (I-ΔS).

Two cases may occur.

If $ETP > (I\text{-}\Delta S) >= 0$, then $ET = (I\text{-}\Delta S)$ and $D=0$ [8]

If $ETP < (I\text{-}\Delta S) > 0$, then $ET = ETP$ and $D=(I\text{-}\Delta S)\text{-}ETP$ [9]

The case where $(I\text{-}\Delta S) < 0$, was not possible for our case since it would imply that the soil profile has gained water from another source than from infiltration.

In the above equations ETP stands for potential evapotranspiration. ETP was calculated using The Penman's equation and data from the national weather station at 50 km from the experimental site.

The above method is the most widely used technique in water balance studies in the Sahel (Stroosnijder and Koné, 1982; Vachaud et al., 1991; Hien, 1995), but one should keep in mind that its drawback is that the accuracy of ET and D depend on the accuracy of the variables I and ΔS.

Data analysis

The student Newman-Keuls test for multiple comparisons (Miller,1981) was used for all the relations to assess significant differences between treatments. Precipitation (P) data were divided into four classes: $P < 10$ mm, 10 mm $< P <$ 20 mm, 20 mm $<P<$ 30 mm and $P>$ 30 mm.

Results

Rainfall characteristics

The rainfall characteristics for 1993, 1994 and 1995 are presented in Table 5.2. The annual totals for the 1993 and 1995 rainy seasons were close to the 1984 -1993 mean rainfall but were less than in previous years (Table 5.1). In 1993, 40 showers with a total amount of 457 mm fell on the site but in 1994, 45 showers (the smallest rainfall was 5 mm and the greatest 71 mm) with a total amount of 808 mm occurred. This was the largest annual total rainfall for 30 years. During the 1995 rainy season only 30 rainfall events occurred, with a total amount of 484 mm. The 1993, 1994 and 1995 rainy seasons were characterized by minimum rainfall in May and June and the wettest period in July - August (Table 5.2).

	1993		1994		1995	
	mr (mm)	ne	mr (mm)	ne	mr (mm)	ne
April						
May	0		52.4	4		
June	29.9	4	66.4	4	48	3
July	142.6	12	150	9	176.5	6
August	168.2	12	247	11	142.5	11
September	95	8	164	11	88.5	7
October	20.8	4	127	6	28.5	2
Annual	457	40	808	45	484	30

Table 5.2: *Rainfall characteristics of 1993, 1994 and 1995 measured on the site. mr = monthly rainfall amount, ne = number of events*

Classifying the rainfall for the three years into four classes of rainfall amount shows that half of the rainfall in 1993 fell in big showers of more than 30 mm but only 28% of rainfall in 1994 and 21% in 1995 fell in showers of more than 30 mm (Table 5.3).

	1993	1994	1995
P < 10 mm	23%	14%	10%
10 mm < P < 20 mm	11%	33%	26%
20 mm < P < 30 mm	15%	23%	24%
P > 30 mm	50%	28%	21%

Table 5.3: *Precipitation classes in Bourzanga (experimental site) in 1993, 1994 and 1995. P = precipitation amount.*

Infiltration

Infiltration (expressed in % of annual rainfall amount) increased in both [T] and [NT] plots in 1993-1995. The increase was significantly larger in [T] plots. From Table 5.4 it appears that the termite effect was much clearer in 1994 and 1995. Therefore, for these two years the null hypothesis that the termite activity has no effect was very unlikely.

Mulch treatment did not show a statistically significant effect in 1993, but in 1994 and 1995 it emerged that Composite and Straw mulches had the greatest effect on infiltration, followed by Woody material and then Bare plots (Table 5.5).

Analysis of annual data did not show a statistically significant interaction of Termite and Mulch, but an interaction did occur when the data of all years were examined together, with time as a factor ($P<0.001$) (Table 5.6). The interaction effect showed that [NT] did not differ from B plots. Infiltration increased significantly ($P<0.001$) (Table 5.5) in all the subplots between 1993 and 1995. However, time did not interact with Termite or Mulch variables. (Table 5.6).

Soil water storage

Soil water storage in the soil profile (0-120 cm) was greater in [T] plots than in [NT] plots for 1993 and 1994 (Figure 5.1) and, 1995 (Figure 5.2) for all periods investigated. Statistical analysis (Table 5.7) indicated a significant difference between [T] and [NT] plots for all dates except during the wetting period, i.e. the beginning of the rainy season: July 1994 and July 1995.

		I(mm)	I(%ΣP)	df	P	cv(%)
1993	T	148 a	32	1	0.03	20.4%
	NT	98 b	21			
1994	T	429 a	53	1	<0.01	15.3%
	NT	300 b	37			
1995	T	334 a	69	1	<0.01	17.1%
	NT	247 b	51			

Table 5.4: *Anova of Termite effect on annual water infiltration during the 1993, 1994 and 1995 rainy seasons. T: Termite plots; NT: Non Termite plots. Treatments with different letters within a year are significantly different. I: seasonal cumulative infiltration, %I: Infiltration expressed as a percent of annual rainfall, df: degrees of freedom; P: Probability level, cv: coefficient of variation.*

C, S and W mulches formed a distinctive group that differed from B plots for all the periods of the years in question. During the wet periods of 1994 and 1995 the data analysis indicated a statistically significant interaction between Mulch and Termite. TC and TS plots did not differ statistically and the latter did not differ from TW either. The [NT] mulched plots and the B plots could be grouped together.

Throughout the experiment the greatest soil water storage was recorded in August for all the plots. In [T] or [NT] plots the C and S subplots had the greatest water storage for all years and periods of the year, followed by W and B plots, except for 1995, where average TW water storage was greater than TS. The maximum amount of water stored in a year increased steadily from 1993 to 1995 in [T] plots despite the lower rainfall in 1995. Maximum water stored in [NT] plots increased from 1993 to 1994 but decreased in 1995.

		I (mm)	I(%ΣP)	df	P	cv(%)
1993	C	148 a	32	3	0.14	33.5
	S	135 a	29			
	W	127 a	28			
	B	85 a	18			
1994	C	453 a	56	3	<0.01	17.4
	S	413 ab	51			
	W	330 bc	41			
	B	261 c	32			
1995	C	345 a	71	3	<0.01	17.1
	S	323 a	70			
	W	297 a	61			
	B	196 b	40			

Table 5.5: *Anova of mulch effects on water infiltration in crusted soil during the 1993, 1994 and 1995 rainy seasons. Treatments with different letter(s) within a year are significantly different from each other. C : Composite mulch S: Straw mulch; W: woody mulch; B: Bare. Other symbols as in Table 5.4*

	df	P	cv(%)
Bl	2	0.50	
Y	2	<0.01	16.1
T	1	<0.01	16.3
Y*T	2	0.88	16.3
M	3	<0.01	16.3
Y*M	6	0.08	16.3
T*M	3	<0.01	16.3

Table 5.6: *Statistics of Time, Termite and Mulch effects on Infiltration. df = degrees of freedom, cv: coefficient of variation; Y: Year, T: Termite, M: Mulch. P: probability level, Bl: Block*

Evapotranspiration (ET) and Drainage (D)

ET was significantly greater in 1993 and 1994 in [T] plots compared with [NT] plots (Table 5.8 and Figure 5.3). In 1995 the mean values of ET were slightly greater on [NT] plots than on [T] plots. Mulch treatments did not show significant differences, except in 1995, where the values for all mulch treatments were greater than those for bare plots (Table 5.8 and Figure 5.4, the mean values of all Mulched subplots are not shown).

Termites significantly affected drainage in all three years, as can be seen by comparisons with NT plots in Figure 5.3. Mean D values increased from 1993 to 1995. Mulch had no effect on drainage except in 1994, the year of abundant rainfall (Table 5.8 and Figure 5.4). For that year, the interaction effect of Mulch and Termite (T*M) indicated that only Termite mulched subplots differed from B subplots. [NT] mulched plots could be grouped together with B. For normal years like 1993 and 1995, drainage was greater in [T] plots than in [NT] mulched plots whose drainage was almost nil; even bare crusted plots had greater drainage than [NT] mulched plots during those years.

Discussion

Infiltration

Our results prove that termite activity is a key element in the efficacy of mulching to improve the infiltration capacity of crusted soil in the Sahel. In 1993 mulching did not show any effect on the crusted soil's infiltration but during that first year termites already significantly improved crusted soil infiltration. In 1994 and 1995 all mulch types formed a distinct group that differed from the bare plots. The consequences of the improved infiltration during the first year, such as the revegetation of Termite mulched plots, may have enhanced the infiltration in mulched plots compared with B plots during the following years. This is particularly likely, given that the order of increasing infiltration was the same as the order of termite activity and vegetation cover in mulched plots (Mando, 1991 and Mando et al., 1996): Composite, Straw, Woody material. Furthermore, eolian sediment trapped by mulch may also have improved infiltration in the mulched plots (Chase and Boudouresque, 1987).

The heavier rainfall events in 1993 compared with 1994 and 1995 could be a factor in explaining why the fraction of rainfall that had infiltrated was smaller in that year. Soil infiltration rate is known to be inversely related to the amount of rainfall (Masse, 1992). The decrease of infiltration rate with rainfall was more pronounced on [NT] plots compared with [T] plots (Mando et al., 1996). This is because termites improve infiltration by means of the tunnels they create in the soil. Chase and Boudouresque (1987) stated that a single termite channel of 0.8 cm diameter can sustain a water flow rate of 500-700 ml min^{-1} for 30 minutes. We found (Mando et al., 1996) that termite activity increases the time until ponding and therefore delays the onset of runoff.

Soil water storage, evapotranspiration and drainage

Termites and mulching increased the water storage capacity of the soil. Water storage on [T] plots is related to the amount of water input by infiltration, and this is far greater compared with [NT] plots (Table 5.4), because the soil structure has been modified by termites (Lobry de Bruyn and Conacher, 1990). Mulch may also influence soil water storage by reducing soil temperature (Tian et al., 1993) and thus decreasing convective vapour loss to the air (Chase and Boudouresque, 1987).

ET is not always affected by termites nor always by mulch and this is probably because the prevailing weather is more important for ET than soil cover or soil structure. The relative decrease of ET in Termite plots over the three years is attributable to the improved drainage.

The low values of ET and high values of D on bare crusted soil as compared with [NT] mulched plots in the dry/normal years (1993, 1995) can be attributed to the protective effect of soil crust (Valentin, 1995) and also to the absence of transpiration due to lack of vegetation.

Differences in water storage and drainage between [T] and [NT] plots were greater during the two normal/dry years and are expected to be even greater in drier years than in extremely wet years (1994). This, plus the finding that ET was greater on [NT] plots, especially in dry years, indicates that termite-mediated processes contribute to retaining and conserving water in the soil. The mechanisms underlying this are the increase of water input by infiltration and the water being protected from evaporation when it drains to deeper layers; however, this drained water may diffuse to upper layers when they become dry. This is confirmed by the temporary stability/increase of water storage after the end of the rainy season (Figure 5.1).

		cv (%)	P	df
Aug. 93	Bl		0.07	2
	T	6.2	0.08	1
	M	14.2	0.03	3
	M * T	14.2	0.33	7
Oct. 93	Bl		0.53	2
	T	6	0.01	1
	M	13.9	<0.01	3
	M * T	13.9	0.29	7
Jul. 94	Bl		0.44	2
	T	15.6	0.35	1
	M	17.3	0.16	3
	M*T	17.3	0.90	7
Aug. 94	Bl			2
	T	5.7	0.01	1
	M	16.1	<0.01	3
	M * T	16.1	<0.01	7
Oct. 94	Bl		0.33	2
	T	5.7	0.01	1
	M	16.7	<0.01	3
	M * T	16.7	0.22	7
Dec. 94	Bl		0.45	2
	T	1.8	<0.01	1
	M	26.2	<0.01	3
	M * T	26.2	0.38	7
Jul. 95	Bl		0.51	2
	T	13.8	0.18	1
	M	13.3	0.01	3
	M*T	13.3	0.06	7
Aug. 95	Bl		0.27	2
	T	7.2	0.01	1
	M	7.3	<0.01	3
	M*T	7.3	<0.01	7
Oct. 95	Bl		0.26	2
	T	6.9	0.09	1
	M	11.5	0.04	3
	M * T	11.5	0.14	7

Table 5.7: *Selected statistics of termite and mulch effect on soil water storage. Bl :Block, T: Termite, M: Mulch and M*T: Mulch and Termite interaction effect. cv, P and df as in Table 5.6.*

		df	% cv	P
ET 93	Bl	2		0.39
	T	1	11.8	<0.01
	M	3	24.3	0.87
	T*M	7	24.3	0.12
ET 94	Bl	2		0.79
	T	1	3.3	<0.01
	M	3	46.3	0.08
	T*M	7	46.3	0.11
ET 95	Bl	2		0.09
	T	1	13.9	0.44
	M	3	10.3	<0.01
	M*T	7	10.3	0.83
D 93	Bl	2		0.43
	T	1	57.7	0.01
	M	3	14.9	0.47
	M*T	7	14.9	0.41
D 94	Bl	2		0.09
	T	1	14	<0.01
	M	3	17.3	<0.01
	M*T	7	17.3	<0.01
D 95	Bl	2		0.84
	T	1	116.3	0.06
	M	3	74.9	0.84
	M*T	7	74.9	0.70

