SOIL SALINITY AND ACIDITY: SPATIAL VARIABILY AND EFFECTS ON RICE PRODUCTION IN WEST AFRICA'S MANGROVE ZONE

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A mes parents
A Rougui et Mamy

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PROPOSITIONS

1. In contrast with Vieillefon's views on climate zonality in mangrove soils (1977), spatial variability of soil acidity in coastal lowlands results from a complex interaction of climate, coastal morphology, river hydrology, vegetation, landform and tidal flooding.
This thesis.
Vieillefon, J. 1977. Les sols des mangroves et des tannes de Basse Casamance (Sénégal). ORSTOM Paris.

2. Marius (1984) incorrectly claims that what distinguishes mangrove soils of Sénégal from other mangrove soils worldwide is that the former all contain an appreciable amount of pyrite, while elsewhere potential acid sulfate soils coexist with non-acid soils. In fact, potential acid sulfate soils and non-acid soils coexist also in the mangrove ecosystem of Senegal.
Marius, C. 1984. Contribution à l'étude des mangroves du Sénégal et de La Gambie: écologie, pédologie, géochimie. Mise en valeur et aménagement. ORSTOM, Paris.

3. The high spatial variability of soil properties in acid sulfate soils requires a combination of free surveys and probability sampling to characterize soils for agricultural purposes.
Andriesse, W. 1993 and Bregt et al. 1993. In: Dent and Mensvoort (ed): Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils. ILRI. Publ. No. 53, ILRI, Wageningen.

4. Current agronomic research for limited resource farmers all too often comes face to face with microvariability of soils that is not reflected by the usual methods of analysis.
R.W. Arnold and L.P. Wilding, 1991. The need to quantify spatial variability. In: M.J. Mausbach and L.P. Wilding. SSSA Pub. 28.

5. Most of the development attempts in mangrove swamps of West Africa have been disastrous, because of lack of clear notion of their fragile nature.
This Thesis.

6. Projects aimed to small farmers lead to the risk that insufficiently tested packages will be recommended and imposed in highly variable soil conditions. This enhances the farmer's vulnerability, unless a new approach of 'site specific management' is developed.
Aart van Laar. The World Bank and the poor.

7. Liming acid sulfate soils is only effective in rice when the molar ratio of Fe^{2+} to Ca^{2+} + Mg^{2+} in the soil solution is high.
This Thesis.

8. Visual diagnosis of bronzing (iron toxicity in rice) is better related to the molar ratio of Fe^{2+} to Ca^{2+} + Mg^{2+} in the rice flag leaves at panicle initiation than the absolute amount of Fe in the leaf.
This Thesis.

9. The number of panicles per square meter is not an adequate parameter for the selection of rice varieties in acid sulfate soil conditions.
This Thesis.

10. West African farmers are especially good i) at solving ecological problems of the kind that arise when human and 'wilderness' ecosystems intersect, and ii) at exploiting the risk-spreading possibilities of ecological boundries and landscape sequences e.g. the possibilities of integrating land use up and down soil catenas. Lack of attention to these points continues to bedevil agricultural planning today.
Paul Richards (1985). Indigenous Agricultural Revolution. Ecology and food production in West Africa. Westview Press, Boulder, Colorado.

11. As indigenous knowledge is 'the single largest knowledge resource not yet mobilized in the agricultural development enterprise', we must built a partnership between 'formal' science and 'community ecological knowledge'.
Chambers, R. (1983). Rural development: putting the last first, Harlow: Longman.

12. Land use planning as a process requires special attention to involve the users for whom land is a primary source of livelihood. True interaction with the users throughout the process of land use planning is still to come.
Fresco,L.O. Planning for the people and land of the future. In: Fresco et al.(eds) (1994). The Future of the Land (in press).

13. Science undermines its own foundations if scientists fail to concern themselves with the wider debates concerning human welfare.
Maxwell,N. (1984). From knowledge to wisdom. Oxford: Blackwell.

14. In a Balinese legend, the lord *Vishnu*, god of fertility and water, came to earth to provide better food for the people who had only sugarcane juice as food. *Vishnu* make Mother Earth give birth to rice and then fought *Indra*, lord of the heavens, to force him to teach men to grow rice. Thus rice, as a source of life and wealth and as a gift from gods, was born from the union of the divine creative forces represented in earth and water.
Datta, S.K. 1981. Principles and Practices of Rice Production. John Wiley & Sons. New York.

15. "The traveller may tell all he has seen on his journey, but he cannot explain all."
Ashanti saying.

Mabeye Sylla 7 September 1994

SOIL SALINITY AND ACIDITY: SPATIAL VARIABILITY AND EFFECTS ON RICE PRODUCTION IN WEST AFRICA' MANGROVE ZONE

PhD Thesis, Wageningen

PREFACE

Many people and Research Institutes have contributed to the research that is described in this thesis.
The work reported here was conducted with the collaboration of the National Agricultural Research Institutes of Gambia, Senegal, Guinea Bissau and Sierra Leone and partly financed by the West African Rice Development Association (WARDA) at Bouké, Côte d'Ivoire. Without their help this work will never be completed. I take this opportunity to express my thanks to all of them. My thanks go to the Wageningen Agricultural University for allowing me a sandwich scholarship and most for the invaluable education that I received during this thesis work. I am much indebted to my promotors Prof. Dr.ir. van Breemen and Prof. Dr. ir. Fresco for their daily invaluable guidance, assistance, enthusiastic support during this thesis and most for their unfailing kindness and the inexplicable attachment built in a so short time that certainly helped me forget the long distance from home. I extend thanks and gratitude beyond measure to my host family particularly to Riekje, Barbara, Sanneke, Onno and Marjolein for their kindness and moral support. My thanks are due to Dr. Matlon, Scientific Director of WARDA, for his help and encouragements during all this thesis. To Dr. Habib Ly, Directeur General de l'ISRA, *je lui transmet mes plus vives remerciements.* I take this opportunity to thank all the staff of the Soil Science and Geology and Agronomy Departments for their daily assistance. My thanks go to Dr. Stein, Tiny van Mensvoort, Nico de Ridder, Bart de Steenhuijsen Piters, Dr. Jongmans, Dr.Harry Booltink and all my colleagues. I am much indebted to my friend Wim Andriesse and his family, to him I will say *mille fois merci pour tout.* I extend my thanks to Dr. Eric Smalling for his friendship and kindness. I am thankful for Dr. Jean Pierre Ndiaye of ISRA St. Louis, Ablaye Dramé, Couloubaly, Sagna, Samba Sall, Souleymane Diallo, Saliou Djiba, Lamine Sonko, Khalifa, Laye Gueye, Dr. Sall, Abibou Niang, Touti, Mamadou Lo, Barry, Mankeur, Astou, Md. Sall, Alioune Fall, Badiane, Thomas, J.P. Coly, Mamadou Diop, Bolle, Takieu and Contey, Dixon, Dr. Sampong and Guei, Dr. Monde, Diaga Dieng, Justin and Pape Ablaye Seck, Dr. Mbaye Doye and Dr. Moctar Touré, to Dr. Mbodj, Thiendou Niang (CTA) and his family, Mustafa Ceesay and Djiba, Thierno Mballo and Lamine. My thanks and gratitude go to the former "trainees" Pascal, Heleen, Linda and beyond measure to my 'little sister' Simone. My thanks are due to Jacintha and Potin for their friendship. I am also indebted to my friends and brothers Magatte, Aziz, Penda, Elhadji Samba, Moussa, Elhadji Moustapha Diouf (UNICEF), Zal, Matar, Cheikh Sow, Yaya, Abi, Bonze, Abou Tall, Claude Diop, Marie Andre. My thanks go in full measure to the farmers of Gambia, Senegal, Guinea Bissau and Sierra Leone to whom I express my full respects for the hard work in the muddy mangrove swamps.
I am indebted to my father in love Elhadj Birahim Ba and his family, to Prof Moustapha Sow and family and to Tonton Dr. Mady Sylla and Tata Niebe. I express here all my thanks and gratitude to my parents for their efforts to give me the opportunity to pursue a good education.
And finally to Rougui and Mamy, love and appreciation beyond words.

CONTENTS

CHAPTER 1

GENERAL INTRODUCTION AND BACKGROUND

GENERAL INTRODUCTION AND BACKGROUND

In the mangrove zones of West Africa, spatial and temporal variability of specific soil stresses to rice production have always been a problem for technology transfer, land use planning and soil water management. Such variability exists at macro scale, within river basin, but also from point to point within a single soil unit along a catena (Dent, 1986).
In the past, National and International Agricultural Centers were not concerned with agro-ecological characterization of the environments where their newly developed technologies had to be applied. Their improvement programs were based mainly on selection of new varieties and testing through international nurseries. Although some of the new cultivars were widely adapted in homogenous environments, more heterogenous situation such as the mangrove zones many problems arose. Hazel et al. (1986) indicate that failure to adopt new varieties was mainly due to specific environmental stresses such as those related to soils and climate imposed by the variability and distribution of rainfall, soil acidity, excess of exchangeable Al, Fe^{2+}, high salinity, and low nutrient status of soils.
Recently, environmental characterization and classification has become increasingly important in planning agricultural research and technology transfer. So far however, little attention has been paid to marginal environments such as the mangrove zones, especially in developing countries. Brinkman (1986) suggests that agro-ecological characterization should be used to guide the practical application of research results.
Many research findings are applicable only within specific environmental limits. WARDA (West African Rice Development Association) has divided its work among distinct rice-growing environments with objectives generally geared towards the needs of the people (farmers level). Its mandate within the mangrove rice environment in West Africa comprises the development of methods that can serve as a base line for optimal adoption of improved technologies by the farmers.
Mangrove sediments and related soils, including potential and actual acid sulfate soils, in West Africa are found along the Atlantic coast from Senegal through Gabon. Their area is estimated at around 2,800 million ha (Langenhoff, 1986). The long tradition of rice cultivation in these areas and the continuous population growth currently lead to increased clearing of mangrove lands and of adjacent upland forest. The environmental problems caused by this are obvious, in particular in the irreversible disturbance of the ecologically vulnerable mangrove habitat, in soil acidification and in increased salinization. There is a clear need, therfore, to counter this degradation by defining options for improved land use and management methods, aiming at increased but sustainable productivity of existing cultivated lands, while safeguarding the natural mangrove ecosystems. To target research and management more effectively, a characterization of the West African mangrove environments is undertaken, with a special emphasis on the physical and chemical aspects of potential and actual acid sulfate soils associated with mangroves.
In West Africa various attempts have been undertaken to characterize rice growing environments (Kilian and Teissier, 1973; Buddenhagen, 1978; WARDA, 1980; IRRI, 1984; Raunet, 1985; Bunting, 1986; Andriesse and Fresco, 1991). These systems give only broad classifications for mangrove rice. However, the approach of Andriesse and Fresco (1991), for the upland-lowland continuum included sufficient agronomic and landscape factors for a more detailed classification. In the mangrove environments, the approach requires complex targeting in terms of physical and agronomic factors because of the high spatial variability of soil conditions. Research in process-oriented studies of acid sulfate soils have greatly enhanced our knowledge on the causes and effects of acidification (van Breemen, 1973, 1976, 1993;

Pons et al. 1982 and Dent, 1986, 1992). However, this knowledge has not yet been utilized to characterize the mangrove environment.

The method adopted in this thesis to characterize mangrove rice environments is based on central concepts derived from the necessary pre-conditions for acid sulfate soil formation (van Breemen, 1976 and Pons et al., 1982). The selected central concepts are:

- Climate: climate plays a decisive role as soil forming factor and physiological driver of crop growth. It is interrelated with the river hydrology and largely determines the degree and the extent of salinity, and is one of the most important factors in water management. The factor climate is used at the macro-level.

- Hydrology and tidal regime: the most important constraints considered are the distribution and dynamics of soil salinity along the river and actual acidification of naturally drained area. Within the same climatic zone the balance between fresh water river discharge and tidal propagation during the rainy season governs the process of natural desalinization.

- Physiography and pioneer vegetation: organic matter plays an important role on pyrite formation (van Breemen, 1976). Its origin and distribution can be a clue to segregate zones of high and low potential acidity. As indicated in many studies *Rhizophora* sp. tends to be associated to high soil organic mater and *Avicennia* sp. with much less soil organic mater, reflecting differences in their root configuration and density. Also, vegetation distribution in these ecosystems generally follows salinity levels. Highly saline areas are generally occupied by *Avicennia*, while at lower salinity *Rhizophora* predominates. Therefor their distribution along and across the river basin can help detect sub-zones.

-The rate of coastal sedimentation may affect pyrite formation (Pons et al.,1982). Low pyrite content is associated with fast sedimentation rate in accreting coasts.

- Landscape and catena: Both salinity and acidity can be strongly influenced by topography across the river basin due to differences in tidal flooding regime and vegetation distribution along catenas.

These factors were organized to build a framework describing the distribution of acid sulfate soil and of saline soils.

The main objectives of this thesis were: 1) to design a comprehensive characterization framework for the West African mangrove environments with emphasis on the possibilities of and constraints for rice cultivation; 2) to determine the significant causal factors of soil salinization and acidification; 3) to test whether the temporal variability of soil chemical composition will allow a sufficient time window of minimum stresses for rice growth; 4) to relate the response of rice to improvement techniques to specific environments and to provide means to characterize rice growing environments; 5) to test rice varietal responses to saline and acid soils under different improved agronomic practices; and 6) to relate yields and yield components to the nutrient contents in the leaves in order to diagnose physiological disorders.

BACKGROUND RESEARCH ON ACID SULFATE SOILS

Acid sulfate soils are generally found on marine and estuarine sediments rich in reduced sulfur compounds. Upon drainage and aeration, they undergo a definite and severe acidification due to the oxidation of mainly pyrite (FeS_2) and production of sulfuric acid. They are generally located in relatively flat areas that are frequently flooded and that are potentially suitable for rice cultivation. But because of frequent high acidity and salinity, and associated toxic elements, these soils generally gives low yields (about 1 t ha^{-1}) and limitations are sometimes so severe that crops fail completly ("sols ingrats", Beye, 1974).

1) Chemical processes in acid sulfate soils

1.1 Potential Acidity

The formation of pyrite in waterlogged marine environments and its following oxidation, either naturally or by artificial drainage, yields the essential chemical processes involved in acid sulfate soils. The topic has been reviewed by van Breemen (1976), Goldhaber and Kaplan (1982), and Dent (1986). The processes are:

- Formation of pyrite which involves several steps:

i) the reduction of sulfate ions from sea water to sulfide via sulfate-reducing-bacteria through the decomposition of organic mater (O.M.) according to:

$$SO_4^{2-} + 2\ CH_2O \text{ ------> } H_2S + 2\ HCO_3^-$$

ii) the partial oxidation of sulfide to S or polysulfide

iii) dissolved iron from iron-III oxides or silicates in the sediment is combined with the dissolved sulfide to form iron monosulfide (FeS)

vi) iron monosulfide and elemental S will then form FeS_2 or ferrous Fe will precipitate directly with polysulfide to form FeS_2.

The following equation may summarize the process:

$$Fe_2O_{3\,(s)} + 4SO_4{}^{2-}{}_{(aq)} + 8CH_2O + 1/2\ O_2 \text{ --> } 2FeS_{2\,(s)} + 8HCO_3{}^{-1}{}_{(aq)} + 4H_2O$$

So the pre-conditions for pyrite formation are:

i) a waterlogged environment to provide for the very slow supply of O_2 to reach a strong reduction

ii) a source of sulfate ions

iii) organic matter as an energy source for sulfate-reducing bacteria

iv) a source of iron

v) time : the rate of pyrite formation is not yet clearly elucidated, but it is known that solid-solid reaction between FeS and S is too slow whereas the precipitation of Fe^{2+} and polysulfate may be rapid. Also if the rate of sedimentation is rapid, as in the case of an accreting coast, Pons et al. (1982) observed little pyrite formation.

These pre-conditions are met in mangrove areas best on slowly-accreting non-calcareous sediments where sulfate is supplied from sea water, iron from sediments, organic matter from the vegetation and tidal flooding removes bicarbonates and supplies a limited amount of O_2 necessary for complete pyritization of sulfide.

1.2 Acid neutralizing capacity.

The waterlogged soil in a marine environment is a potential acid sulfate soil only if the potential acidity represented by the amount of pyrite is greater than the soil acid neutralizing capacity. Acid neutralizing capacity is provided by carbonates, exchangeable bases and weatherable silicates. One percent (mass fraction) of pyrite-S is neutralized by 3% of $CaCO_3$; smectite can neutralize up to 0.5% pyrite-S; kaolonite has little neutralizing capacity at a pH around 4. The most effective neutralizing substance in marine sediments is carbonate derived from shells and coral. But the presence of CO_2 from the root respiration and the decay of organic matter, of H_2S and the oxidation process during low tide generally maintain slightly acid conditions in mangrove sediments, which limit the precipitation of $CaCO_3$, and help to remove allochtonous carbonates.

1.3 Actual Acid Sulfate Soil

Pyrite is stable under reduced conditions, e.g. at low redox potential. When a potential acid sulfate soil is aerated, either naturally (reduced frequency of tidal cover) or by artificial drainage (lowering of the water table by drainage or building of small scale dams), oxidation of pyrite takes place in several stages, involving both chemical and microbial processes.
These stages of oxidation do not usually occur in the same place. Van Breemen (1976) illustrated with a model the seasonal dynamics of the processes and the place within the soil profile where each process takes place.
The solid products of the pyrite oxidation include iron oxides, jarosite, and gypsum:

- At pH above 4, FeIII-oxide and hydroxides precipitates directly by oxidation of dissolved iron II. Generally goethite is the most common iron oxide, while hematite may occur in old acid sulfate soils.
- At pH below 3.7 and Eh > 400 mVolts, jarosite is likely to form.

In describing the effects of pyrite oxidation on soil chemistry, the following two stages are important:
First, pyrite oxidizes to dissolved ions and sulfuric acid:

$$FeS_2 + 2O_2 + H_2O \text{ ----> } Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+$$

Further oxidation of dissolved ferrous sulfate gives a ferric precipitate and more sulfuric acid; e.g.

$$Fe^{2+} + SO_4^{2-} + 1/4\ O_2 + 3/2\ H_2O \text{ ----> } FeOOH + 2\ H^+ + SO_4^{2-}$$

Generally jarosite ($KFe_3(SO_4)_2(OH)_6$) is formed, but when K^+ is very scarce, natrojarosite or hydronium jarosite can be formed.
At higher pH values they can hydrolyze to iron oxide.
When calcium carbonate is present to neutralize the acidity, gypsum is often formed:

$$CaCO_3 + 2\ H^+ + SO_4^{2+} + H_2O \text{ ----> } CaSO_4.\ 2\ H_2O + CO_2$$

- At very severely acid conditions, rapid weathering of silicate minerals take place yielding Al^{3+} and dissolved silica.

1.3 Reduction process under flooding of acid sulfate soils

Under flooded conditions, the dissolved O_2 is depleted by aerobic micro-organisms, and organic matter is decomposed by anaerobic bacteria while nitrate, manganese oxides and iron-III oxides and sulfate are reduced. The process induces an increase of CO_2, HCO_3^-, Fe^{2+} and in some cases, exchangeable Ca is displaced by iron.
The flooding condition will increase the pH with the consumption of hydrogen ions in time (Ponnamperuma, 1955):

$$Fe(OH)_3 + 2\ H^+ + 1/4\ CH_2O \text{ ----> } Fe^{2+} + 11/4\ H_2O + 1/4\ CO_2$$

But the process of reduction in acid sulfate soils due to flooding can be slowed down by the extreme acidity, the low nutrient status and the low content of easily decomposable organic matter. Prolonged flooding, however, can eventually lower the acidity, but in many cases the pH remains below 5 due to strong buffering at low pH.
The pH increase upon flooding causes a lowering of dissolved Al^{3+}. In young acid sulfate soils, high Fe^{2+} concentrations usually develop upon flooding.
In arid zones with a pronounced dry season, the acidity generated at greater depths by pyrite oxidation during the lowering of the water table, can migrate upwards to produce even acid salts in the soil surface ($NaAl(SO_4)_2$; $MgAl_2(SO_4)_4$; $FeSO_4$; $Al_2(SO_4)_3$). In the subsequent rainy period, these acid salts are dissolved and produce acidity. Then Fe-II is produced which in its turn can oxidize at the soil-water interface to produce more acidity:

$$Fe^{2+} + 1/4\ O_2 + 5/2\ H_2O \dashrightarrow Fe(OH)_3 + 2\ H^+$$

2) Potential acid sulfate soils environments

The most representative potential acid sulfate soil environments in West Africa are characterized by saline and brackish-water tidal swamps and marshes with dense vegetation of *Rhizophora sp., Avicennia sp., Phragmites, Paspalum vaginatum* etc..
This dense vegetation is the source of organic matter needed by bacteria in the process of reduction of sulfate from the sea water. The tidal cycle brings sediments, renews the supply of sulfate and removes the bicarbonate produced during pyrite formation.
Within a mangrove environment, important differences may exist in potential acidity due to i) the type of pioneer vegetation ii) the rate of sedimentation. The spatial variability of these two factors will affect the amount of pyrite formed. Some authors (Tomlinson, 1957; Hesse, 1961; Jordan, 1964; Giglioli and Thornton, 1965 and Kalawec, 1977) have observed differences in the amount of pyrite between soils having been influenced either by *Rhizophora* or *Avicennia* or *Phragmite* vegetation during genesis, with decreasing potential acidity respectively).

3) Soil related constraints for rice in acid sulfate soils environments

The constraints for rice growth in acid sulfate soils have been reviewed many times (Rorison, 1972; Bloomfield and Coulter, 1973; van Breemen, 1976; Sylla and Touré, 1988; Dent 1986).
The main constraints in aerated conditions are:
- severe acidity per se
- aluminum toxicity
- low available phosphorus
- low base status and nutrient deficiencies
- high salinity

Under flooded conditions, acidity and high Al tend to diminish, but other problems appear:
- ferrous iron toxicity (bronzing)
- hydrogen sulfide toxicity (suffocation disease)
- excess carbon dioxide and organic acids

To improve rice production in mangrove environments, the chemistry and biochemistry behind theses physiological stresses should be clearly understood.

3.1 Aluminum toxicity

Concurrent with a pH-decrease during pyrite oxidation, dissolved Al is released by dissolution of clay minerals. Al hazards occur generally under low pH (pH values less than 3.5). Under such condition Al inhibits rice growth. Soluble Al accumulates in the root tissues and prevents the division of cell tissues and elongation and possibly also inhibits enzymes involved in synthesis of cell-wall material (Rorison, 1972).
Over a wide range of acid sulfate soils and actual pH, van Breemen (1973) showed a high correlation between Al^{3+} activity and pH. The relation found for Thailand soils over a wide range of pH was :

$$[Al^{3+}] [SO_4^{2-}] [OH^-] = 17.3$$

Apparently, a basic sulfate, $AlOHSO_4$, controls the concentration of dissolved Al^{3+}. Groenenberg (1990) confirmed the relationship with soils from Indonesia where Jurbanite, ($AlOHSO_4.5H2O$), was suggested to control the equilibrium. Yet, that particular mineral has never been found in acid sulfate soils (van Breemen 1993). Nevertheless the relationship describing the equilibrium with jurbanite is useful in predicting the concentration of Al^{3+} in acid sulfate soils. Since $SO_4{}^{2-}$ activity in most acid sulfate soils is roughly constant, a one unit increase in pH corresponds approximately to a 10 folds decrease in the concentration of Al^{3+} (Satwathananont, 1986; Hanhart and Ni, 1991 and van Breemen, 1993).

3.2 Iron toxicity (Bronzing) during flooding of acid sulfate soils.

Ferrous iron toxicity can limit rice growth on acid sulfate soils. In old acid sulfate soils where most of the iron is in a form of well-crystallized goethite and hematite, very little soluble iron is likely to be produced during flooding. In such soils with moderate acidity (pH 4-6), flooding induces an increase in pH to values up to 6-7 after a few weeks (Ponnamperuma, 1972). The peak of Fe^{2+} is reached in a few weeks of waterlogging condition and then decreases. The rate of the reaction and the amount of Fe^{2+} produced can be quite variable depending on the presence or absence of organic matter, the type of proton donors (exchangeable Al, CO_2 and adsorbed SO_4) with and without formation of exchangeable Fe^{2+}. This is well illustrated in an hypothetical model developed by van Breemen (1988).
In young acid sulfate soils rich in colloidal iron, the concentration of Fe^{2+} produced after flooding is likely to be high. Therefore bronzing is common in such young soils.

3.3 Hydrogen sulfide toxicity (" Akiochi")

During flooding, sulfate reduction produces $H_2S(g)$. Even at concentrations as low as 1 to 2 10^{-6} mol/m3, H_2S can affect the plant-root system (suffocation) especially in young seedlings. Plants affected by H_2S toxicity can be very susceptible to disease.
H_2S toxicity is generally associated with soils rich in organic matter and low in iron content. If iron is present, H_2S can react with Fe to form FeS and ultimately pyrite. Since the bacteria responsible of the reaction operate only at pH greater than 5, H_2S toxicity occurs only in soils that reach such a pH level upon flooding.

3.4 CO_2 and organic acids

During organic matter decomposition CO_2 is produced and may accumulate in flooded soils. At a partial pressure of 15 kpa, CO_2 can retard root development and reduce nutrient uptake. The decomposition of organic matter produces also organic acids. Under acid conditions, they may become toxic to plants.

3.5 Salinity problems within acid sulfate soils

When soluble salts are present, as often in tidal marshes and recently reclaimed sulfidic soils, their osmotic effects can inhibit the uptake of water and nutrients. Toxicity of Na^+ and Cl^- are also common. Within Senegal, the Gambia and Guinea Bissau, with a pronounced dry season and a decrease of the annual rainfall over the last 20 years, salinity levels with ECe values of 80 mS cm^{-1} are not uncommon in the top soil. By comparison, sea water has an EC of about 45 mS cm^{-1}.

When the soil is sufficiently permeable and sufficient fresh water is available, leaching of salt by rain water and flooding with fresh water can occur and the EC may become low enough (ECe < 8 mS cm^{-1}) for rice growth. But in many cases, if the soils have inadequate drainage and insufficient fresh water supply is available, salinity hazards are the main limiting factor for rice production.

3.6 Low fertility problems

Nutrient deficiencies are common in acid sulfate soils. In old acid sulfate soils, leached acid sulfate soils, and highly organic soils, P-availability is low and P-fixation may be high due to active Al and Fe. Strongly leached acid sulfate soils have low contents of Ca, Mg, K, Mn, Zn, Cu, and Mo and deficiency symptoms may appear.

At low pH, symbiotic fixation of N is restricted, and mycorrhiza stimulating P-uptake can be affected.

3.7 Problems related to trace elements

Deer et al. (1965) report that trace elements such as Ni, Co, Cu, Zn, Pb, and As may accumulate together with Fe in sedimentary pyrite. During oxidation these elements can be released. Little work has been done on the release of trace elements during pyrite oxidation in potential acid sulfate soils. However there is evidence that pyritic soils indeed release higher amount of trace elements than "normal" soils (Satawathananont, 1986).

4) Soil landscape and classification.

This section deals with soil variability, and with the relationships between soil characteristics and other facets of the landscape where acid sulfate soils can be expected.

4.1 Landform

As explained earlier, pyrite accumulates only under certain conditions favorable for its formation. These conditions are found along deltas, sheltered estuaries, and coastlines protected by offshore islands and bars.

Generally the topographically low parts of inter-tidal zones are flooded frequently. The soil is reduced most of the time and usually pyrite content are highest and potential acid sulfate soils (Sulfaquents) are formed.
In the highest part of the tidal landscape, the top soil is generally aerated at low tide. The tidal range and the effectiveness of the drainage influence the depth of the oxidized soil layer. These areas, such as levee zones and some high backswamp areas, are generally occupied by Aeric Sulfaquents .
Since time is important and several years are needed for pyrite accumulation in excess of the soil's neutralizing capacity, only stable systems with slow sedimentation rate can provide potential acid sulfate soils. In general, rapidly depositional landforms such as levees have less pyrite than the stable systems.
The drainage system within the landscape should be effective in order to remove the excess bicarbonate formed during pyrite formation. Landscapes with a dense layout of creeks will be ideal for optimum pyrite accumulation. If not the carbonates accumulate and little potential acidity will be formed, therefore the type of soils expected is Fluvaquents or Hydraquents with low TPA (total potential acidity).
The variability of these conditions along the landscape induces micro-variation on TPA as well as the depth on which pyrite accumulates in the soil profile. Such factors are important while reclaiming the soils in the mangrove zone. Mapping of such spatial variation is the clue of the success of soil-water-management in mangrove zones.

4.2 Vegetation

In the ecology of tidal zones, both climate and salinity affect the contrast in vegetation types. The type of vegetation varies along the river basin and within a transect. *Rhizophora* sp. is generally located in marine environments with daily tidal flooding. *Avicennia* sp. is more halomorphic and tend to occupy the areas of high salinity where tidal flooding is less frequent and evaporation tends to accumulate salts. Reeds such as *Phragmites* are generally situated at the limit of tidal influence with more fresh water flooding. Halophytic herbs such as *Sesevium* and *Paspalum* follow the *Avicennia* in more saline environments.
Dead roots of such vegetation are the main source of energy for the bacteria responsible for pyrite formation. The correlation between vegetation and soil TPA is complex because the actual vegetation may differ from the one responsible for pyrite accumulation. Table 1 illustrates some observed differences along a transect in the Gambia.
The importance of these zones can vary along the river depending on the proximity to the mouth. Climate can also influence the extent of such zones. In the dryer area of Senegal and Gambia, *Avicennia* and bare salina can be predominant. In wetter area *Rhizophora* seems to be more dominant. Dent (1986) established a sequence in Gambia with *Rhizophora racemosa* in tidal sites with best surface drainage along the river and creek channels with daily tidal flooding, followed by *Rhizophora mangle*, succeeded by *Avicennia africana* above high-water neap tidal level followed by *Sesevium portulacastrum* in saline areas and by *Phragmites karka* in less saline areas.

Table 1: Landscape position, vegetation, and soil type along the Gambia River.

Landscape position	Soil type	Vegetation and land use	Pyrite accumulation
A (Terraces)	Sandy and coarse loamy soils	Savanna woodland	- - -
B (low terraces/ high backswamps)	Ripe clay soil with or without saline sub-soil	Rice cultivation only in the wet season	- - +
C (high backswamps)	Half ripe to ripe soil; extremely saline underlying a pyritic layer "Tanne"	Bare salina former rice fields	- + +
D (low backswamps)	Half ripe soil saline with a pyritic layer at depth	*Avicennia* partially flooded by tidal water	- + +
E (low backswamps with fresh water)	Half ripe to unripe soil slightly saline with or without pyritic layer at depth	*Phragmites*. *Echinochloa* reed swamp	- - +
F (near levee)	Unripe mud pyritic	*Rhizophora*	+ + +

where - - - = no pyrite in the whole soil profile
- - + = pyrite may be present on greater depth
- + + = pyrite may be present except near the soil surface
+ + + = pyrite is present throughout the soil profile.

5) Reclamation and improvement of acid sulfate soils

Reclamation and improvement of acid sulfate soils has been reviewed recently (Dent, 1992 and van Breemen, 1993) in relation to the process regulating the concentrations and emissions of the potentially harmful toxins such as H_2S, H^+, SO_4^{2-}, Fe^{2+}, Al^{3+}, trace elements and salinity.

5.1 Measures to reduce pyrite oxidation.

Van Breemen (1993) suggested that the only sure way to curtail pyrite oxidation is to cut down the supply of O_2 by waterlogging. Hampering oxidation using a bactericide or ligand that chelates Fe^{3+} (Pulford et al., 1988) is certainly unfeasible in West African agriculture.

5.2 Decreasing soil salinity

Efficient salt leaching by shallow drainage is the most effective way to decrease salinity levels to acceptable limits for rice cultivation. Leaching can also increase the pH, lower the specific conductance and the concentration of Al and other salts as well as the partial pressure of CO_2 (Hesse, 1961 ; Pounamperuma, 1972). In Senegal, Beye (1973) observed beneficial effect of shallow drainage in acid sulfate soils. Sylla and Touré (1988) showed that ridging by plowing as done in the Diola zone is efficient to control salinity as well as iron toxicity. Detrimental acidity and salinity can be overcome by daily leaching with brackish to fresh water tide in Sierra Leone (RRS Annual report, 1956 and Sylla et al., 1991). Rice straw mulching experiments in Senegal proved to be an efficient practice to avoid salinity build-up during the dry season (Beye, 1974).

5.3 Decreasing soil acidity

Two processes can decrease TAA (total actual acidity): leaching and neutralization. Excess H_2SO_4 formed as well as soluble Fe and Al salt crusts in the surface soil can be removed by leaching. With brackish or salt water an exchangeable Al can be removed in exchange for Na, Ca and Mg followed by leaching of Al^{3+}. This seems to be an efficient way to remove exchangeable Al prior to amendments.
However, leaching efficiency, among other things, depends on soil structure. If water drains through macro pores rapidly, it bypasses the interior soil aggregates and therefore removes fewer salts. To increase the time of contact between water and the soil peds, puddling and water ponding can be very effective. In many cases intermittent drainage can be an effective leaching method (Sylla and Touré, 1988). However, while leaching of salt is a cheap way to improve soils, it also removes soil nutrients.

5.4 Liming

Soil acidity can be overcome by liming (Dent 1992). But, under severely acid conditions, the lime requirement for complete neutralization of acidity produced by the oxidation of oxidizable sulfur is often prohibitive for normal agricultural usage. Dent, (1992) and van Breemen (1993) both pointed out the huge amount of lime (30 t/ha) needed to neutralize the acidity potentially present in 1% oxidizable sulfur.
In some cases, a small amount of lime (1 to 2 t/ha) can be effective on rice under flooding condition (Sylla and Touré, 1988 and Sylla et al., 1993). Liming can supply Ca and remove toxic effects of Al on rice fields. It can also counteract the poor physical conditions brought about by leaching. Liming under flooded conditions increases soil nitrogen mineralization and available P. Liming stimulates the rate of organic matter decomposition by micro-organism. Liming can increase the availability of most plant nutrients (Truog, 1948), and can decrease the content of ferrous iron (Ponnamperuma, 1958; 1964; Subramoney and Balakrishmakurup, 1961; and Tanaka and Navasero, 1966). Combined leaching and liming has been effective in acid soils of Senegal (Beye, 1973; and Sylla and Toure, 1988). Sylla et al., 1993, and Moore et al., 1993, indicated the negative interaction of Ca and Fe in reducing iron toxicity in rice.

5.5 Self-liming or pre-flooding

During flooding Fe-III is reduced to Fe-II, a reaction which consumes acidity. The soil pH then increases. The trade-off is the high production of FeII and H_2S (Van Breemen, 1993). However, exchangeable acidity is effectively neutralized by the reduction of FeIII oxide without an increase in dissolved Fe^{2+}. This is not true in all cases. The soil pH can remain low after flooding in the case of insufficient reduction or a low FeIII content. Van Breemen (1988) observed a beneficial side effect of flooding at the soil-water interface caused by a transfer of acidity from the soil to the surface water due to the oxidation of FeII $SO_{4\,(aq)}$ followed by the precipitation of FeIII oxide on the soil and the release of H_2SO_4 in the surface water.

OUTLINE OF THE THESIS

This thesis is organized in a series of chapters to be separately submitted to scientific journals. Therefore some repetitions will be found throughout.

CHAPTER 2 is a comprehensive characterization of the West African mangrove environments, with emphasis on the possibilities of and constraints for rice cultivation. A multiple scale approach was followed, ranging from macro- to micro-level based on the main causal factors of saline acid sulfate soils formation.

In CHAPTERS 3 and 4 the spatial variability of soil salinity and acidity were studied by means of nested models and geostatiscal methods to test the significance of the main causal factors of soil salinization and acidification. In parallel, hierarchically structured frameworks to account for the causal factors at different scales were designed and used to interprete soil chemical data.

In CHAPTER 5 temporal and spatial variability of soil solution chemistry was studied to determine a time window for minimum soil stresses on rice plant.

In CHAPTER 6 a series of network rice trials implemented in different mangrove environments was used to determine rice response under different improved agronomic practices in relation to the soil constraints.

In CHAPTER 7 differential responses of rice varieties to the main soil constraints in mangrove environments are presented.

In CHAPTER 8 the main conclusions of this thesis are summarized and future challenges outlined.

REFERENCES

Andriesse, W. and L. Fresco. 1991. A characterization of rice growing environments in West Africa. Agric. Ecosyst. Environ., 33:377-395.

Béye, G. 1973. Acidification of mangrove soils after empoldering in low Casamance. Effects of the type of reclamation system use. In: Dost, H.(ed) Acid sulphate soils. Proc. Int. Symp. Wageningen, ILRI publ. 18. vol. II: 359-371.

Béye, G. 1974. Sols ingrats et remèdes. WARDA Seminaire.

Bloomfield, G. and J.K. Coulter. 1973. Genesis and management of acid sulfate soils. Advance in Agronomy p. 266-319.

Buddenhagen, I.W.. 1978. Rice ecosystems in Africa. In: Buddenhagen, I.W. and Persley (Eds), Rice in Africa. Academic Press, London, UK. p. 3-10.

Bunting, A.H. (Ed). 1987.Agricultural environments; characterization, classification and mapping. Proceedings of the Rome workshop on agro-ecological characterization, classification and mapping, 14-18 April, 1986. CAB International, Wallingford, UK. 335pp.

Breemen, N. van 1973. Soil forming processes in acid sulfate soils. p 66-130 In Dost, H. (ed). Acid sulphate soils. ILRI Publ. 18, vol I, Wageningen.

Breemen, N. van 1976. Genesis and solution chemistry of acid sulfate soil in Thailand. Agr. Res. Rep. 848. PUDOC, Wageningen. 263p.

Breemen, N. van 1988. Effects of seasonal redox processes involving iron on the chemistry of periodically reduced soils. In: J.W. Stucki et al. (eds) Iron in soils and clay minerals, D Reidel Publ. Co, Dordrecht, The Netherlands, pp. 797-809.

Breemen, N. van 1993. Environmental aspects of acid sulphate soils. p 391-402. In: Dent, D.L. and M.E.F. van Mensvoort (ed). Selected papers of the Ho Chi Ming City Symposium on acid sulphate soils. ILRI publ. 53. ILRI, Wageningen, The Netherlands.

Brinkman, R. 1986. Agro-ecological characterization, classification and mapping. Different approaches by the international agricultural centres. In: A.H. Bunting (ed) Agricultural environments. Characterization, classification and mapping. Proc. workshop on agro-ecological characterization, classification and mapping, 14-18 April 1986, Rome. CAB publ, pp. 31-42.

Deer, W.A., R.A. Howie and J. Zussman. 1965. An introduction to the rock forming minerals. Longmans, London.

Dent, D. 1986. Acid Sulphate Soils: The baseline for research and development. ILRI Publ. 44. Wageningen.

Dent, D. 1992. Reclamation of acid sulphate soils. Adv. Soil Science 17, 79-122. Springer Verlag New York Inc.

Giglioli, M.E.C. and I. Thornton. 1965. Mangrove swamps in The Gambia. J. of Applied Ecology 2:81-103 and 257-269.

Goldhaber, M.B. and I.R. Kaplan. 1982. Controls and consequences of sulfate reduction rates in recent marine sediments. In: Acid sulfate soils weathering. SSSA special Publ. 10, Madison, Wisc.

Groenenberg, J.E. 1990. Modeling of solute transport and chimical processes in acid sulphate soils. In: AARD & LAWOO: Papers Workshop on Acid Sulphate Soils In the Humid Tropics, Bogor: 182-194.

Hanhart, K. and Doung Van Ni, 1991. The effect of water management treatments on the cultivation of an irrigated dry season rice crop on a severe acid sulphate soil in Hoa An Station, Vietnam. VH 10 Report.

Hazel, C.H. and W. Goeber. 1986. Objectives, Needs and activities in agro-ecological characterization, classification and mapping. In: Bunting, A.H.(ed) Agricultural environments. Characterization, classification and mapping. Proc. workshop on agro-ecological characterization, classification and mapping, 14-18 April 1986, Rome. CAB publ, pp 5-10.

Hesse, P.R. 1961. Some differences between the soils of Rhizophora and Avicennia mangrove swamps in Sierra Leone. Plant and Soil 14 (4) 335-346.

IRRI, 1984. Terminology for rice growing environments. IRRI Los Baños, Laguna.

Jordan, H.D. 1964. The relation of vegetation and soil to development of mangrove swamps for rice growing in Sierra Leone. J. Appl. Ecology 1:209-212.

Kalawec,A. 1977. La genèse et l'évolution des sols sur alluvions marines. Varsovie, Poland.

Kilian, J. and J. Teissier, 1973. Methodes d'investigation pour l'analyse et la classification des bas-fonds dans quelques régions de l'Afrique de l'Ouest. Proposition de classification d'aptitude des terres à la riziculture. Agron. Tropicale, 28 (2), pp. 156-171.

Langenhoff, R. 1986. Distribution, mapping, classification and use of acid sulphate soils. A literature study. STIBOKA International Communications No. 74. The Netherlands Soil Survey Institute, Wageningen, The Netherlands.

Moore, P.A. and W.H. Patrick jr. 1993. Metal availability and uptake be rice in acid sulphate soils. p: 205-224. In: Dent, D.L. and M.E.F. van Mensvoort (ed). Selected papers of the Ho Chi Ming City Symposium on acid sulphate soils. ILRI publ. 53. ILRI, Wageningen, The Netherlands.

Ponnamperuma, F.N. 1955. The chemistry of submerged soils in relation to the growth and yield of rice. PhD thesis, Cornell Univ.

Ponnamperuma, F.N. 1958. Lime as a remedy for a physiological disease of rice associated with excess iron. Int. Rice Comm. Newsl. 7 (1): 10-13.

Ponnamperuma,F.N.,1964. Dynamic aspects of flooded soils and the nutrition of the rice plant. In: Proc. Symp. Mineral Nutr. Rice Plant, Mariland, USA. John Hopkins Press.

Ponnamperuma, F.N. 1972. The chemistry of submerged soils. Adv. Agron. 24: 29-96.

Pons, L.J., N. van Breemen and P. Driessen. 1982. Coastal sedimentary environments influencing the development of potential soil acidity. In: Acid Sulfate Soils Weathering. Soil Sc. Sc. Soc. Am. Special Publ. 10, Madison, Wisc, pp. 1-18.

Pulford, I.D., C.A. Backes, and H.J. Duncan. 1988. Inhibition of pyrite oxidation in coal mine waste. In: Dost (ed) Selected papers of the Dakar symposium on acid sulphate soils. ILRI Publ. 44, Wageningen, The Netherlands, pp. 59-67.

Raunet, M. 1985. Bas-fonds et riziculture en Afrique. Approche structurale et comparative. Agronomie Tropical, 40 (3), pp. 181-201.

Rickard, D.T. 1973. Sedimentary iron sulphate formation. In: Dost, H. (ed). vol. 1 pp 28-65.

Rorison, I.H. 1972. The effect of extreme soil acidity on the uptake and physiology of plants. In: Dost, H. (ed). first symposium on acid sulphate soils. ILRI Publ. 18 vol. 1 Wageningen, pp. 223-254.

RRS, 1956. Annual report. Rokupr, Sierra Leone.

Satawathananont, S. 1986. Redox, pH and ion chemistry of acid sulphate rice soils in Thailand. PhD thesis, Louisiana State Univ.

Subramoney,N. and T.K. Balakrishmakurup. 1961. A physiological disease of paddy to iron toxicity. Agr. Res. Journ. of Kerala 1(1): 100-103.

Sylla, M. and M. Toure. 1988. Edaphic constraints, current remedies and rice research requirements. WARDA/88/ARRM/10.

Sylla, M., N., Van Breemen, L. Fresco, A. Stein and C. Dixon. 1993. Spatial and temporal variability of soil constraints along the Great Scarcies River, Sierra Leone. p: 247-259. In: Dent, D.L. and M.E.F. van Mensvoort (ed). Selected papers of the Ho Chi Ming City Symposium on acid sulphate soils. ILRI publ. 53. ILRI, Wageningen, The Netherlands.

Tanaka, A. and S.A. Navasero, 1966. Interaction between iron and manganese in the rice plant. Soil Sci.and Plant Nutr. 12: 197-201.

Tomlinson, T.E. 1957. Relationship between mangrove vegetation, soil texture and reaction of surface soil after empoldering saline swamps in Sierra Leone. Trop. Agric. 34(1)41-50.

Truog, E. 1948. Lime in relation to the availability of plant nutrients. Soil Sci. 65: 1-7.

WARDA, 1980. Classification of types of rice cultivation in West Africa. WARDA, Monrovia.

CHAPTER 2

AN AGRO-ECOLOGICAL CHARACTERIZATION OF MANGROVE ECOSYSTEMS IN WEST AFRICA, WITH SPECIAL EMPHASIS ON RICE CULTIVATION.

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AN AGRO-ECOLOGICAL CHARACTERIZATION OF MANGROVE ECOSYSTEMS IN WEST AFRICA, WITH SPECIAL EMPHASIS ON RICE CULTIVATION.

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ABSTRACT

A comprehensive characterization of the West African mangrove environments is undertaken, with emphasis on the possibilities of and constraints for rice cultivation. A multiple-scale approach is followed, ranging from macro- to micro-level. Central classificatory concepts are climate, hydrology, physiography, vegetation and rice cropping system. 6 different environments are distinguished. Their characteristics are summarized, by agro-ecological zone, in tables 4 to 9. Constraints to rice production in these environments are discussed, and the potential for agricultural development of these valuable habitats are matched with environmental conservation issues. The ensueing classification matrix, provides an outline for detailed classification of mangrove environments outside the geographic scope of this study.

Keywords: mangrove agro-ecosystems, agro-ecological characterization, acid sulphate soils, rice, West Africa.

INTRODUCTION AND BACKGROUND

Broadly, mangrove rice-growing environments have been grouped into one single category (WARDA, 1988). Ecological conditions within mangrove ecosystems, however, are highly variable, particularly with respect to climate, hydrology and soils. In West Africa, rice is grown in these environments as a staple food and it is one of the most important commercial land uses, particularly in The Gambia, in southern Senegal (the Casamance), Guinea Bissau, Guinea and Sierra Leone. Rice is also grown in the mangrove ecosystems of Nigeria, Cameroon and Gabon, but to a much lesser extent.

Because of the apparent potential for development of mangrove ecosystems, many West African governments have planned and implemented large-scale interventions in these environments. The urge to develop coastal lands is also caused by the fact that, in West Africa, population density and increase and, thus, land pressure are highest in this zone. It is the area where most of the capitals and major cities are located (viz. Dakar, Bissao, Conakry, Freetown, Abidjan, Lagos, Douala).

Most of the development attempts have been disastrous, generally because of the lack of a clear notion of the significance of, and the fragile conditions and processes in, mangrove ecosystems. Mangrove lands, in West Africa as elsewhere, comprise acid sulphate soils. These are alluvial soils derived from marine and estuarine sediments that are rich in pyrite (FeS_2). Upon drainage and subsequent aeration of the soil this pyrite oxidizes into sulphuric acid (H_2SO_4), leading to severe acidification, associated deficiencies in plant nutrients (e.g. phosphorus) and toxicities (iron and aluminium; Van Mensvoort et al, 1984; Dent, 1986). Moreover, due to the prevailing and strong tidal and seasonal water movements in mangrove ecosystems, the acidity formed is quickly spread over large areas, killing fish and other fauna in the process.