Table 5.8: *Statistics of Mulch and Termite effect on Evapotranspiration (ET) and Drainage (D). For data on ET and D see Figure 5.3. Treatments as in Table 5.7.*

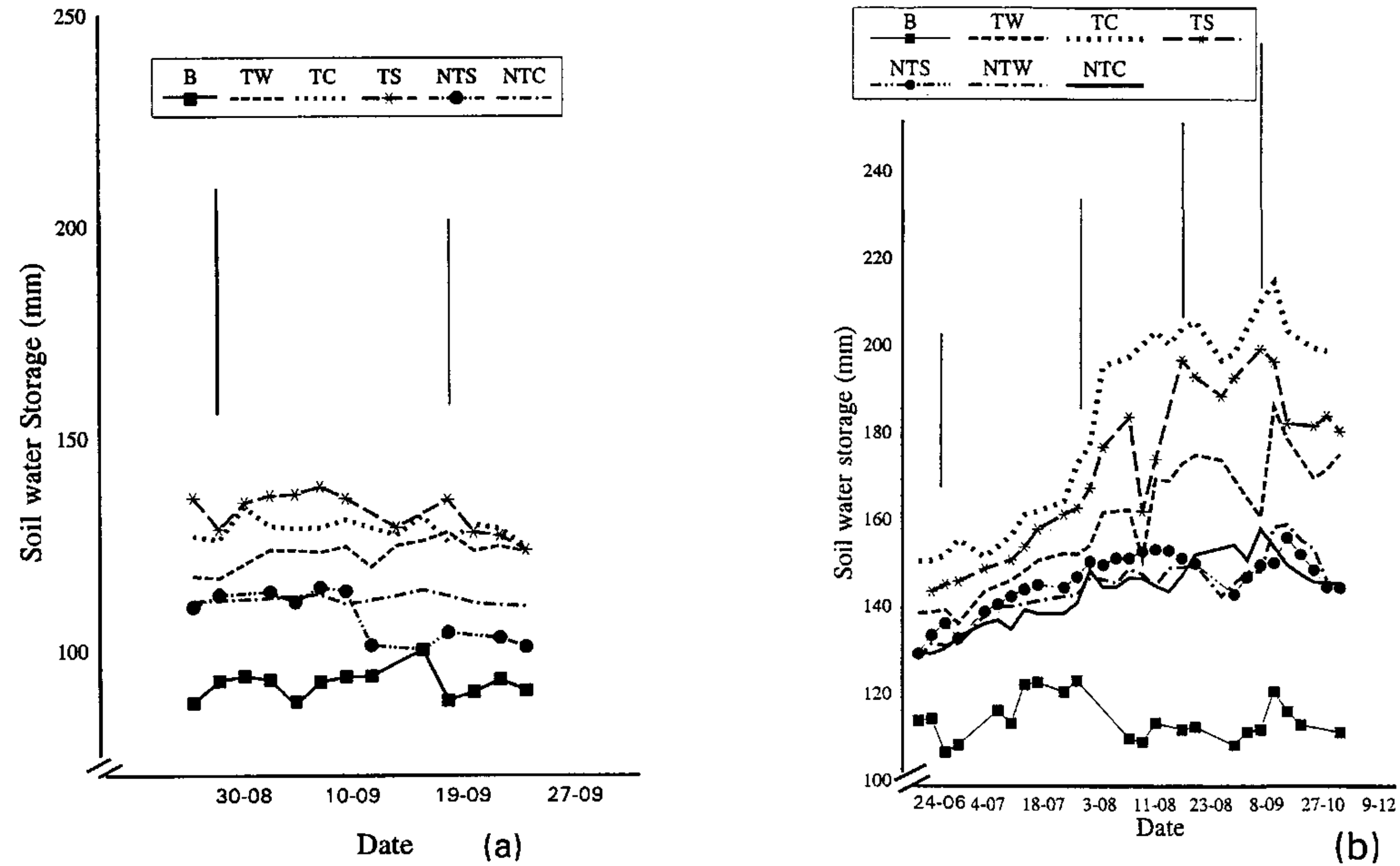

Figure 5.1: *Dynamics of soil water storage (0 - 120 cm) in 1993 (a) and 1994 (b). Effect of termite and mulch type. Errors bars represent LSD (0.05). TC = Termite Composite, TS = Termite Straw, TW = Termite Woody material NTC = Non Termite Composite, NTS = Non Termite Straw and B = Bare.*

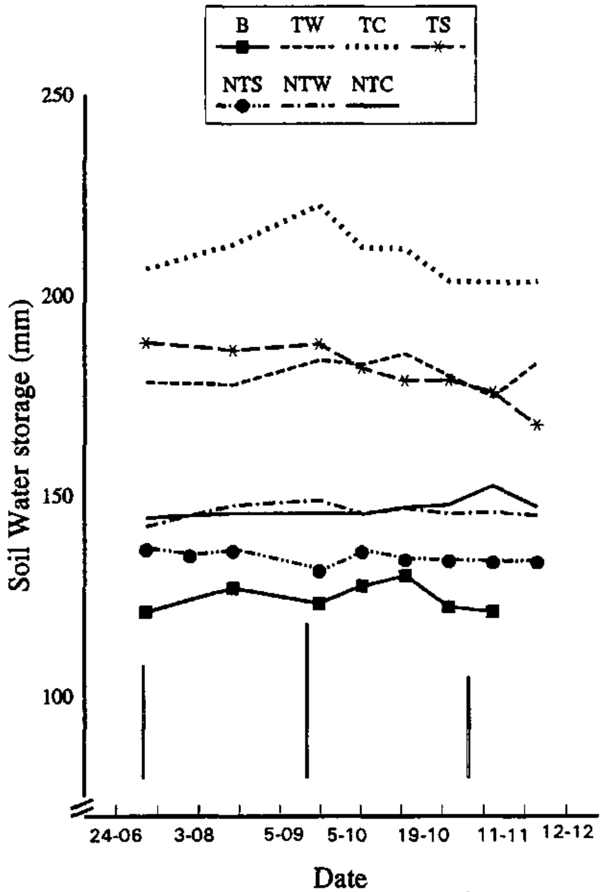

Figure 5.2: *Dynamics of soil water storage (0 - 120 cm) in 1995. Effect of termite and mulch type. Error bars represent LSD (0.05). TC = Termite Composite, TS =Termite Straw, TW = Termite Woody material NTC = Non Termite Composite, NTS = Non Termite Straw, NTW = Non Termite Woody material and B = Bare.*

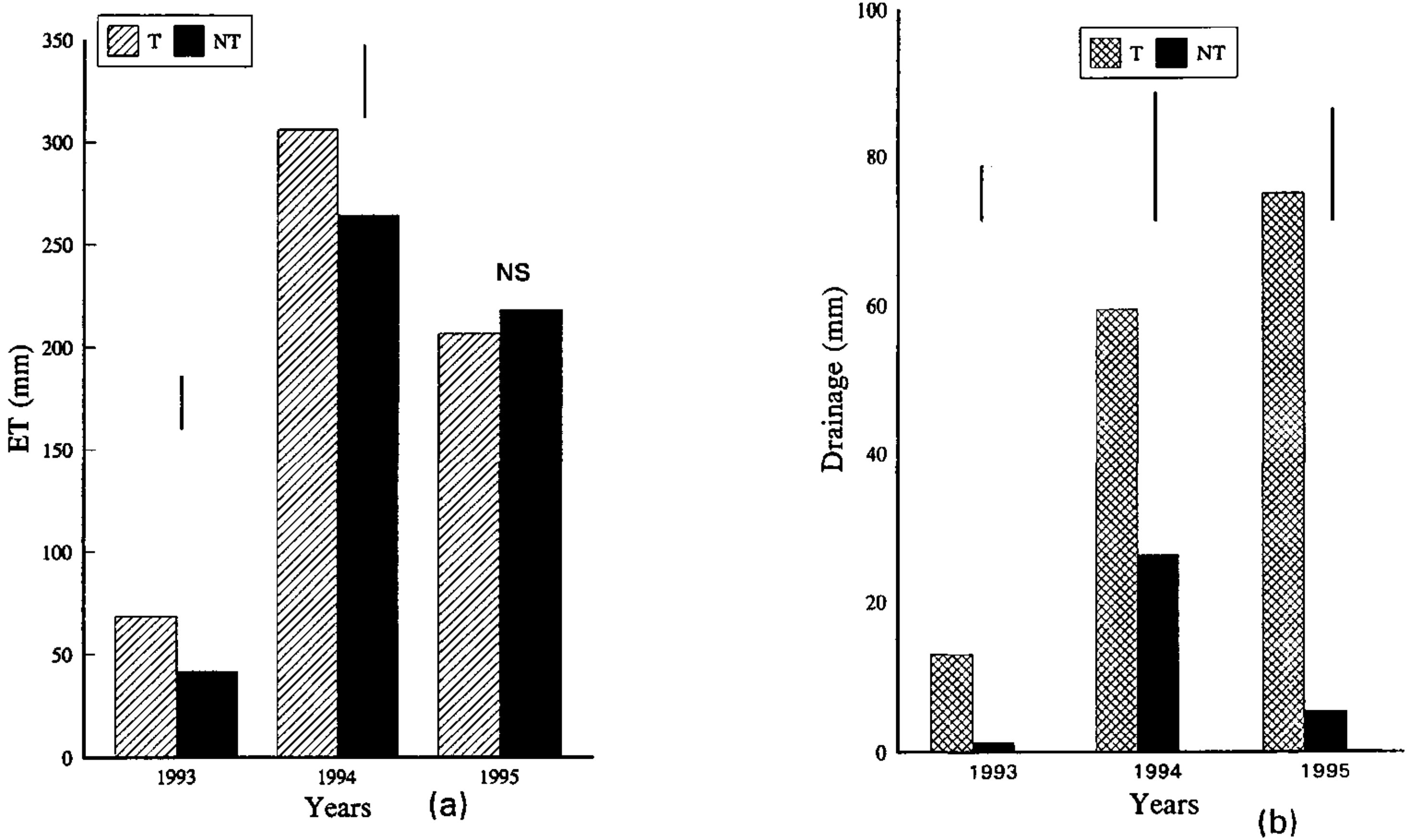

Figure 5.3: *Cumulative evapotranspiration (a) and Drainage (b) in Termite and Non Termite plots (July to October). Error bars represent LSD (0.05). T = Termite plots and NT = Non Termite plots.*
NS =Not Significant

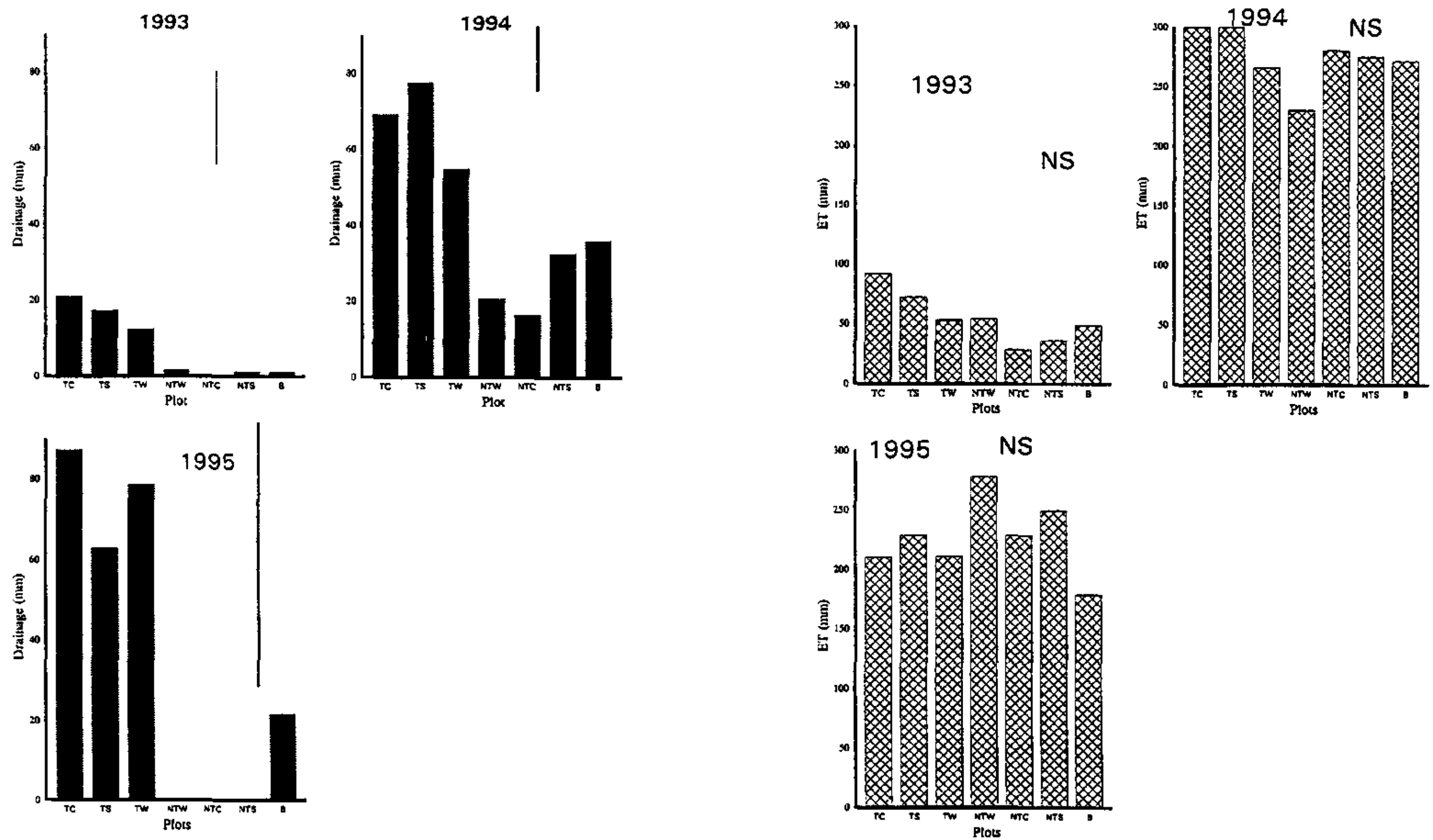

Figure 5.4: *Interaction effect of mulch and termite on cumulative evapotranspiration and cumulative drainage (July to October). Error bars represent LSD (0.05). Legend as in Fig.5.1*

Conclusion

The study confirms that termite activity has a great effect on the soil water balance of crusted soils. It increases infiltration amount, soil water storage and drainage. The physical effect of mulch is less important in the effectiveness of the mulch technique on the rehabilitation of the crusted Sahelian soils. Termite activity should therefore be taken into account when characterizing catchment hydrology and in land management in the Sahel. Indeed, it is clear that the response of natural vegetation or crops to the improved water availability due to termites is a relevant field to explore when considering the effectiveness of soil and water management techniques.

Acknowledgements

Thanks are due to Prof. L. Stroosnijder and Prof. L. Brussaard for the interesting discussion during the field work and for useful comments on the manuscript.

References

Bunasol, 1995. Etude morpho-pédologique de la province du Bam (échelle 1/50.000). Rapport Technique n⁰ 97, Bunasol, Ouagadougou, Burkina Faso, 195 pp+annexes.

Charles, R.W., 1979. The pesticide manual: A world compendium. British Protection Council; 6 th edition, London, 295 pp.

Chase, R. and Boudouresque, E. 1987. Methods to stimulate plant regrowth on bare, sahelian forest soils in the region of Niamey, Niger. Agriculture, Ecosystems and Environment, 18:211-221.

Gardner, C.M.K., Bell, J.P., Dean, T.J. and Martin, G.H., 1991. Soil water content. In K. A. Smith and C.E. Mullins (editors), Soil analysis - physical methods, Marcel Dekker, New York, 1-73.

Hien, F.G., 1995. La régénération de l'espace sylvo-pastoral au Sahel. Une étude de l'effet de mesures de conservation des eaux et des sols au Burkina Faso. Tropical Resource Management Papers, n⁰ 7, Wageningen Agricultural University, Wageningen, 194 pp.

Kaboré, V., 1994. Amélioration de la production végétale des sols dégradés ("Zippellés") du Burkina Faso par la technique des poquets (Zai). Thèse de doctorat. EPFL, Lausanne, 201 pp.

Lal R., 1991. Current research on crop water balance and implication for the future. In Sivukumar, M.V.K, Wallace, J.S, Renard, C. and Giroux, C. (editors). Soil water balance in the soudano sahelian zone. IAHS Publication, 191:31-43

Lobry de Bruyn, L.A and Conacher, A.J., 1990. The role of termites and ants in soil modification: a review. Australian Journal of Soil Research, 28:53-93.

Mando, A., Stroosnijder L. and Brussaard, L., 1996. Effects of termites on infiltration into crusted soil. Geoderma 74:107-113.

Mando, A., 1991. Impact de l'activité des termites sur la dégradation de la biomasse végétale et quelques propriétés physiques des sols dégradés: Etude menée à Zanamogo (Burkina Faso). Mémoire de fin d'études, Université de Ouagadougou, ISN/IDR, 76 pp.

Masse, D., 1992. Amélioration du regime hydrique des sols dégradés en vue de leur réhabilitation. Cas des vertisols du Nord Cameroun. Thèse de doctorat d'ingenieur INP Toulouse. IRA/ORSTOM, 137 pp.

Miller, R.G., 1981. Simultaneous statistical inference. 2nd ed. Springer, New York, 299 pp.

Monteith, J.L., 1991. Weather and water in the soudano sahelian zone. In Sivukumar, M.V.K, J.S Wallace, C. Renard and C. Giroux (edidors). Soil water balance in the soudano sahelian zone. IAHS Publ. 191: 1-13.

Stroosnijder, L. and Koné, D., 1982. Le bilan d'eau du sol. In F.W.T. Penning de Vries and M.A. Djitèye (editors). Productivité des pâturages sahéliens. Une étude des sols, de la végétation et de l'exploitation de cette ressource naturelle. Pudoc, Wageningen, The Netherlands, 133-165.

Tian, G., Kang, B.T., Brussaard, L., 1993. Mulching effect of plant residues with chemical contrasting compositions on maize growth and nutrient accumulation. Plant and Soil 153: 171-187.

Unesco, 1977. Carte de la répartition mondiale des régions arides. Notes techniques du MAB, n^0 7 Unesco, Paris 77 pp.

Unesco, 1973. International classification and mapping of vegetation. Ecological Conservation n^0 6, Unesco, Paris. 93 pp.

Vachaud, G., M. Vauclin and L. Cissé, L., 1991. Mesure in situ de la consommation en eau pluviale par humidimètre neutronique. In Sivukumar, M.V.K, J.S Wallace, C. Renard and C. Giroux (editors). Soil water balance in the soudano sahelian zone. IAHS Publ., 191:275-288.

Valentin, C., 1995. Sealing, crusting and hardsetting soils in Sahelian Agriculture. In: So H.B., G.D. Smith, S.R. Raine, B.M. Schafer (editors). 2nd International symposium on sealing, crusting, hardsetting soils: Productivity and conservation. Australian Society of Soil Science: 53-76.

Wielemaker, W.G., 1984. Soil formation by termites. A study in the Kisii area, Kenya. Doctoral thesis, Wageningen Agricultural University.

Wood, T.G., 1976. The role of termites (Isoptera) in decomposition processes. In: Anderson, J.M. and A. Macfadyen (editors). The role of terrestrial and aquatic organisms in decomposition processes. Blackwell, Oxford, pp 145-168.

Chapter 6

Termite and mulch mediated rehabilitation of vegetation on crusted soil in the Sahel

Mando, A., L. Brussaard, and L. Stroosnijder. Termite and mulch mediated rehabilitation of vegetation on crusted soil in the Sahel. Journal of Applied Ecology (submitted).

Abstract

The rehabilitation of vegetation on structurally crusted soils by triggering termite activity through mulch was studied on three soil types in northern Burkina Faso. A split plot design was used in a fenced environment for the experiment. Insecticide (Dieldrin) was used at a rate of 500 g a.i ha^{-1} to create Non Termite and Termite plots. Three mulch types consisting of straw (*Pennisetum pedicellatum*), woody material (*Pterocarpus lucens*) and a composite (woody material and straw) mulch applied at the rate of 3, 6 and 4 t ha^{-1} respectively were used to trigger termite activity. The grasses and woody species on the plots were surveyed.

Non Termite plots responded weakly to mulch treatments, but even in the first year, vegetation established on Termite + mulch plots. Termite activity resulted in the increase of plant cover, plant species number, phytomass production and rainfall use efficiency.

Infiltrated water use efficiency and plant diversity were not statistically significantly different between treatments during the first two years but were in the third. Woody species established only on termite plots.

The three types of mulch plots showed greater vegetation development than Bare plots which, which remained bare throughout the experiment. Analysis of the termite and mulch interaction indicated that mulch plots without termites did not perform better than Bare plots, especially in the case of woody plant regeneration. Vegetation rehabilitation was best with composite and straw mulches, followed by woody mulch, and was worst on Bare plots.

Key words: termite; plant cover; biomass; crusted soil; rehabilitation; mulch.

Introduction

In the Sahelian zone, the combined effect of soil organic matter depletion and the decrease in rainfall has resulted in the extension of crusted and unproductive land. Such land is characterized by very low infiltration capacity, nutrient imbalance, reduced biodiversity and very low to zero primary production. Until 20 years ago, the most common response to these phenomena was abandonment. But the ever increasing population on ever diminishing arable land resources has increased awareness of the urgent need to act, not only to curtail further degradation, but also to restore the productivity of already degraded land. Therefore people in this region are now attempting to develop a range of essentially physical and cultural measures against degradation (constructing of bands of stone lines, sowing grass and planting trees, etc.). However, all these attempts are seriously hampered by the crusted status of the degraded soil which limits the infiltration necessary to enable land rehabilitation (Hien, 1995).

The hypothesis tested in this paper is that the presence of dry vegetal material on structurally crusted soil can trigger termite activity and may thereby improve soil infiltration sufficiently to activate vegetation establishment. Termites are a major component of the soil fauna in the tropics (Lee and Wood, 1971) and their importance in modifying soil properties is generally recognized (Lobry de Bruyn and Conacher, 1990; Lavelle et al., 1992). When established on degraded soil, termites can improve soil physical properties within a short time (Mando, in press data). They also play a key role in the decomposition process (Whitford et al., 1991). Yet, despite the relative abundance of information on termite ecology, little is known on the effect of termite- mediated processes on the overall system productivity. In this study the aim was to evaluate to what extent termite-mediated processes in crusted soil can rehabilitate the vegetation. Both vegetation structure and production dynamics were investigated.

Methods

Site Description

The investigation was conducted near Bourzanga in northern Burkina Faso, West Africa (about 4° West, 13° North). The climate here is Sahelian Sudanian according to Unesco (1977). Rainfall is monomodal and occurs for 4 months from June to September. Its distribution is irregular in time and space, and annual means have been decreasing for several years (Table 6.1).

The vegetation is of the steppe type according to Unesco's (1973) classification, with large bare areas. The life form of the grasses is dominantly annual therophytes, and perennial grasses are rare (Mando et al., 1994). The woody component is dominated by shrubs. The most important families are *Mimosaceae* and *Combretaceae*. The common termite genera are *Microtermes, Macrotermes* and *Odontotermes*.

Lixisols and Cambisols are the commonest soil types in the area (Bunasol, 1995). The soil types on the experimental site are:

- Chromic Cambisol with a pH between 5 and 8 from 5 cm to 120 cm depth, CEC < 17 cmol(+) kg^{-1} from 0 cm to 120 cm depth. The textural classes according to USDA system are sandy clay loam in the top 5 cm (49% sand, 29% silt and 21% clay) and clay below 70 cm depth (45% clay, 20% sand and 35% silt). Average bulk density is 1.6 g cm^{-3}

Period	mean rainfall
1964 to 1973	572 mm
1974 to 1983	547 mm
1984 to 1993	456 mm

Table 6.1: *Mean annual rainfall in the experimental area from 1964 to 1993*

at 0-5 cm layer and 1.7 g cm^{-3} at 120 cm depth. Soil organic matter content is 0.6% between 0 cm and 20 cm depth and 0.2% at 120 cm depth.

- Ferric Lixisol with a pH of about 4.1 at 5 cm and of 6.1 at 110 cm depth. CEC is 6 cmol(+) kg^{-1} at 5 cm depth and 12.4 cmol(+) kg^{-1} at 120 cm depth. The textural class is sandy loam (20% clay, 43% silt and 37% of sand). The average bulk density is 1.5 g cm^{-3} at 5 cm depth and 1.7 g cm^{-3} at depths below 70 cm. Soil organic matter content is 0.51% at 5 cm depth but decreases to 0.17% at 120 cm depth.

- Haplic Lixisol with pH< 5, CEC < 9 cmol(+) kg^{-1} and sandy loam textural class (53% sand, 25% silt and 21% clay). Average bulk density is 1.4 g cm^{-3} at 5 cm depth and 1.6 g cm^{-3} at 120 cm depth. Soil organic matter content is 0.3% at 5 cm depth and 0.17% below 100 cm depth.