In West Africa, mangroves and related soils, including potential acid sulphate soils (i.e. pyrite-containing soils that have not yet acidified) and actual acid sulphate soils (i.e. soils that have acidified), are found along the Atlantic coast from Mauritania through Gabon. Their area is estimated at approximately 3,350,000 ha (CEC, 1992; Diop et al., 1993).

Natural mangrove ecosystems are of great importance for many reasons: they act as flood buffers; they promote nutrient enrichment near the shore by catching fresh sediment, thus providing rich nurseries and breeding and feeding ground for fish, shellfish and other marine life, as well as for birds and animals; they are genepools for a great diversity of floral and faunal species; they act as stabilizers of the shoreline against longshore erosional currents; they provide fuel (firewood and charcoal), timber, construction poles, thatch, salt, dyes and tannines, etc. (Maltby, 1986).

Mangrove rice growing began in the middle of eighteenth century in Sierra Leone and Guinea (CEC, 1992). Traditional cultivation systems are still the most widespread and they are applied, for example in Senegal (the diola system), Guinea Bissau (the bolanha system), Guinea and Sierra Leone. The diola and bolanha systems consist of small basins or strips of land that are surrounded by small dikes. Within these 'polders' the rice is cultivated on ridges. The tidal rice-cultivation system practiced in the Gambia, Guinea and Sierra Leone consists of flooded rice cultivation during the seasonal period of fresh-water flows of the major rivers. The system is tied to the length of the salt-free period. In order to reduce production risks, both the salt-free period and the rice variety should be appropriate.

The traditional systems of rice cultivaton have functioned well until persisting droughts started in 1969. Paired with injudicous interventions these droughts have created hyper-salinization and acidification of large areas with former potential acid sulphate soils to the extent that both the mangrove vegetation and the cultivation of rice have been strongly affected. The most affected zones are mainly in the northern, and drier, part of coastal West Africa, including Senegal, The Gambia, Guinea Bissau and to some extent Guinea. In the Casamance alone, Marius (1984) estimated that some 70% of the mangrove area has been destroyed since 1975.

Interventions taken to alleviate the risks of salinization and acidification have included large-scale empoldering as well as the construction of reservoirs and anti-salt barriers. The lack of knowledge, however, and the mismanagement of the structures to control the watertable above the pyritic layer, increased the problems rather than solving them. Consequently, farmers abandoned their rice fields, reclaimed new mangrove lands only to suffer from similar problems, or they moved to adjacent uplands. The shift to the higher, and steeper, parts of the landscape subsequently increased soil erosion on their fields, and sedimentation in lower areas. All processes together have yielded general ecological degradation.

Van Breemen (1993), reviewed the dominant chemical processes involved in chemical degradation and environmental problems related to acid sulphate soils. Success and failure on managing such land have been reported by many authors (e.g. Beye, 1973; Vieillefon, 1977; Marius, 1985, Maltby, 1986, Dent, 1986 and 1992 and CEC, 1992). In spite of this awareness of the importance and the vulnerability of mangrove ecosystems, however, trial and error approaches to their development continue to be applied.

Various steps have been taken by national and international institutes and organizations (e.g.

ISRA, Senegal; OMVG, The Gambia, Senegal and Guinea Bissau; PEC, Guinea; WARDA; UNESCO; UNEP; IUCN and the Ramsar Convention) to safeguard mangrove ecosystems, partly under the umbrella of global actions for the preservation of 'wetlands'. The programmes developed include:

- Conservation programmes focussing on genetic resources because of the importance of preserving biodiversity, genepools and natural functions of (mangrove) ecosystems;
- Sustainable management of mangrove ecosystems for specified kinds of land use (in West Africa mainly rice cultivation) in order to limit area expansion, increase yields per unit area, and reduce shifting cultivation practices in the mangrove areas.

Whatever the strategy for conservation and management of mangrove resources, in order to help provide a sustainable livelyhood for the coastal communities of West Africa, the characterization of these ecosystems forms an essential step. Such characterization can serve as a baseline for research targetting (Andriesse and Bos, 1994), as well as for site selection and development of conservation, reclamation and use packages, including, among others, afforestation, agroforestry and sustainable mangrove rice production. Conversely, proper characterization will enable the extrapolation of the technologies developed to similar areas elsewhere. The high spatial and temporal variability of physical and biotic characteristics in mangrove environments, however, form a real problem for technology transfer, land use planning and land management. Therefore a multiple-scale approach is developed here, to characterize the mangrove agro-ecosystems of West Africa. The objective of this chapter, which focusses mainly on rice agro-ecosystems, is:

- To characterize the West African mangrove ecosystems into macro environments based on climate and coastal morphology, and to subdivide them accordingly;
- To proceed, at meso level, the zoning according to the variability of hydrology, morphology, vegetation complexes and soils within the main coastal landforms; and
- To define micro environments, along the catena or toposequence, according to variations in relevant soil properties, including (potential) acidity, salinity and drainage class.

Rice production and mangrove conservation are not incompatible objectives. Proper characterization of the mangrove ecosystems with respect to rice cultivation is needed however, at different levels of detail for the development of suitable technologies for their sustainable use. Van Gent and Ukkerman (1993) characterized the different rice-growing environments for the Balanta system in Guinea Bissau. Sylla et al. (1993) studied the spatial and temporal variability of soil-related constraints in the tidal rice-cultivation system of Sierra Leone. So far, however, a comprehensive across-scale characterization of the mangrove environments is lacking.

CENTRAL CONCEPTS

The approach taken in this study is to combine the most important factors related to the formation of mangrove ecosystems with those that are relevant for their sustainable exploitation. Geographic emphasis is on the mangrove ecosystems of West Africa.

The different specific environmental conditions necessary for the formation of mangrove ecosystems, including acid sulphate soils, have been widely reviewed (Bloomfield and Coulter, 1973; Chapman, 1976 and 1977; Van Breemen, 1982; Pons, Van Breemen and Driessen, 1982, Dent, 1986). From these, climate, hydrology, physiography, vegetation and soils emerge as the major environmental factors determining the conditions and processes in mangrove ecosystems. They are discussed in the sections below.

Climate

Climate plays an important role in soil formation in general: the rate of weathering of rocks is directly determined by the temperature; leaching processes are governed by the volume of water passing through the soil, which is mainly a function of rainfall; and evaporation and capillary rise of groundwater in dry climates may cause salinity to build up at, or near, the soil surface. Also, high evaporation in dry climates causes stronger ripening (i.e. the irreversible extraction of water from fresh, unripe sediment) and at a faster pace than in humid zones.

Another effect of climate is through its influence on organisms, and particularly on vegetation. Physiological processes are generally determined by temperature, radiation, rainfall and evaporation. This applies to the synthesis of organisms (plant growth and crop performance), as well as to decomposition and subsequent mineralization of organic matter.

Climate, or rather seasonality of precipitation, affects the discharge and, thus, the sedimentation regimes of rivers. In turn, these have an effect on physiography: in per-humid climates river discharges are generally continuously high, creating less pronounced physiographic differentation than under alternatingly wet and dry seasons. Lastly, precipitation co-determines the need for, and possibilities of, water management in agricultural systems.

At the macro-level of this agro-ecological characterization the concept of Length of Growing Period as developed by FAO (1978) is adopted: it is defined as the continuous period in which precipitation is more than half the potential evapotranspiration ($P > \frac{1}{2}ET_p$), plus a number of days required to evaporate an assumed 100 mm of water stored in the soil after the rains have ceased. The growing period must exihibit a distinct humid period during which the precipitation exceeds the evapotranspiration ($P > ET_p$).

In West Africa, the main agro-ecological zones can be broadly described by the length of their growing period and related prevailing vegetation complexes: the Sahel, the South-Soudan Savanna, the Guinea Savanna and the Equatorial Forest zones (Andriesse and Fresco, 1991; Windmeijer and Andriesse, 1993; Table 1). These zones stretch from north to south, in more or less parallel bands across the region. Figure 1 shows their distribution as well as the occurrence of the major mangrove ecosystems within them. It should be noted that within these agro-ecological zones, the coastal parts along the Atlantic Ocean (i.e. from Senegal through Guinea) have a somewhat higher total annual rainfall. As, however, the distribution

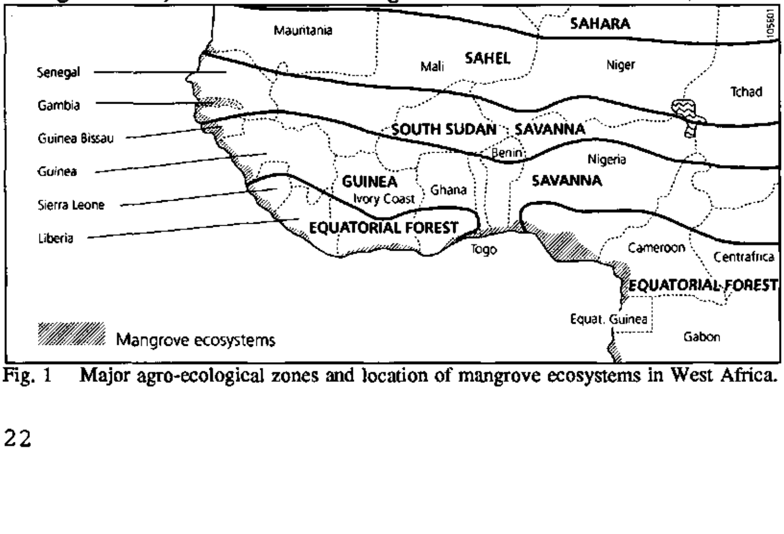

Fig. 1 Major agro-ecological zones and location of mangrove ecosystems in West Africa.

Table 1 Main characteristics and extent of the major agro-ecological zones in West Africa.

Agro-Ecological Zone	Growing period (days)	Annual rainfall (mm)	No. of months P>200 mm	Rainfall pattern	Temperature (°C)	ET_p (mm/yr)	Area of mangroves (1000 ha)
Sahel	< 90	< 550	0	monomodal	Tmax: 42 Tmin: 12	> 2000	50
South-Sudan Savanna	90-165	550-1000	0-3	monomodal	Tmax: 33 Tmin: 15	1500-2000	500
Guinea Savanna	165-270	1000-1500	3-5	mono / bimodal	Tmax: 33 Tmin: 17	1000-1500	750
Equatorial Forest	> 270	> 1500	>5	(pseudo-) bimodal	Tmax: 36 Tmin: 21	< 1000	2050

of the rains corresponds with that defined for the various agro-ecological regimes, the lengths of the growing periods in these (wetter) parts of West Africa remain the same and, from an agricultural point of view, no adjustments are necessary.

Hydrology and tidal regime

By nature of their origin, mangrove ecosystems occur exclusively in the intertidal zones of coastal wetlands. Coastal wetlands comprise deltas, estuaries, littoral zones and lagoons.

Deltas are formed where rivers, carrying large volumes of suspended load, flow into the oceans. Where the stream velocity suddenly drops the suspended material is deposited. This sedimentation is enhanced by the saline sea water which breaks up the flocculent masses of fine particles. In West Africa, a typical delta is formed by the Niger river, showing a characteristic sequence of fresh-water swamps in the upstream part -which is subject to seasonal flooding-, saline mangrove swamps in the lower part -subject to tidal flooding-, and a complex of sandy beach ridges along the coastal fringe (Faniran and Jeje, 1983; Figure 2).

Estuaries are funnel-shaped river mouths, characterized by a tidal sedimentation regime. Sediment supply relative to river discharge, is low. Salt marshes occur along the sides of the estuary, and intertidal mudbanks and islands in the centre. The proportion of these banks and islands increases headward in the estuary (Allen, 1970a; Figure 3). A good many West African rivers have an estuarine mouth, e.g. the Gambia river, the Casamance (in Senegal), the Geba and Corubal rivers (Guinea Bissau), the Great and Little Scarcies rivers (Sierra Leone) and the Cross river (Nigeria). Based on the salinity regime, two types of estuaries can be distinguished: the normal estuary, characterized by a decrease of salinity gowing upstream during the rainy season (e.g. the Gambia and Geba rivers), and the inverse estuary characterized by increasing salinity from the mouth upward (e.g. the Saloum and Casamance rivers). Within both these estuary types, further differentiation of mangrove ecosystems is made according to the relative position along the river course; the littoral zone, and the lower, middle and upper estuary zones respectively. In places where the estuarine mangrove ecosystem forms a relatively narrow belt along the cost only, the middle estuarine zone may be absent. This is the case, for instance, along the coast of Guinea.

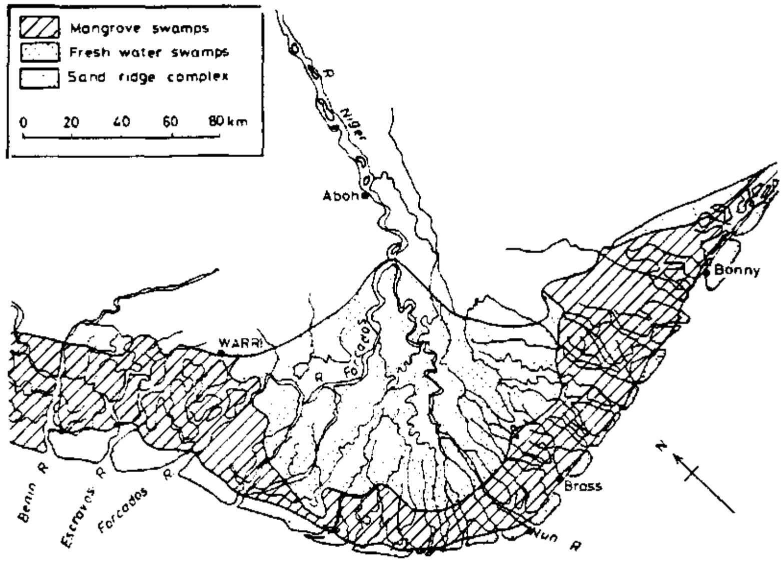

Fig. 2 Hydrology and morphology of the Niger delta (Source: Faniran and Jeje, 1983)

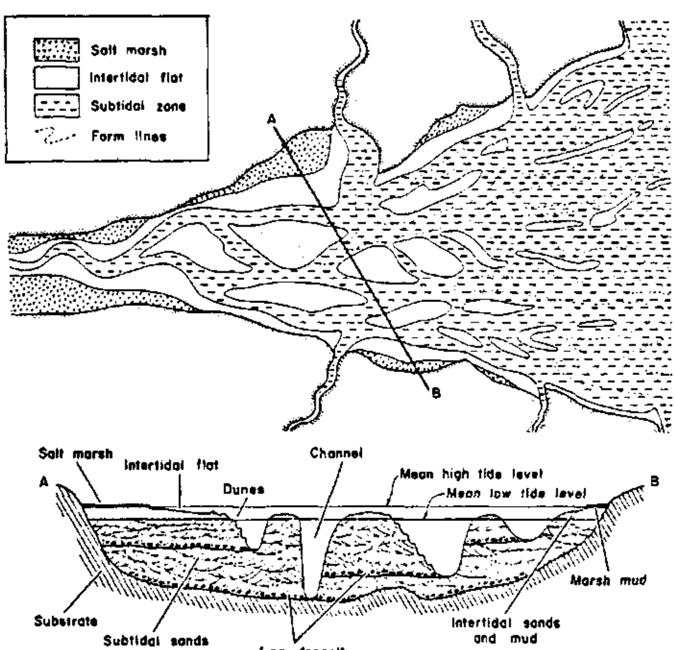

Fig. 3 Hydrology and morphology of an idealized estuary (Source: Allen, 1970)

The **littoral zones** consist of a coastal fringe of mangrove swamps of some 10 to 20 km wide, which occurs mainly along the coast of Guinea. Locally, estuaries of major rivers cut through this zone. The littoral zone comprises of tidal mud flats, located at the seaward side of a complex of parallel, relatively small beach ridges, and a sequence of creek ridges, backswamps and landward fringes.

Lagoons are longshore tidal sedimentation areas that are usually sheltered from wave action by protective sand barriers at their outer fringes. Locally, inlet channels cut through these barriers, to allow for tidal flooding (Figure 4). Typical lagoons occur along the West African coastline, mainly between Côte d'Ivoire and Nigeria.

In all these coastal environments, the most important aspects of hydrology in relation to mangrove ecosystems are the distribution and temporal dynamics of the discharge and flooding regime of the rivers, and the balance between the seasonal discharge of fresh water and the tidal propagation of salt water. The latter, which varies strongly according to agro-ecological zone, largely determines the occurrence of salinization and acidification. For example, in the Gambia river the tidal amplitude varies from about 170 cm at its mouth, to some 10 cm 350 km upstream. Even in the dry season, the rate of ebb outflow (0.9 m/s) is generally faster than the tidal inflow (0.7 m/s), creating a net outflow. Similarly, in the

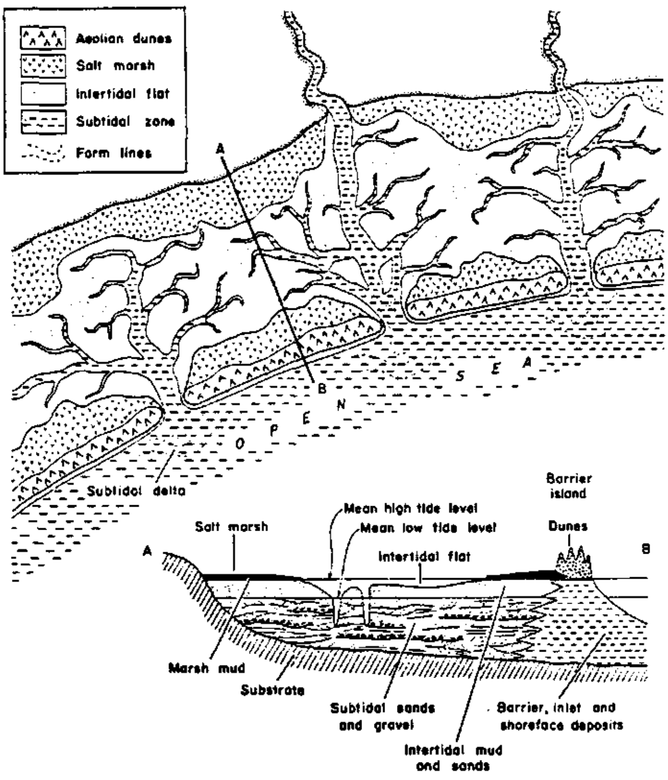

Fig. 4 Hydrology and morphology of a coastal lagoon (Allen 1970)

Casamance, the tidal range is 170 cm at its mouth to slightly over 50 cm at Ziguinchor, some 60 km upstream. Along the Geba river, in Guinea Bissau, the tidal range varies between some 560 cm near the coast to 250 cm about 100 km upstream.

In western West Africa, the size of the catchments of the major rivers, coincides largely with the agro-ecological zones: river basins in the South-Sudan Savanna zone are mostly (very) large relative to the catchments in the Guinea Savanna zone. The Gambia river, for example, in the South-Sudan Savanna zone, has a catchment area of some 42,000 km^2, whereas the catchments of the Geba, Kogon, Fatala and Konkouré in the Guinea Savanna zone are between 10,000 and 15,000 km^2. Similarly, in the (western) Equatorial Forest zone the catchments of the Little and Great Scarcies rivers are 7,000 and 10,000 km^2 respectively, which is small in comparison to Sassandra, Bandama, Volta, Niger and Sanaga rivers, further east.

This difference in catchment area, of course, affects total river discharges and discharge patterns, but not proportionally: larger rivers cut across different agro-ecological zones, catching different amounts of rainfall along their courses. The Niger river is perhaps the most outstanding example of this phenomon, particularly as, in central Nigeria, it joins with another giant, the Benue.

In Table 2, tidal flooding classes as applicable to the mangrove environments of West Africa are described according to the intensity of the floods. Main vegetation complexes occurring in the different flooding zones are also given.

Physiography and pioneer vegetation

In West Africa, as elswhere in the tropics, the characteristic vegetation of intertidal swamps is mangrove forest. This characteristic vegetation complex extends over the tidal zone between mean sea level and mean high-water springtide. Closest to the sea, in areas which are flooded daily, *Rhizophora racemosa* and *Languncularia racemosa* occur and, particularly in the Guinea Savanna and Equatorial Forest zones *R. harrissonii*. Tall rhizophora trees (*R. racemosa* and *R. harrisonii* prevail along the creek ridges and levees. Landward, and mainly in the backswamps *Rhizophora mangle*, *Avicennia africana* or, in the Guinea Savanna zone, *A. nitida*[1] gradually take over. Rhizophora species are characterized by their downward-poking stilt roots, avicennia trees by their pneumatophores sticking-up from the mud. *Nypa fruticans* is a palm species typically occuring in the mangrove forests of Nigeria, Cameroon and Gabon.

Higher still, on less-flooded parts of the landscape (higher backswamps and terraces) herbaceous species take over, like *Paspalum vaginatum*, *Sesuvium portulacastrum*, *Philoxerus vermicularis*, *Heleocharis spp.* and *Acrostichum aureum*. *Phragmites* and *Echinochloa spp.* occur in positions where salinity is low or absent. In areas of high rainfall (i.e. Equatorial Forest zone) lowland rainforest or swamp forest may succeed in the highest parts of the tidal zone and beyond, on the adjacent uplands. In the drier Guinea Savanna zone, vegetation growth is restricted by salinity that develops on the higher tidal flats. This reaches extremes

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[1] Confusion exists among botanists whether *Avicennia africana* and *A. nitida* are different species (Walsh, 1974). As in most studies of West African mangrove systems these species are recognized to occupy different habitats, this view is adhered to in the present paper.

particularly in the South-Sudan Savanna zone, where these flats (local, francophone name 'tannes') are bare and hyper-saline (Chapman, 1977; Marius, 1985; Dent, 1986; Langenhoff, 1986; Sadio, 1991). Table 2 shows the distribution of the vegetation complexes in relation to tidal flooding classes.

The role of pioneer vegetation as a source of organic matter in the process of pyrite formation has been studied extensively. Reviews have been given, among others by Bloomfield and Coulter (1973), Van Breemen (1976 and 1982), Pons et al. (1982), Dent (1986), and Langenhoff (1986). For West Africa such studies were carried out by Diop et al. (1993) and by Tomlinson (1957), Hesse (1961), Jordan (1964), all in Sierra Leone, by Giglioli and Thornton (1965) in The Gambia, Kawalec (1977) in Guinée, and Vieillefon (1977) and Marius (1985) in Senegal.

The type and distribution of the mangrove vegetation can be a clue to segregate zones of high and low potential acidity. As indicated in many studies, Rhizophora species, having a dense, fibrous root system, tend to be associated with high contents of soil organic matter whereas Avicennia species, having a root system that is much less dense, produce less organic matter. The presence of organic matter in waterlogged, saline sediments stimulates the accumulation of pyrite (FeS_2). The latter is the main source of sulphate acidification, if the sediments are drained. Therefore, indirectly vegetation co-determines the levels of potential acidity in coastal wetlands. The rate of sedimentation and accretion of the coast is an important factor in pyrite accumulation. If the coastline advances slowly, the mangroves may prevail over a long period, and conditions for pyrite formation are favourable (Pons et al.,1982).

It is also known that vegetation distribution generally follows the salinity level of the soils. Highly saline soils are generally occupied by Avicennia species which have a higher tolerance

Table 2 Tidal flooding classes and prevailing vegetation in West Africa

Tidal flooding class	Number of consecutive days without tidal flooding	Main vegetation
1	0-10	*Rhizophora racemosa, R. harrissonii* (in Guinea Savanna and Equatorial forest zones mainly), *Laguncularia racemosa*
2	10-110	*Rhizophora racemosa, R. Harrisonii* (in Guinea Savanna and Equatorial Forest zones mainly), *R. mangle, Avicennia africana, A. nitida* (in South-Sudan Savanna zone), *Languncularia racemosa, Conocarpus erectus, Nypa fruticans* (in Nigeria, Cameroon and Gabon only)
3	110-160	*Avicennia africana, A. nitida* (in South-Sudan Savanna zone), *Conocarpus erectus, Nypa fruticans* (in Nigeria, Cameroon and Gabon only), *Raphia spp., Sesuvium portulacastrum, Philoxerus vermicularis, Heleocharis spp., Paspalum vaginatum, Acrostichum aureum*
4	160-360	*Sesuvium portulacastrum, Philoxerus vermicularis, Heleocharis spp., Paspalum vaginatum, Acrostichum aureum*; or bare hyper-saline flats (particularly in South-Sudan Savanna zone, and in 'dry corridor' of Ghana-Benin)
5	> 360	(Open) woodland savanna, derived savanna, lowland rainforest, swamp forest, depending on agro-ecological zone and setting

level (up to 75 mS/cm) than rhizophora mangroves (up to 40 mS/cm; CEC, 1993; Mitsch and

Gosselink, 1993). Thus, the distribution of the various vegetation complexes in coastal wetlands river basin can help detect sub-zones of different salinity.

Catenary sequences of land elements

All along the course of the main rivers, soil salinity and acidity are strongly determined by the topographic position along the catena. This topography in itself, is a derivative of climatic conditions, and of flooding and sedimentation sequences: during periods of high river discharges and at high tides, riverbank overflow causes sedimentation. The coarsest particles are deposited first, at relatively high velocities of the flood water, and they form the levees and creek ridges nearest to the river and creek beds. Finer particles are transported beyond the levees and deposited, at low stream velocities, in the basins or backswamps further inland. The low topographical position of these backswamps may be enhanced by subsequent subsidence once the floods recede. Quite commonly within the backswamps, lower and higher parts may be distinguished, having height differences of some 50-100 cm. Further away from the riverbed, higher river terraces may occur as remains of former sedimentation periods. Such terraces have been described to occur along the Gambia, Casamance and Corubal rivers, where height differences may be up to 150-200 cm (Thomas et al, 1979; Marius, 1985; DREI, 1988).

Soils

The soils in mangrove environments are relatively young, alluvial soils with little profile development. They are formed in marine (tidal sea deposits) or fluviatile sediments (tidally-influenced river deposits). Locally, soils have developed from organic materials (peats and mucks), or from eolian deposits (dunes). Both, marine and fluviatile sedimentation processes, which are still active over most of the mangrove environments, cause soil differentiation in lateral as well as in vertical direction. Lateral differentiation results, for example, in the formation of generally lighter-textured soils on creek ridges and levees where, at the time of sedimentation, water velocities were relatively high. Finer-textured sediments are deposited in calmer environments, farther away from the main rivers or creeks, such as the backswamps. Coarse sands may occupy point bars of river systems and beach ridges, where deposition took place from fast-flowing water or under influence of strong waves. Dunes that have formed locally on the beach ridges are generally fine-sandy.

Vertical textural differentiation, or stratification, is caused by periodic changes in water movement like seasonal and tidal floods or changes in the river course. Naturally, with an increasing height of deposition, floods become shorter and the flows slower. If such a system is not disturbed, the particle size of the deposits decreases gradually in upward direction in the profile.

Soils in mangrove ecosystems are obviously low-lying and they are subject to tidal and seasonal flooding by the sea and by river bank overflow. Soil drainage is generally restricted. Even though they occupy higher positions in the landscape, soils of the levees and creek ridges are mostly moderately-well drained at best. Soil drainage in the backswamps is poor to very poor. Under saturated conditions reduced iron compounds, which are easily soluble, prevail in the soil. They give rise to the bluish and greenish grey colours characteristic of the (very) poorly drained soils in the backswamps. In soils with better drainage (e.g. on the levees and creek ridges), ferric iron compounds are formed. These are non-soluble and they cause yellowish brown and reddish soil colours. Alternating conditions for oxidation and reduction cause both, grey and brown/red colours which are usually mottled. In poorly and imperfectly drained soils in arid and semi-arid conditions salinity can build up at or near the soil surface due to evaporation and the capillary rise of saline groundwater.

Profile development in soils of mangrove environments is mainly confined to physical processes like soil ripening and subsequent structure formation, shrinkage and subsidence, and desalinization, and chemical processes like oxidation (change of colour and acidification), and decalcification.

Physical ripening is the process of water extraction from newly deposited sediments. This dehydration can be due to drainage, evaporation, or water uptake by plant roots. Fresh, soft sediment is unripe. If, eventually, it has developed into firm material, the soil is called ripe.

A specific chemical process that may occur in marine sediments, is the oxidation of pyrite (FeS_2) to sulphates and sulphuric acid (H_2SO_4). This may cause extreme acidification in what is referred to as acid sulphate soils. Pyrite can be formed microbiologically in sediments, under conditions of flooding with saline or brackish water, and in the presence of large amounts of organic matter. The latter are associated particularly with *Rhizophora spp.* and, to a lesser extent, with *Avicennia spp.* and reeds (*Phragmites spp.*). Under strongly oxidizing, severely acid conditions, jarosite ($KFe_3(SO_4)_2(OH)_6$) is formed from oxidizing pyrite. Jarosite precipitates as straw-yellow mottles, pore fillings and coatings, characteristic of young acid sulphate soils. Soils containing pyrite, and which have not yet acidified, are called potential acid sulphate soils.

(Potential) acid sulphate soils are problem soils. If oxidized, toxic amounts of aluminium, hydrogen, manganese and ferric-iron prevail at low soil pH. This, together with the resulting low availability of phosphorous, restricts and inhibits plant growth. Root development may also be affected if acid layers occur at shallow depths in the soil. This may not only cause water stress to crops but also restricts further ripening of the soil. Under flooded conditions (e.g. in rice fields or in fishponds), toxic levels of ferrous-iron, hydrogen sulphide and carbon dioxide prevail.

Table 3 provides a simplified and schematic overview of the main soils of mangrove ecosystems according to the classification system of the USDA Soil Taxonomy (SSS, 1992). The classification names shown in this table are used in the descriptions of the mangrove ecosystems in the subsequent sections. Wherever relevant further distinction has been made upto the subgroup level of classification. In a few cases, use has been made of proposals by Pons et al. (1986) for the improvement of Soil Taxonomy as for better classification of acid sulphate soils.

CLASSIFICATION MATRIX FOR MANGROVE AGRO-ECOSYSTEMS

All the factors discussed in the previous sections are included in the classification matrix for mangrove environments of West Africa as shown in Figure 6. The matrix takes the format of a hierarchical framework. Rainfall and evapotranspiration (length of the growing period) figure at the highest level of distinction, followed by coastal morphology, being the resultant

Table 3 Simplified classification scheme for the main soils of mangrove ecosystems according to USDA Soil Taxonomy (SSS, 1992)

YOUNG SOILS WITH LITTLE OR NO PROFILE DEVELOPMENT						
ORDER	ENTISOLS					
Suborders	if wet:	Aquents	if not wet, but sandy:	Psamments	if not wet and sandy, but stratified:	Fluvents
Great groups	if potentially acid if unripe if sandy if stratified other Aquents	*Sulfaquents* *Hydraquents* *Psammaquents* *Fluvaquents* *Endoaquents*	if with quartzitic mineralogy if in tropical climate	*Quartzipsamments* *Tropopsamments*	if in seasonal moist climate if in tropical climate	*Ustifluvents* *Tropofluvents*
RELATIVELY YOUNG SOILS WITH SOME PROFILE DEVELOPMENT DUE TO AERATION, ACIDIFICATION, RIPENING, STRUCTURE FORMATION, ETC.						
ORDER	INCEPTISOLS					
Suborders	if wet:	Aquepts	if not wet, but in tropical climate:	Tropepts		

Great groups	if sulphate acid
	if saline
	if in tropical climate
		Sulfaquepts
		Halaquepts
		Tropaquepts
			if with acidic humic (sub)surface:
			if seasonally moist:
			if with low base saturation:
				Humitropepts
				Ustropepts
				Dystropepts		

PEATS, HAVING ORGANIC LAYERS (ORG. MATTER > 20-30%), OF AT LEAST 40 CM THICK, STARTING WITHIN 40 CM FROM THE SURFACE.						
ORDER	HISTOSOLS					
Suborders	if with undecomposed organic material:	Fibrists	if with partially-decomposed organic material:	Hemists	if with highly decomposed organic material:	Saprists

Great groups	if in tropical climate:	*Tropofibrists*	if sulphate acid:
			if potentially acid:
			if in tropical climate:
				Sulfohemists
				Sulfihemists
				Tropohemists
					if sulphate acid:
					if potentially acid:
					if in tropical climate:
						Sulfosaprists
						Sulfisaprists
						Troposaprists

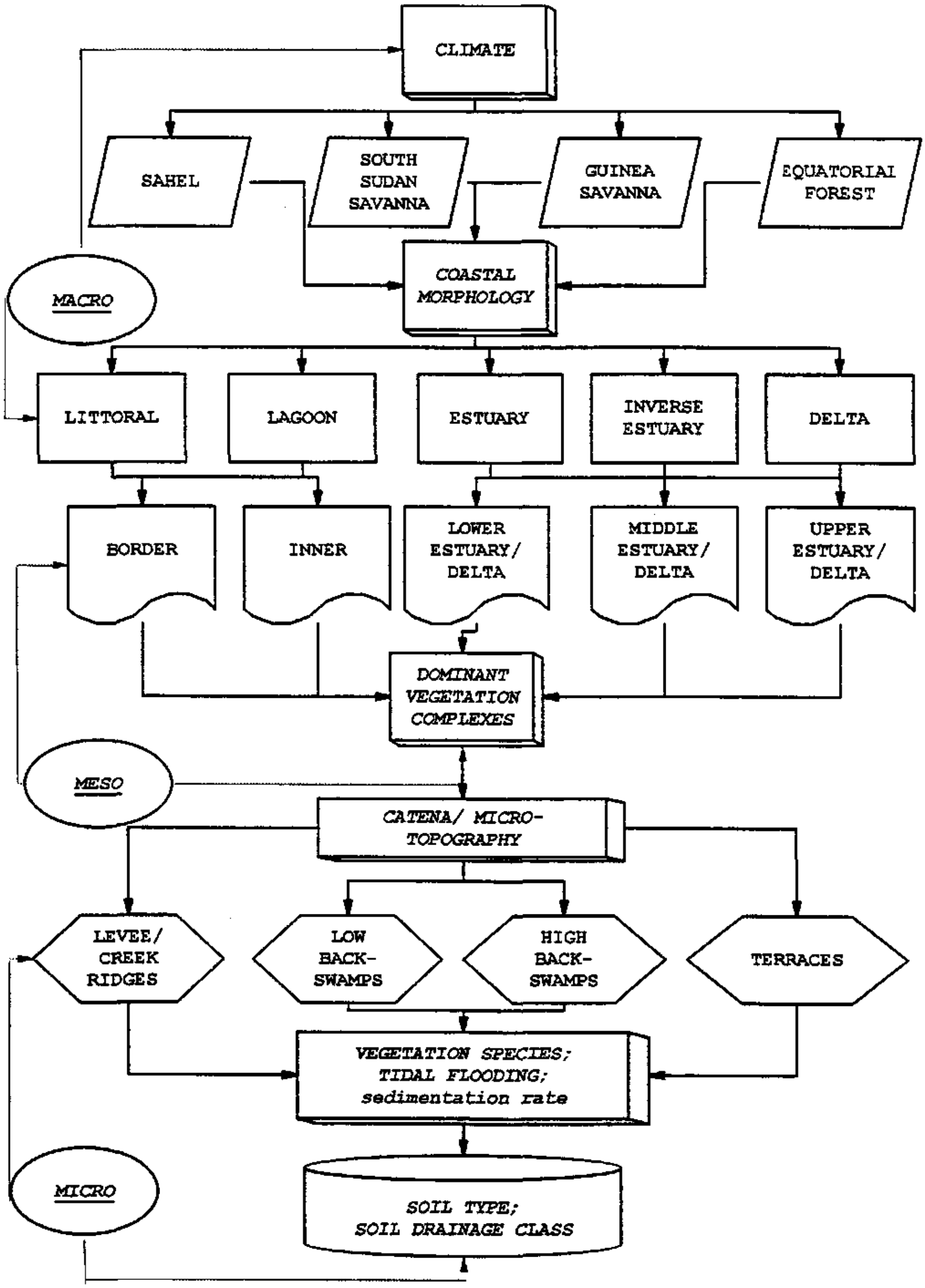

Fig. 6 Classification matrix of mangrove agro-ecosystems

of the combined effect of saline or brackish tidal-water movement and seasonal fresh-water river discharge. Together these exert a profound effect on the microtopography and on the composition of the vegetation complexes, and, therefore, on the formation of pyrite and the flushing of dissolved alkalinity formed during pyrite formation.

All the above factors are interrelated and the plethora of their possible combinations accounts for the characteristic extreme spatial heterogeneity of mangrove ecosystems. Such a variability can not be absorbed in any practical classification system. Therefore the present attempt can only be used as a broad outline which, at the same time, allows flexibility for the identification of individual mangrove environments.

Rice can be grown in a limited number only of the mangrove agro-ecosystems shown in Figure 6. A practical classification of rice-growing environments should consider only those environments where conditions for sustainable rice cultivation are feasible and compatible with the objectives of environmental protection. The matching between the potential for, and the contraints to rice cultivation with environmental conservation issues is discussed in the next section.

MAIN MANGROVE RICE-GROWING ENVIRONMENTS

The South-Sudan Savanna zone

The South-Sudan Savanna zone has a growing period of 90-165 days, which occurs from May/July through September. Along the western coast of West Africa, where this agro-ecological zone occurs, total annual rainfall increases from some 600 mm in Les Niayes, north of Dakar, to 1100 mm in The Gambia, and 1500 mm in the Casamance. Total potential evaporation varies between 1500 and 2000 mm/yr.

This zone comprises the estuaries of Siné-Saloum and of the Gambia and Casamance rivers.

Estuarine environments

The estuaries in the South-Sudan Savanna zone can be subdivided into three agro-ecological units, the lower, middle and upper estuary, according to the distance from the sea:

The **lower estuary** occurs near the river mouth and has dominant marine influence, which is characterized by strong tidal action, and by high salinity levels throughout the year. The vegetation in the backswamps is predominantly *Avicennia africana* and some *Rhizophora mangle*. Narrow fringes of *Rhizophora racemosa, Laguncularia racemosa* and some *R. mangle* border the rivers and creeks. Levees and creek ridges may be bare and hyper-saline (tannes). Halophytic herbs including *Sesuvium portulacastrum, Paspalum vaginatum* and *Heliocharis spp.*, and the fern *Acrostichum aureum* occupy higher places in the landscape, i.e. the higher backswamps and the terraces. Locally both the latter are bare and hyper-saline (tannes).

The soils of the creek ridges and the levees are generally Sulfaquents and Fluvaquents. They may have surface layers consisting of newly-deposited sediment of variable depth, with low contents of pyrite. Where these layers exceed 50 cm in depth, the soils are classified Sulfic Hydraquents (Pons et al., 1986). For instance at the mouth of the Casamance these layers can be important in terms of their thickness, which may be more than 80 cm. Soils in the lower backswamps are Sulfaquents, Hemists and Fibrists (peats) and Hydraquents. The soils of the backswamps have clayey textures, except in the Siné-Saloum, where surface layers are generally sandy (Marius, 1985; Sadio, 1991). On the higher backswamps and the terraces, where drainage is better and soils may have acidified, Sulfaquepts and Tropaquepts occur in intricate patterns. In the Casamance, Typic Tropaquepts prevail on the higher backswamps and the terraces, as opposed to the situation along the Gambia river where most of the soils are acidic (Sulfaquepts and Sulfic Tropaquepts; Marius, 1985). The main soil limitations are salinity and soil acidity in the levees and backswamps. Desalinization of the soils occurs during the rainy season but only at topographically-higher ground: the higher backswamps and the river terraces. Generally the creek ridges and levees as well as the lower backswamps, which are flooded daily to monthly by tidal action, remain saline throughout the year.

Rice is cultivated mainly on the saline and potentially acid sulphate soils in the lower backswamps, and at slightly elevated parts of the landscape, if the lenght of the 'salt-free period' is greater than the rice varietal duration and if the transplanting date is adequate. The salt-free period is defined as the period in which soil salinity levels are relatively low (ECe < 8 mS/cm). The rice is grown under rainfed conditions in polders. This system is known as the 'diola system' in the Casamance, and as the 'bolanha system' in Guinea Bissau. Average rice yields are between 800 and 1200 kg/ha. Water management is required in terms of timely drainage to flush the salts and acids that have accumulated in the polders during the dry season. Naturally, proper maintenance of the polder dikes is required.

The **middle estuary** has marked, seasonal salinity levels. The mangrove vegetation in this unit is generally more luxuriant with a wider fringe of rhizophora along the levees followed, landward, by bands of avicennia and halophytic herbs. On the higher parts the vegetation gives way to bare tannes.

Soils on the levees have a relatively high potential acidity (Sulfaquents). In the backswamps however, potential acidity is less, either because of the lower content of pyrite-S, or because the pyritic layers appear deeper in the soil profile (Sulfaquents, Sulfic Tropaquents, Sulfic Fluvaquents and Hydraquents). Sulfic Tropaquepts prevail in the higher backswamps, whereas, similar to the conditions in the lower estuary, soils on the terraces are generally Typic and Sulfic Tropaquepts.

Rice is cultivated on all parts of the toposequence. Soil salinity is a minor limitation when late transplanting is practiced. Acidity of the soils, as well as that of the surface water, can affect rice production. Two systems of rice cultivation are found in this area: the rainfed polder system, as described above, and tidal swamp rice. The latter makes use of fresh-water flooding caused by the tides during the rainy season. With the tides, the water is allowed into, and drained from, small basins which may be surrounded by small dykes (e.g. in the Casamance). In The Gambia this system is practised without such small protective dykes. The rice is transplanted late (i.e. end of August) so as to allow sufficient leaching of salts and acids prior to transplanting. Yields vary from 800 to 2200 kg/ha.

The **upper estuary** is characterized by low salinity levels in the case of normal estuaries, and by hyper-salinity in inverse estuaries. In normal estuaries, rhizophora is bordering the river levees, whereas reeds are dominant in the lower backswamps (*Phragmites spp.)* and in the higher backswamps (*Phragmites spp.* and *Echinochloa spp.*). On the terraces, where salinity and acidity are less prevalent, (open) woodland savanna forms the main vegetation. The extreme salinity occurring in inverse estuaries has killed most of the rhizophora along the levees. Locally the rhizophora is now being succeeded by avicennia and halophytic grasses. Bare tannes are abundant.

Table 4 Characterization, limitations and potentials of mangrove ecosystems in the South-Sudan Savanna Zone of West Africa (estuarine environments)

	Creek ridges/levees	Lower backswamps	Higher backswamps	Terraces
Tidal class	2-3	1-2	3-4	4-5
Main soil characteristics	Poorly to somewhat poorly drained, deep, medium to fine-textured, unripe to half-ripe, saline to hyper-saline soils, with sulphidic layers mainly at shallow depths; in places stratified	Poorly to very poorly drained, fine-textured, deep, unripe, saline to hyper-saline soils with sulphidic layers at variable depth; in places peats; sandy textures in Siné-Saloum	Poorly drained, fine-textured, deep, half-ripe to unripe, saline to hyper-saline soils with sulphidic layers at variable depth; sandy textures in Siné-Saloum	Somewhat poorly to moderately-well drained, deep, ripe, slightly saline soils of variable texture; in places jarosite in lower horizons
Soil classification	Haplic and Typic Sulfaquents, Sulfic and Aeric Tropic Fluvaquents, Sulfic Hydraquents	Histic, Haplic and Typic Sulfaquents, Sulfic Hydraquents, Sulfihemists, Tropofibrists; Psammaquents in Siné-Saloum	Hydraquentic and Typic Sulfaquepts, Sulfic and Typic Tropaquepts; Aeric and Typic Tropaquepts in upper estuaries; Psammaquents in Siné-Saloum	Sulfic, Aeric and Typic Tropaquepts, Hydraquentic and Typic Sulfaquepts
Main vegetation	*Rhizophora racemosa, R.mangle, Laguncularia racemosa*; bare tannes	*Avicennia africana, Rhizophora mangle; Phragmites spp.* in upper estuary	*Avicennia africana, Sesuvium portulacastrum, Paspalum vaginatum, Heliocharis spp., Acrostichum aureum*, bare tannes; *Phragmites spp.* in upper estuaries	*Sesuvium portulacastrum, Paspalum vaginatum Heliocharis spp., Acrostichum aureum*, bare tannes; *Phragmites spp. and Echinochloa spp.* in upper estuaries; (Open) woodland savanna
Main rice limitations	Tidal flooding, salinity, potential acidity, riverbank erosion	Tidal flooding, high salinity, acidity, Fe/Al toxicity	Tidal flooding, very high salinity, acidity, Fe and Al toxicity	Low fertility, Fe-toxicity, water availability
Possible use	Natural reserve	Rice cultivation	Rice cultivation	Relay cropping (rice and vegetables)
Management requirements	Protection, reforestation	Water management, liming, N-fertilizer, tall varieties resistant to lodging and tolerant to salinity and acidity	Water management, lime dressing, NP-fertilizer, short duration varieties, tolerant to Fe and Al toxicity	Water management, NPK-fertilizer, very short duration varieties, tolerant to Fe toxicity

Soils are generally less acid than in the mid-estuary. In the levees and low backswamps pyritic layers may occur deeper in the soil profile (Sulfic Hydraquents and Sulfic Fluvaquents). In the higher backswamps soils are partly acidified (Sulfaquepts and Sulfic Tropaquepts). Aeric and Typic Tropaquepts, not having potential or actual acidity, prevail on the terraces.

In normal upper estuaries, tidal swamp rice is cultivated from the high backswamps upto the fringe of rhizophora bordering the levees. In inverse estuaries, dykes are built along the river to minimize saline water intrusion, and rice is transplanted on ridges. Generally, yields are high in normal estuaries (2500-3000 kg/ha), and low in inverse estuaries (500-800 kg/ha).

The characteristics, limitations and potentials of the mangrove ecosystems in the estuarine environments of the South-Sudan Savanna Zone are summarized in Table 4.

The Guinea Savanna zone

In the Guinea Savanna zone the growing period extends over 165-270 days. In the western coastal part of this zone, total annual rainfall is high, ranging from 2000 mm at Bissao, to over 3500 mm at Conakry. Along the southern coast, rainfall is relatively low, ranging between 1000 and 1500 mm/yr in the so-called 'dry corridor' of Ghana, Togo and Benin (see Figure 1). In the west, rainfall distribution is monomodal: rains fall from May through October/November mainly. In the dry corridor the pattern is bimodal: rainy periods occur from April through July and from September through October. The total potential evaporation is between 1000 and 1500 mm per year.

This agro-ecological zone comprises the estuaries of major rivers in Guinea Bissau and Guinea, the littoral mangrove zone of Guinea and the lagoons of Ghana, Togo and Benin.

Estuarine environments

The estuarine environment in the Guinea Savanna zone can be divided into two agro-ecological units: lower and upper estuaries. As opposed to the estuaries in the South-Sudan Savanna zone, a middle estuary is lacking in the Guinea Savanna zone. This is mainly because the estuaries in this zone are relatively short (some 40 to 80 km) compared to those in the South-Sudan Savanna zone (100-250 km).

Because of the relatively high tidal amplitudes prevailing in this environment (e.g. up to 250 cm at Conakry), saline water intrusion during the dry season is widespread. In the rainy season, however, river discharges are high, causing a rapid decline of salinity levels in the rivers and creeks. In the Melakorée river for example, the water in the mouth of the estuary contains approximately 35 g/l of salts, and the salt content decreases to values below 10 g/l within 50 to 70 km upstream (Diop, 1991).