Annual runoff is very high: 60-80% of annual rainfall on Cambisols and 50 to 90% on Lixisols because of the degraded status of these soils. Soil crusting is the major problem, but these soils also suffer from nutrient deficits.

Experimental design

A split plot design was used, with three blocks, one on each soil type. The main treatment was the use of an insecticide, to obtain termite infested plots [T] and non termite plots [NT]). We used dieldrin at a rate of 500 g a.i ha^{-1} spread on [NT] plots just before the experiment began. Dieldrin is an organochlorine whose common name is HEOD. It is a persistent and non systemic insecticide of high contact and stomach activity to most insects (Charles, 1979). Dieldrin was used after Dursban EC (at the rate of 400 g a.i ha^{-1}) had failed to keep termites away from [NT] plots.

The main plots were 50 * 50 m and were 50 m apart. The subplots were two groups of four plot, 15 m * 8 m each and 8 m apart. The two groups of subplots in each main plots were 15 m apart. Mulch treatments were randomly applied in these plots. These were straw of *Pennisetum pedicellatum* [S] applied at 3 t ha^{-1}, woody material of *Pterocarpus lucens* [W] applied at 6 t ha^{-1} and composite [C] (woody material and straw) treatments applied at 4 t ha^{-1}. In addition there was a control with no mulch. Different rates of mulch were used to achieve the same degree of cover of organic mulch on the subplots. Earlier research (Mando et al., 1994) established that it is the degree of mulch cover that it is important for termite activity impact on the soil, rather its mass.

The experimental site, established in June 1993, was fenced to exclude large herbivores. Data were collected every year from 1993 until November 1995.

Field data

Vegetation (herb) parameters were recorded on the plots during three rainy seasons (1993, 1994, 1995). The point quadrat method (Daget and Poisonnet, 1971) was used to assess the probability of species occurrence, the total cover and the dynamics of the species composition. In this method, points arranged in a line are sampled at 5 cm intervals to assess the presence of vascular plant species. This yielded data on the absence or presence of species. Two 17 m transects were used in every plot to ascertain the probability of occurrence of a species (i) in a sample. Probability of occurrence (Pi) of species (i) was calculated as follows:

$$Pi = (FSi/\Sigma FSi)*100 \quad (1)$$

Where FSi expresses the frequency of the species i in the sample.

The total cover $R = \Sigma FSi/N * 100$ (2)

where N is the sample size (number of intercepts along transect)

Life forms were recorded and plants were identified to species level. Plant biomass was assessed at maximum standing crop (September) using the integral cut method, i.e by cutting all living plants found in 1 m^2 quadrat. Forty samples were taken from each main plot (five samples per plot). Plant biomass data were used to calculate Rainfall Use Efficiency (RUE) and Infiltrated Water Use Efficiency (IUE) for each main plot and each plot. Rainfall Use Efficiency is the quantity (expressed in Kg) of aboveground phytomass produced per 1 mm of rainfall and Infiltrated Water use Efficiency is the quantity of aboveground phytomass produced per 1 mm of infiltrated water. Infiltration was estimated as the difference between rainfall and runoff, assuming that surface water storage is part of the infiltration. RUE and IUE serve in drylands as excellent indicators of soil and hence, of ecosystem productivity (Aronson et al., 1993).

In 1995, the woody component of the vegetation was surveyed by systematically counting and identifying all woody species on the plots to establish their density.

Data analysis

The following classical indexes of diversity were used to study the effect of the treatments on plant community development:

- Shannon-Weaver index of diversity (H').

$$H' = -\sum_{i=1}^{N} p_i \log p_i \quad (3)$$

- Hill's (1973) diversity number $S1 = e^{H'}$ (4)

where p_i is the probability of occurrence of species i and N the total number of species. The dynamics of these indexes enable the effects of the treatments on the vegetation to be studied. ANOVA was used to establish the difference between treatments, and the Newman Keuls test was used to compare the means. The Student's t-test was used for the statistical analyses of pairs of treatments in the case of the indices, using data from [T] and [NT] plots.

Results

Rainfall characteristics

Average rainfall characteristics of the 1993, 1994 and 1995 rainy seasons are presented in Table 6.2. In 1993 and 1995 the annual rainfall totals were close to mean rainfall for 1984-

1993 but less than mean rainfall of previous decades (Table 6.1). In 1993 forty (40) showers with a total amount of 457 mm fell on the site, but in 1994, forty five (45) showers (the smallest rainfall was 5 mm and the greatest 71 mm) with a total amount of 808 mm occurred. This was the highest annual rainfall in the area for more than 30 years. During the 1995 rainy season only thirty (30) rainfall events occurred, with a total amount of 484 mm. The 1993, 1994 and 1995 rainy seasons were characterized by the lowest amount of rainfall falling in May and June and the highest in August.

Plant cover

In all three years the [T] plots had more vegetation cover compared with [NT], but the differences were statistically significant during 1994 and 1995 and not in 1993 (Tables 6.3-6.5). The statistical parameters for significant difference between [T] and [NT] treatments improved between 1993 and 1994 (P decreased during that period). Mulch affected the vegetation cover in all the years, but the three mulch types (Woody, Straw and Composite) were always a homogeneous group that differed from Bare, except for the first year where Woody plots did not differ from Bare plots (data not shown). Data on the 1994 and 1995 rainy seasons revealed a significant interaction of Mulch and Termite on plant cover (Tables 6.4 and 6.5). In 1994 TS (Termite+ straw plots) had more plant cover than the homogeneous group TW and TC. At the same time, [NT] plots did not differ from each other and from Bare plots.

	1993		1994		1995	
	mr (mm)	ne	mr (mm)	ne	mr (mm)	ne
April	0		0			
May	0		52.4	4		
June	29.9	4	66.4	4	48	4
July	142.6	12	150	9	176.5	6
August	168.2	12	247	11	142.5	11
September	95	8	164	11	88.5	7
October	20.8	4	127	6	28.5	2
Annual	457	40	808	45	484	30

Table 6.2: *Rainfall characteristics at the experimental site in 1993, 1994 and 1995. mr = monthly rainfall; ne = number of events.*

In 1995, [NT] plots and Bare plots were still a homogeneous group and Termite + Mulch plots also became a homogeneous group that differed from Bare and [NT] plots. Plant cover increased from 1993 to 1995 on all plots except the Bare plots where no vegetation developed.

1993		%Cover	NE
TS		20.93 a	(3-13) a
TC		11.19 a	(1-15) a
TW		9.29 a	(1-11) a
NTC		4.7 b	(1-8) a
NTS		8.68 b	(1-7) a
NTW		1.97 b	(0-6) a
Ba		0 b	0 a
	B	df= 2 P=0.26	df=2 P=0.30
	T	df=1 P=0.14	df=1 P= 0.11
	T*M	df=7 P=0.45	df=7 P=0.12
	M	df=3 P=0.012	df=3 P=0.003

Table 6.3: *Effects of Termites and Mulch on selected vegetation parameters in 1993. NE: Number of species. TS = termite straw; TC = Termite composite; TW = Termite woody; NTS = Non Termite straw; TNC = Non Termite composite; NTW = Non Termite woody and Ba = bare. B = Block; T = Termite; T*M = Termite and Mulch interaction; M = Mulch.*
P is the probability of treatment being not different; cv = coefficient of variation; df = degrees of freedom.

Plant biomass and water use efficiency.

In 1993 the vegetation on all plots was sparse and biomass could not be estimated accurately. In 1994 and 1995 [T] plots had greater biomass compared with [NT] plots (Tables 6.4 and 6.5).

The mulch types did not differ much in their effects but this homogeneous group differed from Bare plots, which remained bare during the three years. Termite and Mulch interaction did not have a statistically significant effect on biomass in 1994 (P = 0.13). Plant biomass decreased in the order TS, TC, TW, NTC, NTS, NTW and B. In 1995 Termite and Mulch interaction was significant (P= 0.03). [T] mulched plots formed a homogeneous group that differed from the homogeneous [NT] mulched plots and the Bare plots group. The order remained the same as in 1994 in [NT] plots but in [T] plots Composite and Woody plots performed better than Straw. Mean values of biomass data showed that plant biomass had increased in 1995 compared with 1994 on TC and TW plots but had decreased on TS and on all [NT] plots.

The rainfall use efficiency (RUE) was significantly affected by termites in 1994 and 1995, with [T] plots having the greatest rainfall use efficiency. Mean values of RUE increased from 1994 to 1995.

Infiltrated water use efficiency (IUE) was not affected by termites in 1994 but was affected in 1995, with [T] plots having the greatest values. In both cases the effect verged of significance at the 5% level. The mulch effect resulted in statistically significant differences between Mulch and Bare plots in 1994, but no such significance was observed in 1995. In both cases, Composite, Straw and Woody treatments formed a homogeneous group (data not presented).

Termite and Mulch interaction affected RUE during the two years but only affected IUE in 1995, where statistical analysis of the data revealed that differences only existed between Bare and all the other plots.

Plant species number

There were more plant species on [T] plots than on [NT] plots in 1994. There were no statistically significant differences between [T] and [NT] treatments in 1993 and 1995 but P value was low in 1995 (P=0.07). Mulch affected species number in 1993 and 1994 but not in 1995. There was no statistically significant interaction effect of Termite and Mulch on species number. Species number increased from 1993 to 1995.

All the vascular plants were therophytes. Diversity indexes (Table 6.6) and plant occurrence probability indicated extreme dominance of two species in all plots: *Aristida adscensionis* and *Schoenefeldia gracilis* (Table 6.7). They accounted for over 70% of total plant cover, in 1994 (Table 6.7). *Pennisetum pedicellatum* whose seeds were also brought with the mulch regressed with year in all plots except in the [T] plot on the Cambisol. It virtually disappeared from [NT] plots on the Lixisol in 1995 (table 6.7).

The diversity indices (H', S1) were not statistically significant by different between the treatments except in 1994 and in 1995, where S1 was different among the treatments in 1994, and H' and S1 were statistically greater in Termite plots in 1995 (Table 6.6). The statistical parameters for significant difference between treatments improved from 1993 to 1995 (Table 6.6).

1994	%Cover	Biomass (t ha^{-1})	IUE (kg ha^{-1}mm^{-1}	RUE (Kgha^{-1}mm^{-1})	NE
TS	114.7 a	3.7 a	7.26 a	4.6 a	(11-21)a
TC	76.84 b	3.37 a	6.3 a	4.18 a	(8-18)a
TW	68.9 b	2.44 a	5.79 a	3.04 a	(5-11) a
NTS	30.73 c	1.42 a	3.68 b	1.25 b	(6-10)a
NTC	21.49 c	1.46 a	3.72 b	1.45 b	(6-14) a
NTW	33.10c	1.20 a	4.7 b	1.76 b	(2-12) a
Ba	0.36 c	0 a	0 b	0 c	0 a
B	df=2 P=0.66	df=2 P=0.08	df=2 P=0.13	df=2 P=0.62	df=2 P=0.2
T	df=1 P<0.00	df=1 P=0.01	df=1 P=0.07	df=1 P=0.01	df=1 P=0.03
T*M	df=7 P= 0.02	df=7 P=0.13	df=7 P=0.52	df=7 P=0.06	df=7 P=0.20
M	df=3 P<0.001	df=3 P<0.001	df=3 P<0.001	df=3 P<0.001	df=3 P<0.001

Table 6.4: *Effects of Termites and Mulch on selected vegetation parameters in 1994. NE: Number of species. Legend as in Table 6.3.*

Tree density

Three years after the establishment of the experiment, the following woody species were found on the plots: *Piliostigma reticulatum, Pterocarpus lucens, Guierra senegalensis, Acacia senegalensis, A.seyal, Terminalia avicinoïdes* and *Zizuphus mauritiana*. They are all well adapted to the Sahelian Sudanian conditions (Grouzis, 1991) but they only succeeded in establishing on [T] plots, without any significant difference between the Mulch treatments (Table 6.5). No tree managed to survive on [NT] mulched plots or Bare plots.

1995	%Cover	Biomass t ha^{-1}	IUE kg $ha^{-1}mm^{-1}$	RUE $kgha^{1}mm^{-1}$-	NE	W_d n ha-1
TS	186.7 a	2.94 a	7.9 a	6.08 a	(26-35)a	417 a
TC	222.02 a	3.89 a	10.63 a	8.03 a	(18-32)a	665 a
TW	124.24 a	3.05 a	8.69 a	6.31 a	(18-30)a	417 a
NTS	83.64 b	1.30 b	3.51 ab	2.69 b	(8-21) a	0 a
NTC	69.01 b	1.16 b	2.79 ab	2.40 b	(6-20) a	0 a
NTW	33.35 b	0.56 b	2.73 ab	1.15 b	(8-24) a	0 a
Ba	0 c	0 b	0 b	0 b	0 a	0 a
B	df=2 P=0.13	df=2 P=0.22	df=2 P=0.63	df=2 P=0.22	df=2 P=0.37	df=3 P=0.3
T	df=1 P<0.001	df=1 P<0.001	df=1 P=0.04	df=1 P<0.001	df=1 P=0.07	df=1 P<0.001
T*M	df=7 P=0.05	df=7 P= 0.03	df=7 P=0.01	df=7 P<0.001	df=7 P=0.50	df=7 P= 0.10
M	df=3 P<0.001	df=3 P<0.001	df=3 P<0.001	df=3 P=0.389	df=3 P=0.62	df=3 P=0.10

Table 6.5: *Effects of Termites and Mulch on some selected vegetation parameters in 1995. NE: Number of species. Wd: Woody species density. Legend as in Table 6.3*

Discussion

A soil crust (especially a structural crust) is a severe constraint to plant development. Valentin (1995) has indicated its effects on seed emergence and infiltration rate. The zero production on Bare plots and the very low production in the [NT] mulched plots indicated that neither the removing of human or animal pressure from already crusted soil, nor protecting it against rain drops impact or increasing sediment trapped by the many tiny physical barriers due to mulch can rehabilitate the productivity of structurally crusted soil in a short period. The diverse physical effects of mulch alone appear to be ineffective in structurally crusted conditions, as [NT] mulched plots do not perform better than bare soil.

But mulch attracts termites, and termite-mediated processes create conditions necessary and sufficient for both woody vegetation and herbs to reestablish. It has been proven (Mando et al in press) that the Composite and Straw mulches are associated with more termite activity features on soil than Woody plots mulch. The degree of vegetation rehabilitation matched the termite response (more vegetation on Composite and Straw mulch plots, less on Woody mulch plots and zero on Bare plots). Weak herb response was observed on [NT] plots, and woody vegetation failed to appear on these plots.

Termite effects on infiltrated water use efficiency (IUE) verged on significance at 5% level in 1994 and 1995 (P=0.07 in 1994 and P=0.04 in 1955), when Termite effects on RUE were highly significant in both years. This indicates that the gap between the performance of [T] and [NT] plots is greatly reduced once the infiltration constraint has been removed. This demonstrates that the effect of termites on water infiltration is one of the most important mechanisms promoting the revegetation of crusted soil. The preponderant role of infiltration improvement in vegetation rehabilitation has previously been pointed out by Hien (1995) but the important fact here is that the improvement in infiltration brought about by termites is enough to trigger vegetation development resulting in enough plants to cover the soil (Tables 6.3 -6.5) and to produce a high biomass.

The productivity of vegetation on Termite mulched plots was considerably greater than the average productivity of natural ecosystems in the area. Grouzis (1991) has stated that the average IUE in Oursi (northern Burkina Faso) is around 2.9 kg ha^{-1} mm^{-1} and the work of Diarra and Breman (1975) in the Sahel and those of Lehouerou and Hoste (1977) in semi arid zones revealed an average IUE of between 2.6 and 3 kg ha^{-1} mm^{-1}. The higher IUE on [T] mulched plots compared with the natural ecosystem is probably due to the nutrient input through the mulch and also to the increase in nutrient availability in soil while it remains bare. Stroosnijder (1992) has stated that a soil that has been bare for some time undergoes similar processes to soils under fallow, i.e an increase in nutrients in the soil through mineralization of the residual soil organic matter.

The persistent small difference in infiltrated water use efficiency between [T] and [NT] plots points to the existence of factors other than infiltration that control the re-establishment of the vegetation. We can exclude seed availability from these factors, since our data showed that seed shortage is not a problem. In our experiment no seed was introduced, except for the *Pennisetum pedicellatum* seeds brought in with the straw mulch.

	1993	1994	1995
H'	T= (0.39-1.02) ns NT=(0.42-65)	T= (0.65-0.73) ns NT= (0.55- 60)	T= (0.84-0.91) ** NT= (0.41-0.70)
S1	T=(1.47-1.99) ns NT=(1.52-1.91)	T= (2.05-2.94) ** NT= (1.73-1.82)	T= (2.3-4.10) ** NT=(1.56-2.01)

Table 6.6: *Effects of termites on Shannon-Weaver Index of diversity (H') and Hill's diversity number S1, * P<0.05, ** P<0.01, ns: not significant. T: Termite, NT: Non termite*

The results of the experiment indicated that *Pennisetum pedicellatum* was not the dominant plant in the field but was among the least in important species and has been decreasing over the years. It was even absent on some [NT] straw plots in 1994 and 1995. The direct effects of dieldrin on plants cannot be used to explain the difference of the vegetation in [T] and [NT] plots as it is not a phytotoxic pesticide (Charles, 1979). It has been established (Mando in press) that termite activity improves soil physical characteristics like bulk density, resistance to penetration and porosity. These factors probably account for the better IUE on [T] plots.

The vegetation performed better in Termite Straw than in Termite Composite and Termite Woody during the first two years of the experiment but the vegetation biomass in the latter two treatments increased over the years and in 1995 surpassed the vegetation biomass on Termite Straw. This is probably because straw decomposes at a faster rate than woody material probably because of the higher lignin content of the latter (Berendse et al.,1987). The protective effect of mulch and its biological effect on soil characteristics decline as the mulch decomposes. Tian et al. (1993) have established that termites prefer mulch which decomposes slowly and thus can retain its protective effects longer.

The regenerated vegetation in the plots was dominated by annual grasses and especially by *Schoenefeldia gracilis* and *Aristida adscensionis* in the herb component and by *Acacia spp.* and *Piliostigma recticulatum* in the woody species, which is typical of the Sudano-Sahelian zone (Guinko,1984). Having the greatest number of plant species in the termite plots did not prevent the two annual species mentioned above to be extremely dominant and did not increase plant diversity indices in 1993 and 1994. These two mentioned species germinate rapidly according to Breman et al. (1982) and are C4 plants. According to Penning de Vries (1982) C4 plants have a number of advantages in the Sahel compared with C3 plants, such as greater photosynthesis capacity and higher water use efficiency.

The rehabilitation of crusted soil vegetation through termites and mulch proceeded in a short time span. Significant improvement in infiltration has been found in termite plots within six months (Mando et al., 1996). Even though our experiment was set up late in 1993 with regard to the onset of the rainy season (June), the vegetation has responded to the treatments in the first year, a response that was amplified in 1994 and 1995.

Conclusion

The application of organic matter on crusted soil can trigger termite activity creating within a short time scale the conditions necessary for effective plant development. Our findings suggest that termites are useful as a biological agent that accelerates crusted soil revegetation through mulch. Some aspects merit further investigation in order to perfect the studied technology. It would be useful to investigate the effect of the mulch quality and soil management on the termite population. And the efficient mulch rate for revegetating crusted soil and sustaining termite populations and the socio-economic aspects of using termite mediated process in land management should also be explored further.

	Year	TFL (%)	NTFL (%)	THL (%)	NTHL (%)	TCC (%)	NTCC (%)
Schoenefeldia gracillis	1993	38	45	59	63	79	66
	1994	40	70	20	56	42	52
	1995	42	65	41	39	48	66
Aristida adscensionis	1993	5	6	5	8	2	3
	1994	41	7	63	0	32	23
	1995	16	23	10	34	7	20
Pennisetum pedicellatum	1993	11	17	15	13	4	13
	1994	3	1	5	1	9	14
	1995	6	0	10	0	14	1

Table 6.7: *Frequency of occurrence of the two most common plant species and Pennisetum pedicellatum occurrence in Termite and Non Termite plots of the three soil types. TFL:Termite plot on Ferric Lixisol, NTF: Non Termite plot on Ferric Lixisol, THL:Termite plot on Haplic Lixisol, NTHL: Non Termite plot on Haplic Lixisol, TCC: termite plot on Chromic Cambisol, NTCC: Non Termite plot on Chromic Cambisol.*

Acknowledgements

We thank Dr. Han Olff for constructive criticism of the manuscript. Issa Pakode is acknowledged for his assistance during the field work.

References

Bunasol, 1995. Etude morpho-pédologique de la province du Bam (échelle 1/500.000). Rapport technique n^0 97, vol 1, 155 pp +annexes.

Berendse, F., Berg, B. & Bosatta, E., 1987. The effect of lignin and nitrogen on the decomposition of litter in nutrient poor ecosystems: a theoretical approach. Canadian Journal of Botany, 65:1116-1120.

Breman, H., Cissé, A.M., Djitèye, M.A. & Elberse, W.Th., 1982. Le potential botanique des pâturages sahéliens. La productivité des pâturages sahéliens (eds F.W.T Penning de Vries et M.A. Djitèye), pp. 98-122. Pudoc, Wageningen.

Charles, R.W., 1979. The pesticide manual: A world compendium. British Protection Council; 6th edition, London, 90-95.

Daget, P. & Poisonnet, J., 1971. Une méthode d'analyse phyto-sociologique des prairies; critères d'application. Annales d' Agronomie, 22:5-41.

Diarra, L. and Breman, H., 1975. Influence de la pluviosité sur la production des pâturages. Actes du colloque de Bamako (Mali). Inventaire et cartographie des pâturages tropicaux Africains:171-174

Grouzis, M., 1991. La production végétale: évolution et seuil de rupture. "Un Espace Sahelien:la mare d'Oursi, Burkina Faso (eds J. Claude, M. Grouzis, P. Mille), Edition ORSTOM, 126-143.

Guinko, S., 1984. Végétation de la Haute Volta. Thèse de doctorat. Université de Bordeaux II.

Hien, G.H., 1995. La régéneration de l'espace sylvo-pastoral au Sahel: Une étude de l'effet de mesures de conservation des eaux et des sols au Burkina Faso. Ph D thesis, Wageningen Agricultural University.

Hill, M.O., 1973. Diversity and evenness: A unifying notation and its consequences. Ecology 72:1374-1382.

Lavelle, P., Blanchart, E. & Martin, S., 1992. Impact of soil fauna on the properties of soils in the humid tropics. Myths and science of soils of the tropics (eds R. Lal & P.A. Sanchez), SSSA Special Publication no.29: 157-183.

Le Houerou, H.N. & Hoste, C.H., 1977. Rangeland production and annual rainfall relation in the Mediterranean basin and in the African Sahelo- Sudanian Zone. Journal of Rangeland Management 30:181-189.

Lee, K.E. & Wood, T.G., 1971. Termites and soils. Academic press, New York .

Lobry de Bruyn, L.A. & Conacher, A.J., 1990. The role of termites and ants in soil modification: A review. Australian Journal of Soil Research, 28: 55-93.

Mando, A., in press. Effect of termites and mulch on the physical rehabilitation of structurally-crused soils in the Sahel. Land Degradation and Rehabilitation (in press).

Mando, A., Stroosnijder, L. & Brussaard, L., 1996. Effects of termites on infiltration into crusted soil. Geoderma 74:107-113.

Mando, A., Van Driel, F.W.W & Zombré, N. P., 1994. Rôle des termites dans la restauration des sols ferrugineux tropicaux encroutés au Sahel. Gestion durable des sols et de l'environnement en Afrique tropicale. Colloque International de L'AOCASS.

Penning de Vries, F.W.T., 1982. Le potentiel physiologique des pâturages sahéliens. La productivité des pâturages sahéliens (eds F.W.T Penning de Vries et M.A. Djitèye), pp. 87-98. Pudoc, Wageningen.

Stroosnijder, L., 1992. Desertification in sahelian Africa. The Courier 133:36-39.

Tian, G., Brussaard, L. & Kang, B.T., 1993. Mulching effects of plant residues with contrasting chemical compositions under humid tropical conditions. Effect on soil fauna. Soil Biology and Biochemistry, 25:731-737.

Unesco, 1973. International classification and mapping of vegetation. Ecological Conservation n^0 6, Unesco, Paris. 93 pp.

Unesco, 1977. Carte de la répartition mondiale des regions arides. Notes techniques du MAB, n^0 7. Unesco, Paris. 77 pp.

Valentin, C., 1995. Sealing, crusting and hardsetting soils in Sahelian Agriculture. International Symposium on Sealing, Crusting and Hardsetting Soils: productivity and conservation" (eds H.B So , G.D. Smith, S.R. Raine, B.M. Schafer & R.J.. Loch), Australian Society of Soil Science, 53-76.

Whitford, W.G., John, A.L. & James, C., 1991. The importance of subterranean termites in semi-arid ecosystems in South-eastern Australia. Journal of Arid Environments 22:87-91.

Chapter 7

Using soil-dwelling termites and mulches to improve nutrient release and crop performance on Sahelian crusted soil.