The **lower estuary** is predominantly a marine environment where river salinity levels are comparable to sea water. Along the creek ridges and levees the vegetation is mainly *Rhizophora harrisonii* with some *Laguncularia racemosa*, *R. racemosa* and *Avicennia nitida*. In the lower backswamps *R. harrisonii* is dominant. In the higher backswamps the latter is gradually replaced by *A. nitida*, followed by *Paspalum vaginatum*, *Philoxerus vermicularis* and *Sesevium portulacastrum*.

The soils are generally Sulfaquents on the levees and in the lower backswamps, which are flooded daily. Potential acidity levels, however, are generally low. Sulfaquepts prevail in the slightly elevated, and better drained, higher backswamps. Soils on the terraces are mainly Tropaquepts. Actual acidity, if formed, seems to create less problems than in the South-Sudan Savanna zone. Higher rainfall in the Guinea Savanna zone may contribute to this (CEC, 1992).

Tidal rice cropping is practiced in the rainy season on cleared mangrove land that is flooded daily with fresh water. In the 1980's, several anti-salt barriers have been constructed in the tidal creeks of Guinea Bissau, to minimize the intrusion of saline tidal water. As stated before, so far these have not shown to be succesful.

In the **upper estuary**, soil salinity is not a major limiting factor for rice production. *Rhizophora harrisonii* is dominant along the levees and in the lower backswamps, whereas *Avicennia nitida* prevails in the higher backswamps, followed by reeds (*Phragmites spp.* mainly) on still higher ground (i.e. the higher levees and terraces). Locally, the terraces as well as the higher backswamps may be bare and hyper-saline in the dry season. Where salinity is absent, gradually (woodland) savanna vegetation becomes dominant. The soils of the levees are Sulfaquents, Hydraquents and Fluvaquents mainly. Sulfaquents, Hydraquents, Sulfihemists and Tropfibrists prevail in the lower backswamps, whereas Tropaquepts and Sulfaquepts occur in the higher backswamps. Main soils on the terraces are Tropaquepts.

Tidal swamp rice is practiced exceptionally, mainly because of labour shortage in this area of low population density. Nevertheless, potential rainfed paddy adjacent to the mangrove is suitable for rice production.

Table 5 summarizes the characteristics, limitations and potentials of the mangrove ecosystems in the estuarine environments of the Guinea Savanna zone.

Littoral environments

The littoral environment consists of a zone of mangrove swamps of some 10 to 20 km wide, mainly along the coast of Guinea. Locally, estuaries of major rivers (e.g. the Kandiafara, Konkouré and Forécariah rivers) cut through this zone.

The littoral zone is under the direct influence of the sea. It comprises of tidal mud flats, which occur mainly on the seaward side of a complex of parallel, relatively small beach ridges, and a sequence of creek ridges, backswamps and landward fringes, bordering the coastal uplands. The main vegetation on the mud flats is *Avicennia nitida*, with some *Laguncularia racemosa*, but large parts are bare. Mixed forest, including coconut trees, thrives on the beach ridges, whereas *Rhizophora harrisonii*, *Laguncularia racemosa* and *R. racemosa* together with *A. nitida* form bands of dense vegetation along the creek ridges. Towards the backswamps *Avicennia nitida* remains dominant, though in complexes with halophytic herbs such as *Paspalum vaginatum*, *Sesuvium portulacastrum* and *Philoxerus vermicularis*. The latter also colonize the landward fringes, together with *Heliocharis* and *Cyperus spp.*.

The soils of the mudflats show only little accumulation of organic matter and pyrite, mainly because they have been formed under conditions of quick sedimentation. As a consequence, they do note pose serious acidification problems upon drainage (Hydraquents and some Sulfaquents; Kawalec, 1977). Locally, peat soils occur in the mud flats (Sulfihemists, Tropofibrists, Histic Sulfaquents; HARZA, 1969). The mudflats are flooded daily, with the tides. The beach ridges, emerging some 1-3 m from the mudflats up till above mean high-tide levels, mainly comprise fine-sandy soils (Tropopsamments and Psammaquents). Soils of the creek ridges contain pyritic layers, but generally at greater depths in the profile (Sulfic

Table 5 Characterization, limitations and potentials of mangrove ecosystems in the Guinea Savanna Zone of West Africa (estuarine environments)

	Creek ridges/Levees	Lower backswamps	Higher backswamps	Terraces
Tidal class	2	1-2	2-3	4-5
Main soil characteristics	Poorly to somewhat poorly drained, deep, medium- to fine-textured, unripe to half-ripe, saline soils, with sulphidic layers at variable depths; in places stratified	Poorly to very poorly drained, fine-textured, deep, unripe, saline soils, with sulphidic layers at variable depth; in places peats	Poorly to somewhat poorly drained, deep, fine-textured, half-ripe to unripe, saline soils, with sulphidic layers at variable depth	Somewhat poorly to moderately- well drained, deep, ripe, slightly saline soils of variable texture; in places jarosite in lower horizons
Soil classification	Haplic and Typic Sulfaquents, Sulfic Hydraquents, Sulfic and Aeric Tropic Fluvaquents	Histic, Haplic and Typic Sulfaquents, Sulfic Hydraquents, Sulfihemists, Tropofibrists	Sulfic, Aeric and Typic Tropaquepts, Hydraquentic and Typic Sulfaquepts	Aeric, Typic and Sulfic Tropaquepts
Main vegetation	*Rhizophora harrisonii*, *R. racemosa*, *Laguncularia racemosa*; *Phragmites spp.* in upper estuary	*Rhizophora harrisonii*, *Avicennia nitida*	*Avicennia nitida*, *Paspalum vaginatum*, *Philoxerus vermicularis*, *Sesuvium portulacastrum*; bare tannes; *Phragmites spp.* in upper estuaries	*Paspalum vaginatum*, *Philoxerus vermicularis*, *Sesuvium portulacastrum*, *Heliocharis spp.*, *Cyperus spp.*, bare tannes; *Phragmites spp.* in upper estuaries; (woodland) savanna
Main rice limitations	Tidal flooding, salinity, potential acidity, riverbank erosion	Tidal and seasonal flooding, moderate potential acidity, salinity, Fe and Al toxicity	Tidal flooding, salinity, moderate acidity, Fe and Al toxicity	Low fertility, slight acidity, Fe-toxicity, water availability
Possible use	Natural reserve	Rice cultivation	Rice cultivation	Relay cropping (rice, cassava, maize, vegetables)
Management requirements	Protection, reforestation	Water management, lime dressing, N-fertilizer, varieties tolerant to salinity and acidity	Water management, lime dressing, NP-fertilizer, varieties tolerant to Fe and Al	Water management, NPK-fertilizer, short duration varieties, tolerant to Fe toxicity

Hydraquents, Sulfic, Aeric Tropic and Typic Sulfaquents). Soils in the backswamps have high potential acidity, although not as high as in the South-Sudan Savanna zone (Typic and Haplic Sulfaquents, Sulfic Hydraquents). The backswamps also include peats and peaty clays (Sulfohemists, Tropofibrists and Histic Sulfaquents). The landward fringes comprise soils that have formed from quickly deposited sediments which are generally low in pyrite contents (Tropaquepts and Endoaquents, some Sulfaquepts and Sulfaquents). The littoral zone is affected by severe coastal erosion. This is caused by strong long-shore currents which pass much closer to the coast than in the South-Sudan Savanna zone, due to a much narrower continental shelf off the Guinean coast.

In the mudflats, rice is cultivated, in the rainy season in small polder-like bunded fields, from which the heavy rains have flushed the salts. Rice yields are relatively high, up to 2500 kg/ha, but the cultivation is labourious. Rice cultivation is much easier, and much more common, on the landward fringes where salinity and (potential) acidity are less. Here, rice is cultivated in free draining-fields, from which any salts are flushed by rainwater or by fresh-water tidal floods, at the start of the cropping season. As the soils in this part of the littoral zone are older and, therefore, less fertile than in the mudflats, rice yields are somewhat lower (1500-2000 kg/ha).

Table 6 summarizes the characteristics, limitations and potentials of the mangrove ecosystems in the littoral environments of the Guinea Savanna zone.

Lagoon environments

The lagoons in the Guinea Savanna zone form narrow discontinous coastal strips along the coast of Ghana, Togo and Benin. These are protected from the sea by sandy beach ridges. In general, the connections to the sea, in between the beach ridges, are narrow. The 'Bouche du Roi' for example, in Benin, forms such a connection which is only 500 m wide. These narrow connections reduce the effect of tidal flushing on the formation of pyrite. This may be the reason why, in general, potential acidity of the soils in the tidal flats of the lagoons is low. Distinction is made, mainly according to the prevailing vegetation complexes, into lower and higher tidal flats. Soils in the lower tidal flats, which are daily flooded, are mainly (Sulfic) Hydraquents and Sulfaquents. Locally, peats may occur (Hemists and Fibrists). The higher tidal flats are flooded only during spring tides. Soils, therefore, are better drained and slightly acidified (Sulfaquepts, Tropaquepts and Sulfaquents).

The vegetation sequence landward from the beach ridges (which are mostly bare), shows a band of *Rhizophora racemosa* followed by *R. harrisonii* and *Avicennia nitida* in the lower tidal flats, whereas the higher tidal flats are colonized by halophitic grasses (e.g. Paspalum vaginatum, Sesuvium portulacastrum, Acrostichum aureum), or it is turned into tannes. (Potential) acidity being relatively low, soil salinity is the most limiting factor for rice production. Only a few large tracts of rice fields occur in Ghana, mainly in association with salt extraction plans.

Table 7 summarizes the characteristics, limitations and potentials of the mangrove ecosystems in the lagoon environments of the Equatorial Forest zone.

The Equatorial Forest zone

The length of the growing period in the Equatorial Forest zone is more than 270 days. Total

Table 6 Characterization, limitations and potentials of mangrove ecosystems in the Guinea Savanna Zone of West Africa (littoral environment)

	Mud flats	Beach ridges	Creek ridges	Backswamps	Landward fringes
Tidal class	1	3-5	2-3	1-2	3-4
Main soil characteristics	very poorly drained, (very) deep, fine-textured, unripe, saline soils, with sulphidic layers at shallow depths; in places peats;	Moderately-well to well drained, deep, coarse-textured soils	Moderately-well drained, deep, medium- to fine-textured, halfripe, saline soils, with sulphidic layers at greater depth; in places stratified	Poorly to very poorly drained, deep, fine-textured, unripe, saline soils, with pyritic layers mainly at shallow depths; in places peats	Somewhat poorly to moderately-well drained, deep, medium- to fine-textured, half-ripe, slightly saline soils; in places with pyritic layers at greater depths; in places acid at greater depths
Soil classification	Sulfic and Typic Hydraquents, Typic and Histic Sulfaquents, Sulfihemists, Tropofibrists	Tropopsamments, Psammaquents	Sulfic Hydraquents, Sulfic and Aeric Tropic Fluvaquents	Typic, Histic and Haplic Sulfaquents, Sulfic Hydraquents, Sulfohemists, Tropofibrists	Tropaquepts, Endoaquents, some Sulfaquepts and Sulfaquents
Main vegetation	Bare, *Avicennia nitida, Laguncularia racemosa*	Mixed forest, coconuts	*Rhizophora harrisonii, R. racemosa, Laguncularia racemosa, Avicennia nitida*	*Avicennia nitida, Rhizophora harrisonii, Paspalum vaginatum, Sesuvium portulacastrum, Philoxerus vermicularis*	*Paspalum vaginatum, Sesuvium portulacastrum, Philoxerus vermicularis, Heliocharis spp., Cyperus spp.*; bare tannes
Main rice limitations	Tidal flooding, salinity, potential acidity, unripeness, coastal erosion	Coastal erosion, low fertility	Tidal flooding, salinity, potential acidity, riverbank erosion	Tidal and seasonal flooding, potential acidity, salinity, Fe/Al toxicity	Slight (potential) acidity, low fertility, Fe-toxicity
Possible use	Rice cultivation, fisheries, shrimp cultivation	Natural reserve, coconuts	Natural reserve	Rice cultivation	Rice cultivation
Management requirements	Water management, lime dressing, N-fertilizer	Protection, NPK-fertilizer	Protection, reforestation	Water management, liming, N-fertilizer, tall varieties resistant to lodging and tolerant to salinity and acidity	Water management, NP-fertilizer, varieties tolerant to Fe-toxicity

Table 7 Characterization, limitations and potentials of mangrove ecosystems in the Guinea Savanna zone of West Africa (lagoon environments)

	Beach ridges	Lower tidal flats	Higher tidal flats
Tidal class	4-5	1-2	2-3
Main soil characteristics	Moderately-well to well drained, deep, coarse-textured soils	Very poorly drained, deep, fine-textured, unripe, saline soils, with sulphidic layers at variable depths; in places peats	Poorly to moderately-well drained, deep, fine-textured, unripe to half-ripe, saline to hyper-saline soils, with acid or sulphidic or layers at variable depths
Soil classification	Quartzipsamments, Tropopsamments, Psammaquents	Typic and Sulfic Hydraquents, Typic and Histic Sulfaquents, Sulihemists and Tropofibrists	Typic and Hydraquentic Sulfaquepts, Typic and Sulfic Tropaquepts, Typic Sulfaquents
Main vegetation	Bare; coconuts	*Rhizophora racemosa, R. harrisonii, Avicennia nitida*	*Paspalum vaginatum, Sesuvium portulacastrum, Acrostichum aureum*, bare tannes
Main rice limitations	soil texture, water availability, low fertility	tidal flooding, salinity, acidity	flooding, very high salinity, acidity, low fertility
Possible use	conservation, coconuts	conservation	salt extraction, shrimp and fish cultivation
Management requirements	protection	protection	water management, bunding, excavation, liming, N-fertilizer

annual rainfall is high, particularly along the western coast of West Africa (Sierra Leone: 2500-3000 mm/yr, mainly falling between May and November) and along the Gulf of Guinea (Nigeria, Cameroon: 3000-4500 mm/yr). In the latter zone rainfall distribution is bimodal: the rains occur from March through July and from September through October/December. In between these blocks of very high rainfall, climatic conditions are drier. Total annual rainfall is about 2000 mm in Abidjan, and 1500 mm in Lagos. The distribution is (pseudo) bimodal, as the rains fall from March through November, with a slight dip between July and September. Due to higher cloudiness in the Equatorial Forest zone, total evaporation is less than in the South Sudan and Guinea Savanna zones: it ranges between 800 and 1000 mm/yr. As rainfall exceeds the evaporation by far, salinity beyond that of the sea water is a minor problem only at the beginning of the rainy season.

This agro-ecological zone comprises a number of mangrove ecosystems, including the estuaries of Sierra Leone, Cameroon and Gabon, the lagoons of Côte d'Ivoire and the Niger delta.

Estuarine environments

Estuarine environments in Sierra Leone include those of the Great and Little Scarcies rivers, the Rokel and Sewa. As the tidal amplitude along the coast of Sierra Leone is high, (e.g. up to 3 m at Freetown) saline water intrudes far upstream during the dry season. In the rainy season, a net fresh-water outflow pushes this saline water beyond the river mouth, thus allowing rice cultivation on the estuarine lands. The Cameroon estuaries comprise those of the rivers Akpra, Yafe Ndian, Lokele and Meme, the Cameroon estuary and at the mouth of Nyong, Lokoundje and Ntem. As, due to the convergence of oceanic currents in the Gulf of Guinea, sedimentation rates along the coast are high, sediments near the mouth of the estuaries tend to contain relatively little pyrite. The tidal amplitude is up to 3 m. In Gabon, estuaries occur near the mouths of the Muni, Mondah and Komo rivers. The tidal amplitude near Libreville is up to 2 m.

The estuaries of the Equatorial Forest zone can be subdivided into two ecologies, similar to those in the Guinea Savanna zone: the lower and upper estuaries.

In the **lower estuaries**, *Rhizophora harrisonii* and *R. racemosa* occupy relatively narrow fringes along the levees and creek ridges, whereas *Avicennia africana* occurs landward in wide bands in the backswamps. Small tannes develop locally on higher backswamps in the dry season. Further upstream *Rhizophora harrisonii* occupies much wider bands in the backswamps while *Avicennia africana* is less important. Towards the higher positions in the estuary (higher backswamps and terraces) *Paspalum vaginatum* and other halophytic herbs take over. *Phragmites spp.* prevail on terraces in the upper estuaries.

Soils in both the **lower and upper estuaries** are generally potential acid sulphate soils (Sulfaquents). Pyrite contents, however, are much higher in the upper estuaries than in the lower stretches. Also, in the levees and creek ridges, potential acidity is less than in the backswamps. Peats occur in the lower backswamps (Hemists, Fibrists). Acidification has taken place in the soils of the higher backswamps and some of the terraces, particularly in the upper estuaries. These soils are classified as Sulfaquepts and (Sulfic) Tropaquepts.

Tidal swamp rice cultivation is widespread in Sierra Leone. It is rare however in Cameroon and Gabon. This may be attributed to lower land pressure and different food preference in these countries. As stated before, salinity at the beginning of the rainy season may be a limitation to rice cultivation. Soil acidity, however, forms the main limitation, and more so in the upper estuaries than downstream. Both, salinity and acidity are more severe in the higher backswamps than in the levees. Due to the prevailing high rainfall in this area, however, the length of the salt-free period matches short- to medium-duration rice varieties. Yields generally vary between 1200 and 3500 kg/ha.

Table 8 summarizes the characteristics, limitations and potentials of the mangrove ecosystems in the estuarine environment of the Equatorial forest zone.

The Niger Delta

The Niger delta (20,000 km^2, Figure 2) comprises the largest mangrove ecosystem of West Africa (appr. 10.000 km2). It has three major zones, i.e. the fresh-water swamp zone, the brackish-water or mangrove zone and the beach ridge complex (Allen, 1970b). Near the coastline the tidal amplitude ranges from some 300 cm at Calabar in the eastern part of the delta, to 90 cm at Escravos in the west.

The **fresh-water swamp zone** does not comprise mangrove ecosystems. It consists of an extensive and intricate system of river floodplains, including levees and backswamps, and terraces along rivers that radiate from Onita at the apex of the delta, into the mangrove zone lower down. It is luxuriantly colonized by dense swamp forest comprising raphia palms (*Raphia vinifera* and *R. hookeri*) and diverse tree species, including mahoganies (*Khaya spp.*). Organic debris from this vegetation forms an important part of the sediment accumulating in the lower deltaic zones.

The **brackish-water or mangrove zone** comprises an association of estuary-like intertidal flats including creek ridges and backswamps. *Rhizophora racemosa* is the dominant vegetation along the creek ridges. In the lower backswamps *Avicennia africana* and *R. harrisonii* take over, together with nipa palm (*Nypa fruticans*). On the higher terraces nipa palm and raphia (*R. hookeri*), are present as well as herbaceous species like *Sesuvium*, *Philoxerus*, *Heleocharis* and *Paspalum*. The soils in this tidal zone are generally influenced by fast sedimentation rates, in places leading to little pyrite having been formed.

Soils of the creek ridges are slightly potentially acid (Hydraquents, Sulfaquents and Fluvaquents). Potential acidity is somewhat higher in the lower backswamps. Here, soils are mainly Sulfaquents, or, if they are peats, Sulfohemists. On the higher terraces, acidification has taken place (Sulfaquepts and Sulfic Tropaquepts).

The **beach ridges** on the seaward side of the brackish-water zone comprise of a number of huge beach ridges (up to 10 m high) parallel to the coastline. Locally dunes have formed on these beach ridges. The vegetation is mixed forest, mainly. Locally coconuts are grown. The beach ridges are, of coarse, not subject to tidal flooding and they do not present any potential acidity or salinity danger. The sandy soils, however, are very poor in nutrients (Quartzipsamments and Tropopsamments).

Rice was introduced in the delta around 1960 in the zone of fresh-water swamps. Potential and actual acidity levels in the brackish-water zone being relatively low, and rainfall being high, little soil constraints to rice cultivation exist. Flooding, however, can be limiting and flood protection and drainage will be required in order to attain reasonable rice yields.

Table 9 summarizes the characteristics, limitations and potentials of the mangrove ecosystems of the Niger delta, in the Equatorial Forest zone.

Table 8 Characterization, limitations and potentials of mangrove ecosystems in the Equatorial Forest Zone of West Africa (estuarine environments)

	Creek ridges/Levees	Lower backswamps	Higher backswamps	Terraces
Tidal class	2	1-2	2-3	4-5
Main soil characteristics	Poorly to somewhat poorly drained, deep, medium- to fine-textured, unripe to half-ripe, saline soils, with sulphidic layers at variable depth; in places stratified	Poorly to very poorly drained, fine-textured, deep, unripe, saline soils, with sulphidic layers at variable depth; in places stratified; in places peats	Poorly to somewhat poorly drained, deep, fine-textured, half-ripe to unripe, saline soils, with sulphidic layers at variable depth	Somewhat poorly to moderately- well drained, deep, ripe, slightly saline soils of variable texture; in places jarosite in lower horizons
Soil classification	Sulfic Hydraquents, Haplic and Typic Sulfaquents, Sulfic and Aeric Tropic Fluvaquents	Typic, Histic and Haplic Sulfaquents, Sulfic Hydraquents, Sulfohemists, Tropofibrists	Typic and Hydraquentic Sulfaquepts, Sulfic, Aeric and Typic Tropaquepts	Aeric, Typic and Sulfic Tropaquepts, Typic and Hydraquentic Sulfaquepts
Main vegetation	*Rhizophora racemosa, R. harrisonii*	*Avicennia africana, Rhizophora harrisonii*	*Avicennia africana, Paspalum vaginatum, Sesuvium portulacastrum, Heliocharis spp.*; bare tannes	*Paspalum vaginatum, Sesuvium portulacastrum, Heliocharis spp.; Phragmites spp.* in upper estuaries; *rain forest, derived savanna*
Main rice limitations	Tidal flooding, slight salinity, potential acidity, riverbank erosion	Tidal and seasonal flooding, potential acidity, Fe and Al toxicity	Tidal flooding, slight salinity, acidity, Fe and Al toxicity	Low fertility, acidity, Fe-toxicity, water availability
Possible use	Natural reserve	Rice cultivation	Rice cultivation	Relay cropping (rice, cassava, maize, vegetables)
Management requirements	Protection, reforestation	Water management, lime dressing, N-fertilizer, varieties tolerant to salinity and acidity	Water management, lime dressing, NP-fertilizer	Water management, NPK-fertilizer, short duration varieties, tolerant to Fe toxicity

Table 9 Characterization, limitations and potentials of mangrove ecosystems in the Equatorial Forest Zone of West Africa (Niger delta environment)

	Creek ridges	Lower backswamps	Higher backswamps	Beach ridges
Tidal class	2-3	1-2	2-3	5
Main soil characteristics	Moderately well drained, deep, medium- to fine-textured, halfripe, slightly saline soils, with sulphidic layers at greater depth; in places stratified	Poorly to very poorly drained, deep, fine-textured, unripe, saline soils, with pyritic layers mainly at shallow depths; in places peats	Somewhat poorly to moderately-well drained, deep, medium- to fine-textured, half-ripe, slightly saline soils; in places with pyritic or acidic layers at greater depths	Well drained, deep, coarse-textured soils
Soil classification	Sulfic and Aeric Tropic Fluvaquents, Haplic and Typic Sulfaquents,	Typic, Histic and Haplic Sulfaquents, Sulfic Hydraquents, Sulfohemists, Tropofibrists	Aeric, Typic and Sulfic Tropaquepts, Typic and Hydraquentic Sulfaquepts	Quartzipsamments, Tropopsamments
Main vegetation	*Rhizophora racemosa, R. harrisonii, Avicennia africana*	*Avicennia africana, Rhizophora harrisonii, Nypa fruticans*	*Avicennia africana, Paspalum vaginatum, Sesuvium portulacastrum, Philoxerus vermicularis, Heliocharis spp., Cyperus spp., Raphia hookeri, Nypa fruticans*	*Mixed forest, coconuts*
Main rice limitations	Tidal flooding, slight potential acidity, creekbank erosion	Tidal and seasonal flooding, potential acidity, Fe and Al toxicity	Slight (potential) acidity, low fertility, Fe-toxicity	Coastal erosion, low fertility
Possible use	Natural reserve	Rice cultivation	Rice cultivation, Relay cropping (rice, maize, cassava, yam)	Natural reserve, coconuts
Management requirements	Protection, reforestation	Water management, liming, N-fertilizer, tall varieties resistant to lodging and tolerant to acidity and Fe and Al toxicity	Water management, liming, NPK-fertilizer, varieties tolerant to Fe-toxicity	Protection, NPK-fertilizer

DISCUSSION

Mangrove ecosystems; heterogeneity and dynamics

Mangrove ecosystems, occurring in a wide range of climatic and hydrological conditions, consisting of highly variable soils in topographically different positions, and comprising of a range of different vegetation species, are very heterogeneous and complex environments. The system of agro-ecological characterization presented here, deals with this heterogeneity by means of a multiple-scale approach which characterizes the environments at macro-, meso- and micro-levels respectively. This is in recognition of the fact that data and characterization criteria are scale-dependent. Moreover, also the importance of certain variables for agro-ecological characterization is scale-dependent (Andriesse et al., 1994). This implies that multiple-scale characterization involves aggregation of variables when going from large scales up to smaller ones (i.e. from micro- to macro-level) and desaggregation when going down. Aggregation is achieved by the replacement of detailed data by average values, class values, or more general groupings, as for example, in the sequence of land elements (e.g. levees, lower and higher backswamps and terraces) through parts of estuary systems (lower, middle and upper estuaries) to the entire estuary, or by the exclusion of variables that are not considered relevant at a higher level like, for instance, identification at species level of the vegetation. Desaggregation is done on the basis of insight in the importance of the spatial distribution of the variables at lower characterization levels. Here, the relationship between specific types of vegetation and the formation of pyrite serves as an example: certain mangrove species are known to produce large amounts of organic matter, an essential component in the pyrite-accumulation process.

Temporal dynamics in mangrove ecosystems are multiple. They act at micro-level (e.g. daily tidal flooding), at meso-level (seasonal river flooding and cropping systems) and at macro-level (periodic changes in rainfall and increasing land pressure). With increasing level of detail, characterization data refer to increasingly-limited time frames, as they are collected in shorter periods of time. As in the case of spatial heterogeneity, this change in time frames is accommodated in the characterization system by means of aggregation, while going up the scale ladder, and by desaggregation, while going down. Examples are in the averaging of rainfall data at macro-level, and that of the general flooding regimes for individual land sub-elements (e.g. levees, backswamps, terraces) towards broad mangrove zones (e.g. lower, middle and upper estuaries) and major mangrove ecosystems (e.g. estuaries, deltas, littoral zones and lagoons).

The value of the characterization

Mangrove environments in West Africa are highly variable. This variability occurs in the physical as well as in the biotic component of the mangrove ecosystems. Also, the heterogeneity of both these components is extremely scale-dependent. Even at the lowest unit of characterization, i.e. the catena, soil properties relevant to aspects of environmental conservation, land reclamation or rice production, vary greatly.

Dent (1986 and 1992) points out that sustainable development of coastal lands with acid sulphate soils is possible only by means of integrated approaches of soil, water and crop management over whole landscapes. Such approaches require comprehensive and structured information on the basic natural resources. The combined use, in the present characterization, of climate, coastal morphology, hydrology, vegetation sequences and the catena concept, matched, at three levels of detail, with the different environmental conditions necessary for the formation of acid sulphate soils, provides a logical framework to describe the mangrove environments of West Africa. In turn, these multiple-scale descriptions provide the information required to cater for the needs of the various decision-makers and land use planners to develop scenarios and to implement projects for the reclamation or conservation of mangrove ecosystems. Also, possible mitigating measures can be drawn from the characterization, for both the conservation of the ecosystem as well as for their sustainable agricultural use.

This characterization system also provides a key to the selection of representative sites to design monitoring and control systems for environmental protection and to develop technology packages for intensified and sustainable use. Conversely, the stepped characterization can also be used for the extrapolation of site-specific information to geographically different areas, with similar characteristics. This will greatly contribute to the optimum use of both natural and financial resources.

Potentials of mangrove ecosystems for rice cultivation

With the danger of acidification lurking, it will be no surprise that many acid sulphate soils have been wasted by thoughtless drainage or, as is the case locally in West Africa, as a result of the lowering of the groundwater table, due to extended periods of drought. Broadly, there are three options for the use of acid sulphate soils:

- Leave as is, especially if alternative land is available for development: mangroves swamps, salt marshes and mud flats have essential ecological functions for example as natural coastal defense barriers, as breeding grounds for fish and wintering grounds for migratory birds and for the gathering of natural products;
- Reclaim, but with minimum disturbance in order to prevent, as much as possible, the oxidation of pyrite: flooded rice cultivation, shallow fishponds (shrimps if tidal water is available), dryland cropping under (controlled) high water table, forestry and grazing are possible options;
- Total reclamation aiming at complete drainage and ripening of the land and flushing or neutralization of the acidity formed.

Because of the overall effect of water management on the behaviour of acid sulphate soils, any attempt to reclaim them must take into account the interaction between soil, groundwater and floodwater (Dent, 1992). In this respect, seasonality of rainfall and availability of irrigation/leaching water largely determine the use possibilities of these soils. If a large water surplus exists, the main management problem is drainage. Maintenance of a high watertable (i.e. above the pyritic layer) will prevent, or at least limit, soil acidification. Dry periods, even as short as some 2-3 weeks, create increasingly severe acid conditions. In such conditions, water availability for crop growth depends on the thickness of the non-acid/non-pyritic topsoil. In even drier climates, salinity is an additional, if not the sole, constraint. Here, the situation is aggreviated by the fact that water for leaching of the salts and acids is scarce.

Further research

As stated before, elaboration and validation of this system for agro-ecological characterization of mangrove environments is still needed. After all, the final objective of the system is the complete and comprehensive characterization and accurate zoning of the mangrove systems in West Africa. As a first step in validation, queries to respond to questions organized in a knowledge-based decision-support system as proposed by Dent (1993), can be undertaken within our framework, to guide coarse land evaluation at different scales. If more information becomes available, and if questions related to the use of the land, including environmental conservation and protection of biodiversty, become more specific, this land evaluation can be increasingly of a quantitative nature. Eventually, fully-quantitative land evaluation, using detailed characterization and inventory data, linked with model-based studies and geographic information systems can lead to realistic land use planning, including the analysis of many, and contrasting, use alternatives.

REFERENCES

Ahn, P.M., 1970. West African Soils. Oxford University Press, London, UK. 332 pp.

Allen, J.R.L., 1970a. Physical processes of sedimentation, an introduction. Earth Science Series, 1. Allen and Unwin, London, UK. 248 pp.

Allen, J.R.L., 1970b. Sediments of the modern Niger delta: a summary and review. In: Morgan (ed.): Deltaic sedimentation, modern and ancient. Soc. Econ. Paleontologists and Mineralogists, Tulsa, USA. p. 138-151.

Andriesse, W., 1986. Area and Distribution. In: Juo and Lowe (eds): The Wetlands and Rice in Sub-Saharan Africa. Proceedings of an international conference. Ibadan, November 1985. IITA, Ibadan, Nigeria. p. 15-30.

Andriesse, W. and L.O. Fresco, 1991. A Characterization of Rice-growing Environments in West Africa. Agric., Ecosystems and Environ., 33: 377-395.

Andriesse, W. and M.G. Bos, 1994. Sustainable agricultural development and environmental conservation in coastal lowlands; Priority setting for research. Paper presented at the Regional Workshop on the Sustainable Use of Coastal Land in South-east Asia. April 1994, Bangkok. Asian Institute of Technology, Bangkok, Thailand. 9 pp.

Andriesse, W., L.O. Fresco, N. Van Duivenbooden and P.N. Windmeijer, 1994. Multi-scale characterization of inland valley agro-ecosystems in West Africa. Netherlands Jnl. of Agric. Sci. 42-2:247-265.

Béye, G., 1973. Acidification of mangrove soils after empoldering in Lower Casamance. Effects of the type of reclamation system used. In: Dost (ed.): Acid Sulphate Soils. Proceedings of the First International Symposium. August 1972, Wageningen, The Netherlands. ILRI Publication 18 (2 Vols). International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. p. 359-371.

Bloomfield, C. and J.K. Coulter, 1973. Genesis and Management of Acid Sulphate Soils. Adv. Agron. (25) 265-326.

Bowles, E.J. and D.P. Garrity, 1988. Development of a Comprehensive Classification for Rice Ecosystems. IRRI Special Seminar, December 1988, Los Baños. International Rice Research Institute, Los Baños, The Philippines. 47 pp.+ Annexes.

Buddenhagen, I.W., 1978. Rice ecosystems in Africa. In: Buddenhagen and Persley (eds): Rice in Africa. Academic Press, London, UK. p. 3-10.

Bunting, A.H. (ed), 1987. Agricultural Environments; characterization, classification and mapping. Proceedings of the Rome workshop on agro-ecological characterization, classification and mapping. Rome, April 1986. CAB International, Wallingford, UK. 335 pp.
CEC, 1992. The Mangroves of Africa and Madagascar. Office for Official Publications of the European Communities (CEC), Luxembourg. 273 pp.
Chapman, V.J., 1976. Mangrove Vegetation. Cramer Publishers, Vaduz, Lichtenstein. 447 pp.
Chapman, V.J., 1977. Ecosystems of the World, Vol 1: Wet Coastal Ecosystems. Elseviers Publishers, Amsterdam, The Netherlands. 428 pp.
Dabin, B. and R. Maignien, 1979. Les principaux sols d'Afrique de l'Ouest et leurs potentialités agricoles. Cah. ORSTOM Sér. Pédol., XVII: 235-257.
Dent, D., 1986. Acid Sulphate Soils: A baseline for research and development. ILRI Publication No. 39. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. 200 pp.
Dent, D., 1992. Reclamation of acid sulphate soils. In: Lal and Stewart (eds.), Advances in Soil Science, Vol. 17. Springer Verlag, New York, USA. p. 79-122.
Dent, D., 1993. From land evaluation to land use planning. In: Dent and Van Mensvoort (eds.), Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils. March 1992, Ho Chi Minh City, Vietnam. ILRI Publication 52. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. p. 289-298.
Diop, S., 1990. La Côte Ouest-Africaine du Saloum (Sénégal) à la Mellacorée (Rép. de Guinée). Editions de l'ORSTOM, Collection Études et Thèses. Paris, France. 310 pp.
Diop, E.S., C.D. Field and M. Vanucci (eds.), 1993. Conservation and Sustainable Utilization of Mangrove Forests in Latin America and Africa Regions. Proceedings of a workshop. January 1993, Dakar, Senegal. ITTO/ISME Project PD114/90(F). International Society for Mangrove Ecosystems, Okinawa, Japan. 35 pp.
DREI, 1988. Rural Engineering Project, Bissàssema, Guinea-Bissau. Final Report Phase II, Vol V: Soils. Department of Rural Engineering and Irrigation, Wageningen Agricultural University, Wageningen, The Netherlands. 50 pp.+ 4 maps.
Faniran, A. and L.K. Jeje, 1983. Humid Tropical Geomorphology. A study of geomorphological processes and landforms in warm humid climates. Longman Group Ltd., London, UK. 414 pp.
FAO, 1977. FAO/Unesco Soil Map of the World, 1:5 000 000. Vol. VI, Africa. Unesco, Paris, France. 299 pp.
FAO, 1978. Report on the agro-ecological zones project. Vol.I. Methodology and results for Africa. World Soil Resources Rep. 48. FAO. Rome, Italy. 158 pp.
Giglioli, M.E.C. and I. Thornton, 1965. Mangrove Swamps in The Gambia. Journal of Applied Ecology 2:81-103 and 257-269.
HARZA, 1969. Étude d'un programme d'aménagement hydro-agricole des terres rizicultivables de la Basse-Guinée. Rapport Final, Vol. II: Pédologie. HARZA Engineering Company International, Chicago, USA. 186 pp.
Hesse, P.R., 1961. Some differences between the soils of Rhizophora and Avicennia mangrove swamps in Sierra Leone. Plant and Soil 14 (4) 335-346.
Huke, R., 1976. Geography and climate of rice. In: Climate and Rice. Proceedings of a Symposium. September 1974, IRRI, Los Baños. International Rice Research Institute, Los Baños, The Philippines. p. 31-50.
IRRI, 1984. Terminology for Rice-growing Environments. International Rice Research Institute, Los Baños, The Philippines. 35 pp.
Jordan, H.D., 1964. The relation of vegetation and soil to development of mangrove swamps

for rice growing in Sierra Leone. Journal of Applied Ecology 1:209-212.
Kawalec, A., 1977. La genèse et l'évolution des sols sur alluvions marines. Varsovie, Poland.
Langenhoff, R., 1986. Distribution, mapping, classification and use of acid sulphate soils. A literature study. STIBOKA Internal Communications No. 74. The Netherlands Soil Survey Institute, Wageningen, The Netherlands. 133 pp.
Loyer, J.Y., P. Boivin, J.Y. le Brusq and P. Zante, 1988. Les sols du domaine fluvio-marin de Casamance (Sénégal): Evolution récente etreevaluation des contraintes majeures pour leur mise en valeur. In: Dost (ed.), Selected Papers of the Dakar Symposium on Acid Sulphate Soils. January, 1986, Dakar, Senegal. ILRI Publication 44. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. p. 16-23.
Maltby, E., 1986. Waterlogged wealth. Why waste the world's wet places? Earthscan, International Institute for Environment and Development, London, UK. 200 pp.
Marius, C., 1985. Mangroves du Sénégal et de la Gambie. Ecologie, Pédologie, Géochimie et Mise en Valeur et Aménagement. Collection Travaux et Documents No 193. ORSTOM, Paris, France. 357 pp.
Mitsch, W.J. and J.G. Gosselink (eds.), 1993. Wetlands. Von Nostrad Reinhold Publishers, New York, USA. 722 pp.
Moormann, F.R. and N. Van Breemen, 1978. Rice: Soil, Water, Land. International Rice Research Institute, Los Baños, The Philippines. 185 pp.
Pons, L.J. M.E.F. Van Mensvoort and Le Quang Tri, 1986. Proposal for the classification of mineral Vietnamese acid sulphate soils according to Soil Taxonomy. Paper presented at the Third International Symposium on Acid Sulphate Soils in Dakar, Senegal, January 1986. 10 pp. (mimeograph).
Pons, L.J., N. Van Breemen and P.M. Driessen, 1982. Physiography of Coastal Sediments and Development of Potential Soil Acidity. In: Acid Sulphate Weathering. SSSA Special Publ. 10. Soil Science Society of America. Madison, Wisc. USA. p. 1-18.
Sadio, S., 1991. Pédogenèse et potentialités forestières des sols sulfatés acides salés des tannes du Sine Saloum, Sénégal. Editions de l'ORSTOM. ORSTOM, Bondy, France. 270 pp.
SSS, 1992. Keys to Soil Taxonomy. SMSS Technical Monograph No. 19 (5th edn.). Soil Management Support Services/Soil Survey Staff. Pocahontas Press, Inc., Blackburg (Va), USA. 541 pp.
Sylla, M., N. Van Breemen, L.O. Fresco, C. Dixon and A. Stein, 1993. Temporal and spatial variability of soil constraints affecting rice production along the Great Scarcies mangrove swamps, Sierra Leone. In: Dent and Van Mensvoort (eds.), Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils. March 1992, Ho Chi Minh City, Vietnam. ILRI Publication 52. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. p. 247-259.
Thomas, P., J.A. Varley and J.E. Robinson, 1979. The sulphidic and associated soils of the Gambia estuary above the proposed barrage at Yelitenda, The Gambia. Project Report 89. Overseas Development Administration, Land Resources Development Centre, Tolworth, UK. 95 pp.+ 1 Annex.
Tomlinson, T.E., 1957. Relationship between mangrove vegetation, soil texture and reaction of surface soil after empoldering saline swamps in Sierra Leone. Trop. Agric. 34(1)41-50.
Van Breemen, N., 1973. Soil forming processes in acid sulphate soils. In: Dost (ed.): Acid Sulphate Soils. Proceedings of the First International Symposium. August 1972, Wageningen, The Netherlands. ILRI Publication 18 (2 Vols). International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. p. 66-130.
Van Breemen, N., 1976. Genesis and solution chemistry of acid sulphate soils in Thailand.

Agric. Res. Rep. 848. Centre for Agricultural Publishing and Documentation (PUDOC), Wageningen, The Netherlands. 263 pp.
Van Breemen, N., 1982. Genesis, Morphology and Classification of Acid Sulphate Soils in Coastal Plains. In: Acid Sulphate Weathering. SSSA Special Publ. 10. Soil Science Society of America. Madison, Wisc. USA. p. 95-108.
Van Breemen, N., 1993. Environmental aspects of acid sulphate soils. In: Dent and Van Mensvoort (eds.), Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils. March 1992, Ho Chi Minh City, Vietnam. ILRI Publication 52. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. p. 391-402.
Van Mensvoort, M.E.F., R.S. Lantin, R. Brinkman and N. Van Breemen, 1984. Toxicities of Wetland Rice Soils. In: Banta (ed.), Wetland Soils: Characterization, Classification and Utilization. International Rice Research Institute, Los Baños, The Philippines. p. 123-138.
Van Gent, P.A.M. and R. Ukkerman, 1993. The Balanta rice farming system in Guinea Bissau. In: Dent and Van Mensvoort (eds.), Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils. March 1992, Ho Chi Minh City, Vietnam. ILRI Publication 52. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. p. 103-112.
Vieillefon, J., 1977. Les sols des mangroves et des tannes de Basse Casamance, Sénègal. Mémoires ORSTOM 83. ORSTOM, Bondy, France. 291 *pp*.
Walsh, G.E., 1974. Mangroves: a review. In: Reimold and Queen (eds.): Ecology of Halophytes. Academic Press, New York, USA. p. 51-118.
WARDA, 1988. Strategic Plan 1990-2000. WARDA, Monrovia, Liberia. 66 pp.
WARDA, 1980. Classification of types of rice cultivation in West Africa. WARDA, Monrovia, Liberia. 23 pp.
Windmeijer, P.N., and W. Andriesse (eds.), 1993. Inland Valleys in West Africa: An Agro-ecological Characterization of Rice-Growing Environments. ILRI Publication 32. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. 160 pp.

LIST OF ABBREVIATIONS

FAO:	Food and Agriculture Organization of the United Nations
ISRA:	Institut Sénégalais pour la Recherche Agronomique, Sénégal
IUCN:	International Union for the Conservation of Nature
OMVG:	Organisation pour la Mise en Valeur du fleuve Gambia, The Gambia, Senegal and Guinea Bissau
PEC:	Projet des Études Cotières, Guinea
SSS:	Soil Survey Staff
UNESCO:	Education and Scientific Organization of the United Nations
UNEP:	United Nations Environmental Program
USDA:	United Staes Department of Agriculture
WARDA:	West Africa Rice Development Association

CHAPTER 3

SPATIAL VARIABILITY OF SOIL SALINITY AT DIFFERENT SCALES IN THE MANGROVE AGRO-ECOSYSTEM IN WEST AFRICA.

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Spatial variability of soil salinity at different scales in the mangrove rice Agro-ecosystem in West Africa.

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Abstract

Spatial variability of soil salinity in coastal low lands results from a complex interaction of climate, river hydrology, topography and tidal flooding. This study was aiming to determine the significant effects of these causal factors at different scales in the West African mangrove environment. The driving forces are the penetration of tidal saline waters and subsequent water evaporation in the flood plain, of which the magnitude is controlled by the causal factors. A hierarchical framework of the different factors was designed. Four river basins were selected: The Gambia, The Casamance (Senegal), The Geba (Guinea Bissau) and The Great Scarcies (Sierra Leone). Within each river basin, three strips of land (80 m wide, 500 to 1800 m long) perpendicular to the river at different distances from the mouth were selected. In the dry season of 1991, soil samples were taken from the strips using a 40 by 20 m grid at five soil depths to be analyzed for salinity. The contribution of the different source of salinity spatial variability was analyzed with a nested ANOVA. Geostatistics were used to model spatial variability at micro scale. As a result, main environments at macro scale (between river basins), sub-environments at meso scale (within river basins) and salinity classes at micro scale (within catena) were defined. Nested regression and geostatistics were found complementary to disentangle the complexity of the factors influencing salinity spatial variability.

Introduction

Rice (*Oryza sativa L.*) production in the West African Mangrove zone is limited mainly by high soil salinity. Many attempts by national and international research institutes to introduce improved rice production technology failed, partly because of the highly variable soil salinity. An assessment of this major factor affecting rice production is strongly needed. The first task in studying soil salinity within this wide region is to understand the major factors controlling its spatial variability, both over large regions and within the individual rice field.

Different attempts have been made to classify rivers and soils in West African mangroves and elsewhere according to their salinity spatial distribution (Por, 1972; Le Reste, 1984; Wolansky, 1986; Pages and Debenay, 1987; Debenay et al., 1989; and Diop, 1990). Diop (1990) concludes that after the onset of the drought persisting in the Sahel since 1968, most of the West African rivers north of the Mellacorée River in Guinea, up to the Saloum River in Senegal, became more saline than sea water (hypersaline) in the dry season over a considerable distance upstream. Diop (1990) refers to this reverse trend in river water salinity in confined estuaries as "inverse estuary". Hypersalinity upstream has led to excessive salinity in about one million ha of land in West Africa (41.9 % of the total area of mangrove soil in the region) (Diop, 1990). Farmers abandon the most saline rice fields and move to higher, often sloping, land for cash crops. The intensified use of uplands leads to more soil erosion. Various local groups (individual farmers, village) and decision-makers (government agencies) require information at different levels of detail ("site specific management"; regional planning) which are not provided by a single conventional soil survey.

Traditionally, pedologists have used climatic zones or soil-landscape units for geographic differentiation of soil attributes at different scales (Rozov and Ivanova, 1967; French C.P.C.S. taxonomy, 1967; Hugget, 1975). Micro-variability of soil properties at the scale of individual fields have been studied by geostatistical methods (Webster, 1985; Stein, 1991). Stochasticity in the variability of soil properties is generally recognized and can be used to estimate a property at a non-visited place, as well as to improve sampling efficiency and aid in decision making on soil management (Webster, 1985; Stein, 1991; Yates et al., 1993). Yet, applications of geostatistics to soil salinity are scarce even though saline soils are notoriously variable (Gallichand et al., 1992; Hoogerwerf et al., 1992; and Yates et al. 1993).

The primary goal of this paper was to identify the factors causing soil salinization at different scales in the West African mangrove zone area, by applying both classical statistics and geostatistics. We assume that the following two main actions drive soil salinization i) the penetration of sea water in the estuaries during high tides with subsequent submersion of the river floodplain and ii) the evaporation of water during low tides. The magnitude of these processes is controlled by climate, river hydrology, and toposequence. Therefore we consider the following factors at different scales: i) at the macro-level: gradients in mean annual rainfall and potential evaporation, ii) at meso-level within a river basin: the proximity of the river mouth, and iii) at the detail or micro-level: the position along a catena perpendicular to the river (Fig.1). The approach is illustrated by the hierarchical framework shown in Fig. 2. To quantify these effects at different scales we applied different statistical methods on a data set collected for this purpose from a large region in West Africa, comprising the countries Senegal, Gambia, Guinee Bissau and Sierra Leone.

Material and methods

Study area and characteristics

The study area includes four river basins along the West African Atlantic coast, viz. from north to south: The Gambia River (Gambia), The Casamance River (Senegal), The Geba River (Guinea Bissau) and The Great Scarcies (Sierra Leone) (Fig.1). The total area of salt affected soils in the region is approximately 214.000 ha.