Mando, A. Using soil-dwelling termites and mulches to improve nutrient release and crop performance on Sahelian crusted soil. Arid Soil Research and Rehabilitation (submitted)

Abstract

Studies were carried out on crusted soil in northern Burkina Faso to assess the role of termites and two organic materials differing in chemical composition in improving the productivity of crusted soil. A split plot design was used, the main treatment being the application of an insecticide. This resulted in plots with and without termite activity. Subtreatments consisted of *Pennisetum pedicellatum* straw or cattle dung applied as mulches at a rate of 4 and 7 t ha^{-1} respectively. Four months after mulching, cow pea was sown on the plots as test crop. The chemical and physical properties of soil, the chemical properties of termite sheetings and cow pea performance were measured on all the plots.

It was found that termite plots had higher nutrient contents and more favourable physical properties for plant growth than non-termite plots. Consequently, crops on termite plots had higher biomass and grain yield than on non-termite plots. Correlation analysis indicated a strong relation between termite activity and crop nutrient uptake, change of soil physical properties and crop performance. This relation was stronger than that between chemical composition of mulch and these variables. It is concluded that termite activity can play a key role in organic-material management for the regeneration of crusted soils in the dry conditions of the Sahel Sudanian zone.

Key words: soil-dwelling termites, mulch, crusted soils, nutrient uptake, crop performance

Introduction

Overuse of poor resources and inadequate management of biological and physical resources have resulted in soil degradation in the Sahel, a part of the world in which soil degradation has accelerated rapidly in the last 20 years. Indeed, Stein et al. (1988) stated that extensive areas of formerly productive land in the African Sahel have been added to the Sahara as wasteland. The combination of land degradation and high population growth has resulted in a structural decline in per capita food production; hence the frequent food shortages in these regions. The options for increasing agricultural production and reducing soil degradation include increasing the area of cultivated land by bringing wastelands back into production and increasing the productivity of land already cultivated. Ecological and economic constraints have severely hampered the development of high input agriculture and the implementation of soil and water conservation structures to rehabilitate land. It is for this raison that the productivity of low input agriculture needs to be improved. This can be done through judicious management of organic materials to enhance soil quality.

Organic material contributes nutrients to the soil and greatly affects its physical properties (Hulugalle et al., 1986, Tian et al., 1993a). The extent to which it can contribute to soil quality depends on factors such as soil fauna, organic material quality and climatic conditions. Thus the C/N ratio, lignin and polyphenol contents are known to be important for the rate of decomposition and therefore the release of nutrients for plant growth (Swift et al., 1979). Soil fauna also affect the soil physical environment that is so important in soil biological processes. The role of organic material in agricultural production and the diverse factors on which this role depends are well documented, especially for humid regions. There is still a need, however, to assess the importance of these factors in soil fertility and the improvement of crop production in semi-arid regions, particularly as this is critical for the development of sustainable low input agriculture. In this paper we therefore focus on the role played by soil-dwelling termites in nutrient release from organic materials, in affecting soil physical properties and in the restoration of wasteland productivity in the Sahel.

Methods

Site Description

The investigation was conducted on a fenced area of 4 ha near Bourzanga in the province of Bam (Fig.1.1) in northern Burkina Faso, West Africa (about 4° W, 13° N). Here the climate is Sahelian Sudanian according to Unesco (1977). Rainfall is monomodal and typically occurs for 4 months from June to September. It is irregularly distributed in time and space, and the current trend is for annual means to decrease (Fig 7.1).

The vegetation is of the steppe type according to Unesco's (1973) classification, with large bare areas. The life form for the grasses is dominantly annual therophyte and perennial grasses are rare (Mando, 1991). The woody component is dominated by shrubs, the most important families being *Mimosaceae* and *Combretaceae*. The common termite genera are *Microtermes, Macrotermes* and *Odontotermes*.

Lixisols and Cambisols are the commonest soil types in the area (BUNASOL, 1995). The experiment was laid out on a Ferric Lixisol with a pH of about 4.1 at 5 cm and of 6.1 at 110 cm depth. CEC is 6 cmol(+) kg^{-1} at 5 cm depth and 12.4 cmol (+) kg^{-1} at 120 cm depth. The textural class is sandy loam (37% of sand, 43% silt and 20% clay). Bulk density is 1500 kg m^{-3} at 5 cm depth and 1700 kg m^{-3} at depths below 70 cm. Soil organic matter content is 0.51% at 5 cm depth but decreases to 0.17% at 120 cm depth. Annual runoff is very high: 50%-90% because of the degraded status of the soil. Soil crusting is the major problem, but soils also suffer from nutrient deficits.

Experimental design

A split plot design with three blocks, two main treatments and two subtreatments was laid out on a Ferric Lixisol soil type. The main treatment was the use of an insecticide (Dursban at a rate of 400 g a.i ha^{-1} spread on [NT] monthly) to create non-termite plots [NT] and termite-infested plots [T]. Main plots were 10 m * 4 m and 5 m apart and subplots were 4 m * 4 m. The subtreatments were cattle dung applied at a rate of 7 t ha^{-1} and *Pennisetum pedicellatum* straw applied at a rate of 5 t ha^{-1}. The mulch was applied in November 1993. The experimental area was fenced.

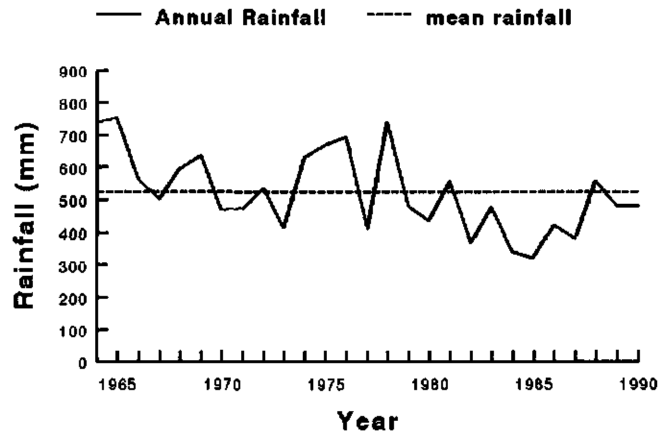

Figure 7.1: Annual rainfall in Bourzanga (near the site) from 1964 to 1990

Crop cultivation

Six months after the application of the mulch, cow pea (local variety) was sown on all the plots at an average density of 20,000 plant holes per hectare with two seeds per hole. During the growing season the plots were regularly weeded by hand; no hoe was used, in order to be able to assess to what extent the treatments alone can affect soil physical conditions. Two weeks after planting, one seedling from each plant hole was removed to assess biomass production. Plant height was monitored every week for one month after sowing. At flowering, 10 % of the plants were sampled to assess dry mass production. Three months later, cow pea grain was harvested and the straw was left on the field. All the dry mass and grain yield data were obtained by sun drying the grain and the phytomass.

Soil and plant analysis

Before applying the mulch, a composite sample of the cattle dung and the straw was prepared and analysed accorded to Walinga et al. (1989) for N, P, K, and the nutrient input through the mulches was calculated (Table 7.1). Just before sowing (i.e in June 1994), at harvest and at the beginning of the following rainy season (i.e June 1995), some composite soil samples were collected from each subplot at 0-10 cm depth and analysed according to Houba et al. (1989). Composite samples of termite sheetings on cattle dung and on straw were collected from termite plots and analysed according to Walinga et al. (1989) for NO_3^-, NH_4^+, total mineral nitrogen, organic carbon and total nitrogen. Plants were sampled and analysed according to Walinga et al. (1989) for N,P,K and Ca two weeks after sowing and at flowering.

	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Straw	6.8	0.4	55.6
Cattle dung	83.3	12.8	112

Table 7.1: *Nutrient input through straw mulch at the rate of 5 t ha^{-1} and cattle dung mulch at the rate of 7 t ha^{-1}. N= nitrogen input; P= Phosphorus input; K=Potassium input.*

Soil saturated hydraulic conductivity (K_{sat}) was assessed from undisturbed soil cores of 100 cm^3 taken from each subplot in October 1994 at the end of the growing season using the constant head method.

Statistical analysis

Analysis of variance was used to establish the significance of the differences, and the Newman Keuls test was used to compare the means at different p levels.

A correlation analysis was done to establish the relative importance of the link between the parameters studied. Quantitative data were used for the correlation analysis, except for the termite data, which were semi-quantitative. Given that the chemical composition of mulch has no effect on termite populations (Tian et al., 1993a) and that the insecticide was effective on all non-termite plots, termite plots were assigned a value of 1 and non-termite plots were assigned the value 0.

Results and discussion

Soil properties

The comparative study of termite sheetings and the surrounding soil indicated that the sheetings had the highest nutrient content. Its total mineral nitrogen and potassium were increased in termite worked material compared to the original material (Table 7.2). This confirms the findings of Basppa and Rajagopal (1991) who measured higher mineral nitrogen and potassium in termite sheetings made on cattle dung than in surrounding soil. In our experiment, the treatments were not significantly different for NO_3^- , NH_4^+ and total P but were significantly different for total mineral nitrogen, K and organic carbon. The mean values of NO_3^- , NH_4^+ and total P were higher in termite sheeting made on straw than in the bulk soil under the straw mulch. Sheetings made on cattle dung plots contained more NO_3^- and NH_4^- than the surrounding soil. The total mineral nitrogen, NO_3^-, NH_4^+ and total P were higher in termite sheetings made on cattle dung than in sheetings made on straw because the

	Sheetings on cattle dung	Sheetings on straw	Cattle dung plot	Straw plot
NO_3^- (mg kg^{-1})	20.6 a	15.3 a	10.3 a	5.3 a
NH_4^+ (mg kg^{-1})	16.3 a	11 a	8.6 a	0.6 a
total mineral nitrogen (mg kg^{-1})	41.6 a	28.6 ab	20.6 ab	7.3 b
K (mg kg^{-1})	55.6 a	9.3 b	17.3 b	3.3 c
Total P (mg kg^{-1})	131.3 a	128.3 a	109 a	86 a
Organic cabon (%)	0.97 a	0.53 b	0.57 b	0.23b
Total nitrogen (%)	0.05 a	0.03 a	0.04 a	0.03a

Table 7.2: *Chemical properties of termite sheetings built on cattle dung and straw and of soil mulched with cattle dung and soil mulched with straw. Treatments having the same letters within a row are not significantly different.*

dung contains more nitrogen and phosphorus. K was significantly higher in termite sheetings on cattle dung than in surrounding soil and in the sheetings on straw. This suggests that the chemical composition of the organic material from which termites build their sheetings determines the mineral contents of those sheetings. It has previously been shown that the increase of nutrient availability in sheetings results from the decomposition of the material from which the sheetings are made, and not from chemicals secreted by termites (Basppa and Rajagopal, 1991; Abbadie and Lepage, 1989).
No clear differences in soil chemical properties between the treatments were found when the soil samples collected from the plots were analysed. However, the trend was for termite plots to contain more nutrients, organic carbon and nitrogen than non-termite plots (Table 7.3) at the beginning of the 1994 and 1995 rainy seasons, because there was better nutrient release in these plots. The nutrient content was lower in termite plots at the end of the rainy season, probably because of better plant performance on these plots (higher nutrient uptake).

Soil saturated hydraulic conductivity (K_{sat}), an indicator of the soil's physical quality, was significantly greater in termite plots than in non-termite plots ($p < 0.01$), but was not significantly different between the two mulch treatments (table 7.4). The increase of the K_{sat} in termite plots can be attributed to the many voids open to the air on these plots (Mando et al., 1996). These results confirm that termite activity is the key element in the effectiveness of mulch techniques in improving soil physical properties (Mando, 1996a) and also the findings of Tian et al. (1993b) that mulch quality has no significant effect on termite populations.