Charcteristics of climate, hydrology, salinity regime, landscape, and soil types are summarized in Table 1. The main land use in the low-lying alluvial areas was low-input rice cultivation. Water management for controlling salinity involves hand-made small dikes or anti-salt small dams; in some areas farmers plant on ridges to maximize salt leaching from the root zone. The aquatic zone was used for fishing and for oyster harvesting.

Sampling at different scales and laboratory analyses

In each river basin, three strips perpendicular to the river were defined according to their distance from the river mouth. Each strip comprised the levee, the adjacent backswamp area and the transition to the low river terraces (Fig.1). The distances between the strips were chosen in relation to the extent of salinity intrusion in the estuary, as reported elsewhere (Brunet-Moret, 1969; Vieillefon, 1977; Marius, 1984; Diop, 1990). In all cases one strip was at the river mouth, one close to the limit of high salinity in a normal year and one in the zone with high seasonal salinity variation (Fig.1). Seasonal variation in salinity was not considered here, and is discussed elsewhere (Sylla et al, 1993). To minimize effects of such seasonal

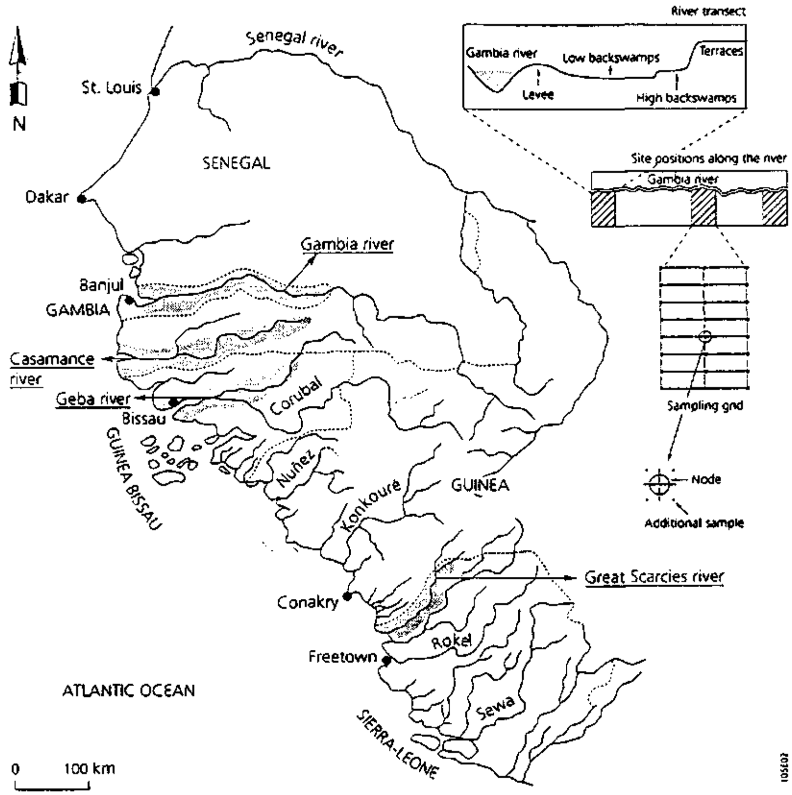

Figure 1: Location of the study area, the position of the four river basins of the Gambia (Gambia), the Casamance (Sénégal), The Geba (Guinea Bissau) and the Great Scarcies river (Sierra Leone).

variation, samples were collected at the end of the dry season of 1991 (April-May) when soil salinity was at its maximum. In each strip (80 m wide, 500 to 1800 long) soil samples were taken at the nodes of a 40 by 20 m grid, and at four randomly selected points within 1 to 1.5 m of each node (Fig. 1) yielding three 40 m spaced transects of 20 m spaced observation points. Soil samples from every 20 cm layer to a depth of 1 m, were collected by means of a gauge auger of about 0.05 m diameter. The five samples obtained for each depth interval were mixed to reduce the horizontal spatial variability at very small distances. The soil samples were air- dried and ground to pass a 2-mm sieve. Sub-samples of 0.1 kg were taken to characterize salinity by means of the electrical conductivity (EC) in a 1:5 (by weight) soil/water suspension. At each of the major landscape units of each strip (levee, low backswamp, and high backswamp), four soil pits of about 1.5 m in depth, were hand-dug. The soil profiles were described, and sampled by horizon according to standard procedures (Soil Survey Staff, 1975). In addition to EC (1:5), soluble cations were determined on these samples: Na and K, by flame spectrophotometry using air-acetylene with a solution enriched with Cesium Chloride (1.25 g L^{-1}), and Ca and Mg by Atomic Absorption Spectrophotometry with air-acetylene in a solution enriched with 1.25% Lanthanum and hydrochloric acid.

Statistical procedures

The statistical approach was twofold. First, nested analysis of variance was applied to estimate the contribution of different factors influencing soil salinity at various scales. To do so, data collected from the central transect of the strip were used. Second, geostatistical methods were applied to the data collected from the strips to model spatial variability patterns at the most detailed scale, and to prepare salinity contour maps.

Nested ANOVA

For each river basin several sources of variation are distinguished, each operating at a specific scale. The total variation σ^2, therefore, is composed as $\sigma^2 = \sigma^2_{Pos}+\sigma^2_{Form}+\sigma^2_{Depth}+\sigma^2_e$, where σ^2_{Pos} denotes the variance component due to the distance to the river mouth, σ^2_{Form} the variance component due to the landform, σ^2_{Depth} the variance component due to the depth below the soil surface and σ^2_e the residual variance component. For soils in each river basin, with a river specific average EC-value equal to μ_R, the contribution of the different sources of spatial variability was analyzed with a nested ANOVA, using the following model:

$$EC_{ijkm}=\mu_R+Pos_i+Form_{ij}+Depth_{ijk}+\varepsilon_{ijkm} \quad (1)$$

where EC_{ijkm} denotes the soil salinity at the m*th* observation point, m = 1,...,n, for position along the river i, i=1,2,3, denoted with Pos_i, given by the distance of the observation point to the river mouth, landscape unit j, j = 1, 2, 3, 4, denoted with $Form_{ij}$ and soil depth k, k=1, 2, 3, 4, 5, denoted with $Depth_{ijk}$. The random errors not explained by the model, ε_{ijkm}, are assumed to be independent of each other. The contribution and significance of each effect were tested. The variability of soil salinity contributing at each stage was related to one or more of the factors involved in soil salinization. All statistics using a nested ANOVA were computed using the SAS (SAS Institute, 1985).

Geostatistical Analysis

A nested ANOVA can be very helpful to reveal the important factors affecting soil salinity spatial variability. However, it does not take the spatial dependencies between the observations into account. The spatial variability at the most detailed scale therefore was analysed using regionalized variable theory (Matheron, 1965). Geostatistics, founded on regionalized variable theory, differs from ordinary statistical theory in that the relation between a variable and its location is taken into account. Geostatistics were applied to analyze the electrical conductivity data at each site for a given soil depth. The spatial variability of the regionalized variable "salinity" , EC(**x**), is described by means of a semivariogram. For the variables at two locations separated by a vector **h**, the semivariogram is defined as:

$$\gamma(\boldsymbol{h})=\frac{1}{2}\mathcal{E}\left[EC(\boldsymbol{x})-EC(\boldsymbol{x}+\boldsymbol{h})^2\right] \quad (2)$$

where $\mathcal{E}$ denotes the mathematical expectation. The semivariogram is defined only if for all

h the variance of [EC(**x**) - EC(**x+h**)] is finite and independent of **x** and $\mathscr{E}$[EC(**x**) - EC(**x+h**)] is equal to zero, hence prohibiting the presence of a trend.

The semivariogram has to be estimated for each distance **h** from the available data. A standard procedure to do so is for any distance **h** to consider all N(**h**) pairs of observations, and to calculate the mean of the squared pair differences:

$$\hat{\gamma}(\boldsymbol{h}) = \frac{1}{2N(\boldsymbol{h})} \sum_{i=1}^{N(\boldsymbol{h})} \left[EC(\boldsymbol{x}_i) - EC(\boldsymbol{x}_i + \boldsymbol{h})\right]^2 \quad (3)$$

where EC($\mathbf{x}_i$) and EC($\mathbf{x}_{i+h}$) denotes the i[th] pair of EC observations separated at a distance **h**. For several combinations of rivers, position and depth semivariograms were computed. A semivariogram model was selected to be used for interpolation by ordinary kriging (Webster, 1985).

In the presence of a trend, the intrinsic hypothesis is not valid, and hence the semivariogram is not defined. A procedure to check for the existence of a trend was performed by visual inspection of the data, and of the semivariograms which, in the presence of a trend, show a parabolic behavior, concave upwards near the origin (Webster, 1985). Also predicted and actual data were compared by jack-knifing (Starks and Fang, (1982). In the presence of a polynomial trend, the spatial dependence of the EC data was described by means of a pseudo-covariance function depending upon the lag between observations (Stein, 1991):

$$c(\boldsymbol{h}) = \alpha_0 \delta(|\boldsymbol{h}|) + \alpha_1 |\boldsymbol{h}| + \alpha_3 |\boldsymbol{h}|^3 + \alpha_5 |\boldsymbol{h}|^5 \quad (4)$$

where $\delta(|\mathbf{h}|) = 1$ for $|\mathbf{h}| = 0$ and vanishes for $|\mathbf{h}|$ different to zero and the α_i are the coefficients of the model. The term $\alpha_3 |\mathbf{h}|^3$ is included if the degree of trend exceeds 1, and the term $\alpha_5 |\mathbf{h}|^5$ only if the degree of trend equal 2. Higher degrees of trend were not analyzed.

Coefficients of the model were estimated by means of the Restricted Maximum Likelihood (Stein, 1991). To do so, attention is foccused on increments of the observations Z, i.e. on linear combinations of the observations with a weight vector orthogonal to monomials of the coordinates up to the degree of the trend. In order to discriminate between different degree of trends, Akaikes Information Criterion (AIC) was applied, modified for small data sets of size:

$$AIC_C = -2l(Z|\alpha_0, \alpha_1, \alpha_3, \alpha_5) + \frac{2n*(m+1)}{n-m-2} \quad (5)$$

where $l(Z|\alpha_0, \alpha_1 \alpha_3, \alpha_5)$ is the log-likelihood function of the increments Z, given the values of α_i, n is the number of observations and m the number of parameters (Hurbich and Tsai, 1989). From the original data, three random subsets of 20 observations were created for each of the 12 sites at 5 soil depths to be handled individually by personal computer. Final estimates for the parameters and the AIC_c value were obtained as averages over the three sets. The degree of the trend that minimizes the AIC_C value is considered the best fitting trend.

Both the semivariogram and the pseudo covariance function may be applied for interpolating from points towards areas of lands, using ordinary kriging and universal kriging, respectively (Cressie, 1993).

Table 1: Summarized description of mangrove rice ecosystems along four West Africa river basins: the Gambia, the Casamance, the Geba and the Great Scarcies river.

Country	Gambia	Senegal	Guinea Bissau	Sierra Leone
Watershed	Gambia River	Casamance River	Geba River	Great Scarcies River
Approximate latitude	13°20'	12°25'	11°30'	8°30'
River basin (km^2)	42,000	14,000	12,225	10,000
Mean annual rainfall	800 - 1200 mm	1100 - 1500 mm	1300 - 2000 mm	2000 - 3000 mm
Starting month of rain	Jun/July	Jun/July	May/Jun	May
Ending month of rain	Oct/Nov	Oct/Nov	Oct/Nov	Nov
Annual ETP	2000 - 2500 mm	1965 - 2400 mm	1500 - 1900 mm	1400 - 1500 mm
Climate (*)	South Sudan Savanna	South Sudan Savanna	Guinea Savanna	Equatorial Forest
River outflow (m^3/s)				
upstream	400	7	170 - 800	1000
downstream	2.5 - 5	0	5 - 10	?
Annual river outflow	>100 days	<100 days	100 days	>100 days
Tidal range (m)	0.6-1.6	0.7-1.2	2.5-6.0	2.0-3.0
Max. salinity intrusion	225 km	250 km	175 km	80 km
Flood plain	flat	flat	flat	flat
Soil types	Tropaquepts, Sulfic Tropaquepts, Sulfaquepts, Sulfaquents	Tropaquepts, Sulfic Tropaquepts, Sulfaquepts, Sulfaquents	Tropaquepts, Sulfaquepts, Sulfaquents	Sulfaquepts,Sulfaquents, Sulfohimists,Sulfihimist
Land use type	Forest; salts production; rain water rice polder; tidal rice; honey production.	Forest; salts production; rain water polder rice; honey production.	Forest; salts production; rain water polder rice.	Forest; tidal rice.

(*). After Andriesse and Fresco 1991

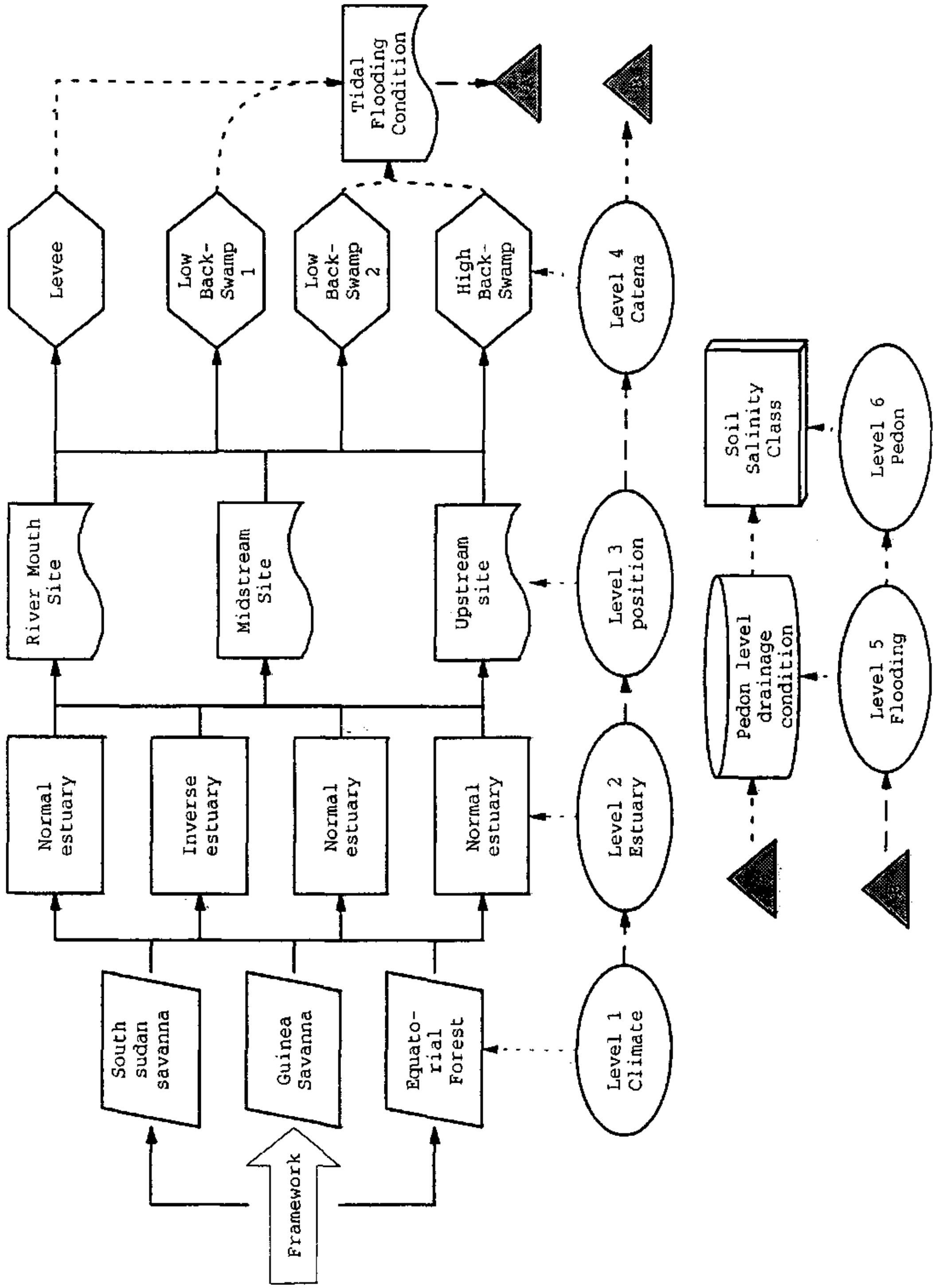

Figure 2: Shematic representation of a hierarchical framework of the different factors contributing to soil salinity along estuaries in West African Mangrove swamps and expected soil salinity classes.

Framework based upon soil salinization processes

We distinguish six factors involved in soil salinization in tidal estuary environments, each operating at a different scale or hierarchical level (Fig 2). At the highest level (1) climatic zones are taken into account (Andriesse and Fresco, 1990). Next we distinguish (2) types of estuary as characterized by the longitudinal salinity regime, (3) distance from the river mouth , (4) the landscape units within a catena, (5) the frequency of tidal flooding and (6) factors playing a role at the pedon level.

At level (1) availability of fresh water and the potential evapotranspitration is crucial. At level (2) effects of river basin hydrology and geometry and factors influencing tidal amplitude (topography and width of the continental shelf) are distinguished. At level (3) salinity of river water at a given point along the river is determined. At level (4) topographic aspects of catena determine, together with tidal flooding (level 5), the degree to which river water and rain water can reach and can be imponded at the individual sites. At level (6) any remaining factors operating at the pedon level (e.g. texture or microtopography) in soil salinization are distinguished.

We defined five soil salinity classes in terms of the EC (in a 1:5 soil water suspension) observed at the end of the dry season, based on salinity tolerance of rice and of mangrove species, and on the degree of equilibrium with sea water (an EC of 10 mS cm^{-1} is typical for a 1:5 suspension of soil in contact with standard sea water)

i) Class 1: non-saline (EC <1 mS cm^{-1}); neither rice nor the mangrove species do suffer from salinity.

ii) Class 2: slightly saline (EC 1 to 2 mS cm^{-1}); rice could be grown providing moderate leaching with fresh water at the beginning of the growing season, mangrove vegetation do not suffer any soil salinity stress.

iii) Class 3: saline (EC 2 to 5 mS cm^{-1}); growth of *Rhizophora* and *Avicennia* is not constrained, rice can be cultivated only after efficient leaching with fresh water at the beginning of the growing season.

iv) Class 4: very saline (EC 5 to 10 mS cm^{-1}); *Rhizophora* and *Avicennia* can grow, rice cultivation is possible only in wet climates providing a sufficiently long growing season to remove salinity in the first part of the wet season.

v) Class 5: hypersaline "tanne" (EC > 10 mS cm^{-1}); *Avicennia* and *Paspalum* can survive locally, but *Rhizophora* strongly suffers from salinity. The true "tanne" (bare saline soil) is so saline (EC> 20 mS cm^{-1}) that no vegetation can survive.

Results

Variation of soil salinity at regional scale (MACRO).

Summary statistics based upon the nested model describing the spatial variation at the macro scale are given in table 2. Mean EC values are generally well above 2 mS cm^{-1}, illustrating the saline nature of the soils. Exceptions are i) the sites upstream of the Gambia and the Geba rivers which are beyond the marine influence (only levee soils show an EC > 2 mS cm^{-1}). The highest mean salinity is observed along the Casamance river ($\mu = 10.0$), the lowest level along the Geba river ($\mu = 4.0$), whereas soils along the Gambia ($\mu = 6.6$) and the Great Scarcies river ($\mu = 6.2$) have intermediate values. CV values range from 0.26 (Great Scarcies river) to 0.43 (Geba river). No clear pattern for the mean of EC variability across climatic zones was found. However EC values frequently exceeded 10 mS cm^{-1} in the

Table 2: Mean soil salinity, EC 1:5 in mS cm^{-1} (soil depth 0 to 1.0 m), at four river basins in West African mangrove ecosystems. For each river basin (Gambia, Casamance, Geba and The Great Scarcies), means are calculated in terms of site position along the river, landscape units per watershed, landscape units per site and general mean per watershed. Number of observations and coefficient of variations are given at the bottom of the table.

	Gambia	Casamance	Geba	Great Scarcies
General mean	6.6	10.0	4.0	6.2
Number of observations	290	275	194	276
CV per river basin	0.31	0.33	0.43	0.26
Site Position				
Mouth	5.58 #	8.32	6.16	6.85
Midstream	11.02	5.21	3.80	6.47
Upstream	3.12	15.50	2.10	5.40
Landscape Position (overall watershed)				
Levee	7.24	19.64	9.17	6.34
Low-backswamp I	7.45 #	11.82	4.24	6.30
Low-backswamp II	6.36 #	6.60	1.63	6.52
High-backswamp	3.93	0.64	0.50	5.81
Landscape Position (analysis per site)				
Site at the mouth				
Levee	3.60	22.41	12.58	6.50
Low-backswamp I	----	7.04	8.46	6.72
Low-backswamp II	----	3.42	2.97	7.60
High-backswamp	0.98	0.40	0.63	6.58
Midstream site				
Levee	14.33	13.24	11.36	6.22
Low-backswamp I	11.88	5.39	2.74	6.20
Low-backswamp II	9.95	1.83	0.69	6.93
High-backswamp	7.93	0.39	0.39	6.55
Upstream site				
Levee	3.78	23.27	3.57	6.30
Low-backswamp I	3.02	23.02	1.52	5.98
Low-backswamp II	2.79	14.57	1.22	5.03
High-backswamp	2.89	1.14	----	4.29

\# = calculated only for restricted number of existing landscape units
CV = coefficient of variation
---- = none existing landscape unitThis relatively poor fit could be attributed in part to a non-

Table 3. Results of a nested ANOVA on soil salinity (EC 1:5 in mS cm^{-1}) for four river basins (Gambia, Casamance, Geba and the Great Scarcies river). The parameters describing the model are: site position along the river (Pos), landscape unit within site (Form (Pos)) and soil depth within landscape unit (Depth(Form*Pos)).

Gambia River (N = 290; R^2 = 0.87)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	49	6066.7	123.8	32.13	0.0001
Pos	2	3438.2	1719.1	446.06	0.0001
Form(Pos)	7	562.7	80.4	20.86	0.0001
Depth(Form*Pos)	40	380.3	9.5	2.47	0.0001
Error	240	924.9	3.85		
Corrected Total	289	6991.6			

Casamance river (N = 275; R^2 = 0.90)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	59	20592.4	349.0	32.66	0.0001
Pos	2	4274.6	2137.3	199.99	0.0001
Form(Pos)	9	15472.3	1719.1	160.86	0.0001
Depth(Form*Pos)	48	1683.5	35.1	3.28	0.0001
Error	215	2297.8	10.69		
Corrected Total	274	22890.2			

Geba river (N = 194; R^2 = 0.88)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	52	3201.9	59.3	19.63	0.0001
Pos	2	391.3	195.7	64.76	0.0001
Form(Pos)	8	2381.2	297.7	98.52	0.0001
Depth(Form*Pos)	44	95.7	2.18	0.72	0.8955
Error	139	420.0	3.02		
Corrected Total	193	3621.9			

Great Scarcies River (N = 276; R^2 = 0.42)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	60	407.4	6.79	2.65	0.0001
Pos	3	106.2	35.4	13.80	0.0001
Form(Pos)	9	85.2	9.47	3.69	0.0003
Depth(Form*Pos)	48	207.3	4.32	1.68	0.0067
Error	215	551.8	2.57		
Corrected Total	275	959.2			

Gambia, the Casamance and the Geba river, while along the Great Scarcies river the maximum EC rarely exceeded the value of 10 mS cm^{-1} typical for soil in equilibrium with sea water.

Variability of Soil Salinity within Watershed (Meso Level)

Hyper saline zones (EC 1:5 of 10 to 20 mS cm^{-1}) occurred in the midstream part of the Gambia and the upstream part of the Casamance rivers (Table 2). The Geba river is the only example of a "normal" estuary , in which the soil salinity decreases from river mouth to upstream. Along the Great Scarcies river soil salinity varies little with distance from the mouth. High coefficients of variation (CV) at individual sites illustrate the strong spatial variability of soil salinity in the mangrove environment. For single soil layers taken from the entire strip, e.g. 0 to 0.20 m depth, CV values larger than 1 were observed for the Gambia river, near the mouth, for the Casamance river at all sites and for the Geba river midstream. For the Casamance river this is caused by extreme salinity related to the inverse estuary condition. For the two sites along the Geba and the Gambia river the cause is probably site-specific. Evidently, all five sites have a very skewed salinity distribution.

Salinity decreased from the levees towards the high backswamps at almost all sites e.g. along the Casamance river, at sites 1 and 2 along the Geba river and at site 2 along the Gambia river. Salinity varied little with landscape position along the Great Scarcies river.

The nested analysis of variance for individual river revealed a highly significant effect of site position along all the river basins (Table 3). ANOVA models for three individual rivers showed highly significant R^2 values, ranging from 0.87 for the Gambia, 0.90 for the Casamance to 0.88 for the Geba. For the Great Scarcies river, however, R^2 was only 0.42. significant depth effect, caused either by the flat topography of this river, or by soil properties along the river of which the causal relationship is not immediately clear.

The variation of the mean EC for the different landscape positions (levee, low backswamp 1 and 2, and high backswamp) and by soil depth showed different gradients of soil salinity along the catena (Fig. 3). The variability per site was generally high in all river basins except e.g. in The Great Scarcies.

Micro-variability of soil salinity within catena

Results of the analysis on micro-variability of soil salinity within each catena are given in table 4, which shows the degree of non-stationarity (drift), as well as the coefficients of the generalized covariance function, together with Akaikes Information Criterion (AIC_C). Table 4 shows that EC exhibits a quadratic trend for most combinations of position, depth and river. This is caused by the fact that salinity is usually high in the levees and low in the backswamps. In general a smooth increase on salinity was observed within the backswamp and its proximate low backswamp, followed by a sharp increase towards the levee leading to an hyperbolic shape on the salinity regime. A linear trend is observed at the Casamance river, site 3, depth 40-60cm and at the Geba river, site 1, depth 80-100 cm. Those two locations differ from the other locations because of the site-specific hypersalinity. The effect of groundwater on subsoil can be the cause of a linear trend because of the smooth diffusion or mass flow of soluble salts from the river landwards. On top soil this effect can be complexed by the evaporation and capilary rise, topography and direct tidal flooding. The coefficients α_i of the pseudo covariance functions show a high nugget coefficients α_0, ranging from 0.1 to 10. Therefore the measurement error or very short distance variability equals 0.3 to 3 mS

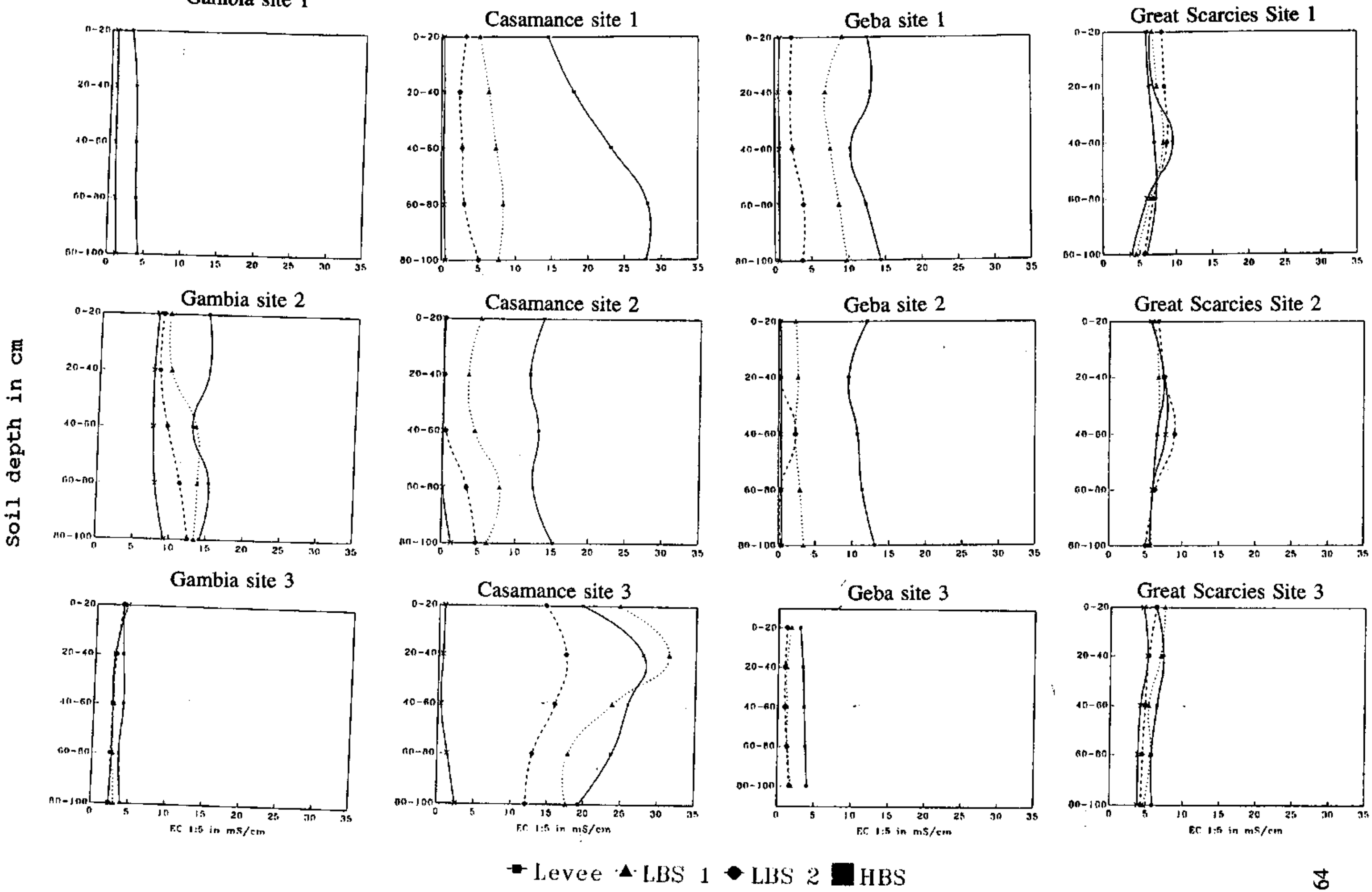

Figure 3: Mean soil salinity distribution by depth (EC 1:5 mS cm^{-1}) in four physiographic units within the low laying part of a catena in mangrove swamps along the Gambia, the Casamance, the Geba and the Great Scarcies river. LBS 1: low backswamp 1, LBS 2: low backswamp 2 and HBS: high backswamp.

cm^{-1}. This is in close agreement with current observation taken on soil salinity, influenced by the micro-topography. The rather high value of the nugget coefficient for the Geba river, site 1, depth 0 to 20 cm is probably due to instability within the estimation procedure, indicated by the relatively high AIC_C value of 42.3. The coefficient α_1 for each combination was in the order of -0.1 to -10. Since the higher order terms were often very small, the spatial structure could be approximated well at most locations by a linear type pseudo-covariance function. Note that the coefficients of the higher order term in few cases can contribute substantially to the value of the pseudo-covariance function, since they have to be multiplied with the distance to the 5^{th} power. Finally, the AIC_C-values were usually in the range from 0 to -300, illustrating that the convergence procedure behaved reasonably well. In four cases the estimation procedure did not yield any. On the basis of twenty randomly selected data, four parameters were determined, which might lead to instabilities. In general, the top layer of the soil was causing the largest difficulties. In three out of twelve cases no convergence was reached, and in one case a pure nugget effect was observed. This indicates that EC in the top soils has a very complex spatial structure, while the spatial structure is simpler at larger depths.

For the sites where Restricted Maximum Likelihood did not provide a solution, semivariograms were estimated. As for several other sites as well, a quadratic semivariogram was obtained, indicating the presence of the trend. Probably, anomalies in the data are the real cause for the convergence problems.

Classification based upon the framework

In the Gambia river (long dry spell, medium tidal amplitude (0.6 to 1.2 m), normal estuary), the site at the river mouth lies on a low river terrace, which is flooded annualy in January-February. Following this submersion with saline water, excess evaporation takes place in the dry season leading to saline environment (class 4 and 3). At the relatively flat midstream site (slope < 0.2%) differences in tidal flooding of the landscape units are slight, yielding only small differences in top soil salinity, mainly with classes 4 and 5. The decreasing salinity from the levee inland with spots of "tanne" was observed earlier by Marius (1984). The upstream site is at the limit of tidal propagation and therefore has little salinity problems in general (Fig.4).

The Casamance river resembles the Gambia river in many respects but has an "inverse estuary". Near the Casamance river mouth, saline soils (class 4) on the levee and in the low backswamp are caused by daily to monthly flooding by saline water. Midstream along the Casamance, salinity is depressed by rain water in the higher parts of the catena, while saline to hyper saline soils occur on the levee and in part of the low backswamp, due to tidal flooding with seasonally hypersaline water. Such patterns are reported by Vieillefon (1977) and Marius (1984). At the upstream site, hypersalinity is confined to the levee and the low backswamp, because the tidal amplitude is too much attenuated to reach higher parts of the landscape (Fig.5).

The Geba river basin differs from the two previous rivers in a higher precipitation and an exceptionally large tidal amplitude. The site at the river mouth is saline in its entire low laying part of the catena (daily to monthly flooding). Only part of the high backswamp, being relatively less frequently flooded, remains at class 3 (tidal flooding several times per year). The midstream site is similar to the site at the river mouth with attenuated tidal range leading to high salinity restricted to the levee and the low backswamp. The upstream site is at the limit of tidal propagation (Fig.6).

Table 4. Estimated drift of degree (k) on soil salinity, coefficients of the pseudo covariance function (α_0, α_1, α_3, α_5) and Akaikes Criterion (AIC_c) for each combination of river basin, site and soil depth. The distances are expressed in multiples of 20 m.

	Site	Depth	k	α_0	α_1	α_3	α_5 (x10-5)	AIC_C
Gambia	1	0-20	2	4.08	-0.004	0.003	0	-94.4
		20-40	2	0.759	-0.396	0.007	-3.20	-0.1
		40-60	2	0.321	-0.049	0.003	0	-2.0
		60-80	2	0.262	-0.058	0	-0.15	-0.1
		80-100	2	0.543	-0.287	0	-0.009	-13.2
	2	0-20	2	0	-12.7	0.003	0	14.7
		20-40	2	0	-83.9	0.074	-54	17.6
		40-60	2	3.61	-2.74	0.001	-0.44	13.6
		60-80	2	0.002	-3.33	0.018	-0.80	-4.2
		80-100	2	0	-34.1	0	0	33.4
		0-20	2	1.73	0	0	0	-409.6
	3	20-40	2	0	-0.542	0.023	-2.9	-49.9
		40-60	2	0.187	-0.378	0.003	0	-31.6
		60-80	2	0.049	-0.339	0.004	-2.9	-39.2
		80-100	2	1.55	-0.444	0.030	0	-65.7
Casamance	1	0-20	-	-	-	-	-	-
		20-40	2	0.591	0	0.002	-2.9	-42.5
		40-60	-	-	-	-	-	-
		60-80	22	0.195	-0.030	0	-1.1	-65.5
		80-100		0.973	-0.125	0.001	-0.021	-11.3
	2	0-20	-	-	-	-	-	-
		20-40	2	0.001	-9.52	0	-120	2.3
		40-60	2	0.026	0	0.685	-0.53	-0.5
		60-80	2	0	-1.63	0	-17	-6.5
		80-100	2	0.918	0	0.109	-1.4	-3.1
	3	0-20	2	0.973	0	0.032	-14	-22.9
		20-40	2	0.019	-0.955	0.001	-5.2	1.1
		40-60	1	1.5	-0.182	0		-16.1
		60-80	2	2.3	-1.25	0.995	-7100	1.9
		80-100	2	0.458	-0.346	0.201	-58	15.7
Geba	1	0-20	2	99.0	-241	0.194	-220	42.3
		20-40	2	0.003	-10.8	0.005	-2.5	-244.5
		40-60	2	4.9	-1.16	0	-3.6	-255.0
		60-80	2	3.73	0	0	0	-16.5
		80-100	1	0.691	-1.73	0.002		14.2
	2	0-20	2	0	-3.59	0.029	-34	14.8
		20-40	2	2.94	0	0.091	-14	15.3
		40-60	2	2.1	-0.967	0	-270	14.6
		60-80	2	3.75	0	0.297	-1.3	19.6
		80-100	2	3.49	-0.007	0	-140	-20.4
	3	0-20	-	-	-	-	-	-
		20-40	2	0	-0.112	0.004	-1.3	-282.1
		40-60	2	0.095	-0.511	0.001	-2.1	-16.2
		60-80	2	0	-2.38	0	0	-152
		80-100	2	0.002	-0.503	0	-153	-9.0
Great Scarcies	1	0-20	2	0.60	0	0	-7.9	-
		20-40	2	7.25	0	0	-51	-105.8
		40-60	2	7.84	-2.05	0	-52	-55.6
		60-80	2	0.73	-0.150	0	0	14.8
		80-100	2	1.75	-1.43	0	-50	-80.2
	2	0-20	2	7.38	-0.077	0	-0.19	-19.9
		20-40	2	7.15	0	0	-4.3	-353.5
		40-60	2	0.118	-0.732	0.006	-2.9	-24.4
		60-80	2	1.15	-0.121	0.003	0	-35.2
		80-100	2	12.5	-0.003	0		-69.9
	3	0-20	2	0.39	-2.46	0	-0.52	-17.7
		20-40	2	0.10	-0.795	0	-0.26	-146.8
		40-60	2	1.33	-1.43	0	-0.55	-48.9
		60-80	2	0.344	-0.272	0.010	0	-121.9
		80-100	2	5.26	-0.440	0	0	-238.4

The Great Scarcies river has a quite homogeneous salinity distribution due to daily to monthly flooding. Class 4 is dominant with slide inclusion of class 5 at upstream site (Fig.7). Both climate and tidal amplitude are responsible of this pattern. The dense creek layout reinforces the homogeneity of salinity in space both by channeling the saline water during dry season and the fresh water during rainy season. The surprisingly high salinity in wet environment is attributed to the sea water intrusion during the dry season up to 80 km from the mouth followed by evaporation. Jonathan Turner (1980) reported the similar observations.

Discussion

Spatial variability of soil salinity

At the **macro-level** no clear trend of mean EC per river basin is observed. The large CV observed at this scale indicates a dispersion due the latitudinal variation in climate and estuary types. As expected, rainfall affects the hydrology of the estuary and subsequently the dynamic of fresh water outflow and the tidal saline water inflow. This confirms previous work by Pagés and Citeau (1990), and, more specifically, the model proposed by Savenije (1988) which relates salinity intrusion in a one-dimensional tidal average salt balance equation with rainfall and evaporation. Results for the Gambia and Casamance rivers strongly support the hypothesis that the longitudinal variability of soil salinity can be related to the salinity regime of the river water. The effect of low rainfall and high evapotranspiration is noticeable in the Gambia and very strong in the Casamance, leading to hypersaline conditions in the latter. The higher salinity in the Casamance is attributable to its small watershed area, the associated low outflow of fresh water, and the flat relief of the area. Therefore, whereas other authors attribute a north-south soil salinity gradient at macro scale to climatic factors only (Giglioli et al., 1965, 1966, for the Gambia; Vieillefon, 1977, for the Casamance; Jacques-Felix et al., 1960a and b, and Jordan, 1964 for Guinea and Sierra Leone respectively), our work indicates the need to take the function of the catchment size and estuary morphology (depth and creek pattern) into account as these affect annual river fresh water outflow.
The resulting opposite trend of salinity regime observed between "normal" and "inverse" estuary within the general north-south climate variation leads to negative values for the parameters of the regression equation (1), and indicates that the application of regression is only useful within individual watersheds.

At **meso-level**, within a single river basin, our results show similar salt intrusion trends as Sanmuganathan (1975), Savenije (1988) and Pagés and Citeau (1990). It is obvious from the coefficient of variation (Table 3) that the strength of the factors influencing the salinity regime varies considerably. Within the "normal" estuary (recession, bell and dome shaped salt intrusion curves) soil salinity decreases from downstream towards upstream (e.g. the Geba River), while within the "inverse" estuary (humpback shape), hypersaline soils are found upstream (Casamance River). At this level, river water is the main source of salt, affecting soil salinity through tidal flooding and ground water. Thus, coupling the existing aquatic models with tidal and ground water models may be a fruitful way to simulate soil salinity patterns.

At **micro-level**, our results confirm that within a given climatic zone, soil salinity patterns within a site can be related to the cumulative effect of tidal regime (amplitude and frequencies) and catena topography. In sites with short range tidal amplitudes, e.g. 0.6 m during the dry season, only a narrow fringe bordering the river is strongly affected by salinity.

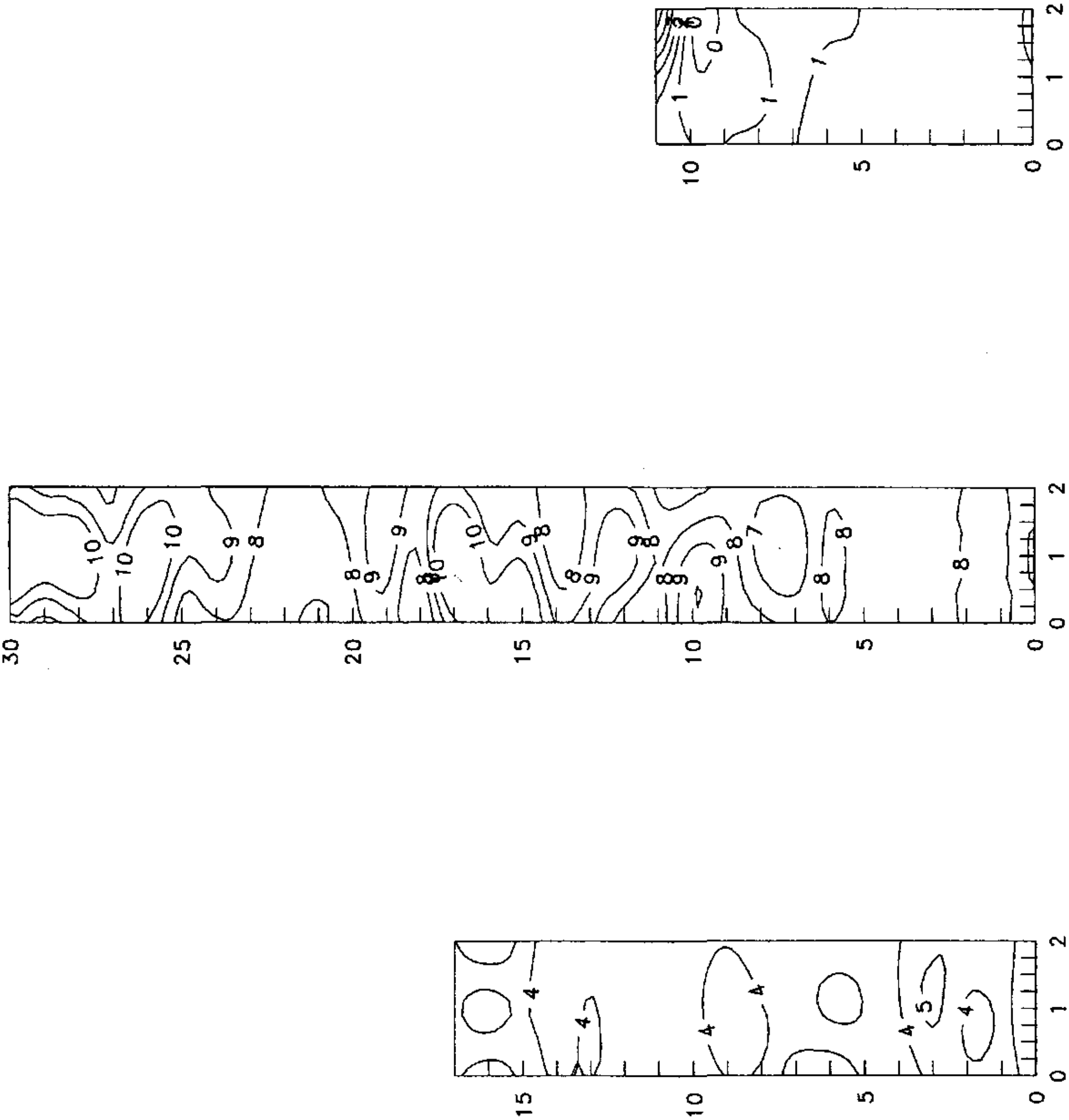

Figure 4: Contour maps of soil salinity (EC 1:5 mS cm^{-1}) at 0 to 0.20 m depth for three sites along the Gambia River (Gambia). Site 1 (left) is at the river mouth, site 2 (centre) at midstream and site 3 (right) at upstream. Coordinates are in multiples of 20 m.

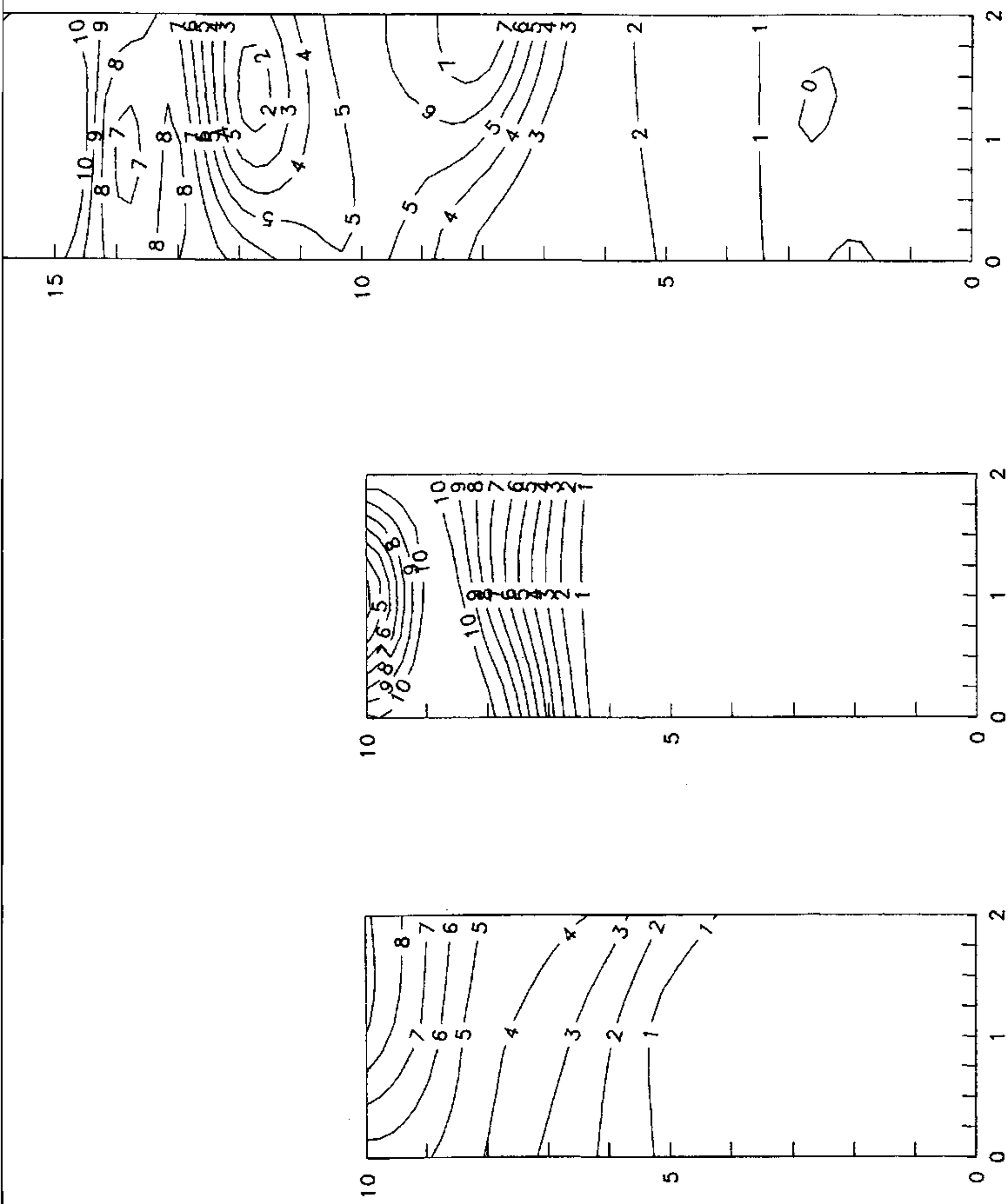

Figure 5: Contour maps of soil salinity (EC 1:5 mS cm^{-1}) at 0 to 0.20 m depth for three sites along the Casamance River (Senegal). Site 1 (left) is at the river mouth, site 2 (centre) at midstream and site 3 (right) at upstream. Coordinates are in multiples of 20 m.