	TCd	TS	NTCd	NTS
May 1994				
pH	4.6 ± 0.0	4.60 ± 0.42	5.1 ± 0.8	4.1 ± 0. 6
NO_3^- (mg kg^{-1})	12.0 ± 5.2	8.03 ± 6.04	3.1 ± 3.0	5.3 ± 5.1
NH_4^+ (mg kg^{-1})	7.0 ± 5.0	0.50 ± 0.50	5.5 ± 2.5	4.8 ± 4.0
Total mineral nitrogen (mg kg^{-1})	21.0 ± 1.0	10.03 ± 6.01	10.5 ± 0.5	10.1 ± 5.5
Na (mg kg^{-1})	14.5 ± 8.8	6.03 ± 3.13	12.1 ± 9.2	49.3 ± 35.5
K (mg kg^{-1})	87.5 ± 11.5	26.03 ± 1.01	50.4 ± 9.0	29.6 ± 16.1
C (%)	0.6 ± 0.1	0.30 ± 0.20	0.4 ± 0.0	0.30 ± 0.1
Total nitrogen (%)	0.0 ± 0.0	0.03 ± 0.01	0.0 ± 0.0	0.0 ± 0.0
Total P (mg kg^{-1})	130.5 ± 6.5	106.5 ± 19.5	140.2 ± 42.0	75.7 ± 34.5
October 1994				
pH	4.6 ± 0.3	4.4 ± 0.5	4.7 ± 0.4	4.5 ± 10.3
NO_3^- (mg kg^{-1})	0.6 ± 0.4	3.3 ± 4.0	28.3 ± 37.9	31.0 ± 36.3
NH_4^+ (mg kg^{1})	2.6 ± 1.2	0.6 ± 0.4	2.6 ± 1.2	4.6 ± 4.1
Total mineral nitrogen (mg kg^{-1})	5.3 ± 2.6	4.6 ± 4.4	34.3 ± 44.3	43.6 ± 36.3
Na (mg kg^{-1})	13.3 ± 14.6	10.3 ± 7.58	27.3 ± 34.4	28.3 ± 30.3
K (mg kg^{-1})	57.6 ± 29.1	47.3 ± 31.4	49.3 ± 33.8	33.6 ± 16.8
C (%)	0.4 ± 0.1	0.3 ± 0.0	0.3 ± 0.0	0.2 ± 0.0
Total nitrogen (%)	0.0 ± 0.0	0.03 ± 0.0	0.0 ± 0.0	0.02 ± 0.0
Total P (mg kg^{-1})	120.0 ± 7.8	104.6 ± 2.8	109.6 ± 0.0	109.6 ± 23.5
August 1995				
pH	4.4 ± 0.2	5.1 ± 0.8	5.1 ± 0.8	4.4 ± 0.2
NO_3^- (mg kg^{-1})	22.6 ± 14.4	13.5 ± 10.5	16.3 ± 14.0	4.3 ± 1.0
NH_4^+ (mg kg^{-1})	3.3 ± 3.2	2.5 ± 1.5	8.6 ± 8.0	5.3 ± 2.0
Total mineral Nitrogen (mg kg^{-1})	29.0 ± 16.2	18.5 ± 14.7	29.3 ± 15.1	12.2 ± 2.2
Na (mg kg^{-1})	9.6 ± 6.2	22.5 ± 12.3	17.3 ± 8.9	5.5 ± 0.5
K (mg kg^{-1})	67.6 ± 15.1	79.5 ± 12.0	66.6 ± 26.4	59.7 ± 24.0
C (%)	0.3 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	0.3 ± 0.1
Total nitrogen (%)	0.0 ± 0.0	0.0 ± 0.0	0.01 ± 0.0	0.0 ± 0.0
Total P (mg kg^{-1})	106.3 ± 3.8	109.6 ± 29.1	113.0 ± 17.9	89.6 ± 1.4

Table 7.3: *Chemical properties of plots in May and October 1994 and August 1995. TCd = plot with cattle dung and termite activity, TS = plot with straw and termite activity. NTCd = plot with cattle dung and without termite activity, NTS = plot with straw and without termite activity. ± standard deviation.*

Crop performance

Crop growth was greater on termite plots [T] than on the non-termite plots [NT]. The difference in cow pea height between the [T] and [NT] was already statistically significant after a few weeks (data not shown). The same trends were observed throughout the growth of the crop. The plants on the cattle dung plots were taller than those on the straw plots. There was no interaction effect of termite and mulch on cow pea growth. The mean values indicated that the tallest plants throughout the season were those on termite plots mulched with cattle dung followed by those on termite plots mulched with straw and then those on non-termite plots mulched with cattle dung and finally those on non-termite plots mulched with straw (Fig. 7.2). The dry weight of cow pea biomass at flowering was significantly greater on [T] plots than on [NT] plots (Table 7.4). Mean values indicated that there was more biomass on straw plots than on cattle dung plots two weeks after sowing (data not shown), but at flowering the mean biomass production on cattle dung plots was twice that on straw plots (data not shown). For all the cases the mean values indicated that productivity was higher on termite straw than on the non-termite straw and non-termite cattle dung plots.

At the harvest, the cow pea on non termite plots did not yield any grain. Yields were higher from cattle dung plots than from straw plots (Table 7.4).

Termite activity enhanced nutrient uptake by cow pea. Nitrogen uptake was six times higher on [T] plots than on [NT] plots ($p= 0.03$). Mean nitrogen uptake was greater on [T] straw than on [NT] cattle dung plots and was significantly higher on cattle dung plots than on straw plots (Table 7.4). Although the results of statistical analyses were not significant, mean values indicated that in the same mulch treatment the uptake of nutrients like P, Ca and K was higher on termite plots than on non-termite plots. Nutrient uptake was always greater on cattle dung plots than straw plots (Table 7.4). Cow pea always had greater nutrient uptake on termite straw plots than on non-termite cattle dung plots, in spite of the higher nutrient content of cattle dung. On the cattle dung plots the K uptake was significantly higher than on the straw plots ($p= 0.05$ and mean values not shown).

It is impossible to regenerate crusted soil unless soil water availability is improved (Hien, 1995; Mando et al., 1996). Mando (1996b) established that termite activity can significantly improve the water status of crusted soils. The data presented here show that this enhances crop performance and improves nutrient uptake. The greater nutrient release from the mulch on termite plots than from the mulch on non-termites plots was another factor accounting for better uptake of plant nutrients and better plant performance on termite plots than on non-termite plots. The poor performance of cow pea on termite straw plots which had a similar K_{sat} to cattle dung termite plots was a clear demonstration that nutrient availability was also a factor limiting plant performance and that the nutrient release from the straw is insufficient to sustain crop growth. This also implies that the impact of termites on the nutrient availability to plants depends on the quality of the material on which they feed. The poor performance of cow pea on the non-termite cattle dung plots was attributable both to physical constraints and to nutrient constraints, as the cattle dung remained undecomposed until the end of the rainy season.

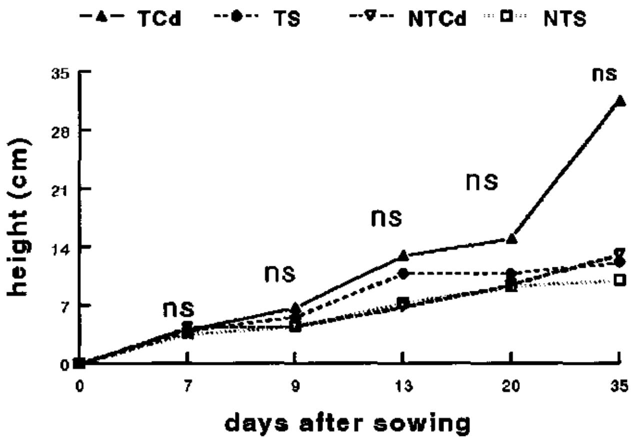

Figure 7.2: *Cow pea growth during the 35 days after sowing in 1994 on Termite cattle dung plots (TCd); Termite straw plots (TS); Non termite cattle dung plots (NTCd) and Non termites straw (NTS) plots. ns: not significant*

	K_{sat} 10^{-5} ms^{-1}	Bwas t ha^{-1}	Bf (t ha^{-1})	Grain (t ha^{-1})	Nutrient uptake (g.kg^{-1})			
					N	P	K	Ca
TCd	1.15 a	0.79 a	2.14 a	1.02 a	90.9 a	49.3 a	69.3 a	39.1a
TS	1.73 a	0.49 a	0.8 a	0.6 b	25.5 b	2.03 a	26.2a	11.6a
NTCd	0.9 a	0.19 a	0.71 a	0.01 b	15.6 c	0.9 a	11.8a	7.12a
NTS	0.45 a	0.09 a	0.09 a	0.0 b	4.16 c	0.17 a	2.6 a	1.23a
	P							
T	0.001	0.001	0.04	0.03	0.05	ns	ns	ns
T*M	ns	ns	ns	0.05	0.04	ns	ns	ns
M	ns	ns	0.06	0.04	0.01	ns	0.05	0.02

Table 7.4: *Termite and mulch with chemically different composition effects on hydraulic conductivity (K_{sat}), Bwas (biomass one week after sowing), Bf = (Biomass at flowering). T = Termite, M = mulch, Cd = cattle dung, S = straw, P = probability level. Treatments having the same letter in a column are not significantly different.*

Relation between soil characteristics and cow pea production

Cow pea biomass and grain yield correlated strongly with termite presence in the plots for cow pea biomass (r^2= 0.66) and grain yield which indicates the importance of termite activity in enhancing and sustaining crop production. There are two main mechanisms by which termites may enhance the productivity of crusted soil: by improving soil structure and soil water status (Mando, 1996) and enhancing decomposition processes, probably through comminution (Swift et al., 1979; Scheu and Wolters, 1991), and by stimulating total microbial activity through their fungus comb chambers (Abbadie and Lepage, 1989). The nutrient input through mulch had a lower correlation coefficient with the biomass production and the grain yield than the relation between termite presence and biomass production (Table 7.5). K_{sat} was strongly correlated with the presence of termites (r^2=0.83) and was better correlated with cow pea biomass production than nutrient input. The above implies that the physical effect of termite activity was more important for the improvement of soil productivity than termite effect on nutrient release under the conditions of the study. Nutrient uptake by plants was equally well explained by the presence of termites as by nutrient input (Table 7.5), indicating that both termite activity and the quality of the mulch are very important in the release of nutrients.

Conclusion

Crusted soils can be brought back to cultivation by appropriate natural resource management. This is a prerequisite for reducing the population pressure on marginal land, increasing food production and combating environmental degradation.

The results of the study demonstrate that in the semi-arid conditions of the Sahel, soil fauna (in particular soil-dwelling termites) are crucial in the attempts to improve agricultural production by managing organic material. Therefore, account should be taken of this fauna

	K_{sat}	NI	PI	KI	NU	PU	KU	Ter	BIO	Grain
K_{sat}	1									
NI	0.045	1								
PI	0.045	1	1							
KI	0.045	1	1	1						
NU	0.49	0.45	0.45	0.45	1					
PU	0.15	0.35	0.35	0.35	0.77	1				
KU	0.48	0.37	0.37	0.37	0.98	0.72	1			
TER	0.83	0.10	0.10	0.1	0.47	0.31	0.49	1		
BIO	0.63	0.27	0.27	0.27	0.92	0.78	0.91	0.66	1	
Grain	0.34	0.53	0.53	0.53	0.81	0.91	0.74	0.51	0.84	1

Table 7.5: *Coefficients of correlation of cow pea biometric data and soil management data. N = Nitrogen input; PI = Phosphorus input; KI = Potassium input; NU = Nitrogen uptake; KU = potassium uptake; PU: Phosphorus uptake; Ter = termite activity; Bio = dry mass production; Grain = Grain yield.*

during soil management. The chemical composition of the organic material used is very important for the release of nutrients but is not very important for the modification of the soil physical properties.

Acknowledgements

Thanks are due to Prof. L. Stroosnijder and Prof. L. Brussaard for the interesting discussion during the field work and for useful comments on the manuscript.

References

Abbadie, L. and Lepage, M., 1989. The role of subterranean fungus comb chambers (Isoptera, Macrotermitinae) in soil nitrogen cycling in a preforest savanna (Côte d'Ivoire). Soil Biology and Biochemistry 21:1067-1071.

Basppa, H. and Rajagopal, D., 1991. Physico-chemical properties of termite-modified soils due to foraging on dung in comparison with the surrounding soil. Sociobiology, 16:175-185.

BUNASOL, 1995. Etude Morpho-pédologique de la province du Bam (échelle 1/50.000), (Rapport Technique n^0 97, vol.1), BUNASOL. Ouagadougou.

Hien, G.H., 1995. La régéneration de l'espace sylvo-pastoral au Sahel: une étude de l'effet de mesures de conservation des eaux et des sols au Burkina Faso. PhD thesis, Wageningen Agricultural University.

Houba, V.J.G., Vark,W., Walinga, I. and Lee, J.J., 1989. Soil and Plant analysis. Part 3, Soil analysis procedures. Department of Soil Science and Plant Nutrition, Wageningen Agricultural University. Wageningen.

Hulugalle, N., R. Lal and Terkuile, C.H.H., 1986. Amelioration of soil physical properties by *Mucuna* after mechanized land clearing of tropical rainforest. Soil Science 141:219-224.

Mando, A., 1991. Impact de l'activité des termites sur la dégradation de la biomasse végétale et quelques propriétés physiques des sols dégradés: Etude menée a Zanamogo (Burkina Faso). Mémoire de fin d'études, Université de Ouagadougou, ISN/IDR, 76 pp.

Mando, A., 1996a. The impact of termites and mulch on the water balance of crusted Sahelian soil. Soil Technology (accepted for publication).

Mando, A., 1996b. Effect of termites and mulch on the physical rehabilitation of structurally-crusted soils in the Sahel. Land Rehabilitation and Development (accepted for publication).

Mando, A., Stroosnijder, L. and Brussaard, L., 1996. Effect of termites and mulch on infiltration into crusted soil in the Sahel. Geoderma 74:107-113.