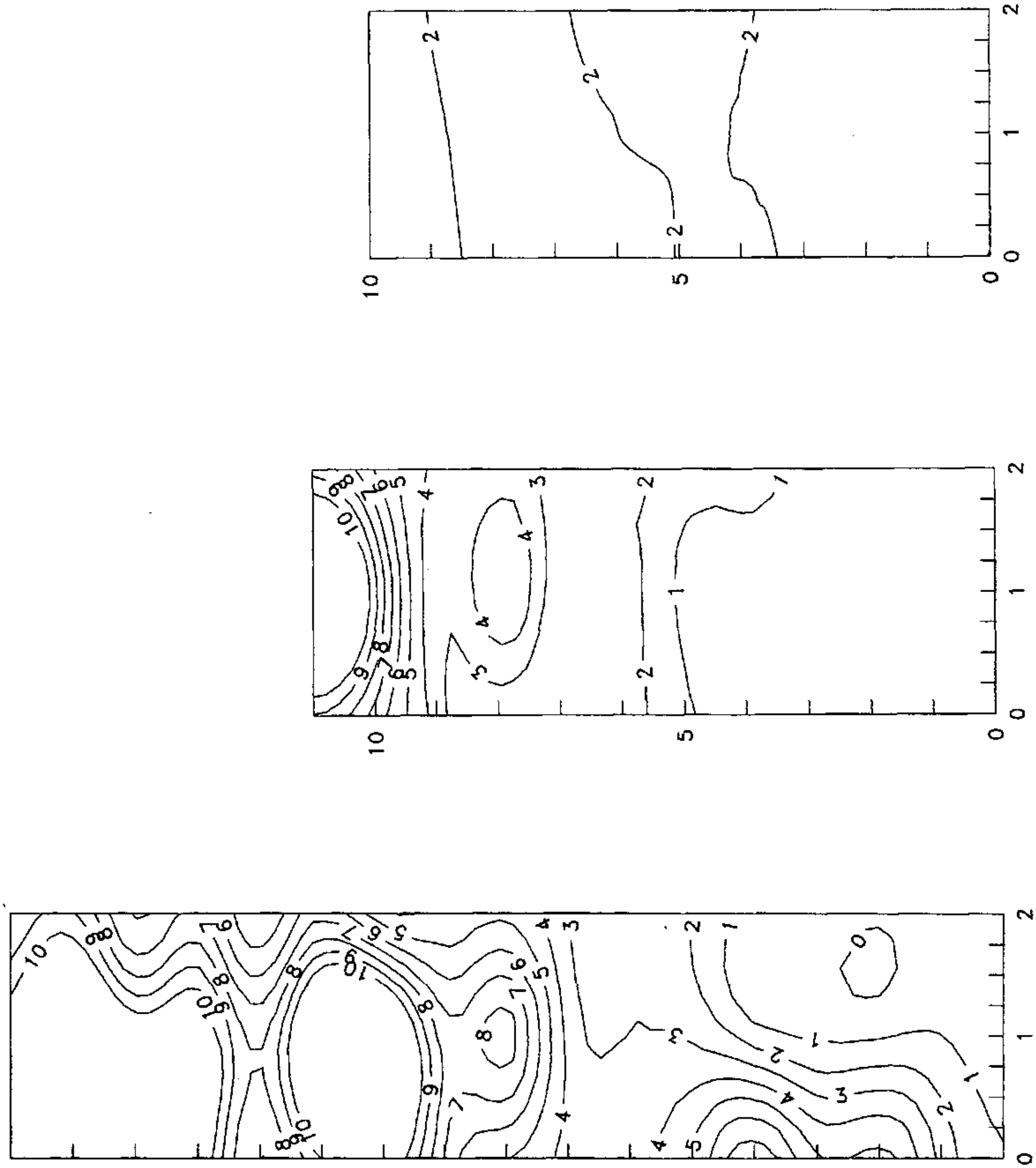

Figure 6: Contour maps of soil salinity (EC 1:5 mS cm^{-1}) at 0 to 0.20 m depth for three sites along the Geba River (Guinea Bissau). Site 1 (left) is at the river mouth, site 2 (centre) at midstream and site 3 (right) at upstream. Coordinates are in multiples of 20 m.

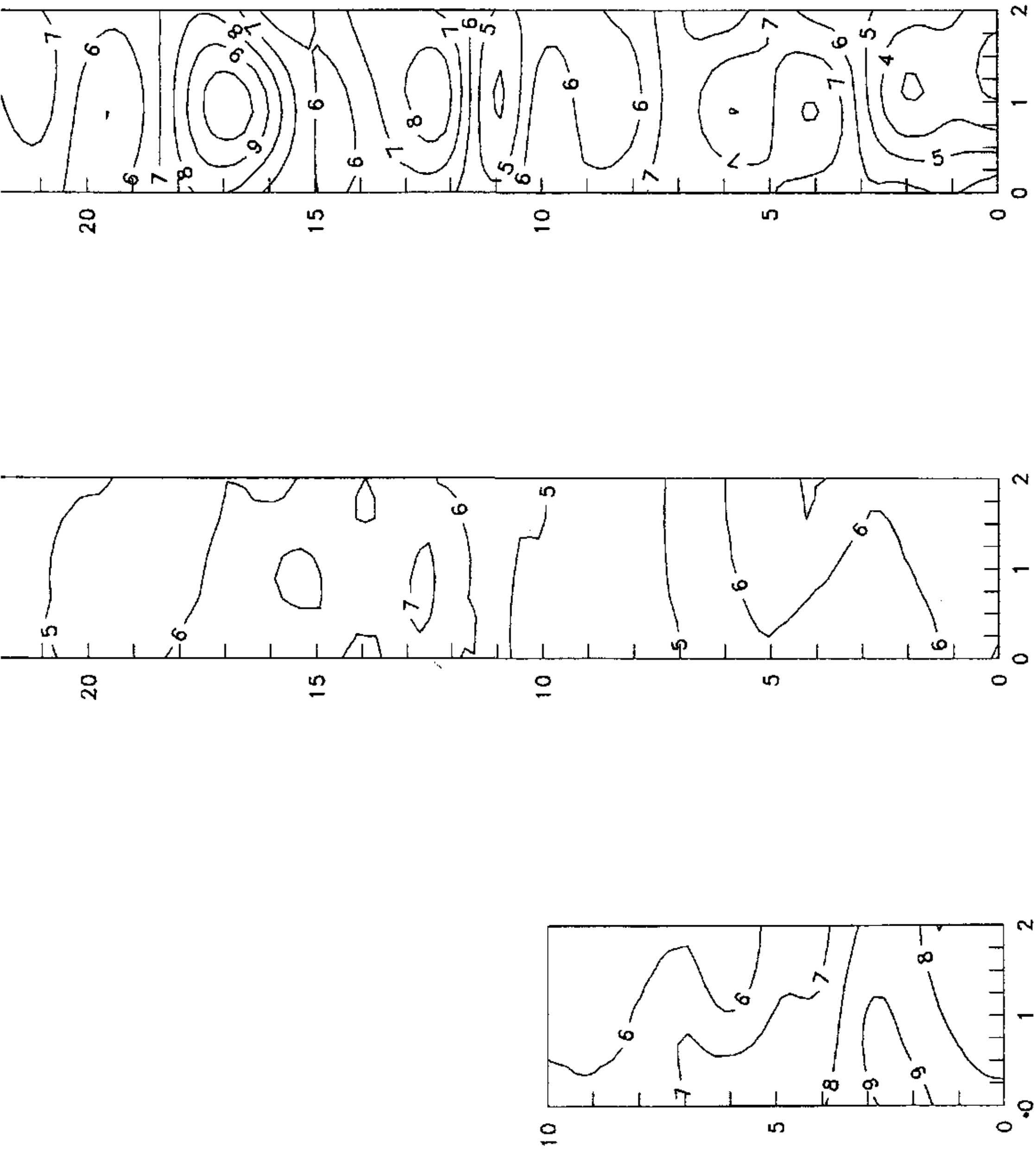

Figure 7: Contour maps of soil salinity (EC 1:5 mS cm^{-1}) at 0 to 0.20 m depth for three sites along the Great Scarcies River (Sierra Leone). Site 1 (left) is at the river mouth, site 2 (centre) at midstream and site 3 (right) at upstream. Coordinates are in multiples of 20 m.

However, saline water intrusion via the groundwater can be observed in the seepage zone. At higher topographical positions there seems to be no influence of saline tidal water except near the river mouth where the amplitude of tide generally is larger than at inland positions. Daily tidal influence lead to soils more or less equilibrated with sea water. When the tidal amplitude is relatively large (2.5 m), saline soils and "tannes" extend inland (e.g. in Guinea Bissau). A combination of high rainfall and relatively wide tidal amplitude (Sierra Leone) leads to saline conditions on almost the entire lower catena. Our findings show good agreement of the patterns hypothesised and indicate the complex interaction between macro-, meso- and micro level variables.

The hierarchical approach

The complexity of factors affecting soil salinity at different scales has been disentangled by an approach based on a hierarchical model, using the combined tools of regression analysis and geostatistics. The results generally support the value of this approach. Because of its clear rainfall gradient decreasing from south to north and the varying morphology of its estuaries, West Africa provides an ideal setting for such a nested hierarchical analysis. The model does not allow an investigation of the temporal (seasonal) dynamics of soil salinity. This will be necessary for further research, in order to take account of the differential rates of change of the factors operating at each level.

Conclusions

Spatial variability in soil salinity in West African mangrove rice environment was studied at three scales. A hierarchical framework was built on the basis of the factors explaining the spatial variability of soil salinity. To test the causal effect of soil salinization we applied different statistical methods. The results show that:

- At macro level, general statistics such as mean and CV give important indications on the magnitude and dispersion of soil salinity. Nested analysis applied to the study area results into a division of the area into salinity eco-regions, the northern rivers with relatively high soil salinity and the southern river with relatively low soil salinity. The decreasing soil salinity towards the south is related to the significantly increasing annual rainfall and to the river hydrology yielding to a wider range of the growing season.
- At meso level (the within watershed soil salinity variability), the nested approach gives a clear evidence of differences between "normal" and "inverse" estuary by their longitudinal soil salinity spatial variability pattern. We could attribute this pattern to the river hydrology and its role on the salinity regime: i) in the "normal" estuary the salinity decreased towards upstream and ii) in the "inverse" estuary salinity increased towards upstream and a hyper saline zone was present upstream. Also, sub-environments are delineated according to the longitudinal soil salinity regime within the river basin.
- At the micro level the interpolated maps show different patterns which are a function of the topography, the proximity of the river and the tidal amplitude, governing the frequency of tidal flooding. Five classes of soil salinity level based on rice and mangrove vegetation salt tolerance as well as the sea water salinity have been defined. The importance of each class was varying both within macro and meso environments.

At each level of aggregation, the soil salinity forming factors are related to the salinity distribution in space: climate at the macro scale, hydrology at the meso scale and topography and tidal amplitude at the micro scale. Nested analysis of variance and geostatistics are complementary statistical techniques in studying the spatial soil salinity variability at different scales. The use of these techniques in connection with a framework based on the hierarchy of the factors that govern the processes of soil salinization yield a reasonable hierarchical classification of soil salinity for rice environmental assessment. This approach also can key to a practical expert system to help respond to the questions related to soil salinity management and transfert of technologies by taking into account soil variability and scale.

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References

Andriesse, W. and Fresco, L.O., 1991. A characterization of rice-growing environments in West Africa. Agric., Ecosystems and Environ., 33: 377-395.

Brunet-Moret, 1969. Etudes hydrologiques en Casamance. Rapport définitif. ORSTOM rapport interne.

C.P.C.S. (Commission de Pedologie et de Cartocraphie des Sols), 1967. Laboratoire de geologie-pedologie, Grignon, France.

Cresie, N.A.C., 1993. Statistics for spatial data. Revised edition. Wiley- Interscience Publ. John Wiley and Sons.

Debenay, J.P., Pages, J. and Diouf, P.S., 1989. Ecological zonation of hyperhaline estuary of the Casamance River (Senegal): Foraminifera, zooplankton and abiotic variables. Hydrobiologia 174: 161-176.

Diop, S., 1990. La cote Ouest-Africaine, du Saloum (Senegal) à la Mellacorée (Rep. de Guinée). Ed ORSTOM Etudes et Thèses.

Galliachand, J., Buckland, G.D and Marcotte, D., 1992. Spatial interpolation of soil salinity and sodicity for a sline soil in Southern Alberta. Canadian J. of Soil Sci. 72, 4: 503-516.

Giglioli, M.E.C. and King, D.F., 1966. The mangrove swamps of Keneba, lower Gambia river basin. 3. Seasonal variations in the chloride and water content of soils. J. Appl. Ecol. 3: 1-19.

Giglioli, M.E.C. and Thornton, I., 1965. The mangrove swamps of Keneba, lower Gambia river basin. 1. Descriptive notes on the climate, the mangrove swamp and the physical composition of their soils. J. Appl. Ecol. 2: 81-103.

Hoogerwerf, M.R., Muchena, F.N., and Stein, A., 1992. Spatial varibility and reclamation of salinity and sodicity in a Kenyan irrigation scheme. Soil Technology 5, 2: 121-134.

Huggett, R.J., 1975. Soil landscape systems: A model of soil genesis. Geoderma 13: 1-22.

Hurbich, C.M. and Tsai, C., 1989. Regression and time series model selection in small samples. Biometrica 76: 297-307.

Jacques-Felix, H. et Chezeau, R., 1960a. Sols et groupement végéteaux de la zone littorale de Guinée dans leur rapport avec la riziculture. 1. L'Ile du Kabak. Agron. Trop. XV: 325-

341.

Jacques-Felix, H. et Chezeau, R., 1960b. Sols et groupement végéteaux de la zone littorale de Guinée dans leur rapport avec la riziculture. 2. La region du Koba. Agron. Trop. XV: 609-623.

Jordan, H.D., 1964. The relation of vegetation and soil to development of mangrove swamps for rice growing in Sierra Leone. J. Appl. Ecol. 1: 209-212.

Lereste, L., 1984. Etude des variations annuelles de la production de crevettes dans l'estuaire de la Casamance (Senegal). In. M.M. Kapetsky and Glasserre (eds). Amenagement des peches dans les lagunes cotitieres. Etud. Rev. C.G.P.M. 61: 253-269.

Matheron, G., 1965. Les variables regionalisées et leur estimation. Masson, Paris.

Marius, C., 1984. Contribution à l'étude des mangroves du Senegal et de la Gambie. Ecologie, Pédologie, Geochimie et mise en valeur et amenagement. Theses de Doctorat. ORSTOM. Paris.

Pagés, J. and Debenay J.P., 1987. Evolution saisonniere de la salinite de la Casamance: Description et essai de modelisation. Revue Hydrobiol. Trop. 20(3-4): 203-217.

Pagés, J., and Citeau, J., 1990. Rainfall and salinity of a sahelìean estuary between 1927 and 1987. J. Hydrology, Elsevier, Amsderdam, The Netherlands, 113: 325-341.

Por, F.D., 1972. Hydrobiological notes on the high salinity waters of the Sinai Peninsula. Mar. Biol. 14: 111-119.

Sanmuganathan, K., 1975. One-dimensional analysis of salinity intrusion in estuaries.Hydraulics Research Station, Wallingford, Oxon, England, Report N° OD/2.

Statistical Analysis Systems Institute, 1985. SAS user's guide: statistics. Version 5 ed.

Savenije, H.H.G., 1988. Influence of rain and evaporation on salt intrusion in estuaries. J. Hydraulic Engineering, ASCE, New York, USA, 114 (12): 1509-1524.

Soil Survey Staff, 1975. Soil Taxonomy. A basic system of soil classification for making interpretating soil surveys. USDA-SCS Agric. Handbook 436. U.S. Government Printing Office. Washington, DC.

Starks, T.H., and Fang,J.H., 1982. On the estimation of the generalized covariance function. J. Math. Geol. 14, 1: 57-64.

Stein, A., 1991. Spatial interpolation. PhD thesis, agricultural University Wageningen.

Sylla, M., Van Breemen, N., Fresco, L.O., Stein, A. and Dixon, C., 1993. Spatial and temporal variability of soil constraints affecting rice production along the Great Scarcies River, Sierra Leone. In: Dent, D.L. and van Mensvoort, M.E.F (Editors): Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils. pp: 247-259.

Turner, J.M., 1980. The response to nitrogen fertilizer of mangrove swamp rice in Sierra Leone. (Unpublished MSc. Thesis) Univ. Reading. United Kingdom.

Vieillefon, J., 1977. Les sols de mangroves et de tannes de Basse Casamance (Senegal). Mem. 83. ORSTOM. Paris.

Webster, S.R., 1985. Quantitative spatial analysis of soil in the field. Adv. in Soil Science. (3): 1-70.

Wolanski, E., 1986. An evaporation-driven salinity maximum zone in australian tropical esturines. East Cost Shelf Sci. 22: 415-424.

Yates, S.R., Zhang, R., Shouse, P.J. and van Genuchten, M.Th., 1993. Use of geostatistics in the description of salt-affected lands. In: Russo, D. and Dagan, G. (Editors). Water flow and solute transport in soils: developments and applications in memorian Eshel Bresler (1930-1991).pp: 283-304. Berlin; Springer. Advanced Series in Agricultural Sci, 20.

CHAPTER 4

CAUSES OF SPATIAL VARIABILITY OF SOIL ACTUAL AND POTENTIAL ACIDITY IN THE MANGROVE AGRO-ECOSYSTEM OF WEST AFRICA.

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Causes of Spatial Variability of Soil Actual and Potential Acidity in The Mangrove Agro-ecosystem of West Africa.

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Abstract

Spatial variability of soil acidity in coastal lowlands results from a complex interaction of climate, coastal morphology, river hydrology, vegetation, landform and tidal flooding. This study was conducted to determine whether the causal factors of soil acidification can be related to soil Total Actual Acidity (TAA) and Total Potential Acidity (TPA) in 12 sites selected along four river basins in West Africa: the Gambia river, the Casamance river (Senegal), the Geba river (Guinea Bissau) and the Great Scarcies river (Sierra Leone). A hierarchical framework was designed, corresponding to the scale at which each factor influences most the process of acidification. In the dry season of 1991, soil samples, to be analyzed for TAA and TPA, were taken from three strips within each river basin, perpendicular to the river at different distance from the mouth, following a 40 by 20 m grid at five soil depths. The contribution of the different causal factors of acidity spatial variability was analyzed with a nested ANOVA and related to the hierarchical framework. Geostatistics were used to study spatial variability at the most detailed scale. Main eco-regions identified between watersheds at macro scale, sub-environments identified with distance from the mouth within watersheds and zones identified with positions within toposequences were defined. Practical implications for water management in acid sulfate were discussed. Nested regression and geostatistics were applied as complementary techniques when studying spatial variability at different scales.

Most of the soils in the West African mangrove ecosystem are potential or actual acid sulfate soils. Soil acidity (actual and potential) is extremely variable in this environment. Potential acid sulfate soils are undrained soils with sulfidic material which acidify upon drainage. Knowledge of the spatial distribution of soil acidity is important to apply results of agricultural research and land suitability planning, both at regional level and within a single field. Dent (1986) in a literature review on acid sulfate soils, identified the gaps between research and its application to soil management. One of the constraints of research application appears to be the high spatial variability of soil acidity, over a wide range of scales. Research in process-oriented studies of acid sulfate soils has greatly enhanced knowledge on the causes and effects of acidification (Brinkman et al. 1968; van Breemen, 1973a b, 1976, 1982, 1993; Vieillefon, 1977; and Pons et al., 1982). In the past 20 years, international symposia and review papers have summarized all available information and the recent advances on acid sulfate soils studies and their management (Bloomfield and Coulter, 1973; Dost, 1973; Dost and van Breemen, 1982; Kittrick et al., 1982; Dost, 1986; and Dent and van Mensvoort, 1993). Only few studies however deal with spatial variability of soil acidity (Burrough and van Mensvoort, 1988; and Bregt et al., 1992, 1993). As a result, knowledge of the relationship between soil acidification (potential and actual) and spatial attributes linked e.g. to climate, vegetation, position along a given estuary basin and landform, is meager. Such studies are needed to improve the application of agricultural results at a wider range of conditions. To determine causal relations, factors involved in acid sulfate soils formation at different scales, ranging from soil profile to region, have to be synthesized. Van Breemen (1976) and Pons et al. (1982) identified the environmental conditions required for potential acid sulfate soil formation. Diemont et al. (1993) related regional differences in acid sulfate soils to the differences in climate. Chapman (1976; 1977) described the distribution of mangrove species, which fuels the processes of pyrite formation, in relation to climate and salinity. Dent (1986) observed some correlation between landscape positions and the occurrence of soil patterns. Brinkman et al. (1993) related different geographical distribution of sulfidic materials in the Mekong delta to the sedimentation process and environmental conditions in early and late Holocene. Bregt et al. (1993) combined physiographic survey, free survey and probability sampling to analyse soil spatial variability in acid sulfate soils. But relations between the soil patterns and the factors affecting soil formation process at specific scale were never made explicit.

This study addresses i) spatial variability of Total Actual Acidity (TAA), Total Potential Acidity (TPA) and Total Sulfidic Acidity (TSA = TPA - TAA) at different scales and ii) the relationships between their spatial patterns and the environmental factors governing the processes of the formation of acid sulfate soil. A framework linking environmental factors to the formation of acid sulfate soils is developed and used as a means to select research sites. We discuss the hypotheses derived from the framework in four estuaries in the West African mangrove environment. Next, we classified the environment into eco-regions, sub-environments within an estuary and zones within a catena. Finally, we indicated some practical implications of soil and water management in these environments.

MATERIALS AND METHODS

Framework

The conceptual framework developed to predict the occurrence of acid sulfate soils within the inter-tidal zones of estuaries along the West Coast of Africa (Fig.1.) consists of a hierarchical structure which ranks the different factors influencing the actual and potential soil acidity. The framework was shaped to conform to the scale at which each factor influences most the acidification process. The factors considered here are climate, distance from the river mouth and topography at each site. Climate can explain regional differences because of the associated vegetation type and the broad drainage conditions. Soil organic matter contents are associated with vegetation which is lower under *Avicennia* than under *Rhizophora* (**MACRO-SCALE**) (Kawalec, 1977). Site position along an estuary or open coastal swamps influences the longitudinal sequence of mangrove species as related to salinity gradient, tidal regime and local drainage conditions and to sedimentation rate (**MESO-SCALE**) (Pons et al., 1982). The topography at a particular site influences different interacting factors, such as vegetation sequence, sedimentation rate and soil textural differences and drainage conditions (**MICRO-SCALE**) (Vieillefon, 1969; Vlek, 1971; Allbrook, 1973; van Breemen et al., 1973; Diemont and Wijngaarden, 1975; Dent, 1986; and Jansen et al., 1990). Figure 1 shows the schematic structure of the framework.

Site Selection

Four estuaries along the West African Mangrove were selected because of their wide range in climatic conditions: the Gambia river (The Gambia), the Casamance river (Senegal), the Geba river (Guinea Bissau) and the Great Scarcies river (Sierra Leone). Within each estuary, sites were selected at the river mouth, midstream and near the limit of marine influence (Fig. 2).

General Information on the Study Area

The area covered by mangrove soils within the study area is estimated to be 8,400 km^2 (SECA and CML, 1987) or about 31 % of the total mangrove area of West Africa. Table 1 summarizes characteristics of the four estuaries environments. The climate is monomodal with two contrasting seasons; the rainy season and the dry season. The vegetation is dominated by mangroves; *Avicennia* in a drier climate and near the river mouths, while *Rhizophora*

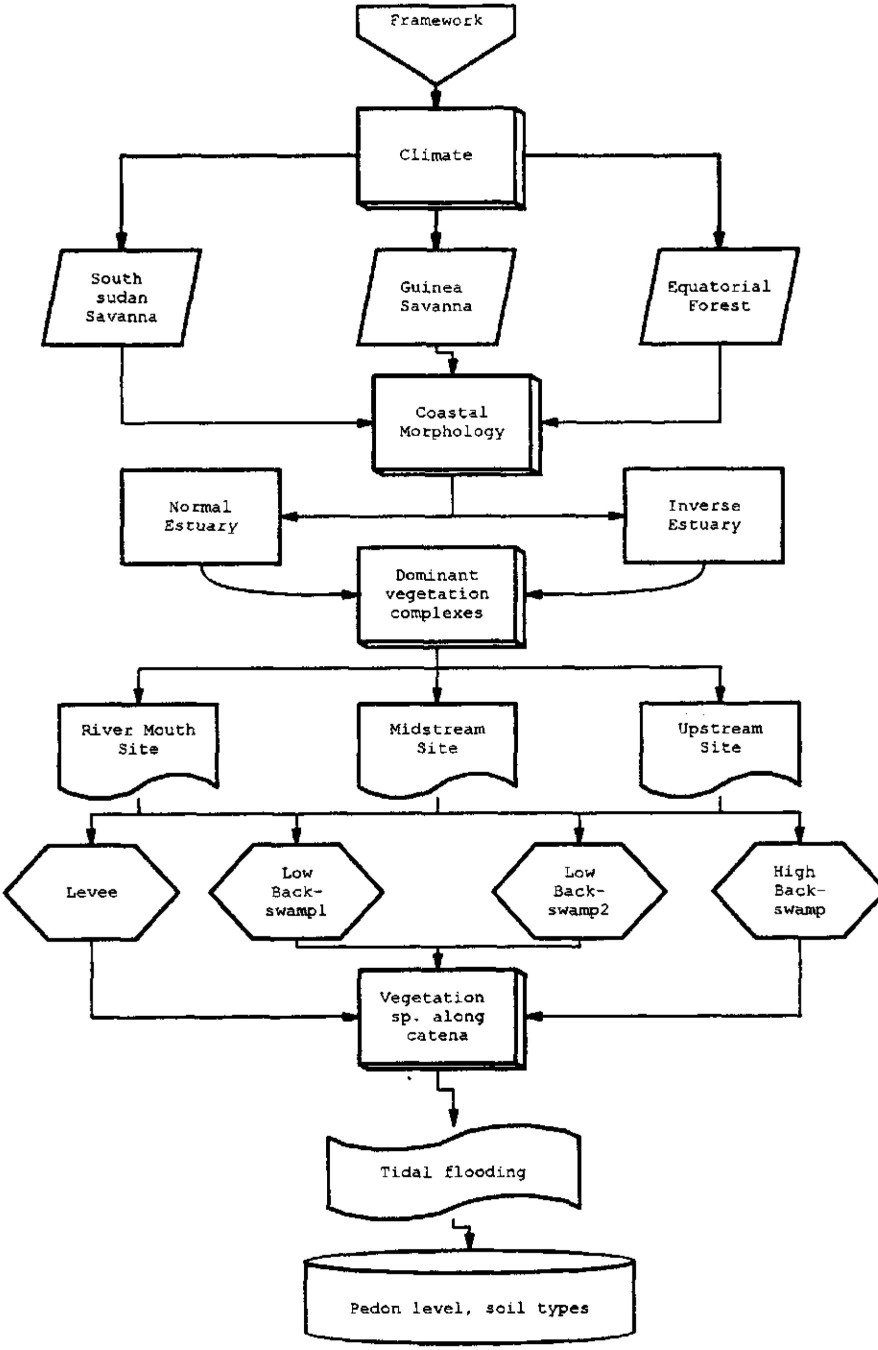


Figure 1: Schematic representation of a hierarchical framework of the different factors contributing to soil acidity along estuaries in West African Mangrove swamps.

predominates in a wetter climate and further inland. At the limit of tidal water intrusion, *Phragmites* reeds colonize the flood plain. A vegetation sequence is also observed perpendicular to the stream, with *Rhizophora* at the river edge, *Avicennia* inland, and halophytic weeds or no vegetation in slightly higher saline lands ("tanne"). Sedimentation rates can vary regionally, within a river basin and along the catena due to sea level rise, river sediment load and favorable topographic conditions. Generally, coarse to loamy sediments are observed near the river mouth and river edges, whereas fine sediments occur at upstream sites and in backswamp areas.

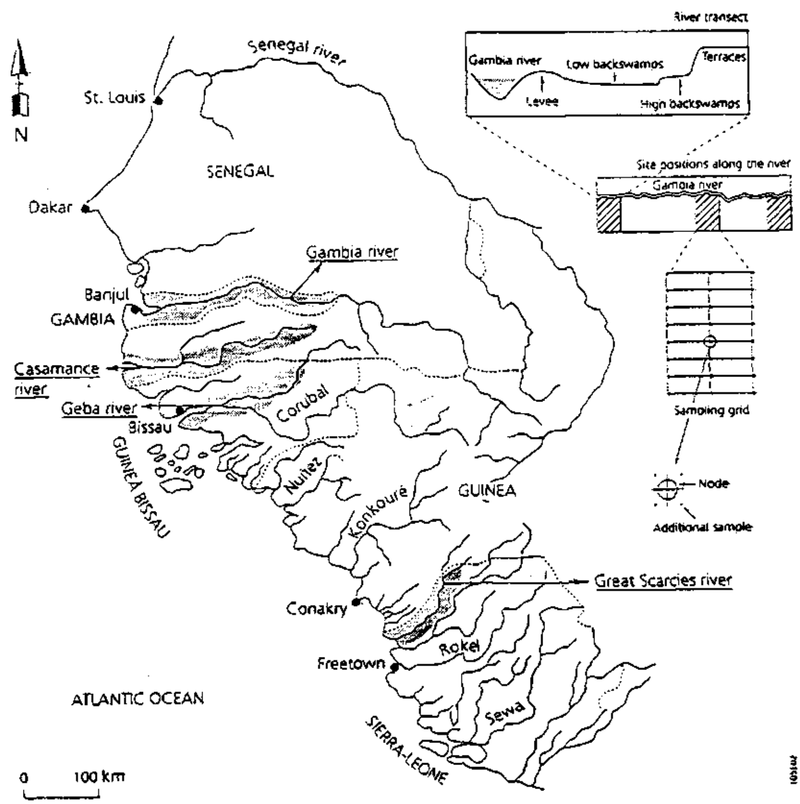


Figure 2: Location of the study area, the position of the sites along the basins of the Gambia, the Casamance, the Geba and the Great Scarcies rivers, the sampling grid and the physiographic units along the low laying part of a catena in the mangrove swamps.

Table 1. Summarized description of the mangrove rice ecosystem along four river basins of West Africa.

Country	Gambia	Senegal	Guinea Bissau	Sierra Leone
Watershed	Gambia River	Casamance River	Geba River	Great Scarcies River
Approximate latitude	13°20'	12°25'	11°30'	8°30'
River basin (km^2)	42,000	14,000	12,225	10,000
Mean annual rainfall	800 - 1200 mm	1100 - 1500 mm	1300 - 2000 mm	2000 - 3000 mm
Starting month of rain	Jun/July	Jun/July	May/Jun	May
Ending month of rain	Oct/Nov	Oct/Nov	Oct/Nov	Nov
Annual ETP	2000 - 2500 mm	1965 - 2400 mm	1500 - 1900 mm	1400 - 1500 mm
Climate (*)	South Sudan Sanna	South Sudan Savanna	Guinea Savanna	Equatorial Forest
River outflow (m^3/s)				
upstream	400	7	170 - 800	1000
downstream	2.5 - 5	0	5 - 10	?
Annual river outflow	>100 days	<100 days	100 days	>100 days
Tidal range (m)	0.6-1.6	0.7-1.2	2.5-6.0	2.0-3.0
Max. salinity intrusion	225 km	250 km	175 km	80 km
Flood plain	flat	flat	flat	flat
Soil types	Tropaquepts, Sulfic Tropaquepts, Sulfaquepts, Sulfaquents	Tropaquepts, Sulfic Tropaquepts, Sulfaquepts, Sulfaquents	Tropaquepts, Sulfaquepts, Sulfaquents	Sulfaquepts,Sulfaquents, Sulfohimists,Sulfihimist
Land use type	Forest; salts production; rain water rice polder; tidal rice; honey production.	Forest; salts production; rain water polder rice; honey production.	Forest; salts production; rain water polder rice.	Forest; tidal rice.

(*). After Andriesse and Fresco 1991

Soil Survey and Laboratory Analyses

In the dry season of 1991 (April-May) 2025 soil samples were collected from the 12 selected sites. The sites are strips of 80 m width, parallel to the river and ranging from about 500 to 1800 m long perpendicular to the river covering the low-laying part of the catena. Data were collected following a grid with a mesh of 40 by 20 m. At each grid node and at four points within 1 to 1.5 m of each node soil samples were taken with a gauge auger of 0.05 m diameter from every 0.20 m to the depth of one meter. The 5 samples for each depth were well-mixed in strong plastic bags, packed air-free and tight to be analyzed within 24 hours or to be frozen to minimize oxidation. Soil color, mottles, texture, depth to jarosite-like mottles (Munsell: 2.5-5 Y 8/3-8/6), depth to unripe material, as well as pH-insitu, Electrical Conductivity (EC), Total Actual Acidity (TAA), Total Potential Acidity (TPA) and Total Sulfidic Acidity (TSA) (Konsten et al., 1988) were measured. The soil pH was also measured after 3 months of aerobic incubation in a dark moist room.

The method of Konsten et al. (1988) is a simple field method to estimate the actual soil acidity and of the potential acidity upon oxidation of the soil:

- TAA is the amount of titratable acidity actually present in a soil sample. From the soil bag packed air-free, about 0.050 kg of soil was suspended in a sodium chloride solution (1 mol/liter) (soil:water ratio 1:2.5 by weight). The soil sample was stirred and left overnight. TAA was measured by fast titration with NaOH solution (0.5 mol/liter) to pH 5.5. Correction was made to account for the slow buffering process of the soils at natural conditions. We selected 24 soil samples from each of the four river basins (4 top soil samples and 4 from the sub-soil at 3 representative soil units along a transect at each site). Next we analysed the samples both by slow and fast titration. The slow titration was done by allowing 2 hours for pH equilibration at each addition of NaOH. Regressions between the two titration methods was calculated and the correction factor estimated for each river basin. The ratio of moist soil to dry soil were used to calculate the TAA in cmol H^+ per kg dry soil.
- TPA is the potential acidity that might develop if all reduced sulfur species in the soil are oxidized. The same procedure as with TAA was applied except that prior to the titration, the soil samples were completely oxidized by continuous addition of hydrogen peroxide.
- The difference between TPA and TAA named Total Sulfidic Acidity (TSA) was defined as the amount of acidity that might be generated by the oxidation of the sulfur fraction.

Statistical Procedures

The statistical approach was twofold. First, nested analysis of variance was applied to the data collected from the central transects of the strips to estimate the effect of each factor contributing to soil acidity prevailing at a specific scale. Second, geostatistical methods were applied to the data collection from the strips to test spatial variability patterns at the most detailed scale.

Nested ANOVA

For each river basin several sources of variation to soil acidity were distinguished, each operating at a specific scale. The total variation σ^2 is composed of different variance components as $\sigma^2 = \sigma^2_{Pos}+\sigma^2_{Form}+\sigma^2_{Depth}+\sigma^2_e$, where σ^2_{Pos} denotes the variance component due to the transect position, given by the distance to the river mouth, σ^2_{Form} the variance component due to the landscape unit along the toposequence, given by the physiographic unit observed, σ^2_{Depth} the variance component due to the depth below the soil surface and σ^2_e the residual variance component. For each river basin which has a river specific average value of TAA or TPA equal to μ_{R1} and μ_{R2} respectively, the contribution of the different sources of spatial variability was analyzed by means of a nested ANOVA, using the following models:

$$TAA_{ijkm}=\mu_{R1}+Pos_i+Form_{ij}+Depth_{ijk}+\varepsilon_{ijkm} (1)$$

$$TPA_{ijkm}=\mu_{R2}+Pos_i+Form_{ij}+Depth_{ijk}+\eta_{ijkm} (2)$$

where TAA_{ijkm} and TPA_{ijkm} denote the soil total actual and total potential acidity respectivelly at the *mth* observation point, m = 1,...,n, for position i, i=1,2,3, denoted with Pos_i, given by the distance of the observation point to the river mouth, landscape unit j, j = 1,2,3, and 4, denoted with $Form_{ij}$ and soil depth k, k=1,2,3,4, and 5, denoted with $Depth_{ijk}$. The ε_{ijkm} and η_{ijkm} indicate random errors not explained by the models, and assumed to be independent of each other. The contribution and significance of each effect was tested. Knowledge of the degree of variability of TAA and TPA at each stage was related to one or more soil forming factors within the hierarchy. The nested ANOVA were calculated using the Statistical Analysis System (SAS Institute, 1985).

Geostatistical Analysis

The nested ANOVA procedure can be quite helpful to distinguish between the different sources of variation that influence the individual observations. However, it does not take into account the spatial dependencies between the observations. To analyze spatial variability at the most detailed scale, regionalized variable theory was used (Matheron, 1965). Regionalized variable theory, or geostatistics, differs from ordinary statistical theory in that the relation between a variable and its location is taken into account. Geostatistics were applied to analyze the data sets in each site for a given soil depth. To do so, TAA and TPA as a regionalized variable will be denoted with TAA(**x**) or TPA(**x**) where **x** denotes the position within a particular site at a certain depth. The spatial variability can be described quantitatively by a semivariogram defined as:

$$\gamma_A(\boldsymbol{h})=\frac{1}{2}\mathscr{E}[(TAA(\boldsymbol{x})-TAA(\boldsymbol{x}+\boldsymbol{h}))^2] (3)$$

$$\gamma_P(\boldsymbol{h})=\frac{1}{2}\mathscr{E}[(TPA(\boldsymbol{x})-TPA(\boldsymbol{x}+\boldsymbol{h}))^2] (4)$$

where $\mathscr{E}$ denotes the mathematical expectation. The semivariograms were applied only if the intrinsic hypothesis could safely be assumed to hold, e.g. for all **h** the variance of [TAA(**x**) - TAA(**x+h**)] is finite and independent of **x** and $\mathscr{E}$[TAA(**x**) - TAA(**x+h**)] is equal to zero, hence prohibiting the presence of a trend.

For all sites semivariograms were calculated for each soil depth. Next, semivariogram models, selected among the permissible models which have to be conditionally positive definite, were fitted and used for interpolation using ordinary kriging (Webster, 1985).

In the presence of a trend, the intrinsic hypothesis is not valid, and hence the semivariogram is not defined. The existence of a trend was checked by visual inspection of the data, of the semivariograms for parabolic behavior, concave upwards near the origin

(Webster, 1985) as well as by comparing predicted and actual data by jack-knifing (Starks and Fang, 1982). If a trend was expected, the spatial dependence of the TAA and TPA data was described by means of a pseudo-covariance function depending upon the lag between observations:

$$c(h) = \alpha_0 \delta(|h|) + \alpha_1 |h| + \alpha_3 |h|^3 + \alpha_5 |h|^5 \quad (5)$$

where $\delta(|h|) = 1$ for $|h| = 0$ and vanishes for $|h|$ different to zero and the α_i are the coefficients of the model. This equation yields a permitted model for polynomial trends up to degree 2. The term $\alpha_3 |h|^3$ was included if the degree is equal to or exceeds 1, and the term $\alpha_5 |h|^5$ if the degree was equal to 2. Higher degrees of trend were not analyzed. Coefficients of the model were estimated by means of the Restricted Maximum Likelihood (Stein, 1991). In order to discriminate between different degree of trends, Akaikes Information Criterion (AIC) was applied, modified for small data sets of size (Sylla et al. 1994, submited).

Both the semivariogram and the pseudo covariance function may be applied for interpolating from points towards areas of land, using ordinary kriging and universal kriging, respectively (Cressie, 1993).

RESULTS

Variability of Soil TAA and TPA at Regional Level (MACRO-LEVEL)

The nested analysis of variance at the macro level gave a highly significant model effect

Table 2: Mean soil Total Actual Acidity (TAA), Total Potential Acidity and Total Sulfidic Acidity (TSA) in cmol $H^+ kg^{-1}$ in 12 sites; 3 along each of four river basins and by position along the toposequence (Levee, Low backswamp 1 (LBS1), Low backswamp 2 (LBS2) and High backswamp (HBS).

Site position	Gambia			Casamance			Geba			Great Scarcies		
	TAA	TPA	TSA	TAA	TPA	TSA	TAA	TPA	TSA	TAA	TPA	TSA
Mouth	5.75	6.01	0.26	2.82	5.25	2.43	9.36	12.75	3.39	20.03	245.8	225.77
Midstream	0.16	18.41	18.25	8.81	15.17	6.36	9.77	11.68	1.91	8.77	234.4	225.67
Upstream	0.00	14.80	14.8	7.85	14.99	7.14	0.52	1.55	1.03	24.72	280.3	255.54
SITE 1 near river mouth												
Levee	2.45	3.98	1.53	----	----	----	15.56	22.08	6.52	17.36	164.78	147.42
LBS1	----	----	----	1.54	4.08	2.54	6.94	10.22	3.28	23.63	271.81	248.16
LBS2	----	----	----	5.33	6.68	1.35	10.42	13.27	2.85	26.23	329.16	302.93
HBS	9.05	8.05	0.00	1.58	5.01	3.43	4.53	5.42	0.89	12.90	217.45	204.55
SITE 2 midstream												
Levee	0.02	27.42	27.40	5.19	15.53	10.34	6.72	13.60	6.88	5.82	179.60	173.78
LBS1	0.00	22.10	22.10	7.33	19.46	12.13	3.61	3.86	0.25	7.27	161.53	154.26
LBS2	0.26	15.23	14.97	14.07	15.73	1.66	14.86	14.50	0.36	11.25	361.10	349.85
HBS	0.33	8.89	8.56	8.64	9.95	1.31	13.91	14.76	0.85	10.75	235.53	224.78
SITE 3 upstream												
Levee	0.00	23.04	23.04	10.25	28.28	18.03	0.00	0.57	0.57	1.74	188.34	186.60
LBS1	----	----	----	9.29	18.48	9.19	0.33	1.06	0.73	1.23	237.48	236.25
LBS2	----	----	----	4.37	6.33	1.96	0.30	1.24	0.94	19.04	324.29	305.25
HBS	0.00	6.56	6.56	7.47	6.89	0.58	0.47	3.34	1.87	76.88	370.93	294.05

---- = missing or no represented landscape unit

Table 3: NESTED ANOVA for soil Total Actual Acidity (TAA) for the four river basins with the following parameters describing the model: site position along the river (Pos), landscape unit within site (Form (Pos)) and soil depth within landscape unit (Depth(Form*Pos)).

Gambia River (N = 295; R^2 = 0.74; CV = 1.29)

SOURCE	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	39	3427.6	87.9	18.96	0.0001
Pos	2	516.5	258.2	55.72	0.0001
Form (Pos)	5	201.0	40.2	8.68	0.0001
Depth (Form*Pos)	32	120.1	3.8	0.81	0.7590
Error	255	1181.8	4.63		
Corrected Total	294	4609.4			

Casamance River (N = 190; R^2 = 0.66; CV = 0.82)

SOURCE	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	54	6861.4	127.1	4.96	0.0001
Pos	2	1011.1	505.6	19.72	0.0001
Form (Pos)	8	874.4	109.3	4.26	0.0001
Depth (Form*Pos)	44	4843.7	110.1	4.29	0.0001
Error	135	3460.6	25.6		
Corrected Total	186	10322.0			

Geba River (N = 180; R^2 = 0.78; CV = 0.69)

SOURCE	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	59	7092.6	120.2	7.07	0.0001
Pos	2	1922.4	961.2	56.53	0.0001
Form (Pos)	9	2255.8	250.6	14.74	0.0001
Depth (Form*Pos)	48	2689.8	56.0	3.29	0.0001
Error	120	2040.4	17.0		
Corrected Total	179	9133.0			

Great Scarcies River (N = 275; R^2 = 0.74; CV = 0.93)

SOURCE	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	59	136410.7	2312.0	10.42	0.0001
Pos	2	12040.2	6020.1	27.14	0.0001
Form (Pos)	9	106570.0	11841.1	53.39	0.0001
Depth (Form*Pos)	48	18385.6	383.0	1.73	0.0001
Error	215	47684.3	221.8		
Corrected Total	274	184095.0			

Table 4: NESTED ANOVA for soil Total Potential Acidity (TPA) for the four river basins with the following parameters describing the model: site position along the river (Pos), landscape unit within site (Form (Pos)) and soil depth within landscape unit (Depth(Form*Pos)).

Gambia River (N = 295; R^2 = 0.66; CV = 0.46)

SOURCE	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	39	19261.7	493.9	12.73	0.0001
Pos	2	2541.5	1270.7	32.76	0.0001
Form (Pos)	5	8068.1	1613.6	41.59	0.0001
Depth (Form*Pos)	32	5741.3	179.4	4.62	0.0001
Error	255	9892.6	38.8		
Corrected Total	294	29154.3			

Casamance River (N = 190; R^2 = 0.87; CV = 0.48)

SOURCE	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	54	18657.5	345.5	15.61	0.0001
Pos	2	3214.0	1607.0	72.60	0.0001
Form (Pos)	8	4354.2	544.3	24.59	0.0001
Depth (Form*Pos)	44	11985.1	272.4	12.31	0.0001
Error	135	2988.1	22.1		
Corrected Total	186	21645.6			

Geba River (N = 180; R^2 = 0.82; CV = 0.59)

SOURCE	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	59	12356.8	209.4	9.49	0.0001
Pos	2	2756.7	1378.4	62.45	0.0001
Form (Pos)	9	3460.2	384.5	17.42	0.0001
Depth (Form*Pos)	48	5769.1	120.2	5.45	0.0001
Error	120	2648.7	22.1		
Corrected Total	179	15005.5			

Great Scarcies River (N = 275; R^2 = 0.60; CV = 0.46)

SOURCE	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	59	4164567.7	70585.9	5.50	0.0001
Pos	2	102969.2	51484.6	4.01	0.0195
Form (Pos)	9	1194089.2	132676.6	10.34	0.0001
Depth (Form*Pos)	48	2682037.6	55875.8	4.35	0.0001
Error	215	2759400.0	12834.4		
Corrected Total	274	6923967.7			

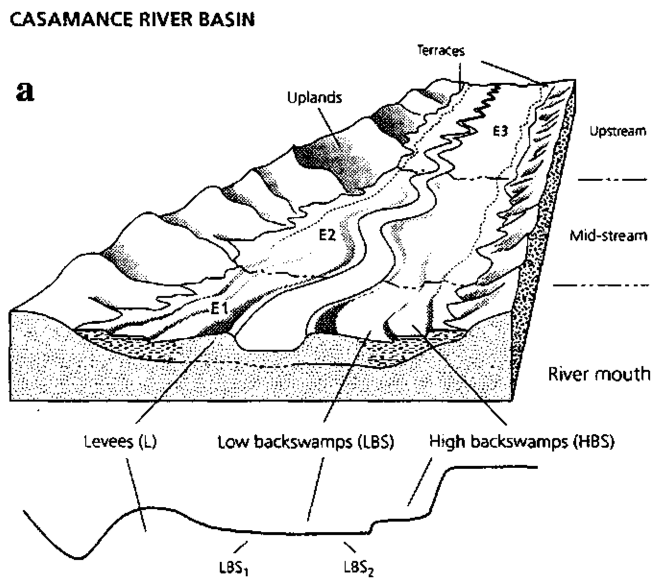
and showed a high goodness of fit: R^2 values equal to 0.77 for TAA and 0.84 for TPA were obtained. The coefficients of variation (CV) were relatively high: 0.78 and 1.14 for TAA and TPA respectively, indicating a high spatial variability of both soil properties. Climate effect was highly significant, yielding two distinct environments: (1) the Gambia, Casamance and Geba rivers and (2) the Great Scarcies river. Both TAA and TPA means were higher in the Great Scarcies river (Table 2).The soil TSA mean was very high in the Great Scarcies river (TSA = 229 cmol H^+/ kg soil), small in the Geba and Casamance rivers (1.93 and 3.58 cmol H^+/ kg soil respectively) and intermediate in the Gambia river (10.98 cmol H^+/ kg soil).

Variability of Soil TAA and TPA within Watershed (MESO-LEVEL)

All the nested models computed for TAA and TPA within river basins were highly significant (Table 3 and 4). The contribution of the position along the river was highly significant as well. ANOVA models applied to TAA for three rivers showed significant R^2 values, ranging from 0.74 for the Gambia and the Great Scarcies rivers, and 0.78 for the Geba river. For the Casamance river an R^2 value equal to 0.66 was observed (Table 3). For TPA, highly significant R^2 values were observed for the Casamance and the Geba rivers, 0.87 and 0.82 respectively. A lower fit was obtained for the Gambia and the Great Scarcies rivers (R^2 values equal to 0.66 and 0.60, respectively) (Table 4). Relativelly higher dispersion (CV) was observed for TAA and relatively low values for TPA. Table 2 summarizes the different means of TAA, TPA and TSA along the four rivers and within the landscape positions. No unique gradient for all rivers basins was found. The TAA values were highest at the river mouth and decreased upstream for the Gambia river. For the Casamance river however, TAA was relatively low at the river mouth and increased upstream. The TAA values near the river mouth and midstream sites of the Geba river were similar and lowest upstream. For the Great Scarcies river, TAA values were lowest at midstream and high near river mouth and upstream. Both TPA and TSA were higher upstream decreasing downstream along the Gambia and the Casamance rivers, while they were highest for the mouth position of the Geba river. TPA and TSA values were high along the Great Scarcies river. A schematical block diagram of the main patterns observed within two main river basins is given in Fig. 3a and b.

Variability of Soil TAA and TPA within Catena (MICRO-LEVEL)

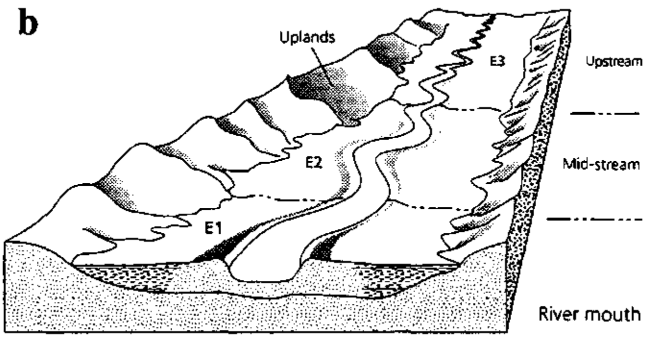
The micro-variability of soil TAA and TPA was analyzed using both the nested model and the geostatistical approach. From the nested model, average TAA and TPA values of 5 soil layers to represent the solum were used to characterize the soils within different catenas. TAA values were generally highest in the backswamp zones (LBS2 and HBS) except near the mouth of the Geba river, the upstream sites of the Casamance river and the Gambia river. TPA values were always highest in the backswamp zones and decreased towards the levee for the Great Scarcies river while for the three other rivers it was site-specific. Note however the high TPA values on the levees decreasing towards the backswamp near the mouth of the Geba river, the midstream site of the Gambia river and to some extent at the upstream sites of the Casamance and the Gambia rivers. TSA values decreased generally from the levee towards the backswamp for the three northern rivers while the reverse was observed for the Great Scarcies river (Table 2). The variation of TAA and TPA with soil depth within each catena shows two extreme cases e.g. the midstream sites of the Casamance and the Great Scarcies rivers (Fig. 4a and 4b respectively). In general TPA increases with soil depth in all river basins while TAA increases with depth in the northern rivers and decreases in the soils along the Great Scarcies river. The soil depth at which TSA exceeds 25 to 30 cmol H^+/ kg soil varies for each river basin and also between different catena positions. Generally, apotential acidy was extremely high (TSA more than 100 cmol H^+/ kg) for the Great Scarcies soils at less than 0.40 m depth. Low TSA values prevail in the soils of the northern rivers, but still noticeable amounts of total sulfidic acidity however can remain in the soils at greater depth mainly near levees and low backswamps.



Zones	Land unit	Mean TAA ($cmol \cdot kg^{-1}$)	Mean TPA ($cmol \cdot kg^{-1}$)	Mean TSA =TPA - TAA ($cmol \cdot kg^{-1}$)
E_1	L	0	5	5
	LBS_1	2	4	2
	LBS_2	5	7	2
	HBS	2	5	3
E_2	L	5	16	11
	LBS_1	7	19	12
	LBS_2	14	16	2
	HBS	9	10	1
E_3	L	10	28	18
	LBS_1	9	18	9
	LBS_2	4	6	2
	HBS	7	7	0

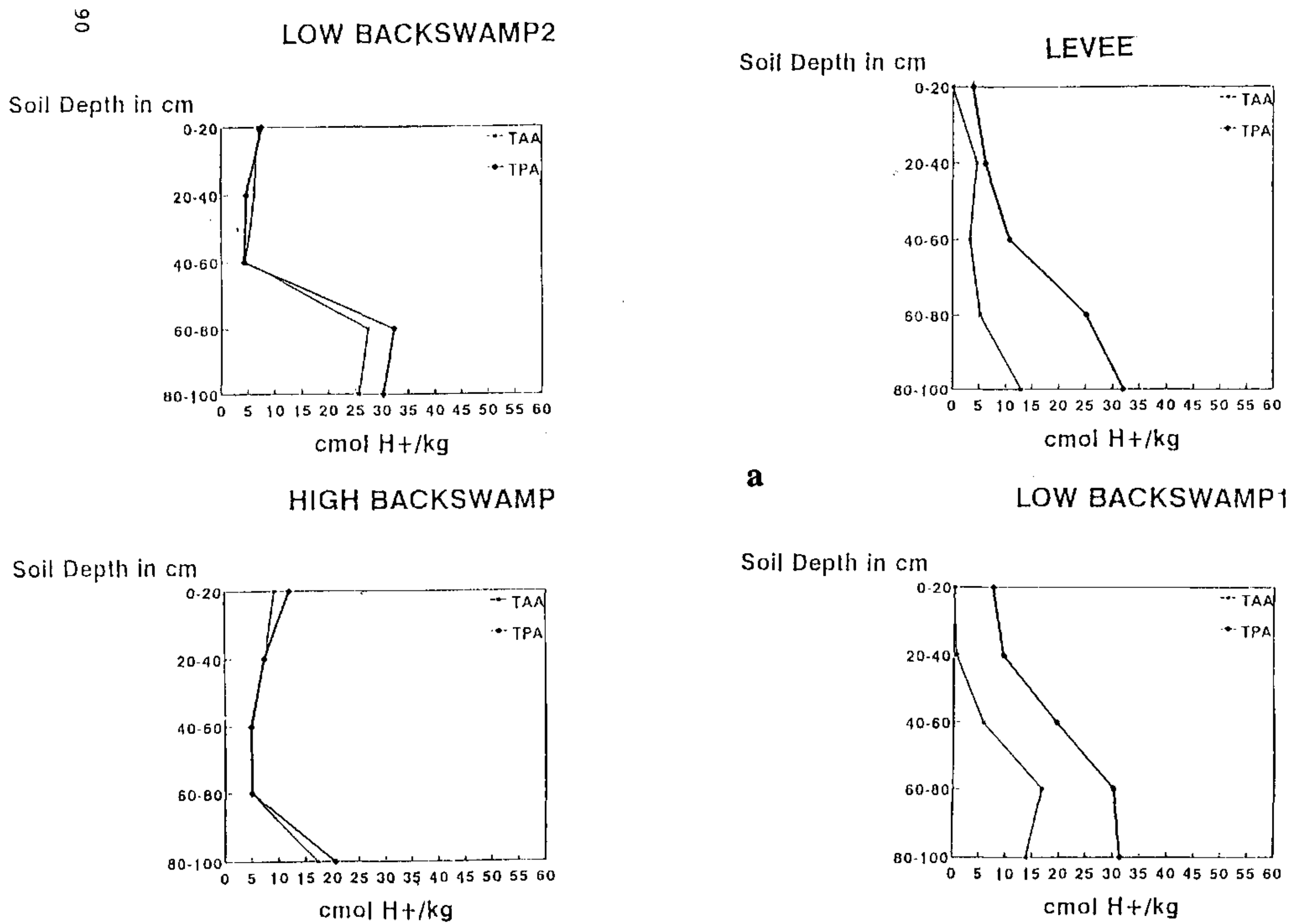
Figure 3: Schematic block diagrams indicating sub-environments within watershed based on the spatial variability of soil total and actual acidity, a) the Casamance and b) the Great Scarcies river basins.

GREAT SCARCIES RIVER BASIN

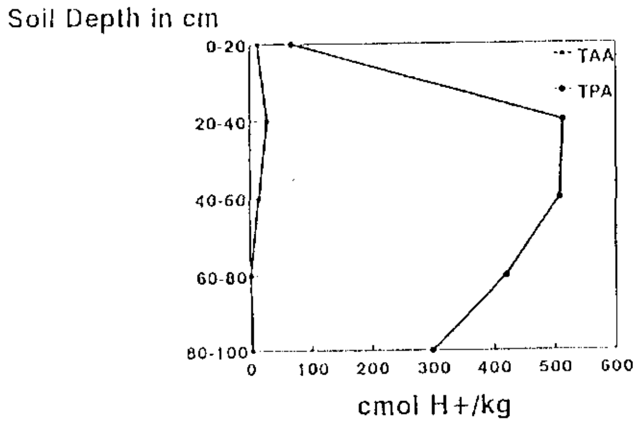


Zones	Land unit	Mean TAA ($cmol\cdot kg^{-1}$)	Mean TPA ($cmol\cdot kg^{-1}$)	Mean TSA =TPA - TAA ($cmol\cdot kg^{-1}$)
E_1	L	17	165	148
	LBS_1	24	272	248
	LBS_2	26	329	303
	HBS	13	217	204
E_2	L	6	180	174
	LBS_1	7	162	155
	LBS_2	11	361	350
	HBS	11	236	225
E_3	L	2	188	186
	LBS_1	1	237	236
	LBS_2	19	324	305
	HBS	77	371	294

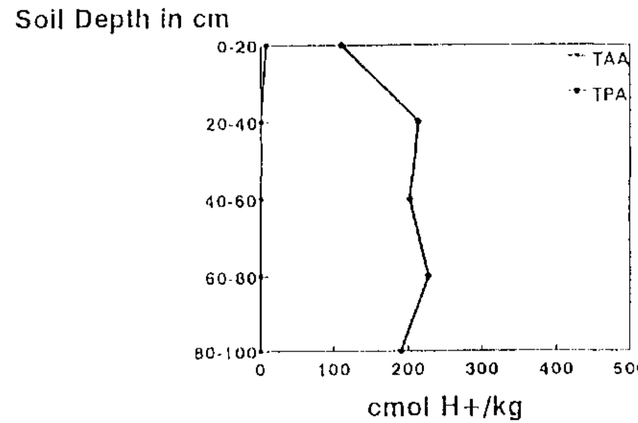
Figure 4: Variation of Total Actual Acidity (TAA) and Total Potential Acidity (TPA) with soil depth at four landscape units for the *midstream sites* of the Casamance (a) and the Great Scarcies (b) river basins.



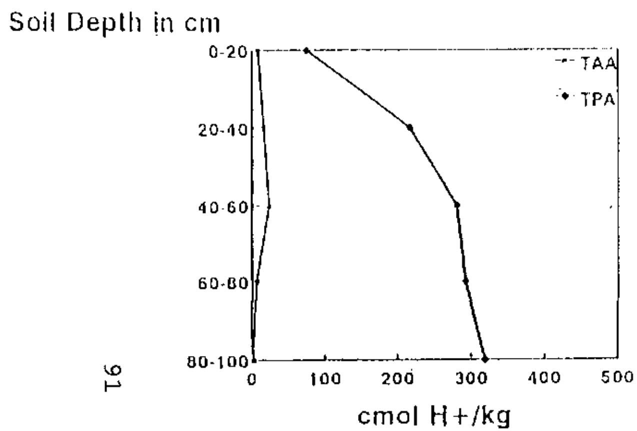
LOW BACKSWAMP2



LEVEE



HIGH BACKSWAMP



b

LOWBACKSWAMP1

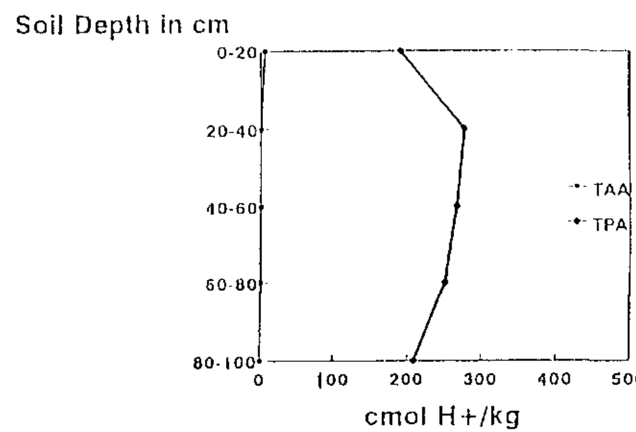
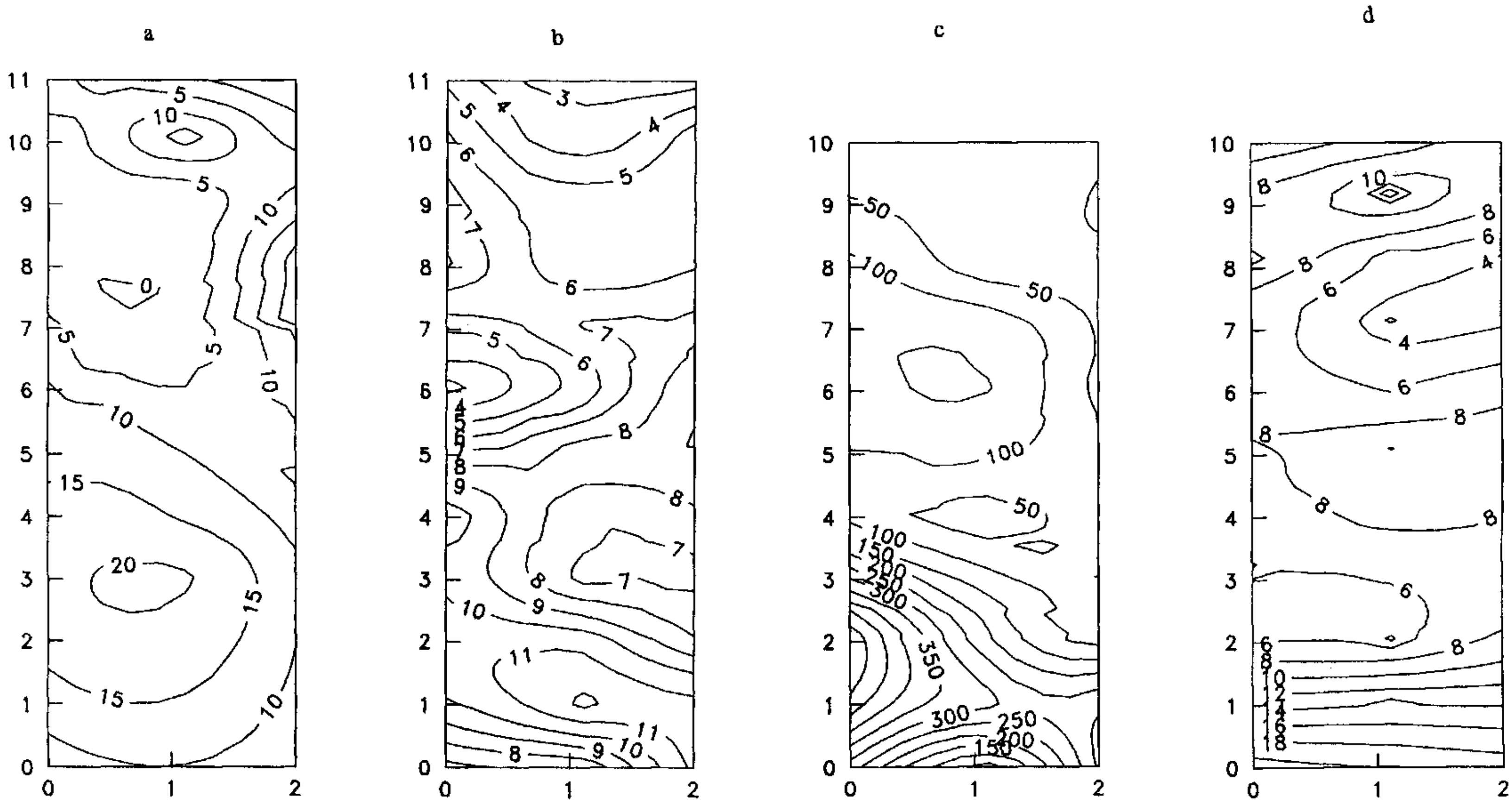


Figure 5: Contour maps of soil Total Actual Acidity (TAA in cmol $H^+ kg^{-1}$) (a) at the midstream site of the Geba river basin (40 - 60 cm) and of soil Total Potential Acidity (TPA in cmol $H^+ kg^{-1}$) (b) at the mouth of the Gambia river basin (0 - 20 cm); (c) at the mouth of the Great Scarcies river basin (20 - 40 cm) and (d) at the midstream site of the Casamance river basin (0 - 20 cm).



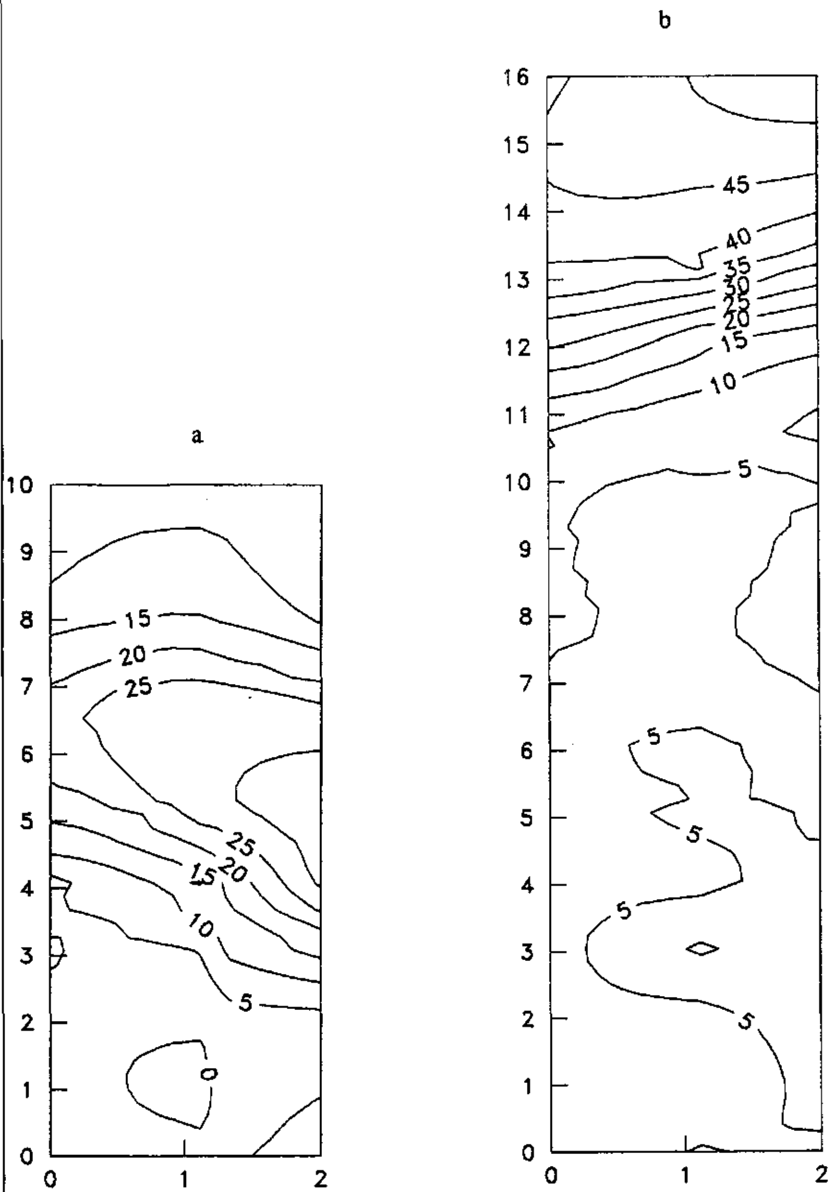


Figure 6: Contour maps of soil Total Actual Acidity (TAA in cmol H^+ kg^{-1}) at the midstream site of the Casamance river basin (60 - 80 cm) (a) and Total Potential Acidity (TPA in cmol H^+ kg^{-1}) (b) at upstream sites of the Casamance river basin (80 - 100 cm).

To analyze spatial dependencies between observations within different catenas we applied geostatistics. Sixty omnidirectional semivariograms were computed both for TAA and TPA at the 12 sites for 5 soil depths. Within each site the spatial structure was not always similar for all soil depths. However a pure nugget effect was observed most often on the soil surface both for TAA and TPA. With increasing depth a better spatial structure was generally observed. Different methods of spatial interpolation, such as ordinary kriging and universal kriging, were applied for each site on each soil depth, depending on the spatial structure found from the semivariograms. Sixty contour maps of TAA and TPA were produced for 5 soil depths at 12 locations. With few exceptions, a general variation pattern of TAA and TPA within a catena emerged. TAA and TPA were highest at the backswamp zones (HBS and LBS2) and lowest at the levees as illustrated in in Fig.5a, b, c, d (at the Y-axes, 0 indicates the location further from the levee and e.g. 11 indicates the river edge). For the few exceptions, TAA or TPA values were higher near levees and lower in the backswamp as observed for the mid and upstream sites of the Casamance river (Fig.6a, b). At greater soil depth (around 1 m) the acidity distribution was rather homogeneous from the levee up to the limits of the HBS (Fig.7).

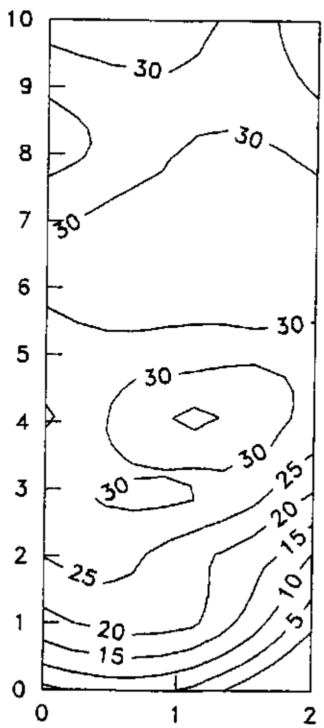


Figure 7: Contour map of soil Total Potential Acidity (cmol H^+ kg^{-1}) at 80 to 100 cm soil depth at the midstream site of the Casamance.

DISCUSSION

Spatial Variability of Soil Acidity

At **macro-level**, the significant effect of climate on the spatial variability of soil acidity was statistically demonstrated. Nevertheless no clear evolutive north south trend following the annual rainfall gradient was found. An earlier study, however, reports that along the West African shoreline, climatic zonality influences soil acidity, and can be used to define a concept of coastal sequence (Vieillefon, 1977). One of the main assumptions underlying the study is the correlation between vegetation distribution and the expected soil types. Tomlinson (1957) observes a zonal distribution of mangrove species along selected catenas in Gambia and finds a strong correlation between vegetation species and amounts of soil pyrite. At regional level, Hart (1959) and Kawalec (1977) conclude to the existence of a zonal distribution of mangrove species in West Africa and recently Diemont et al. (1993) extrapolate such zonal distribution to the expected acid sulfate soil types. This study showed evidence that only two distinct environments characterized from their soil acidity emerged: the northern region (the Gambia, Casamance and Geba river basins) and the southern region (the Great Scarcies river basin). The expected evolutive pattern on soil acidity following a climatic gradient both derived from our framework and described by others was not observed. This new development on spatial variability of soil acidity in the West African mangrove ecosystem can be attributed to the long drought period in the Sahel affecting the chemical conditions of the soils along the northern river basins. The cumulative effect of acidification as well as of salinization and the subsequent acid leaching with saline water has probably affected differentially the soils. In these unstable environments, the longer aeration implies stronger soil development. Therefore the causal effect of climate should be modulated by the specific effects of individual river hydrology, and in particular to its tidal behavior. Nevertheless, the earlier zonality described which is now limited to two broad eco-regions (dry and wet) can have its implication on soil water management in the West African mangrove ecosystem. The Gambia, Casamance and Geba river basins can be further sub-divided based on the remaining soil total sufidic material.

At **meso-level**, the nested approach applied on soil acidity shows clear evidence of the effect of site position along the river basin. The longitudinal pattern of soil acidity variability was specific for each river. Causes for spatial variability of soil acidity at this scale can be related to a complex interaction of vegetation sequences along the river basins, sedimentation rates during soil genesis and recent climatic changes affecting the river hydrology. Along the northern river basins, earlier studies (Vieillefon, 1977 and Kawalec, 1977) report a longitudinal gradient of mangrove sequences from the river mouth towards upstream positions following the salinity regime, e.g. *Avicennia* dominant near the river mouth and *Rhizophora* at upstream positions. The soil map produced in the nineteen seventies for the Casamance river basin shows more potential acid sulfate soils upstream and less near the river mouth. Our results on soil TPA confirmed this pattern along the Gambia and the Casamance river basins but to a lesser extent along the Geba and the Great Scarcies river basins. With the exception of the upstream site of the Geba river, soil TSA was highest at upstream positions and decreasing towards the river mouth. Both vegetation sequences as well as rapid sedimentation rates near the river mouth can be the causal effect. At the meso level the amount of actual soil TAA and TSA can be a clue for practical agronomic implications. Each river basin can be sub-divided into environments from the river mouth to upstream positions.

At **micro-level**, intricate patterns of the soil TAA and TPA were observed. The complexity related to the interaction of all factors favorable for pyrite formation within different landforms have been difficult to cope with because of recent soil evolution as affected by climate change and hydrology. Many authors have studied the effects of landforms on pyrite accumulation and concluded that less pyrite accumulates on levees (or tidal creek ridges) as compared to the backswamp units (Bennema, 1953; Willet and Walker, 1982 and Dent, 1986). Giclioli and Thornton (1965) and Thornton and Giglioli (1965) describe an opposite pattern for the Gambia river and Vieillefon (1977) for the Casamance river. Van Breemen (1976) in a detailed study in Thailand concludes that little potential acidity was present in surface soils of levees and more towards the backswamp positions. But this pattern was not explicitly mentioned for increasing soil depth. The results provided by the geostatistical approach have shown a detailed variation of TAA and TPA within soil catenas for each single soil layer of 0.20 m thick up to 1.00 m depth. For the surface soil (0 to 0.20 m), our results on TPA confirm the conclusions of van Breemen (1976). However two exceptions occur at the mid- and upstream sites of the Gambia river where the levees have higher surface soil TPA. With soil depth the expected high TPA values at the backswamp and lower in levee as described by Bennema (1953), Willet and Walker (1982) and Dent (1986) is confirmed only along the Great Scarcies river. In the drier climatic environments this pattern is exceptional; the TPA values on levee soils are highest and decrease towards the backswamp. This decreasing trend seems to follow a sharp catenary distribution of mangrove species in a dry climate (narrow band of *Rhizophora* bordering the river, followed by a larger band of *Avicennia*). For the Great Scarcies river basin the band of *Rhizophora* is much wider. The relatively lower TPA near the levees along the Great Scarcies river can be related to the accreting process (fast sedimentation rate).

For TAA the highest values are generally located on the more aerated backswamp and less on the daily flooded levee. However, for the Geba river with an exceptionally high tidal range (up to 5 m) even the levees are subject to strong acidification.

Practical implications for soil water management can be based on the so called "site specific management" concept. Within the eco-region comprising the Casamance and the Geba river basins, TSA is relatively low and the soils have already undergone acidification. Leaching with salt water followed by salt leaching with fresh water during the rainy season can improve the soil. Amendments such as lime, rock phosphate and nitrogen in moderate applications can contribute to an increased rice yield (Sylla et al., 1993). At meso and micro-level however, attention has to be focused on the zones having still substantial potential acidity (TSA greater than 25 cmol H^+/ kg soil). A good water management design within the landscape can cope with this micro variability. Within the eco-region of the Great Scarcies river basin the best way to curtail further pyrite oxidation is to keep the soil periodically flooded by tidal action (van Breemen, 1993). Within this environment, substantial acidity in the high backswamp can develop, inducing extreme soil stresses (excess of Al and Fe species). Application of lime or preflooding might be helpful. The relatively high TAA in the top soil along the Great Scarcies river can be related to seasonal processes of acidification and deacidification (van Breemen, 1975) and may not be harmful when rice transplanting is delayed. At any case, the levee zones should not be disturbed, due to remaining potential acidity at some depth and also to their protective role against water erosion, which was not pursued further in the present study.

SUMMARY and CONCLUSIONS

Our study has, through a sampling scheme at different scales and the application of statistical procedures, shown the intricated patterns of soil actual and potential acidity in the

West African Mangrove environment. To disentangle the complexity of causes of soil acidity spatial variability at different scales, a hierarchical framework as a synthesis of the environmental factors favorable for pyrite formation was used parallel to statistical methods. The framework accounts for the processes on acid sulfate soil genesis including the notions of rainfall sequence, biosequence, toposequence and hydrosequence (Jenny, 1980). The results showed that:

- At macro-level, a broad subdivision of the study area into two eco-regions was possible: the northern river basins with low TSA and the southern river basins with high TSA. The earlier defined north south trend on soil acidity was not observed because of rapid chemical changes occuring in the mangrove soils during the persisting drought in the northern regions.
- At meso-level, site position along rivers gave significant explanations for the longitudinal variability of soil acidity. However the pattern of variation seemed to be river-specific, being influenced by mangrove species distribution, sedimentation rate and recent climate change.
- At micro-level, the kriged maps showed different patterns of soil acidity spatial variability, related to the catenary distribution of vegetation species and possibily low pyrite accumulation on depositional topography. At this scale the observed patterns were rather specific to the eco-regions defined at the macro-level.

The approach followed in this study can have direct implication on soil water management. It can i) provide usable information for any manager from farmers to decision-makers, ii) facilitate site selection for modeling and model validation, and iii) help focus on new process-based and environmental research in mangrove ecosystem.

REFERENCES

Allbrook, R.F. 1973. The identification of acid sulphate soils in Northwest Malaysia. p. 131-140. *In* H. Dost (ed.) Acid sulphate soils. Proc. First International Symposium on acid sulphate soils. ILRI Publ. No. 18, Vol. No. 1, Wageningen, The Netherlands.

Bennema, J. 1953. Pyrite and calcium carbonate in polder Mijdrecht. Boor en Spade 6 (1978). STIBOKA, Wageningen (in Dutch).

Bloomfield, C. and J.K. Coulter. 1973. Genesis and management of acid sulfate soils. Ad. Agron. 25:265-326.

Breemen, N. van. 1973a. Soil forming processes in acid sulphate soils. p. 66-130. *In* H. Dost (ed.) Acid sulphate soils. Proc. First International Symposium on acid sulphate soils. ILRI Publ. No. 18, Vol. No. 1, Wageningen, The Netherlands.

Breemen, N. van. 1973b. Dissolved aluminum in acid sulfate soils and in acid mine waters. Proc. Soil Sc. Soc. Am. 37:694-697.

Breemen, N. van. 1975. Acidification and deacidification coastal plain soils as a result of periodic flooding. Soil Sci. Soc. Am. Proc. 39:1153-1157.

Breemen, N. van. 1976. Genesis and solution chemistry of acid sulfate soils in Thailand. Agric. Res. Rep. PUDOC, Wageningen, The Netherlands.

Breemen, N. van. 1982. Genesis, morphology and classification of acid sulfate soils in coastal plains. p. 95-108. *In* J.A. Kittrick, D.S. Fanning and L.R. Hossner (ed.) Acid sulfate weathering. SSSA Special Publ. 10, Soil Sc. Soc. Am., Madison, Wisconsin.

Breemen, N. van. 1993. Environmental aspects of acid sulphate soils. p. 391-402. *In* D.L. Dent and M.E.F. van Mensvoort (ed.) Selected papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils. ILRI Publ. No. 53, Wageningen, The Netherlands.

Breemen, N. van, M. Tandatemiya and S. Chanchareonsook. 1973. A detailed survey on the actual and potential soil acidity at the Bang Pakong Land Dev. Centre, Thailand. p. 159-168. *In* H. Dost (ed.) Acid sulphate soils. Proc. First International Symposium on acid sulphate soils. Vol. II. ILRI Publ. No.18, Wageningen, The Netherlands.

Bregt, A.K., H.J. Gesink and Alkasuma. 1992. Mapping the conditional probability of soil variables. Geoderma, Vol. 53, No 1 (2):15-29.

Bregt, A.K., J.A.M. Janssen and Alkasuma. 1993. Survey strategies for acid sulphate soils. p. 43-50. *In* D.L. Dent and M.E.F. van Mensvoort (ed.) Selected papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils. ILRI Publ. No. 53, Wageningen, The Netherlands.

Brinkman, R., Nguyen Bao Ve, Tran Kim Tinh, Do Phuoc Hau and M.E.F. van Mensvoort. 1993. Sulfidic materials in the West Mekong Delta, Vietnam. Catena, Vol. 20:317-331.

Brinkman, R. and L.J. Pons. 1968. A pedo-geomorphological classification and mapping of the Holocene sediments in the coastal plain of the three Guianas. Soil Survey Paper 4, Netherlands Soil Survey Institute, Wageningen.

Brinkman, R. and L.J. Pons. 1973. Recognition and prediction of acid sulphate soil conditions. p. 169-203. *In* H. Dost (ed.) Acid sulphate soils. Proc. First International Symposium on acid sulphate soils. Vol. I. ILRI Publ. No.18, Wageningen, The Netherlands.

Burrough, P.A., M.E.F. van Mensvoort and J. Bos. 1988. Spatial analysis as a reconnaissance survey technique: an example from acid sulphate soil regions of the Mekong Delta, Vietnam. p. 68-89. *In* H. Dost (ed.) Selected papers of the Dakar symposium on acid sulphate soils. ILRI Publ. No. 44, Wageningen, The Netherlands.

Chapman, V.J. 1976. Mangrove vegetation. J. Cramer, Vaduz.

Chapman, V.J.1977. Ecosystems of the world I. West coastal ecosystems. Elsevier, Amsterdam.

Cressie, N.A.C. 1993. Statistcs for spatial data. Revised Edition. Wiley-Interscience Publ. John Wiley ans Sons, Inc.

Dent, D.L. 1986. Acid sulphate soils: a baseline for research and development. ILRI Publ. No. 39, Wageningen, The Netherlands.

Dent, D.L. and M.E.F. van Mensvoort (ed.). 1993. Selected papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils. ILRI Publ. No. 53, Wageningen, The Netherlands.

Diemont, W.H., L.J. Pons and D.L. Dent. 1993. Standard profiles of acid sulfate soils. p. 51-59. *In* D.L. Dent and M.E.F. van Mensvoort (ed.) Selected papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils. ILRI Publ. No. 53, Wageningen, The Netherlands.

Diemont,W.H. and W. van Wijngaarden. 1975. Sedimentation patterns, soils, mangrove vegetation and land use in the tidal areas of West Malaysia. p. 513-518. *In* G. Walsh, S. Snedaker and H. Teas (ed.) Proc. on the Int. Symp. on Biol. and Man. of mangroves. Univ. of Florida, USA.

Dost, H.(ed.). 1973. Acid sulphate soils. Proc. of the First International Symposium. Vol I and II. ILRI Publ. No. 18, Wageningen, The Netherlands.

Dost, H. (ed.). 1986. Selected papers of the Dakar symposium on acid sulphate soils. ILRI Publ. No. 44, Wageningen, The Netherlands.

Dost, H. and N. van Breemen (ed.). 1982. Proc. of the Bangkok Symposium on Acid Sulphate Soils. ILRI Publ. No. 31, Wageningen, The Netherlands.

Giglioli, M.E. and I. Thornton. 1965. The mangrove swamps of Kenema, Lower Gambia river basin. I. Descriptive notes on the climate, the mangrove swamps and the physical composition of their soils. J. Appl. Ecol. 2:81-103.

Hart, M.G.R. 1959. Sulphur oxidation in tidal mangrove soils in Sierra Leone. Plant and Soil 11:215-236.

Jansen, J.A.M., H. Prasetyo, Alkasuma and W. Andriesse. 1990. Landscape genesis and physiography of Pulau Petak as basis for soil mapping. LAWOO/AARD Scientific Report no. 18. Research Programme of Acid Sulphate Soils in the Humid Tropic, ILRI, Wageningen, The Netherlands.

Jenny, H. 1980. The soil resource. Origin and behavior. Springer Verlag, New York.

Kawalec, A.1977. La genése et l'évolution des sols sur alluvions marines. Varsovie.

Kittrick, J.A., D.S. Fanning and L.R. Hossner (ed.). 1982. Acid sulfate weathering. SSSA Special Publ. 10. Soil Sc. Soc. Am., Madison, Wisconsin.

Konsten,C.J.M., W. Andriesse and R. Brinkman. 1988. A field method to determine total potential and actual acidity in acid sulphate soils. p. 106-134.*In* H. Dost (ed.) Selected papers of the Dakar symposium on acid sulphate soils. ILRI Publ. No. 44, Wageningen, The Netherlands.

Matheron, G. 1965. La théory des variables régionalisées et ses applications. Masson, Paris.

Pons, L.J., N. van Breemen and P. Driessen. 1982. Coastal sedimentary environments influencing the development of potential soil acidity. p. 1-18. *In* J.A. Kittrick, D.S. Fanning and L.R. Hossner (ed.) Acid sulfate weathering. SSSA Special Publication 10, 95-108. Soil Sc. Soc. Am., Madison, Wisconsin.

SAS Institute, Inc. 1985. SAS user's guide: statistics. 5th ed. SAS Inst., Inc., Cary, NC.

SECA/CML. 1987. Mangroves of Africa and Madagascar. Conservation and reclamation. Societe d'écomanagement/ Centre for Environmental Studies. Univ. of Leiden, Leiden, The Netherlands.

Starks, T.H. and J.H. Fang. 1982. On the estimation of the generalized covariance function. Journal of the International Association for Mathematical Geology, 14:57-64.

Stein, A. 1991. Spatial interpolation. PhD Thesis, Soil Science and Geology Dept., Wageningen, The Netherlands.

Sylla, M., N. van Breemen, L.O. Fresco, C. Dixon and A. Stein. Temporal and spatial variability of soil constraints affecting rice production along the Great Scarcies mangrove swamps, Sierra Leone. p. 51-59. *In* D.L. Dent and M.E.F. van Mensvoort (ed.) Selected papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils. ILRI Publ. No. 53, Wageningen, The Netherlands.

Tomlinson, T.E. 1957. Relationship between mangrove vegetation, soil texture and reaction of surface soil after empoldering saline swamps in Sierra Leone. Trop. Agrc. 34(1)41-50.

Vieillefon, J. 1969. La pédogenése dans les mangroves tropicales, un example de chronosequence. Science du sol 2:115-148.

Vieillefon, J.1977. Les sols des mangroves et des tannes de Basse Casamance (Sénégal). Mémoires ORSTOM 83, Bondy.

Webster, S.R. 1985. Quantitative spatial analysis of soil in the field. Adv. in Soil Science, 3:1-70.

Willet, I.R. and P.H. Walker. 1982. Soil morphology and distribution of iron and sulphur fractions in a coastal floodplain toposequence. Australian Journal of Soil Research 20 4: 283-294.

CHAPTER 5

TEMPORAL AND SPATIAL VARIABILITY OF SOIL CONSTRAINTS AFFECTING RICE PRODUCTION ALONG THE GREAT SCARCIES MANGROVE SWAMPS, SIERRA LEONE.

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Temporal and spatial variability of soil constraints affecting rice production along the Great Scarcies mangrove swamps, Sierra Leone

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Abstract

Along the Great Scarcies River (Sierra Leone) potential acid sulphate soils are widespread. Locally, surface soils have oxidized and become highly acidic. Production of rice critically depends on the lowering of acidity and salinity by natural flooding and leaching during the rainy season. When salinity and acidity are high, amendments (lime, phosphate) and extra water management measures are needed. However, most farmers cannot afford amendmends. They depend on selecting a period in the rice growing season during which soil limitations (salinity and acidity) are minimal. Research into the variations of salinity and acidity with time can help to recommend optimum transplanting dates, and appropriate cropping techniques and varieties.

Three sites at various distances from the sea were selected, based on expected relationships between environmental factors (hydrology, vegetation, salinity regime) and formation of potential and actual acid sulphate soils. At each site, soil solution monitoring and agronomic trials were carried out along a transect from the river levee across a low-lying backswamp to the higher backswamp. A geostatistical approach was used to describe variability of soil constraints in time and space.

Rice yields varied considerably within and across sites as a result of variations in salinity, acidity, and degree of iron toxicity. Close to the sea, the optimal 'window' for salinity (the period with EC values less than 8 mS cm^{-1}) is in the order of the growing period of short-duration varieties. At upstream sites, iron toxicity (bronzing) was observed when high concentrations of dissolved Fe^{2+} coincided with low Ca^{2+} concentrations. Near the sea, equally high Fe^{2+} concentrations were associated with higher Ca^{2+} concentrations and did not result in bronzing. Iron toxicity, apparently, did not depend only on the concentration of dissolved Fe^{2+} but also on that of Ca^{2+}. Within the toposequence, soil constraints are less on the levees and more severe towards the backswamps. Furthermore, rice yields depended on fertilizer treatment: a low lime dose (2 t ha^{-1}), 250 kg rock phosphate and 80 kg of urea-N per ha increased yield markedly.

Yield and soil constraints as well as treatment types are well correlated, allowing precise recommendations for improved agronomic practices. Near the sea, short-duration varieties tolerant to salinity are recommended to minimize the risk of salinity

[1] Research jointly undertaken by the West Africa Rice Development Association, the Institut Sénégalais de Recherches Agricoles, and Wageningen Agricultural University

damage. At upstream sites, varieties tolerant of iron toxicity are recommended because the bronzing cannot be avoided by delaying transplanting. To minimize soil-related stresses, transplanting should be sequential, starting at the levees and ending at upper catena zones, except at upstream sites where the order should be reversed.

Introduction

Rice is grown on about 214 000 ha of cleared mangrove swamps in West Africa (WARDA 1983). A further 150 000 ha is potentially suitable for cultivation. Most of the mangrove swamp soils are potential acid sulphate soils. In Sierra Leone more than 35 000 ha of former mangrove swamps are under rice cultivation. Most farmers in these areas must operate with very low inputs and improved technology should be adapted to this input level. In the past, research in the agroecology of 'mangrove rice' has focused on mainly on varietal improvement. However, the impact of improved varieties has been limited because the spatial and temporal variability of soil constraints was disregarded.

Along the Great Scarcies River, rice production critically depends on the lowering of acidity and salinity by natural flooding with fresh water and leaching during the rainy season. In addition, amendments (lime, phosphate) and extra water management measures may be needed. In view of the lack of credit and low per capita income, the first step for sustainable rice production may be based on transfer to varieties adapted to soil constraints and other adverse conditions on farmers' fields. As most farmers are unable to manipulate the growing environment, selecting a period in the rice growing season with minimal salinity and acidity can be the secret of success in varietal transfer. This study deals with the spatial and temporal variability of soil constraints during the growing season with the aim to define this time window.

Materials and methods

The study area is located along the Great Scarcies, Northwestern Sierra Leone, where the annual precipitation (2500mm to 3000mm) falls between the end of May and November, with a peak in August. Salinity intrusion extends more than 80 km upstream where the tidal amplitude is still 2 to 3m. The vegetation along the river is dominated by mangroves; *Avicennia* dominates near the sea, while *Rhizophora* predominates further inland. The salt-tolerant grass *Paspalum vaginatum* thrives in areas cleared of the original mangrove trees.

Site selection

The formation of potential acid sulphate soils depends on the presence of specific environmental conditions: sulphate and sulphate-reducers, organic matter, iron, reducing conditions alternating with limited aeration, removal of dissolved alkalinity formed during reduction, low contents of acid-neutralizing substances, and a sufficiently low rate of sedimentation (Van Breemen 1976, Pons et al. 1980). These factors prevail along the Great Scarcies. Soil organic matter contents tend to vary according to vegetation. Lowest organic matter contents are associated with *Avicennia* mangroves, mainly near the sea. Higher organic matter, as well as higher potential acidity, are associated with *Rhizophora*, further inland. Salinity varies both along the river and the swamp catena. Site selection was based on the variable salinity and potential acid sulphate soil conditions, as follows:

- Site 1 (Balencera) close to the river mouth with high seasonal salinity, high silt, low organic matter content (under *Avicennia*) and, possibly, low pyrite;
- Site 2 (Rowolloh) about 40 km upstream, transitional;
- Site 3 (Katakerra) about 80 km upstream, *Rhizophora* dominant and less saline during rainy season, high clay and high content of soil organic matter, favouring pyrite formation.

Each site comprises a 800-1500 m wide transect of the flood plain leading away from the river, which takes account of the variability in both salinity and acidity as influenced by tidal flooding and topography. Each catena included a levee along the river, a low backswamp, grading to a higher backswamp with a sharp transition to older terraces or plateaux.

Site characterization

A gouge auger was used for profile description at a 20m sample spacing along each catena. The effects of high local variability were avoided by multiple sampling and averages were recorded. In addition to the linear transect, a soil map was made using a 40 × 40m sampling grid.

Soil colour, mottles, texture, depth to jarosite, depth to unripe soil as well as pH-in situ, EC, Total Actual Acidity and Total Potential Acidity (Konsten et al. 1988) were measured at depths of 0-20, 20-40, 40-60, 60-80 and 80-100 cm. The soil pH was also measured after aerobic incubation.

Salinity and acidity were monitored by fortnightly sampling of the soil solution at 0-25, 25-50, 50-75 and 75-100 cm depths from soil-solution extractors permanently installed on the major physiographical units (levee, low backswamp, high backswamp).