Scheu, S. and Wolters, V. 1991. Influence of fragmentation and bioturbation on the decomposition of ^{14}C-labelled beech leaf litter. Soil Biology and Biochemistry 23:1029-1034.

Stein, J.L., Day, J.C., Papendick, R.I., Meyer, R.E. and Bertrand, A.R., 1988. Improving and sustaining productivity in dryland regions of developing countries. In B.A. Stewart, (ed.), Advances in Soil Science. Springer-Verlag, New York, Berlin, Heidelberg, Tokyo, 79-122

Swift, M.J., Heal, O.W. and Anderson, J.M., 1979. Decomposition in Terrestrial Ecosystems. Blackwell Scientific, Oxford.

Tian, G., Brussaard, L. and Kang, B.T., 1993a. Biological effects of plant residues with chemically contrasting compositions under humid tropical conditions - effect on soil fauna. Soil Biology and Biochemistry 25:731-737.

Tian, G., Brussaard, L. and Kang, B.T., 1993b. Mulching effect of plant residues with chemically contrasting compositions on maize growth and nutrients accumulation. Plant and Soil 153:179-187.

Unesco, 1973. International classification and mapping of vegetation. Ecological Conservation n° 6, Unesco. Paris.

Unesco, 1977. Carte de la répartition des régions arides. Note techniques du MAB, n° 7, Unesco. Paris.

Walinga, I., Vark, W., Houba, V.J.G. and Lee, J.J., 1989. Soil and Plant analysis. Part 7, Plant analysis procedures. Department of Soil Science and Plant Nutrition, Wageningen Agricultural University. Wageningen.

Chapter 8

Synthesis and conclusions

Introduction

Soil degradation is a major agricultural problem in the Sahelian zone and thus soil rehabilitation should be a priority. Soil rehabilitation simply seeks to halt degradation and to repair the damaged functions of the soil with the primary goal of raising ecosystem productivity for the benefit of humanity. Raising crusted-soil productivity requires that the conditions of effective water infiltration are created and that the pathways of nutrient cycling are repaired. The first requirement is more important in water limited situations while the second is more important in nutrient limited situations. In this thesis the role of termites and mulch in crusted soil rehabilitation was examined. The main hypothesis was that application of organic material on crusted soil will trigger termite activity and that termite-mediated processes will lead to the rehabilitation of the soil.

Termite and mulch

Chapter 2 indicates that termite activity can be triggered by the application of organic material on soil and Chapter 3 indicates that when mulch is applied on bare and crusted soils, the colonization by termites takes places in a relatively short time. The effect of mulch on termite population dynamics was not studied but termite-made voids have been monitored on termite plots six months after mulch application to get an indirect assessment of termite activity. There was no significant effect of mulch type on termite activity (Table 8.1). Three species of termites were found in the experimental field [*Odontotermes smeathmani* (Fuller); *Microtermes lepidus* (Sjöst) and *Macrotermes bellicosus* (Sjöst)] but Chapters 2 and 3 proved that *Odontotermes smeathmani* (Fuller) was mainly responsible for all termite-mediated processes discussed in this thesis. No other other soil fauna than termites was observed on the plots. No termite activity was observed on plots sprayed with insecticide.

Mulch type	Number of termite-made macropores per square meter
Composite (wood+straw)	126 a
Wood	68 ab
Straw	63 ab
Bare (no mulch)	0 b

Table 8.1: *Effect of mulch type on termite activity. Treatments having the same letter (s) are not statistically different at P = 0.05*

Termites and soil physical properties

Termites had significant effects on soil structure (Chapter 2 and Chapter 3); they opened up large voids on the sealed surface of the soil and throughout the entire soil profile (0-120 cm). The voids resulted from the nesting and foraging activities of termites. The size of the voids and their density per unit soil surface depended on termite species, population size and the contact points between the organic material with the soil. Chapter 2 indicated that termites excavate irregular-shaped voids (channels and chambers) throughout the entire soil profile and that the area occupied by these voids was up to 12 % of the soil in the (0-7 cm) horizon and that these voids accounted for 60% of the macroporosity in this horizon.

Subterranean termites also contribute to the aggregation of the soil through their building structures. Chapter 2 indicated that subterranean termite-made aggregates were mainly sheetings and bridged infillings.

The study clearly demonstrated the significant role of termites in modifying crusted-soil characteristics. The porosity and saturated hydraulic conductivity were greatly improved on termite plots after the application of mulch but remained unchanged on mulched plots without termites (Chapter 4). Soil resistance to cone penetration was reduced greatly on termite plots. Chapter 3 indicated that termites reduce runoff by: (1) delaying the time to ponding, (2) reducing the speed of the decline of infiltration rate with rainfall cumulative amount and (3) increasing the final infiltration rate. Chapter 5 indicated that the increase in infiltration rate on termite plots results in an increase of soil water content throughout the soil profile and throughout the growing period of the year.

The role of mulch in improving soil water status was to protect the soil against the weather impact (evaporation) and to increase the infiltration through its many tiny barriers. The above functions of mulch depended on coverage effect and declined with time due to the decomposition of mulch. The decomposition rate of mulch depended on chemical and physical characteristics.

Chapters 4, 5 and 6 pointed out the fact that the physical effect of mulch is of less importance in crusted-soil rehabilitation as the problem of these soils is less a problem of losing water already stored in the soil than losing water from runoff.

Termites and the revegetation of crusted soils

Mulching a completely bare and crusted soil surface resulted within a year in the rehabilitation of primary production (Chapter 6 and 7). Vegetation growth was very moderate on mulched surfaces on which insecticide was applied to prevent colonization by termites. Plant diversity, plant cover and biomass on mulched plots with termite activity were greater than on the plots without termite activity.

The vegetation performance was better on straw and composite plots, moderate on woody plots but was worst on unmulched (bare) plots in the first years of the experiment. During the consecutive years, the performance of the vegetation on termite plots increased but this phenomenon was more apparent on woody plots compared to straw plots. Straw had a quicker but shorter effect on vegetation performance whereas woody material had a slower but longer lasting effect. Bare plots remained bare throughout the experimental period.

Although mulch without termites did not significantly improve vegetation production of already crusted soils (Chapter 6 and 7), it had some effect on plant growth by the improvement of microclimate conditions and entrapment of wind-blown sediment that improves the rooting condition for plants.

The statistical analysis of natural vegetation and crop performance under the effect of termites and mulch indicated a preponderant role of termites (Chapter 6 and 7) in primary productivity. Termites improved vegetation growth through two processes:

(i) improvement of soil structure, water infiltration and water storage capacity and soil rootability. Chapter 6 demonstrated that the improvement of water infiltration into soil was the most important mechanism of termite-mediated rehabilitation of crusted-soil primary production.

(ii) enhancement of nutrient release into the soil from the mulch due to termite activity. Chapter 7 demonstrated that in semi-arid conditions termite activity plays a key role in nutrient cycling. The main role of termites in nutrient release from mulch is communition and the turn-over of organic material. The quality of the decomposing material is very important in the amount of nutrient release.

All the above-mentioned processes are critical for land rehabilitation but the physical impact of termites was more important in the rehabilitation of vegetation than the chemical impact (Chapters 6 and 7).

Conclusion

The application of organic matter on crusted soil can trigger termite activity within a few months. Termites repair the damage of soil degradation (crusting) by excavating on the crusted surface large voids that improve soil porosity, saturated hydraulic conductivity and the infiltration capacity of the soil.

Termites enhance the decomposition of the applied organic material, stimulating nutrient release. The amount of nutrient released is dependent on the quality of the mulch. Both chemical processes and physical processes result in the rehabilitation of the vegetation production. The organic material produced on the rehabilitated soil provides biomass to maintain termite populations and soil micro-organisms. This creates conditions of sustainable nutrient cycling processes in the soil system.

The above implies that termites are biological agents with activities that can be used in soil rehabilitation by mulching. It seems an ecologically sustainable method as it requires only an initial investment in organic matter to repair the damaged functions of the soil and to create a soil system which has the ability to sustain itself through natural processes.

Résumé

La dégradation des sols est l'un des principaux problèmes de l' agriculture au Sahel. Au cours des dernières décennies les sols de cette zone ont connu une dégradation multiforme des plus sévères, la plus apparente étant l'extension de sols dont les surfaces sont complètement dénudées et encroûtées. Cette thèse met l'accent sur l'utilisation de différents types de paillis et de l'activité des termites pour la réhabilitation des sols encroûtés dans la zone Sahélo-Soudaniènne du nord du Burkina Faso.

Lorsqu'on applique du matériel végétal sur des sols encroûtés au Sahel, il en résulte une colonisation de ce milieu par des termites dans l'espace de quelques mois.

L'activité des termites entraîne des modifications de la structure des sols encroûtés. La surface encroûtée du sol se trouve perforée par l'activité de creusage. Sur tout le long du profil du sol on observe des macropores aux formes et diamètres variés. L'activité des termites entraîne aussi une agrégation des sols liée aux différentes constructions des termites. Il en résulte la modification de la structure du sol et une amélioration de ses autres propriétés physiques: la résistance du sol à la pénétration et la densité apparente sont réduites, la conductivité hydraulique saturée s'accroît et l'infiltration et le drainage de l'eau dans le sol sont améliorés. Les effets combinés de l'augmentation de l'infiltration de l'eau, de la porosité du sol et de la protection du sol par le paillis entraînent une augmentation de la disponibilité de l'eau dans le sol pendant les saisons pluvieuses.

L'activité des termites dans les paillis contribue également à accélérer les processus de décomposition de la matière organique et donc de la libération des éléments minéraux dans le sol. Les quantités d' éléments libérés dans le sol sont fonction de la qualité chimique du matériel utilisé pour le paillis.

Les modifications des paramètres d'un sol encroûté dues aux activités des termites sont d'une ampleur qui permet la réhabilitation de la production primaire de ce sol.

Samenvatting

Landdegradatie is een groot probleem voor de landbouw in de Sahel. Tijdens de afgelopen decennia zijn de gronden in de Sahel op verschillende manieren ernstig gedegradeerd. De meest in het oog springende vorm van degradatie is de uitbreiding van volledig kale en verkorste gronden. Dit proefschrift richt zich op de wijze waarop termieten-activiteit, in gang gezet door verschillende soorten mulch, verkorste bodems in het Sudan-Sahel gebied van noord Burkina Faso kan rehabiliteren.

Mulch, wanneer uitgespreid op een verkorste en kale bodem, kan binnen enkele maanden de activiteit van termieten op gang brengen. Termieten-aktiviteit resulteert in een verandering van de bodemstructuur. Veel termietengangen doorboren het verkorste bodemoppervlak als gevolg van de graafactiviteiten van de termieten. In het gehele bodemprofiel worden macro-poriën van allerlei vorm en afmeting gecreëerd. De aggregatie van grond door termieten door hun bouw-activiteiten is ook bekeken. Als gevolg van veranderingen in bodemstructuur, worden ook andere fysische eigenschappen van de bodem verbeterd. De indringingsweerstand wordt teruggebracht van een kritiek tot een acceptabel niveau voor vegetatie-groei. Het volumegewicht van de grond wordt verminderd en de waterdoorlatendheid aanzienlijk verbeterd. Tevens worden infiltratie en drainage van water verbeterd. De combinatie van een toename in porositeit en infiltratie alsmede het waterconserverend effect van de mulch resulteert in een toename van de water-beschikbaarheid in het bodemprofiel tijdens het groeiseizoen.

Termieten-aktiviteit stimuleert de vertering van de mulch en dus de nutriënten-beschikbaarheid in de bodem. De kwantiteit van de nutriënten-beschikbaarheid zal afhangen van de chemische samenstelling van de mulch.

De verandering van bodemeigenschappen, als gevolg van termieten-activiteit, is afdoende om condities te creëren voor de ontwikkeling van een natuurlijke vegetatie en voor een gewas-produktie op voorheen gedegradeerde en kale gronden.

Curriculum Vitae

Abdoulaye Mando was born on 23 January 1965 in Kaya, Burkina Faso. He obtained his highschool diploma in mathematics and natural sciences in 1986. In the same years he entered the Natural Resources Institute of the University of Ouagadougou where he obtained a Bachelor in chemistry and biology. In 1988 he joined the Institute for Rural Development to study Agronomy. As part of his university training he did pratical field work in Kaya where he participated in an explorative study for the design of an integrated management plan for selected villages in the Kaya region. He did reseach to obtain his engeneer degree at the CIEH (Centre Inter-Africain d'Etude Hydraulique) on land rehabilitation and the effect of soil fauna on soil physical properties. He graduated in 1991 with a specialisation in Rural Development. He carried out research in the CIEH from June 1991 to February 1992 on the role of NGO's and the research institutes in the innovation of soil and water conservation technologies in Burkina Faso. In April 1992 he joined the Antenne Sahélienne of the Wageningen Agricultural University and the University of Ouagadougou as PhD fellow.