Agronomic trials

Along each of the three transects four trials were established, one on the levee, one on the high backswamp and two between, in the low backswamp. Each experiment was a randomized design comprising the following six treatments in a rectangular field with plot sizes of 5 × 5 m, repeated 4 times:

- T0 = a control
- T1 = 2 tonnes/ha of lime
- T2 = T1 + 250 kg/ha rock phosphate
- T3 = T1 + 80 kg/ha N-urea
- T4 = T2 + 80 kg/ha N-urea
- T5 = 10 tonnes/ha of lime + 250 kg/ha Rock-P + 80 kg/ha N-urea

Five- to six-week old seedlings of the rice variety Rock 5 were transplanted with 2-3 seedlings per hill (to minimize the risk of crab damage to very young seedlings) at distances of 20 cm × 20 cm.

Rock-P and lime were incorporated one week before transplanting in wet soil. Urea was broadcast in split doses (2/3 at 20 days after transplanting [DAT]; and 1/3 at 40 DAT). Agronomic parameters were monitored throughout the season and yields were recorded at harvest.

Geostatistical procedures
Soil properties such as acidity and salinity are highly variable in acid sulphate soils, even within the same soil unit (Burrough et al. 1988).

In recent years, considerable efforts have been made to quantify soil heterogeneity and temporal variability for environmental monitoring through geostatistical techniques (Burgess and Webster 1980, Stein et al. 1989, Stein 1991). Each sample is correlated with nearby samples in space or time, so the regionalized variable is a mathematical predictor of similar values for nearby samples and dissimilar values for distant samples. Semi-variograms have been used in this study to estimate values between sampling dates by interpolation using kriging, after assuming second order stationarity (Stein 1991).

Statistical procedures for agronomic trials
ANOVA and F-tests were used to compare treatments within trials. Next, a combined analysis of variance was done, stepwise as follows:
1) Homogeneity of variances with chi-square test;
2) Combined Analyses of Variance over trials within catena and within sites;
3) Partitioning of treatments × trials and treatments × sites within catena.

Results

Soil conditions
Soils (Table 1 and Figure 1) are mostly potentially acid. Potential acidity tends to increase with distance from the sea. Within each catena, potential acidity is generally higher in the backswamps. Acidified surface soils occur everywhere with lowest values in the high backswamp of Katakerra, the only site where actual acid sulphate soils were observed.

Soil solution composition
At Balencera, near the river mouth, the pH in water samples from the surface soil horizon decreased after flooding, later increased up to 5.5 and, finally, decreased again after the flood water receded (Figure 2). At the transitional location (Rowolloh), the pH never fell below 5 and reached values close to 6 after prolonged flooding. At the

Table 1 Soil types according to Soil Survey Staff (1975) at the various sites

Site	Levee	Low backswamp	High backswamp
Balancera	Sulfaquent/ Aeric Sulfaquent	Sulfaquent	Aeric Sulfaquent
Rowolloh	Sulfaquent	Sulfaquent/ Sulfihemist	Sulfaquent
Katakera	Sulfaquent	Sulfaquent/ Sulfihemist	Sulfaquept

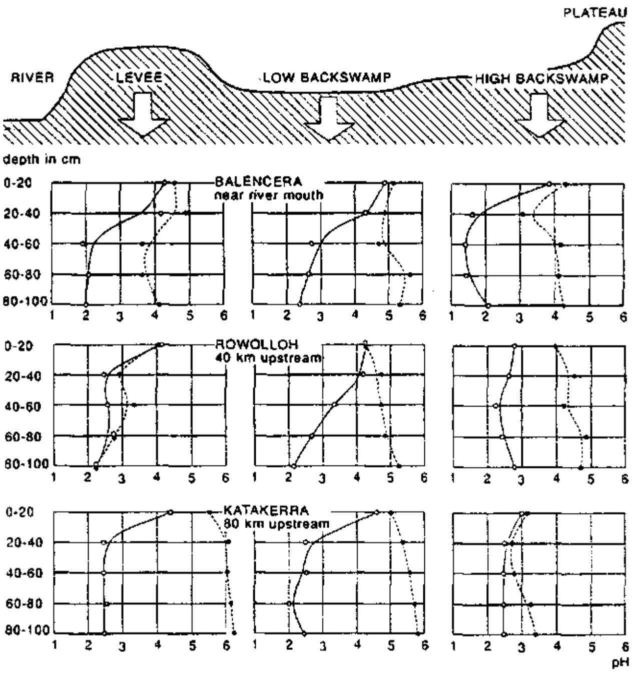

Figure 1 pH of the fresh soil (pecked lines) and pH after incubation (solid lines) along transects at each of the three sites

up-stream (Katakerra) intitially low pH values occured at the high backswamp location.

The highest salinities (with EC values up to 30 mS/cm) were observed near the river mouth while at the upstream locations, EC in the surface soils never exceeded 17 mS/cm.

Within the two upstream sites, Balencera and Rowolloh, salinity was lower on levees, adjacent to the river, and increased towards the high backswamp locations (Figure 3). At Katakerra, farthest upstream, a reverse pattern was observed. Except for an initial increase in EC with time after flooding at Balencera, EC values decreased with time of flooding in the rainy season. At Balencera, the EC in the soil solution in surface horizons (0-25 cm) reached values below 8 mS/cm (tolerable for suitable rice varieties) within 2 weeks (after August 1st) on the levee, within 7-8 weeks in the transitional area and only after 9 weeks in the upper catena site. In the upstream sites, tolerable salinity levels were generally reached within 1-4 weeks after the start of monitoring. In the deeper horizons, the EC remained high at Balencera (data not shown), presenting a risk of secondary soil salinization by capillary rise towards the end of the rainy season. Upstream locations generally had lower subsoil salinity, with inherently lower risk for salinization.

Potentially toxic iron concentrations ($>$ 300 mg/l) were observed only at the high backswamp sites in Katakerra and in Balencera (Figure 4). Fe^{2+} concentrations were

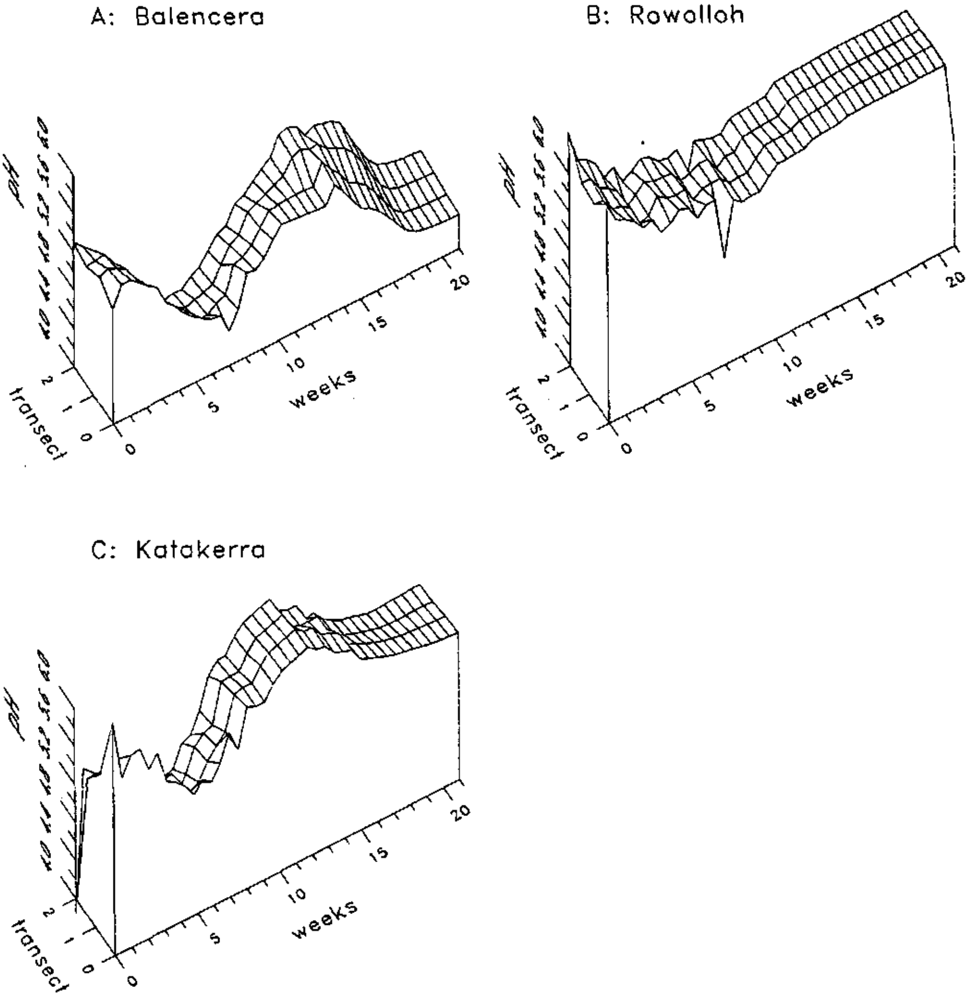

Figure 2 Temporal and spatial variability of pH of the soil solution at 0-25 cm depth in each of the three sites. Along each transect, 0 refers to the river levee, 1 to the low backswamp, and 2 to the high backswamp. Time is weeks after the start of monitoring

already high during the first sampling and, generally, decreased with time. The trend was not clear at Katakerra. Changes in the concentrations of Ca^{2+} (Figure 5) more or less paralleled the EC values suggesting a link between Ca^{2+} and salinity.

Results of the agronomic trials

At all sites, treatments as well as toposequence positions had highly significant effects on rice yield (Table 2). The individual ANOVA showed a very small cv% thus no chi-square test was necessary before carrying out the combined analyses. At each location, the effects of treatments on yield could be ranked as follows

$$T5 > \text{or} = T4 > T3 > T2 > \text{or} = T1 > T0.$$

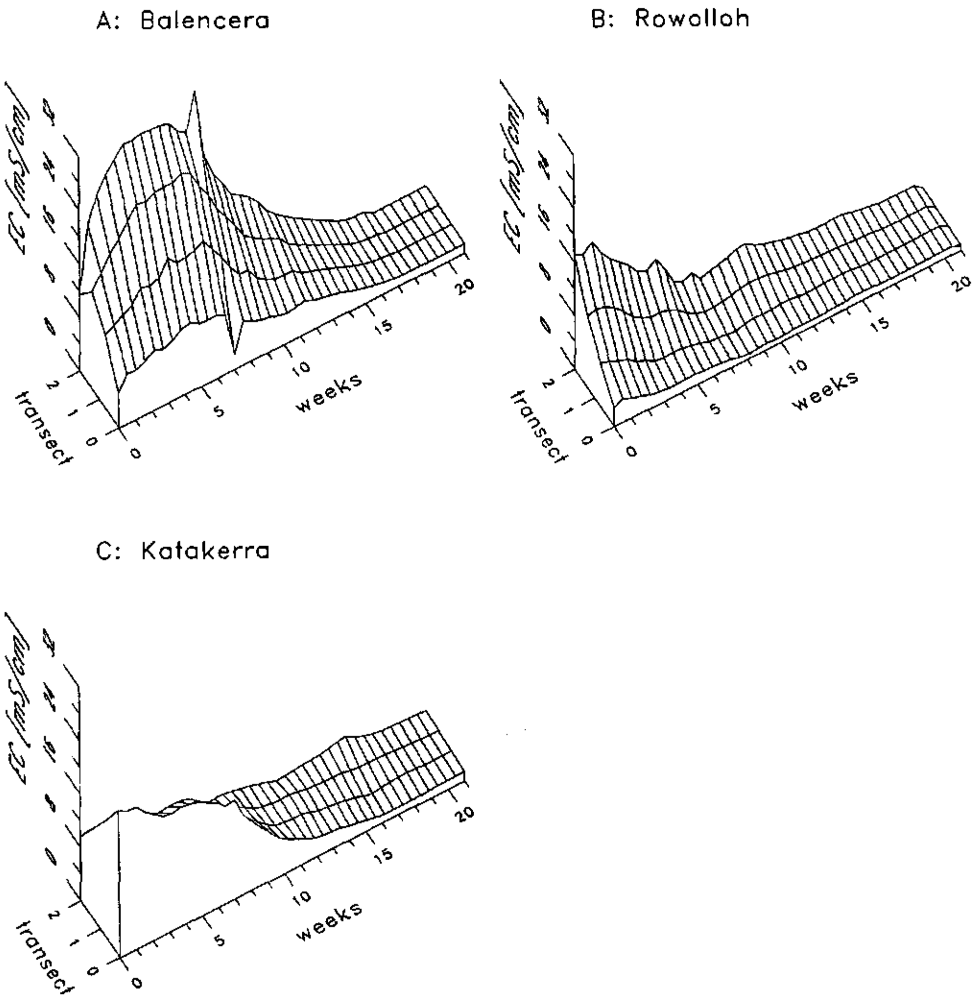

Figure 3 Temporal and spatial variability of salinity (expressed as electrical conductivity) of the soil solution sampled at 0-25 cm depth in each of the three sites. For explanation see Figure 2

Levee sites invariably gave highest yields. The overall analyses indicated highest yields at Rowolloh (4.3 t ha^{-1} paddy), followed by the near sea site (Balencera) (3.5 t ha^{-1} paddy), with Katakera trailing behind with 2.5 t ha^{-1} paddy.

The effect of lime was significant in all trials. The application of 2 t lime per ha alone increased percentage yield by 19 at Balencera, by 13 at Rowolloh, and by 30 at Katakerra. Lime and rock-P increased yield about 44 per cent at Katakerra but less at the other locations. The combined application of lime and N-urea gave higher yields than the lime and rock-P treatments. P treatments are less marked than N treatments.

The combined effect of 2 t lime per ha, rock-P, and N-urea gave the highest yield at all sites, with percentage increases relative to the control of 72 at Balencera, 53 at Rowolloh, and 87 at Katakerra. Increasing the lime application from 2 t ha^{-1} to 10 t ha^{-1} had a small significant positive effect only at Katakerra.

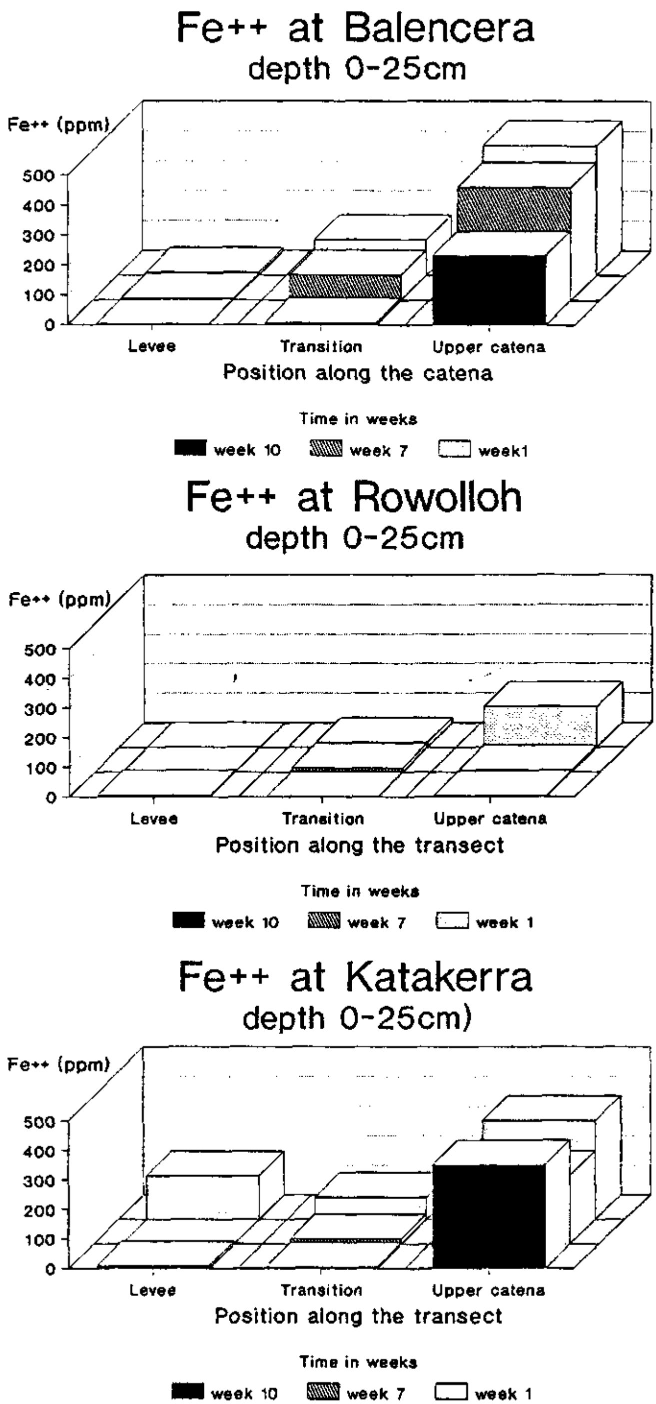

Figure 4 Concentrations of dissolved Fe^{2+} at 0-25 cm depth in each of the three sites, as a function of position in catena, at 1, 7 and 10 weeks after the start of monitoring

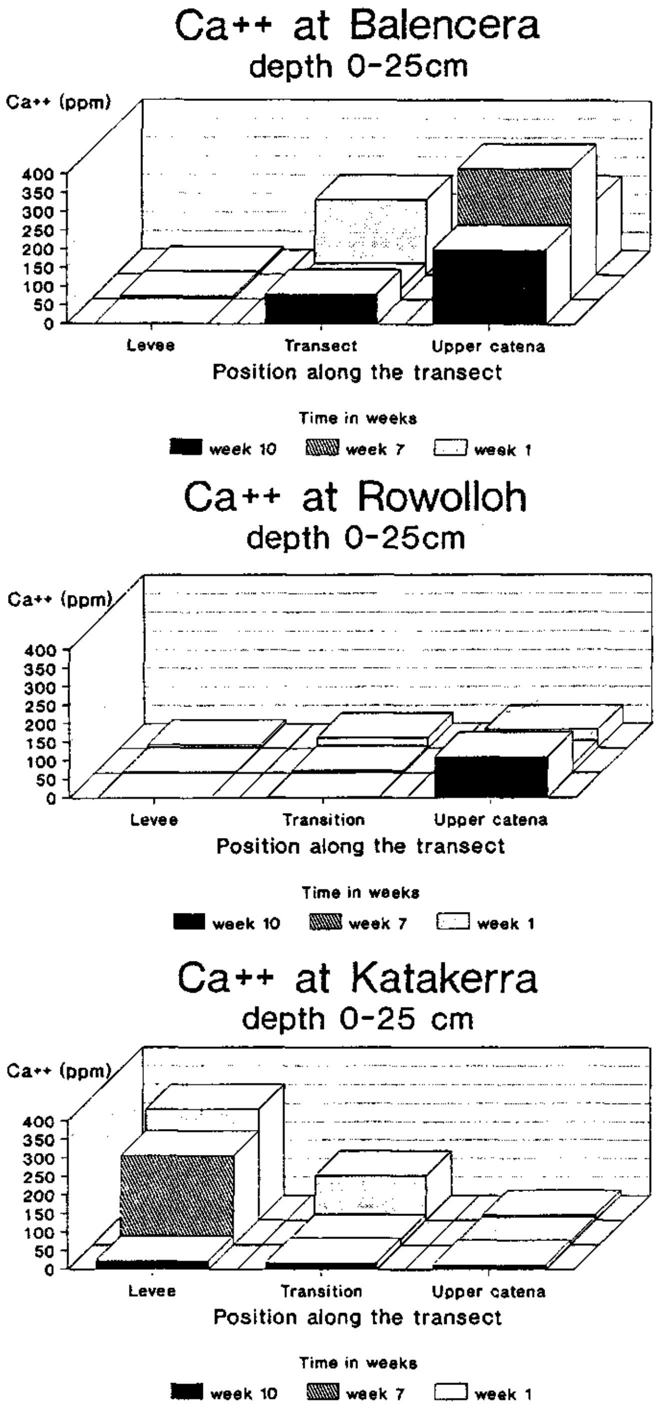

Figure 5 Concentrations of dissolved Ca^{2+} at 0-25 cm depth in each of the three sites, as a function of position in catena, at 1, 7 and 10 weeks after the start of monitoring

Table 2 Soil treatments and environmental effects on rice yield

Locations	Treatments*	Yeild t/ha	Landscape position	Yield** t/ha	CV %
Balancera (S1)	T0	2.47 d	levee	4.20 a	
	T1	3.04 c			
(near river mouth)	T2	3.17 c	low backswamp 1	3.73 b	
	T3	3.70 b			
	T4	4.24 a	low backswamp 2	3.03 c	
	T5	4.40 a			9.03
			high backswamp	3.05 c	
Rowollow (S2)	T0	3.29 e	levee	4.37 ab	
	T1	3.71 d			
(transition)	T2	4.10 c	low backswamp 1	3.99 c	
	T3	4.61 b			
	T4	5.03 a	low backswamp 2	4.57 a	
	T5	5.03 a			4.72
			high backswamp	4.24 b	
Katakera (S3)	T0	1.57 f	levee	3.54 a	
	T1	1.97 e			
(upstream)	T2	2.17 d	low backswamp 1	2.72 b	
	T3	2.57 c			
	T4	2.83 b	low backswamp 2	1.10 d	
	T5	3.09 a			6.71
			high backswamp	2.06 c	

* for an explanation of treatments see text
** within location means followed by the same letter are not different at level 0.05 (Duncan's test)

The low yields in the high backswamp at Katakerra were associated with bronzing of the rice, suggesting that Fe toxicity is one of the major constraints.

Discussion

Soil properties and changes in soil solution chemistry
The surface soils at all sites are somewhat acidified (pH 3-5). Subsoils are potentially acid, except in the high backswamp at Katakerra where soils have acidified strongly to an appreciable depth. Potential acidity is generally higher at the upstream locations and at sites away from the river levees. This pattern seems to be related to the former distribution of *Rhizophora* species, as suggested by the presence of hairy roots. At greater depths, total potential acidity was always high if hairy roots occurred. Actual acidity is generally low, which must be attributed to the general lack of prolonged deep drainage and aeration related to the strong tidal influence.

The spatial and temporal distribution of salinity is correlated with tidal propagation at the scale of the river basin, while the duration of saline water flooding across the transect depends on microtopography. This explains the higher EC at the site near the river mouth and within catena at the backswamp location. The relatively low EC near the levees at Balencera and Rowolloh can be explained by more efficient leaching in these zones. The reverse situation at Katakerra may be due to limited supply of saline water during the dry season, creating relatively little salinization across the catena.

The cause of the relatively high Fe^{2+} concentrations at the high backswamps sites in Balencera and Katakerra is not immediately clear. Both dissolved $FeSO_4$ originating from oxidizing pyrite, and Fe^{2+} derived from soil reduction following flooding can be involved (cf Van Breemen 1993). The fact that low pH values coincided with high Fe^{2+} concentrations in the early part of the wet season suggests that pyrite oxidation, rather than reduction of Fe^{3+} compounds upon flooding, is the main contributer to dissolved Fe^{2+}.

Ca^{2+} concentrations seem to be positively correlated with salinity. This can be attributed only in part to dissolved Ca^{2+} coming directly from seawater: the highest Ca^{2+} concentrations are in the same order as those in seawater (400 mg/l), while the highest salinities are only 5 to 10 per cent of those in sea water. Presumably, most of the dissolved Ca^{2+} is derived from ion exchange reactions associated with acidification and dilution following fresh water flooding.

Effects of amendments and soil conditions on rice yield

Moderate to good rice yields could be obtained at all locations and sites, indicating that stresses were either, at most, slight (in case of salinity) or could be overcome, in part, by amendments. At all sites, all the treatments had a positive effect on rice yield. The effects were greatest in the most acidic sites in Balencera and Katakerra. These results suggest that multiple nutritional stress related to acid sulphate soil conditions is the the cause of relatively low yields. The limited effect of P application may be related to a high P-fixing capacity of the soil.

The very slight extra gain in yield associated with increasing the lime dose from 2 t ha^{-1} to 10 t ha^{-1} suggests that low pH and associated high dissolved Al are not major soil constraints. The positive effect of the low lime dose may be caused by alleviating Ca deficiency. An important role of Ca nutrition, in particular as an antagonist to Fe (Moore and Patrick 1993), is also suggested by the different effects of high dissolved Fe^{2+} in the high backswamps sites at Balencera and Katakerra. Bronzing was absent at Balancera (where both Fe and Ca concentations were high), but strong at Katakerra (where Fe was equally high, but Ca was very low). Iron toxicity is caused by soluble iron, higher than a few hundred mg/l, particularly when associated with insufficient oxidizing ability of the rice roots due to e.g. low contents of Ca and K or high contents of H_2S in the soil solution. Even after 10 weeks, the stress was high so that it is not possible to escape Fe-toxicity by selecting another time window for the rice crop.

Conclusions

In tidal acid sulphate soils, studying spatial and temporal variability helps to determine a time window during the rice growing season when soil constraints are least. The optimal period for rice growing depends on location within the river basin as well as on toposequence position within each location.

In site 1, near the river mouth, salinity was a major constraint. The monitoring of ECs revealed a need of delaying transplanting by 2 to 9 weeks. This delay was less on the levees and increased towards the upper catena zone. The use of short-duration varieties is strongly advised.

In the transitional site 2, both salinity and metal toxicities were less severe. In general, rice yields were higher in this site while, within the site, yield decreased from the levee toward the high backswamp.

In site 3, situated upstream, salinity was not a main constraint but an inversed salinity gradient occurs as compared to the other sites (higher on levee). In the high backswamp zone, not only was dissolved iron III high but calcium and potassium were very low. Iron toxicity, therefore, remained the most limiting factor in this environment. No delay in transplanting rice would be able to reduce substantially the level of toxicity. Thus, only application of amendments and tolerant rice varieties can be recommended. Drainage should be strongly avoided at all sites because of the very high levels of potential acidity.

The following conclusions with respect to agronomic practices can be drawn:

1. At the scale of the river basin, physiographical features such as the distribution of *Rhizophora* and *Avicennia* can be used to define environments of high pyrite content, which will help to identify areas where deep drainage should be avoided. At the catena scale, microtopography seems to be very important in explaining the distribution of crop stress;
2. Near the river mouth, sequential delay of transplanting can be recommended to avoid excess salinity. However, this delay should fit the rain distribution, even if rice can sustain high salinity at maturity stage (Zashariah and Sankasubramoney 1961). Therefore, short duration varieties are strongly advised;
3. A small lime application in combination with N-urea and rock-P can substantially decrease the multiple nutritional stress and improve yield;
4. Iron toxicity cannot be circumvented by delaying transplanting. Liming and varieties tolerant of high Fe^{2+} are advised;
5. Monitoring the gradients of toxic soil substances in space and time during the growing season in relation to rainfall and tidal flooding is a low cost technique which provided useful information for the design of location-specific management practices.

References

Breemen, N. van 1973. Soil forming processes in acid sulphate soils. In: Dost, H. (editor), Acid sulphate soils. Proc. Int. Symp. Wageningen. Vol. I, 66-130. ILRI, Wageningen

Breemen, N. van 1976. Genesis and solution chemistry of acid sulphate soils in Thailand. PUDOC. Wageningen

Breemen, N. van 1993. Selected papers of the Ho Chi Minh City symposium on acid sulphate soils. International Institute for Land Reclamation and Improvement. Publication 53, 391-402, Wageningen

Burgess, T.M. and R. Webster 1980. Optimal interpolation of isarithmic mapping of soil properties. J. of Soil Science. 31: 315-331, 333-341, 505-524.

Burrough, P.A., M.E.F. van Mensvoort and J. Bos 1988. Spatial analysis as a reconnaissance survey techniques: an example from acid sulphate regions of the Mekong Delta, Vietnam. In: H. Dost (editor). Selected papers of the Dakar Symposium on acid sulphate soils. International Intitute for Land Reclamation and Improvement, Publication 44, 68-79, Wageningen

Konsten, C.J.M., W Andriesse and R. Brinkman 1988. A field laboratory method to determine total potential and actual acidity in acid sulphate soils. In: H. Dost (editor) Selected papers of the Dakar symposium on acid sulphate soils. International Institute for Land Reclamation and Improvement, Publication 44, 106-134, Wageningen

Moore, P.A. and W.H. Patrick Jr 1993. Metal availability and uptake by rice in acid sulphate soils. In: D.L. Dent and M.E.F. van Mensvoort (editors). Selected papers of the Saigon Symposium on acid sulphate soils. International Institute for Land Reclamation and Improvement, Publication 53, 205-224, Wageningen

Pons L.J., N. van Breemen and P.M. Driessen 1982. Physiography of coastal sediments and development of potential soil acidity. In: Acid Sulphate Weathering. Soil Sci. Soc. of Am., Special Publication 10, 1-18, SSSA Madison, Wisc.

Soil Survey Staff 1975. Soil Taxonomy, Agric. Hb 436 Washington D.C.

Stein, A., J. Bouma, M.A. Mulders, and M.H.W. Weterings 1989. Using spatial variability studies to estimate physical land qualities of a levelled river terrace: Soil Technology, 385-402.

Stein, A. 1991. Spatial interpolation. PhD Thesis, Soil Science and Geology Dept., Wageningen

WARDA 1983. Annual Report. Regional Mangrove Swamp Rice Research Station. Rokupr

Zashariah, P.K. and H.S. Sankarasubramoney 1961. Pot culture studies on salt tolerance of certain paddy varieties. Agr. Res. J. of Kerala 1, 104-105

CHAPTER 6

IMPROVEMENT OF RICE PRODUCTION ON ACID SULFATE SOILS IN WEST AFRICA.

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Improvement of rice production on acid sulphate soils in West Africa

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SUMMARY

High spatial variability of soil constraints such as acidity and salinity hampers the widespread application of improvement techniques of rice (*Oryza sativa L.*) production in the mangrove zone of West Africa. We studied the response of rice to liming and fertilizer application in relation to soil conditions in order to provide ways to characterize mangrove rice growing environments. Twenty nine trials with six treatments in various combinations of application of lime, rock phosphate and nitrogen were implemented during the 1991 and 1992 rainy seasons in the Gambia, the Casamance and the Great Scarcies river basins. The locations of the trials were selected on the basis of climate, proximity of the river mouth, topography and tidal flooding regime. At each location, soil solution chemistry, nutrient contents of rice flag leaves, grain yields and yield components were monitored throughout the growing period. In 1992, the residual effect on grain yield of the 1991 treatments was also measured. We found that two main rice growing environments can be distinguished : 1) the low rainfall Gambia and Casamance basins, where rice production was limited by high soil salinity, and where liming had little effect, and 2) the wet environment of the Great Scarcies river where soil acidity was the major limitation and where liming was more effective. The response to lime was related to the amount of dissolved divalent cations (Ca and Mg) in the soil solution. The response to rock phosphate was low in all locations. The molar fraction between Fe and (Ca + Mg) in flag leaves was better correlated to iron toxicity than the absolute concentration of Fe.

INTRODUCTION

Rice (*Oryza sativa L.*) is grown on about 214 000 ha of cleared mangrove swamps in Gambia, Casamance (Senegal), Guinea Bissau and Sierra Leone (WARDA 1983). Beye et al. (1975) reported the presence of 6.6 million ha of actual or potential acid sulphate soil in West Africa. Pons & van Breemen (1982) estimated that there are some 12 to 14 million ha of acid sulphate soils in coastal plains and tidal swamps worldwide, mostly in the tropics. The surface horizon of these soils is severely acid, or will become so if drained. The soil chemical problems for crop growth include: severe acidity, aluminum toxicity, low available phosphorous, low base saturation, nutrient deficiencies and high salinity. When flooded, soil pH tends to increase and dissolved Al may decrease, but then concentrations of other substances may reach toxic levels: ferrous iron, hydrogen sulphide, organic acids and carbon dioxide. Rorison (1972), Bloomfield & Coulter (1973), van Breemen (1976; 1993) and Dent (1986; 1992) reviewed the chemical processes in these soils and their constraints for crop growth. The diversity of reasons given for their low productivity and the multiplicity of remedies reported indicate that acid sulphate soils vary considerably in their spatial properties (Andriesse 1993 and Sylla et al. 1994 a, b) and respond differently to agricultural management. Dent (1992) pointed to the need to consider soil spatial variability when searching for the best combination of improved techniques on acid sulphate soils.

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Recently, much experimental work to improve acid sulphate soils for rice cultivation has been done in Asia and Africa (Dent & van Mensvoort 1993). No single reclamation technique for acid sulphate soils is universally applicable. Moormann (1961), Howeler (1974) and Benckiser et al. (1984) pointed to the possible beneficial effects of liming in alleviating soils acidity, and aluminum- and iron toxicity on crops grown in acid sulphate soils. In Malaysia, Ting Chaong Chaang et al. (1993) reported that lime (2 t/ha) and fertilizer application increased rice yields up to four times on pyritic mangrove soils formerly flooded by less than 20% of high tides (Sulfaquepts). But the same technique was ineffective on lower lying soils that were flooded more frequently (Sulfaquents). In Guinea Bissau, Van Gent & Ukkerman (1993) reported effects of fertilizer (N P) application to rice in different physiographic positions with different soil characteristics and hydrology. They observed significant yield increases due to fertilizer applications in low backswamp zones. Successful farmer practices involving consideration of differences in micro topography and related soil differences in acid sulphate soils to cope with specific soil constraints, were reported for tidal swamps of Southern Kalimantan, Indonesia (Watson & Willis 1985 and Muhrizal et al. 1993). Only hydrological factors were considered by characterizing the land according to tidal flooding classes (Kselik 1990), i.e. transplanting rice in relation to flooding conditions to alleviate primary iron toxicity as earlier reported by van Breemen & Moormann (1978) and Prade et al. (1988). Later Kselik et al. (1993) studied the effect of applying lime and fertilizers (N, P, K) in the four defined hydrological classes covering three soil types (Sulfic Tropaquepts, Sulfic Hydraquents and Sulfaquents). He found a significant effect of lime, and to, a lesser extent of N and P, on actual acid sulphate soils, but no lime effect was reported on Sulfaquents. In the Mekong delta (Vietnam), Do Thi Thanh Ren et al. (1993) reported a positive effect of N, P and lime and a negative effect of K on rice grown on Typic Sulfaquepts and Sulfic Tropaquepts. In Sri Lanka, Deturk et al. (1993) found a significant positive effect of lime alone or in combination with applying green manure (Gliricidia) and NPK fertilizers on rice grown on actual and potential acid sulphate soils. Dent (1986) reported positive effects of lime and rock-P on rice yield in Thailand on ripe acid sulphate soils with little effect of just lime. In contrast, in Brunei, Williams (1980) found spectacular positive effects of lime alone on rice yield on acid sulphate soils. Ponnamperuma & Solivas (1982) observed a good response of rice on unripe acid sulphate soils in The Philippines with NPK alone. A similar result was reported by Ottow et al. (1991) in the Casamance (Senegal). In Sierra Leone, Jeffery (1963) observed no significant effects of lime and super phosphate on undrained potential acid sulphate soils, while Turner (1980) reported significant effects of N and P on rice grown near the river edge and the zones of tidal limit, but none on deep-flooded low backswamp areas along the Great Scarcies River.

These findigns demonstrate the need to study in more detail the effects of chemical additions (lime, nitrogen and rock-phosphate) on rice grown in acid sulphate soils in West Africa. The variability of soil conditions affecting rice yields was studied at different scales with the aim to define the best combination of improvement techniques in relation to soil stresses as influenced by climate, distance to the river mouth ("site position") and the location of the rice field along a catena. At the same time, the response of the crop to amendments has been used to characterize rice growing environments.

MATERIALS AND METHODS

Study area and site selection

The study area included three river basins along the West African Atlantic coast, viz. from north to south: the Gambia River (Gambia), the Casamance River (Senegal) and the Great Scarcies River (Sierra Leone) (Fig.1.).

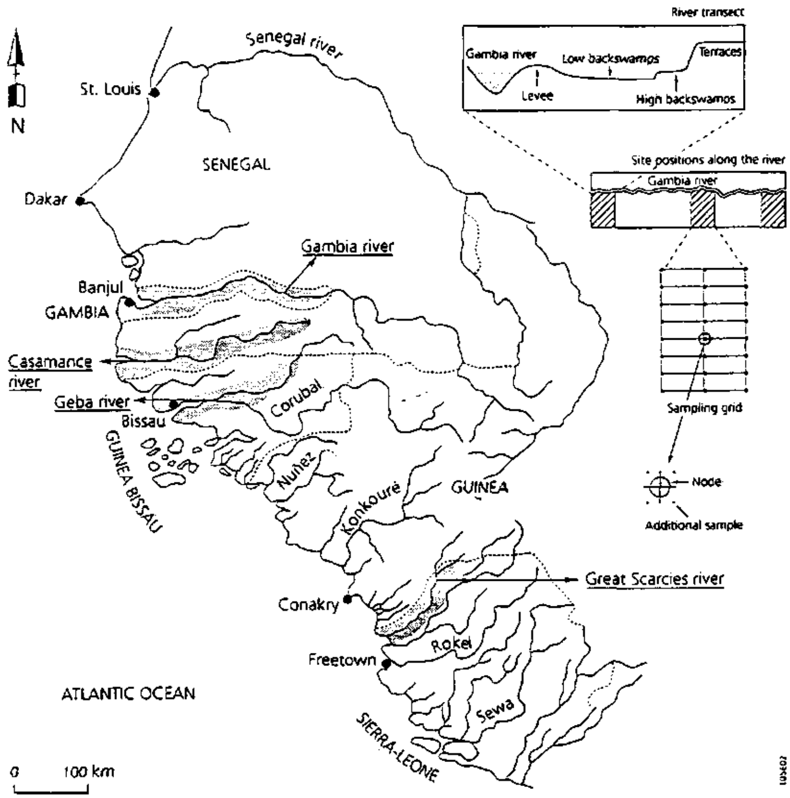


Figure 1: Location of the study area, sites and ~~sampling design along~~ the Gambia, Casamance and the Great Scarcies river basins.

Characteristics of climate, hydrology, salinity and landscape have been summarized elsewhere (Sylla et al. 1994 a). Rice is the main land use in the low-lying alluvial parts of the river basin. Site selection was based on the expected variability of soil salinity and potential acid sulphate soil conditions. Along each river basin, three sites were selected: one near the river mouth (S1), one midstream (S2) and one upstream, near the limit of tidal propagation (S3). Within each site, four landscape units were defined along a catena perpendicular to the river, varying in topographic position, tidal flooding regime and soil characteristics (levee, low backswamp 1 and 2, and high backswamp). In each of these units agronomic trials were implemented.

Representative soil profiles were described and sampled per soil horizon. Soil variability was studied by detailed grid sampling. Soil salinity (EC), total actual acidity (TAA) and total potential acidity (TPA) were measured in the dry season of 1991. Sampling methods and measurements of TAA and TPA are outlined in Sylla et al. (1994b).

Experimental design and treatments

Field trials

Thirty six field trials were planned for the wet seasons (Jun to November) 1991 and 1992 in the selected sites (3 river basins x 3 sites x 4 landscape units). Only twenty nine trials for each year could be implemented in agreement with the landowners and the existance of the landscape units. The missing trials are shown in table 7. In addition, along the Casamance and the Great Scarcies river basins, residual effects of lime and rock phosphate (rock-P) were monitored during the wet season of 1992 using the trials set up in 1991. Each trial consisted of six treatments, in a completely randomized design with four replicates. The treatments were: To= control; T1= 2t/ha lime; T2= 2t/ha lime and 250 kg/ha rock-P; T3= 2t/ha lime and 80 kg/ha N-urea; T4= 2t/ha lime and 250 kg/ha rock-P and 80 kg/ha N-urea ; and T5= 10t/ha lime and 250 kg/ha rock-P and 80 kg/ha N-urea. In 1992 the treatment T5 was not implemented. The 5 by 5 m plots were separated by 0.5 m wide strips. Each plot was surrounded by hand-made bunds, of 25 to 50 cm height, to minimize lateral transfer of chemical amendments by flood water. Lime and rock-P were incorporated in the topsoil (0 to 20 cm) during land preparation according to local farmers' practices, viz. in ridges (Casamance) or in flat ploughed and puddled plots (Gambia and Great Scarcies). N-urea was broadcast in split doses (2/3 at 20 days after transplanting [DAT] and 1/3 at 40 DAT). Five- to six-weeks old seedlings of the rice variety Rok5 (tolerant to high salinity and acidity) were transplanted with 2 to 3 seedlings per hill (transplanting had to take place this late in order to diminish the risk of crab damage to young seedlings), at distances of 20 by 20 cm. The nursery received 100 kg/ha of N-urea, 250 kg/ha of rock-P, 40 kg/ha of K_2O and 2t/ha lime. To reduce damage by insects (stem borers e.i. *Maliarpha separatella*), all trials were treated with Furadan especially at tillering. Hand-weeding was done as required. Seedlings damaged by crabs within the first four weeks after transplanting were replaced. Every 15 days plant height, numbers of tillers and panicles were recorded. At panicle initiation, flag leaves were sampled at each plot, washed with deionized water and dried for further laboratory analyses. At harvest, the net 4.5 by 4.5 m interior part of each plot (excluding the border lines) was harvested by hand, the grains threshed, winnowed and sun-dried. Grain and straw were weighed and samples taken for grain moisture content and the 1000-grain weight. Grain yields were converted to 14% moisture. For the residual trials in 1992, only physiological disorders, if any, were noted, and grain yields were measured at harvest.

Soil solution chemistry

Two different set-ups for monitoring soil solution chemical content were implemented

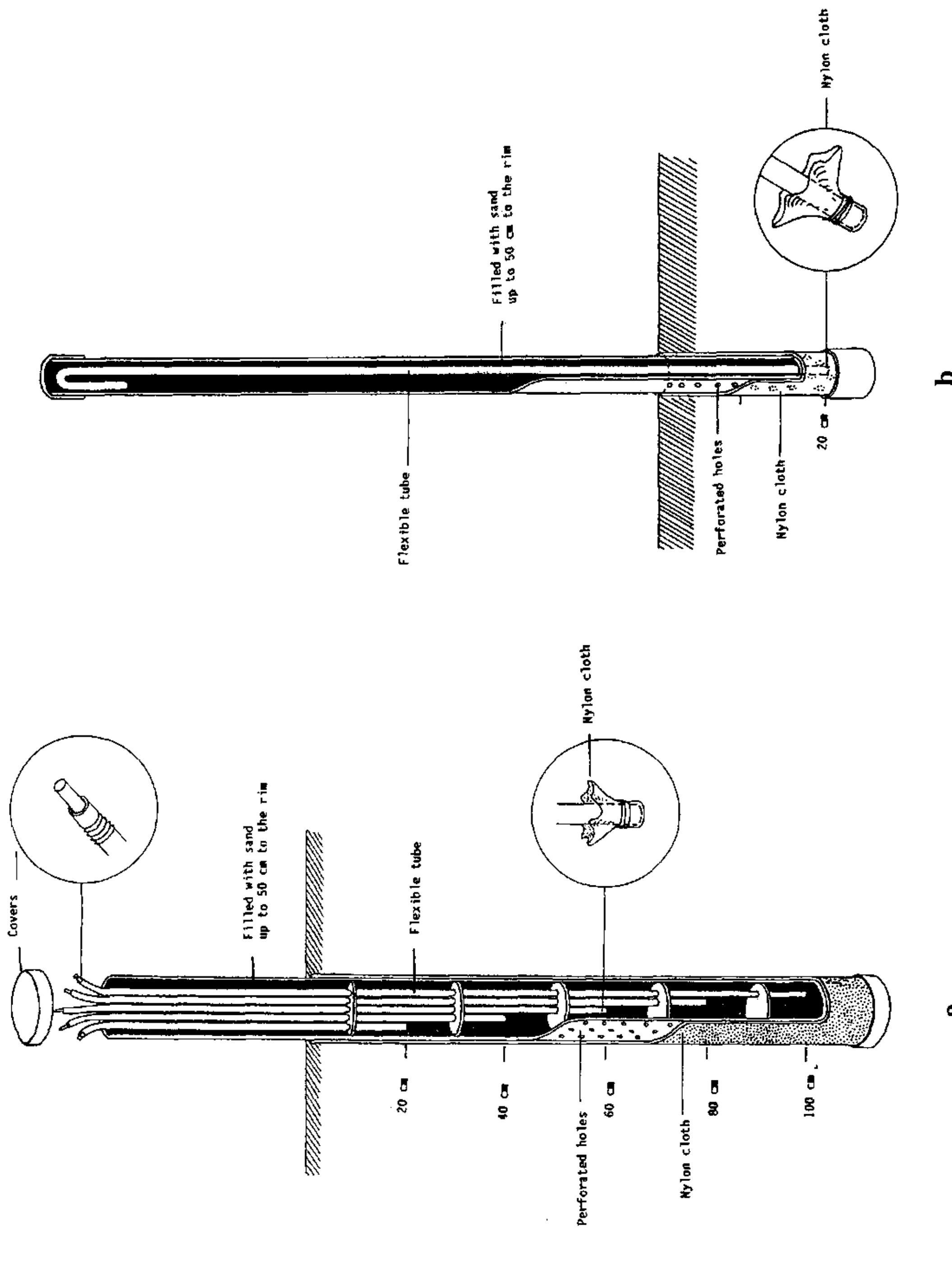


Figure 2: Soil solution extractors.

along the Casamance and the Great Scarcies' sites representing two extreme climatic conditions. In 1991, the soil solution was monitored twice monthly, starting the first week of flooding, using 4 soil solution extractors per site, one in each landscape unit. The extractors were constructed with Polyvinyl (PVC) pipes (Φ = 12 cm) perforated (about Φ = 1 cm) from the bottom up to 1 m. Flexible teflon tubes 4 mm inner diameter were placed at different depths (Fig. 2a). The bottom of each flexible tube was wrapped with nylon cloth. After installing the flexible tubes, the PVC pipes were filled with prewashed coarse silica sand to minimize aeration through the pipe and the perforated part wrapped with nylon cloth; both sand and nylon cloth served as filters. Each sampling depth (0 to 20, 20 to 40, 40 to 60, 60 to 80 and 80 to 100 cm) in the pipe was separated by a plastic ring with a stopper to let through the flexible tubes (Fig. 2a.). Both pipes and tubes were closed at the top to minimize oxidation. A similar setting was used in 1992 with smaller PVC pipes (Φ = 5 cm) perforated only at the bottom 20 cm for extracting water from the topsoil (Fig.2b.) in each plot within all the trials. The soil solution was sampled at 1, 2, 4, 8, 16 and 32 weeks after transplanting. All extractions were done with a hand operated peristaltic pump (3 bar). After discarding the first three aliquots, pH and electrical conductivity (EC) were measured immediately. Polyethylene plastic bottles (250 cc) were used for sampling and storage and were filled to the rim and closed for further filtering and acidification in the laboratory. Filtration was done through a 0.2 μm membrane filter using syringe with polysulfone holders). A few drops of hydrochloric acid (HCl) were added to acidify the filtered samples which were stored in a refrigerator prior to analysis (maximum storage time was 4 month).

Chemical analyses

Soil samples were air-dried, and ground to pass a 2 mm sieve. pH and EC were measured in a 1:2.5 and 1:5 soil-water suspension respectively. TAA and TPA were measured by titration to pH 5.5 in a 1 mol/l NaCl suspension on fresh soil sample or after forced oxidation with hydrogen peroxide respectively (Konsten et al, 1988). Exchangeable Ca and Mg were measured by Atomic Absorption Spectrophotometer (AAS) using an air-acetylene flame after adding $LaCl_3$. Exchangeable Al was measured by AAS with a nitrous oxide-acetylene flame. Na and K were measured by flame photometry (AES) using air-acetylene flame after adding CsCl. Total nitrogen was measured after digestion (Kjeldahl) in a mixture of sulphuric acid and Selenium by Auto Analyzer. Available P was analyzed by the Olsen method.

Plant samples were oven-dried (70 to 80°C) overnight and digested in a mixture of sulphuric and salicylic acids. Na, K and Ca were measured by AES and AAS as for the soil samples. Soil solution and surface water samples were analyzed for pH, EC, Na, Mg, and Al using the same procedures for the soil samples. Iron was analyzed by AAS with an air-acetylene flame; the possible signal reduction by organic acids was prevented by adding a few drops of 1 M HCl.

Statistical procedures for agronomic trials

ANOVA and F-tests were computed to compare treatments within trials. Next, a combined analysis of variance over location was done after a chi-squared test for homogeneity of variance. Duncan's multiple range tests were applied to separate means. By multiple correlation analysis, relationships between yield, leaf nutrients content and soil solution chemical composition were established.

RESULTS AND INTERPRETATION

Soil conditions

Almost all the soils were saline (EC 1:5 > 2 mS /cm) in the dry season of 1991. In the following emphasis will be put on the two extreme cases of the Casamance and the Great Scarcies river basins. Soil salinity along the river basin and across catena's was highly variable along the Casamance river (dry climatic zone), and much less so along the Great Scarcies river (wet climatic zone) (Fig. 3). Different salinity environments across river basin and within catena were defined and could be related to climate, proximity of the river mouth and position along the catena (Sylla et al. 1994a). Soluble soil Na, Mg and, to lesser extent, Ca were closely related to measured EC. The acidity status expressed in terms of TAA and TPA is given in Fig. 4 which clearly differentiates the two environments. Potential acidity was invariably high at all sites along the Great Scarcies river and much lower along the Casamance river. Very high actual acidity (>30 cmol H^+ /kg) in topsoils was observed at S3 along the Great Scarcies river. Such TAA values also occurred along the Casamance river, but only at greater soil depth. The soil classification units observed along the Casamance and the Great Scarcies rivers are given in table 1 showing more soil development along the Casamance river.

Table 1: Soil types at Three sites along the Casamance (Senegal) and Great Scarcies River basins (Soil Survey Staff, 1975). S1 stands for the site near the river mouth, S2 for the site at around mistream and S3 for the site upper stream.

Site		Levee	Low backswamp	High backswamp
Casamance	S1	Clay, very saline Aeric/ Hydraquent or / Sulfaquent	Clay to sandy clay very saline to saline Tropaquept	Sand to sandy clay slightly saline Tropaquept
	S2	Silty clay to sandy clay saline Sulfic hydraquent or in cases Aeric Sulfaquent	Sand to sandy clay saline Rhodic Pale Sulfic Tropaquept	Sandy clay slightly saline Rhodic Pale Sulfic Tropaquept
	S3	Clay extremely saline Aeric Sulfaquent	Clay, saline Typic Sulfaquept	Sandy clay slightly saline Rhodic Pale Sulfic Tropaquept
Great Scarcies	S1	Silty clay saline Sulfaquent or Aeric Sulfaquent	Clay saline Sulfaquent	Clay Aeric Sulfaquent
	S2	Silty clay to clay saline Sulfaquept	Clay saline Sulfihimist or Sulfaquent	Clay saline Sulfaquent
	S2	Clay saline Sulfaquent	Clay saline Sulfaquent or Sulfihimist	Clay saline Typic Sulfaquept

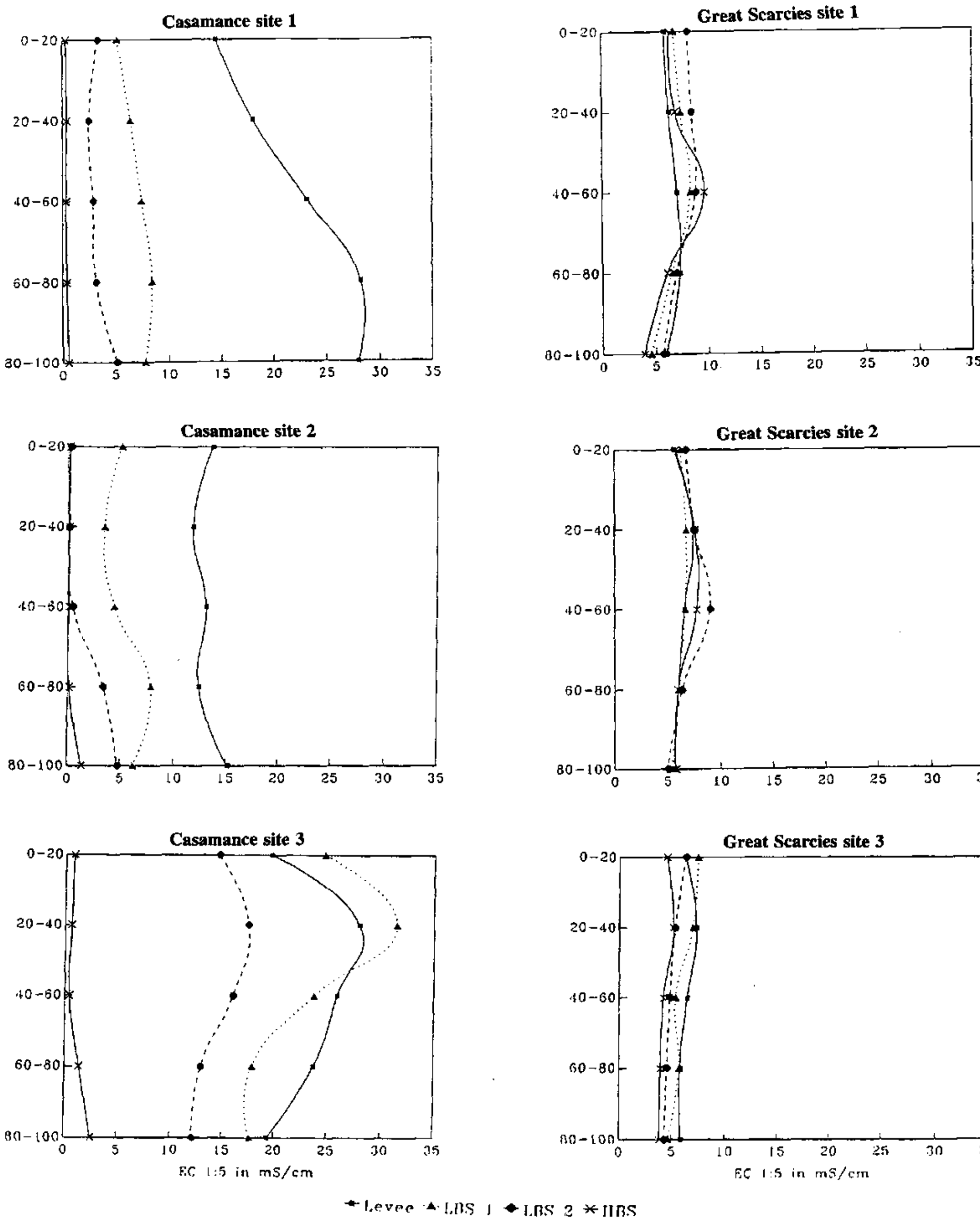


Figure 3: Soil salinity (in EC 1:5 soil water suspension) profiles along the Casamance and the Great Scarcies river basins. Samples were taken during the dry season of 1991. Sites from 1 to 3 are near river mouth, at midstream and at upstream respectively.

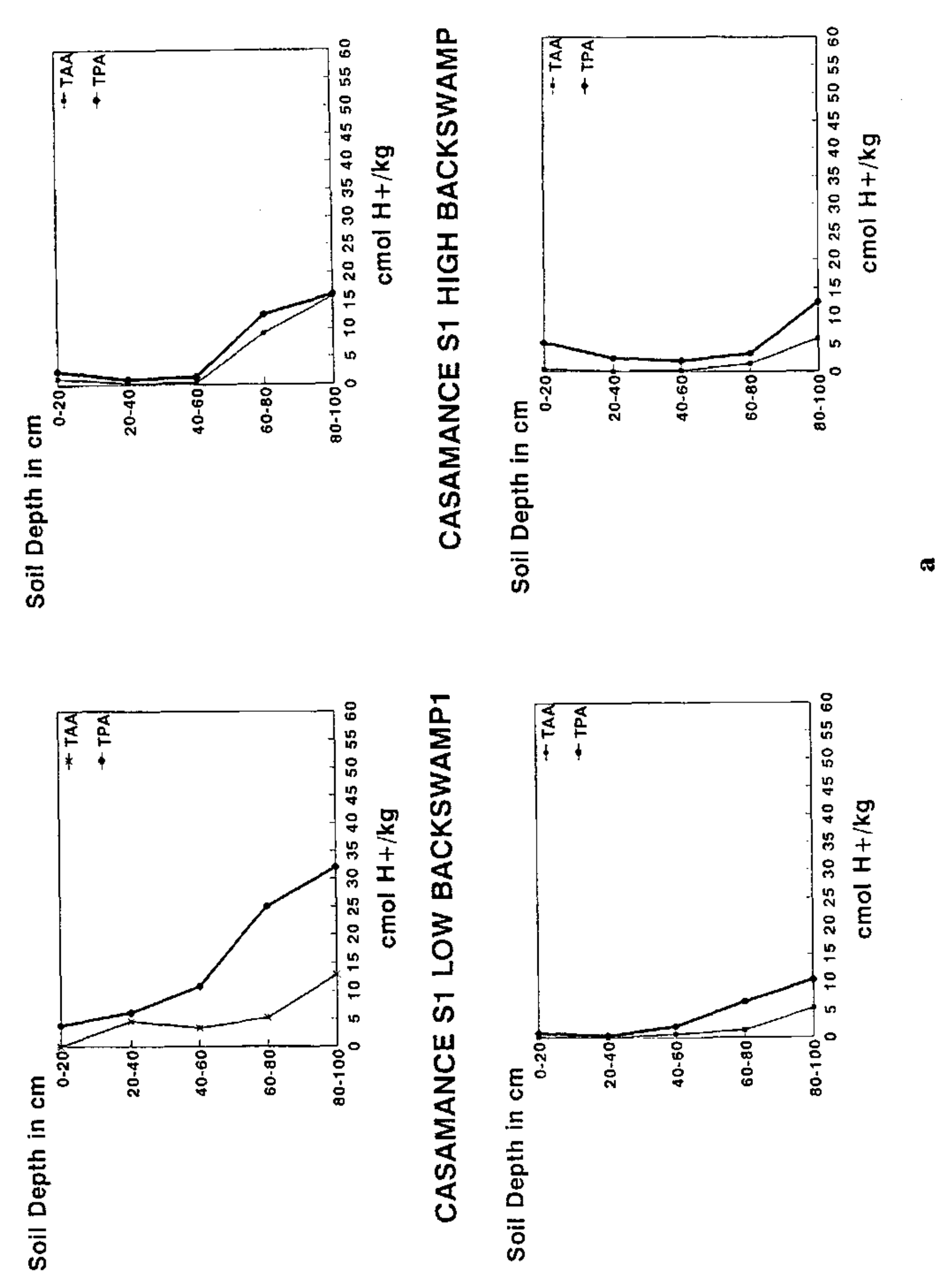


Figure 4: Soil Total Actual Acidity (TAA) and Total Potential Acidity (TPA) profiles along the Casamance (4a-c) and the Great Scarcies (4d-f) river basins. Samples were taken during the dry season of 1991. Sites 1 to 3 are near the river mouth, at midstream and at upstream. TAA and TPA were analysed according to Konsten et al. (1988).

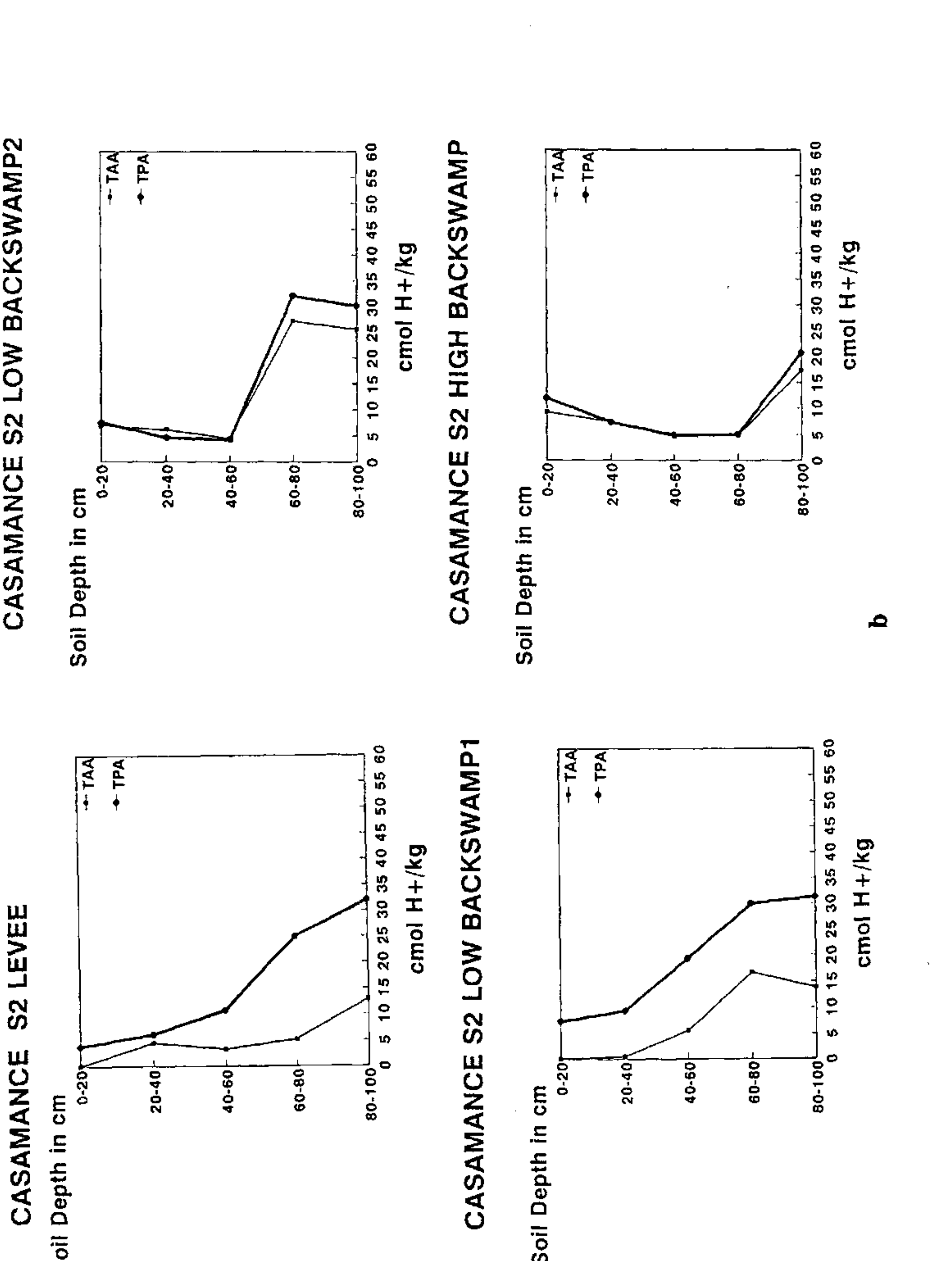
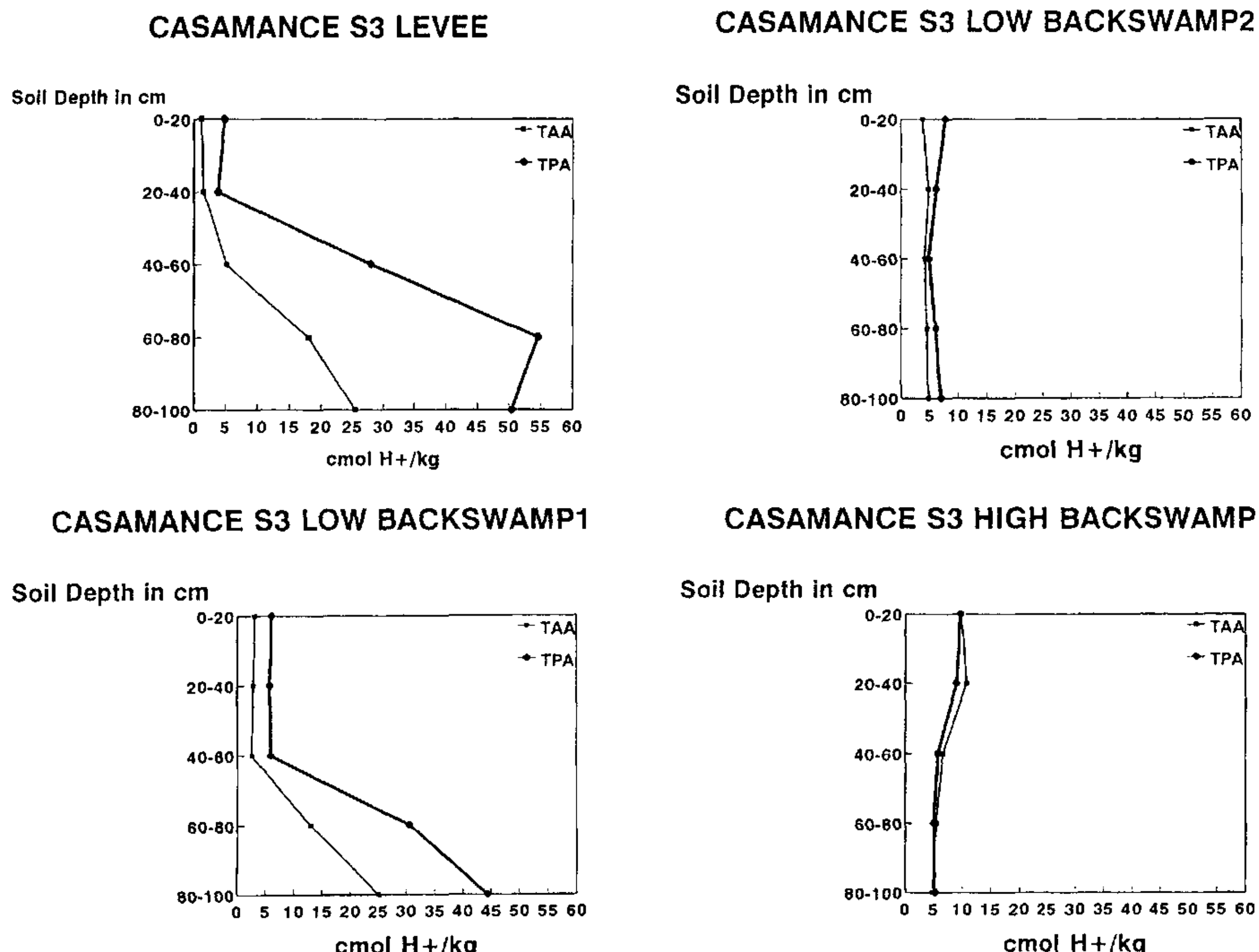


Figure 4: Soil Total Actual Acidity (TAA) and Total Potential Acidity (TPA) profiles along the Casamance (4a-c) and the Great Scarcies (4d-f) river basins. Samples were taken during the dry season of 1991. Sites 1 to 3 are near the river mouth, at midstream and at upstream. TAA and TPA were analysed according to Konsten et al. (1988).


CASAMANCE S3 LEVEE
Soil Depth in cm
0-20
20-40
40-60
60-80
80-100
TAA
TPA
0 5 10 15 20 25 30 35 40 45 50 55 60
cmol H+/kg
CASAMANCE S3 LOW BACKSWAMP2
Soil Depth in cm
0-20
20-40
40-60
60-80
80-100
TAA
TPA
0 5 10 15 20 25 30 35 40 45 50 55 60
cmol H+/kg
CASAMANCE S3 LOW BACKSWAMP1
Soil Depth in cm
0-20
20-40
40-60
60-80
80-100
TAA
TPA
0 5 10 15 20 25 30 35 40 45 50 55 60
cmol H+/kg
CASAMANCE S3 HIGH BACKSWAMP
Soil Depth in cm
0-20
20-40
40-60
60-80
80-100
TAA
TPA
0 5 10 15 20 25 30 35 40 45 50 55 60
cmol H+/kg

c

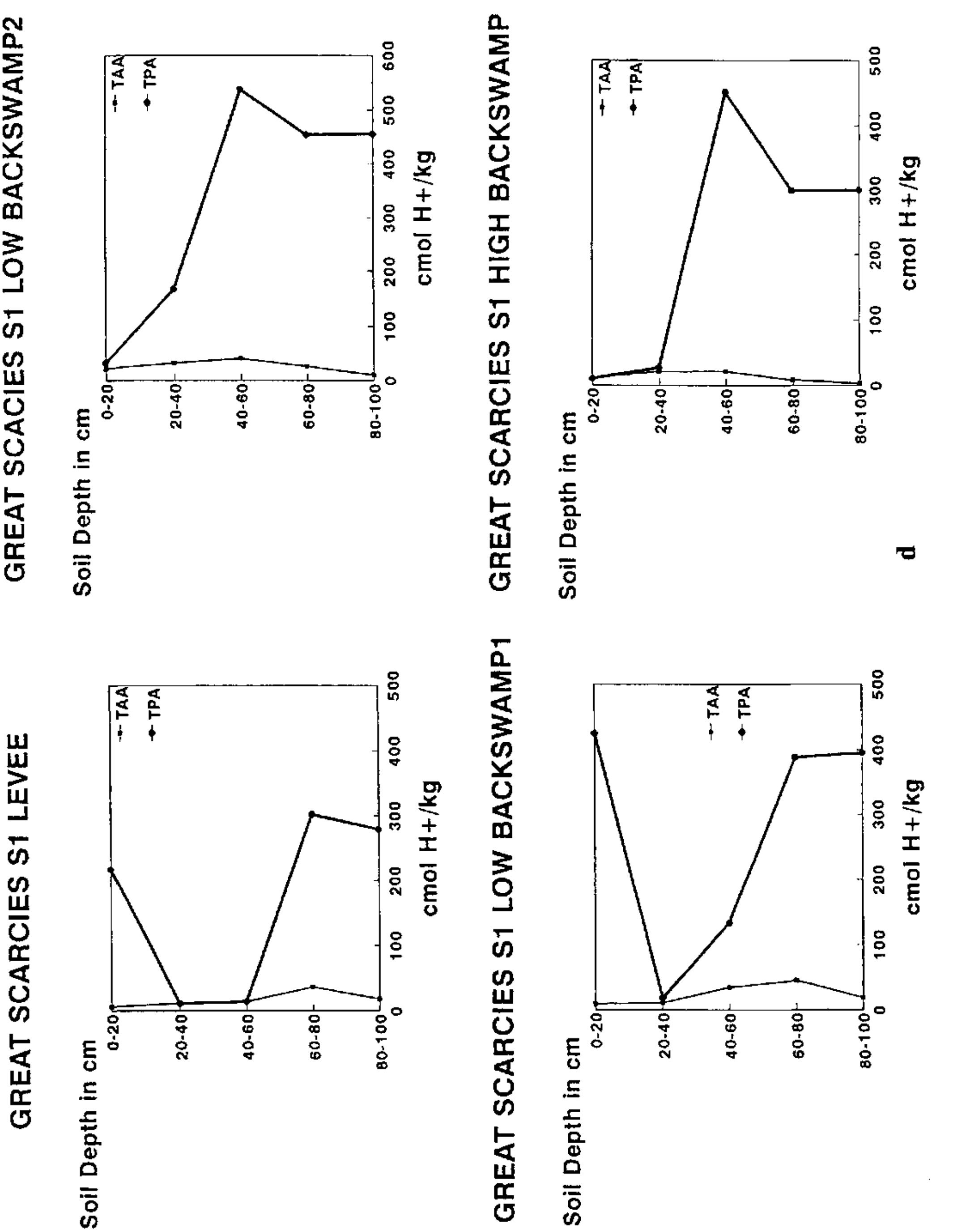
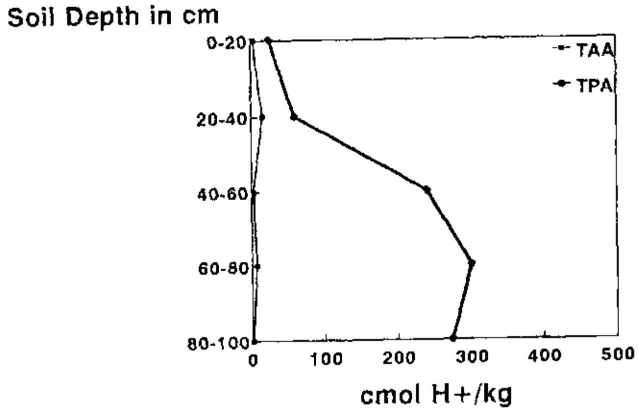
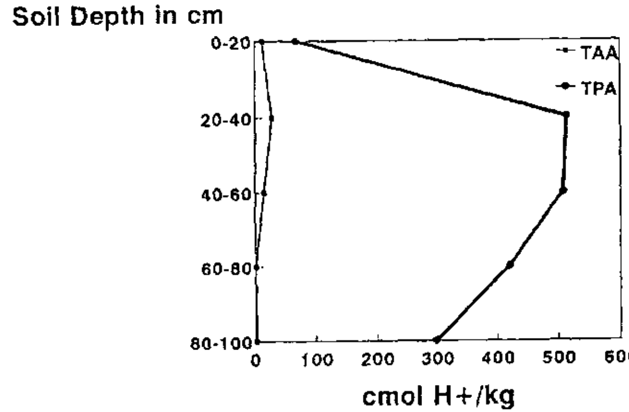


Figure 4: Soil Total Actual Acidity (TAA) and Total Potential Acidity (TPA) profiles along the Casamance (4a-c) and the Great Scarcies (4d-f) river basins. Samples were taken during the dry season of 1991. Sites 1 to 3 are near the river mouth, at midstream and at upstream. TAA and TPA were analysed according to Konsten et al. (1988).

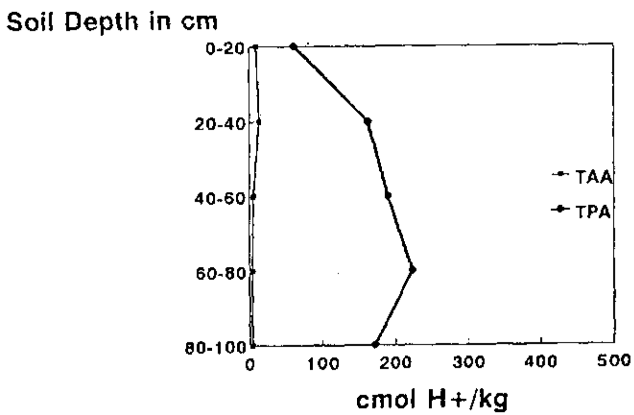
GREAT SCARCIES S2 LEVEE



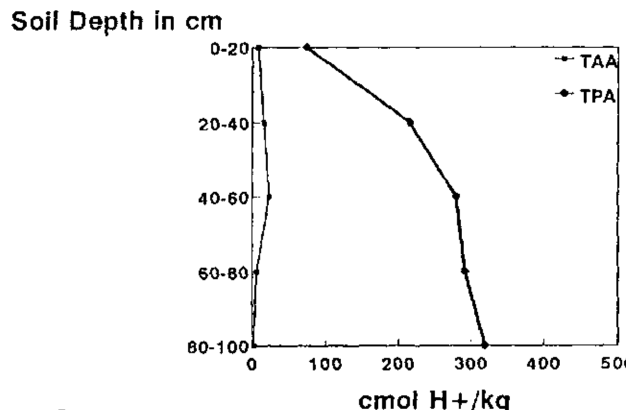
GREAT SCARCIES S2 LOW BACKSWAMP2



GREAT SCARCIES S2 LOW BACKSWAMP1



GREAT SCARCIES S2 HIGH BACKSWAMP



e

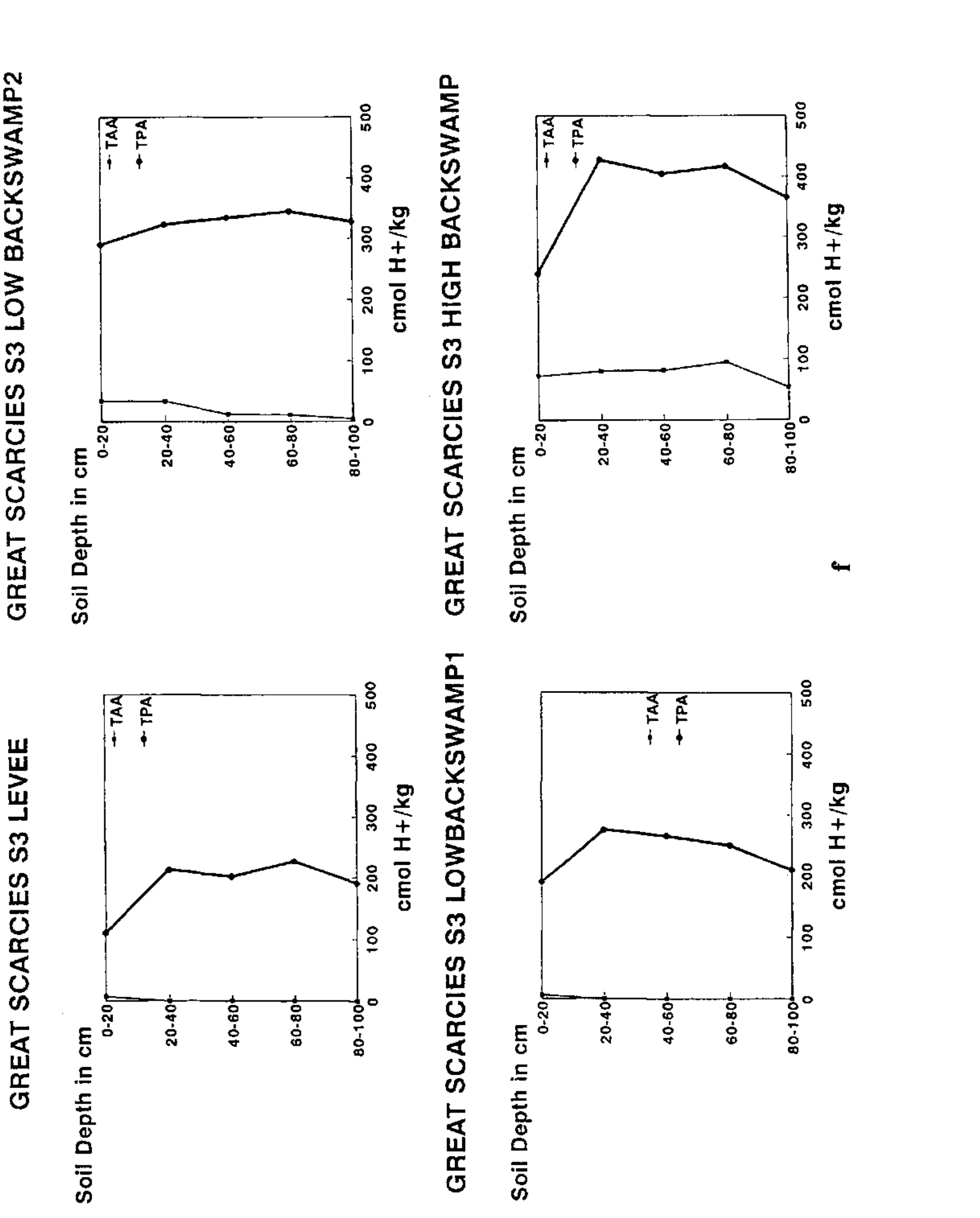


Figure 4: Soil Total Actual Acidity (TAA) and Total Potential Acidity (TPA) profiles along the Casamance (4a-c) and the Great Scarcies (4d-f) river basins. Samples were taken during the dry season of 1991. Sites 1 to 3 are near the river mouth, at midstream and at upstream. TAA and TPA were analysed according to Konsten et al. (1988).

Locations	Soil solution chemical composition at different dates at 0 to 20 cm soil depth																							
	K (mmol l^{-1})				Na (mmol l^{-1})				Ca (mmol l^{-1})				Mg (mmol l^{-1})				pH				EC (dS m^{-1})			
	extraction date				extraction date				extraction date				extraction date				extraction date				extraction date			
CASAMANCE	D1	D2	D3	D4	D1	D2	D3	D4	D1	D2	D3	D4	D1	D2	D3	D4	D1	D2	D3	D4	D1	D2	D3	D4
Kagnoutt (S1)																								
levee	7.96	9.39	8.74	-----	512	667	594	----	54	48	62	----	136	171	213	----	6.27	6.56	6.14	----	38	47	21	---
low backswamp1	4.75	5.89	5.01	-----	291	364	342	----	35	35	42	----	62	86	93	----	6.16	6.61	6.19	----	21	24	17	---
low backswamp2	1.29	1.31	1.18	-----	50	56	55	----	6	5	5	----	6	9	8	----	6.84	7.12	6.77	----	6	6	6	---
high backswamp	0.26	0.23	0.17	-----	6	6	5	----	1	2	2	----	0.5	0.1	1	----	7.32	7.47	6.99	----	1	5	1	---
Fanda (S2)																								
levee	0.44	0.27	0.43	0.28	11	6	11	7	3	2	2	1	3	2	2	2	6.69	6.67	6.62	6.48	3	2	2	2
low backswamp1	0.21	0.20	0.26	0.16	6	6	7	5	2	2	1	1	1	2	1	1	6.52	6.59	6.57	6.43	2	2	1	1
low backswamp2	0.22	0.21	0.27	0.19	5	6	8	6	2	1	1	1	1	1	1	1	6.50	6.72	6.56	6.45	1	1	1	1
high backswamp	0.34	0.27	0.36	0.24	6	6	9	6	4	8	2	3	1	2	1	1	6.39	6.40	6.46	6.62	1	2	2	1
Adeane (S3)																								
levee	2.54	4.82	4.22	3.31	159	312	286	207	18	28	24	29	45	83	71	64	5.17	5.92	5.92	5.90	41	12	22	15
low backswamp1	6.07	6.66	5.87	4.57	440	510	506	338	44	47	43	35	145	153	137	111	5.47	5.90	6.57	5.93	72	15	40	22
low backswamp2	4.02	5.24	5.11	3.80	253	393	357	250	35	40	34	27	80	118	107	88	5.81	5.77	6.36	6.01	44	10	28	20
high backswamp	2.44	3.70	3.58	3.10	141	219	207	193	24	29	22	24	40	61	56	70	5.94	5.92	6.36	6.08	27	8	20	21
GREAT SCARCIES																								
Balencera (B1)																								
levee	0.63	0.95	0.36	0.59	19	22	18	19	0.08	0.67	0.02	0.01	3	2	2	6	6.33	6.50	7.00	6.91	2	2	1	2
low backswamp1	1.23	1.60	0.62	0.92	51	39	29	33	0.93	2.18	2.20	1.46	10	10	5	5	6.40	6.50	6.60	5.87	5	6	3	2
low backswamp2	1.60	2.25	1.16	1.21	76	66	55	46	2.29	2.21	2.32	2.17	15	14	9	7	6.02	6.02	6.50	5.85	7	6	6	5
high backswamp	1.41	2.00	1.08	0.96	66	53	51	35	3.16	2.46	2.16	2.50	13	12	7	6	6.30	6.01	6.50	5.79	7	6	4	4
Rowollow (S2)																								
levee	0.61	0.48	0.44	0.66	24	15	19	15	0.32	0.04	0.02	0.15	4	2	2	2	5.68	6.03	6.00	5.44	2	2	1	1
low backswamp1	0.90	0.52	0.38	0.55	31	14	19	13	1.88	1.66	2.57	1.52	7	3	3	3	6.07	6.25	6.20	5.40	4	2	1	1
low backswamp2	1.15	0.87	0.82	1.40	53	39	32	46	2.79	2.09	2.70	1.89	11	7	7	6	6.01	6.14	6.47	5.19	6	4	4	5
high backswamp	1.06	0.80	0.60	0.90	39	25	29	20	2.79	2.42	2.81	2.00	10	6	5	4	6.26	6.39	6.12	5.40	4	3	2	3
Katakera (S3)																								
levee	1.99	1.12	1.59	1.58	63	52	72	55	5	4	4	4	19	16	18	9	6.43	6.55	5.68	5.68	8	7	2	6
low backswamp1	1.59	0.87	0.96	0.72	39	41	31	29	4	3	3	3	12	9	8	6	6.71	6.92	5.84	5.75	5	5	1	3
low backswamp2	1.68	1.00	1.22	1.00	53	59	54	69	3	3	3	3	14	10	12	9	6.24	6.42	5.16	6.12	6	5	5	5
high backswamp	0.51	0.29	0.16	0.41	13	12	9	62	2	2	2	2	4	9	2	2	4.65	4.14	4.83	5.75	1	1	1	1

Table 2: Soil solution chemistry (0 to 20 cm depth) during the 1992 trials at different times (monthly interval) starting one week after rice transplanting at different sites along the Casamance and the Great Scarcies river basins.

Water analyses

Surface water in the rice field at transplanting was generally acid (pH < 3 to 4) in the backswamps, while the river water was invariably neutral to slightly alkaline. In the course of the growing season the pH of the field surface water increased to almost neutral. River water salinity was high throughout the growing season along the Gambia and Casamance rivers (EC > 12 dS /m). Along the Great Scarcies river EC decreased rapidly after the onset of the wet season, starting upstream, to values less than 8 dS /m. A rapid decrease of flood water salinity was observed along the Great Scarcies river, while along the Casamance river and the Gambia river the decrease was slow. Data from soil solution monitoring using deep piezometers at the four landscape units in each site during 1991 rainy season were analyzed to define a time window within which minimum soil stresses for rice growth were observed for iron, aluminum, and salinity. Along the Great Scarcies river such a time window of low salinity (EC at 0 to 20 cm depth < 8 dS /m) of 3 to 4 months could be identified. Along the Gambia and the Casamance river basins the time window lasted only 1 to 3 months (see also Sylla et al. 1993). The two river basins differed strongly in the content of Na, Ca, and Mg in the soil solution. The concentration of these ions reflected salinity, as indicated by the EC (Table 2). Salinity was high within the Casamance basin except at S2, and lower along the Great Scarcies river basin.

Table 3a: Coefficients of correlation between soil solution chemitry and rice grain yields for the 1992 trials along the Gambia, the Casamance and the Greta Scarcies river basins.

	K	Na	Ca	Mg	Fe	pH	EC	Yield
K	1.000							
Na	0.995	1.000						
Ca	0.981	0.991	1.000					
Mg	0.990	0.997	0.991	1.000				
Fe	0.610	0.637	0.610	0.657	1.000			
pH	-0.178	-0.199	-0.137	-0.225	-0.703	1.000		
EC	0.970	0.980	0.967	0.987	0.747	-0.333	1.000	
Yield	-0.786	-0.822	-0.859	-0.841	-0.625	0.151	-0.852	1.000

Table 3b: Coefficients of correlation between soil solution chemitry and rice grain yields for the 1992 trials along the Gambia and the Casamance river basins (dry environment).

	K	Na	Ca	Mg	Fe	pH	EC	Yield
K	1.000							
Na	0.997	1.000						
Ca	0.995	0.996	1.000					
Mg	0.992	0.997	0.990	1.000				
Fe	0.585	0.632	0.619	0.667	1.000			
pH	-0.443	-0.499	-0.468	-0.544	-0.934	1.000		
EC	0.956	0.970	0.961	0.982	0.786	-0.673	1.000	
Yield	-0.766	-0.796	-0.786	-0.817	-0.884	0.805	-0.894	1.000

In soils of both river basins, EC decreased with time over the growing season. Iron was generally lower than the defined toxic level (300 mg /kg or 5.37 mmol /kg) (Tanaka & Yoshida, 1970) at all sites. No clear effect of soil amendments on soil solution chemistry was apparent. A highly significant multiple correlation was derived between yield and the chemical concentrations of the soil solution (Adjusted $R^2 = 0.87$; Multiple $R^2 = 0.90$) with significant negative coefficients for K, Ca and EC (Table 3a). The unexpected negative correlation between yield and K seemed to be related to high concentrations at high salinity. When computed for each separate environment, multiple correlation gave a poor fit for yield and solute concentrations at the Great Scarcies and a highly significant correlation at the Casamance (Adjusted $R^2 = 0.83$; Multiple $R^2 = 0.92$). The correlation matrix for the Casamance showed again a high, negative correlation between yield and salinity in general (EC, Na, Ca, Mg with high correlation among all of them) and with Fe, while yield was positively correlated with pH (Table 3b).

Leaf analyses

Element concentrations in flag-leaves at panicle initiation differed significantly for different landscape units within a site (Table 4). High contents of Na and Mg (200 and 120 mmol /kg respectively) were typical for the dry saline environment of the Gambia and the Casamance river basins. Mg-contents were in the Mg-deficiency range (less than 82 mmol /kg) along the Great Scarcies river, particularly at site S3. K-contents were generally high (K > 250 mmol /kg) indicating that K availability was generally good. Excessive K-contents (more 550 mmol /kg) were observed at S2 along the Great Scarcies river. Ca-contents were below the deficiency level (less than 22 mmol /kg) at S2 along the Gambia river and at all sites along the Great Scarcies river. Leaf Ca-contents were appreciable, and sometimes even excessive (more than 57 mmol /kg) along the Casamance river basin. Fe-contents were normally close to 5.37 mmol /kg indicative of Fe toxicity (Tanaka & Yoshida, 1970) and P-deficiency appeared to be widespread (P-leaf < 1000 mg /kg).

Correlations between rice yield and flag leaf nutrient contents (Na, Ca, Mg, Fe, P and K:Na molar ratio) computed for the dry saline environment were highly significant ($P < 0.01$) with R^2 equal to 0.92. The matrix of individual correlations (Table 5) showed high positive relations between yield, P-leaf content and K:Na ratio in the leaf, and a negative correlation with Na, Mg and Fe. The high correlation coefficients between yield and contents of Mg (negative) and P (positive) indicate that the main limiting factors were salinity stress (expressed by Mg) and P deficiency. However, in the wet environment of the Great Scarcies river, the multiple correlation was not significantly different from zero for all nutrients. However, a good correlation was obtained between yield and the leaf contents of Mg (positive) and Fe (negative). The effect of soil amendments on the flag leaf nutrient contents is summarized in Table 6. Statistically significant differences between treatments were found in a few cases. At the mouth of the Casamance, liming alone increased the leaf Na-content and the combination of lime and/or N P fertilizer increased the Fe-content of leaves. At the S2 and S3 sites along the Great Scarcies river, liming and combined treatments with lime increased the Ca-content in leaves. The N-content in leaves was increased by the combined lime, N and P treatments at the S2 site of the Casamance river. We expected the Fe contents in leaves to be depressed by liming, but this was not observed.

Locations	Element content in rice flag leaves at panicle initiation						
	K ($mmol\ kg^{-1}$)	Na ($mmol\ kg^{-1}$)	Ca ($mmol\ kg^{-1}$)	Mg ($mmol\ kg^{-1}$)	Fe ($mmol\ kg^{-1}$)	Fe: Ca+Mg %	K:Na
GAMBIA							
* JENOI (S2)							
Levee	---	---	---	---	---	---	---
Low backswamp1	392 a	588 a	9 a	143 b	13.09 a	8.61	0.67
Low backswamp2	495 a	1022 a	10 a	157 b	14.84 a	8.89	0.48
High backswamp	534 a	929 a	12 a	249 a	13.79 a	5.28	0.57
CASAMANCE							
* KAGNOUT (S1)							
Levee	---	---	---	---	---	---	---
Low backswamp1	---	---	---	---	---	---	---
Low backswamp2	347 a	137 a	218 b	119 a	5.25 a	1.56	2.53
High backswamp	290 b	124 a	296 a	134 a	5.25 a	1.22	2.34
* FANDA (S2)							
Levee	366 a	97 a	233 b	73 b	6.62 a	2.16	3.77
Low backswamp1	343 b	78 a	248 b	73 b	7.57 a	2.36	4.40
Low backswamp2	364 ab	118 a	365 a	64 b	10.22 a	2.38	3.08
High backswamp	314 c	103 a	210 b	107 a	11.53 a	3.64	3.05
* ADEANE (S3)							
Levee	324 b	80 b	149 b	159 b	8.89 c	2.88	4.05
Low backswamp1	341 b	853 a	166 b	357 a	12.57 b	2.40	0.40
Low backswamp2	344 b	655 a	178 b	401 a	14.93 a	2.58	0.53
High backswamp	399 a	255 b	231 a	422 a	11.19 b	1.71	1.56
GREAT SCARCIES							
* BALENCERA (S1)							
Levee	266 b	198 a	6 b	67 a	5.85 a	8.02	1.34
Low backswamp1	261 b	188 a	6 b	81 a	6.64 a	7.64	1.39
Low backswamp2	264 b	189 a	6 b	73 a	6.12 a	7.75	1.40
High backswamp	347 a	166 b	19 a	73 a	5.76 a	6.27	2.09
* ROWOLLOW (S2)							
Levee	458 b	172 b	1.34 a	59 a	4.15 b	6.88	2.66
Low backswamp1	845 a	616 a	0.66 b	42 b	5.37 a	12.59	1.37
Low backswamp2	433 b	201 b	1.24 a	54 a	4.21 b	7.62	2.15
High backswamp	360 c	188 b	1.36 a	54 a	5.14 a	9.28	1.91
* KATAKERA (S3)							
Levee	367 ab	148 c	1.57 b	49 a	4.62 b	9.13	2.48
Low backswamp1	341 b	140 c	1.81 b	43 b	4.53 b	10.11	2.44
Low backswamp2	378 a	194 a	3.61 a	48 a	5.10 b	9.89	1.95
High backswamp	351 ab	176 b	3.39 a	32 c	6.79 a	19.18	1.99

Means within the same site followed by the same letter are not different at level (0.05) (Duncan's test).

Table 4: Element content in rice flag leaves at panicle initiation in 1992 trials in plots in the low-lying part of catenas at different sites along the Gambia, the Casamance and the Great Scarcies mangrove swamps.

	Na	Ca	Mg	Fe	P	K/Na	Yield
Na	1.000						
Ca	-0.766	1.000					
Mg	0.495	-0.210	1.000				
Fe	0.800	-0.635	0.540	1.000			
P	-0.722	0.735	-0.690	-0.779	1.000		
K/Na	------	0.613	-0.654	-0.741	0.646	1.000	
Yield	-0.522	0.308	-0.826	-0.579	0.807	-----	1.000

Table 5: Coefficients of correlation between element content in rice flag leaves at panicle initiation and grain yields from 1992 trials along the Gambia and the Casamance river basins (dry environment).

Rice yield variability at different scales

The overall mean rice yield ranged from 0 to 3 t/ha along the Gambia and Casamance river basins (drier climatic zone) and from 2 to 4 t/ha along the Great Scarcies river basin (wet climatic zone) (Table 7). Coefficients of variance (CV) were much higher along the Gambia and Casamance river basins than in the Great Scarcies river basin, reflecting the high spatial variability following a skewed distribution of soil constraints for rice production and differential response to amendments. A steady and good response of rice yield to lime, phosphate (rock-P) and Nitrogen (Urea-N) was generally obtained along the Great Scarcies river. Such a treatment effect was sometimes absent and generally unsteady in the dry environment (Fig.5).

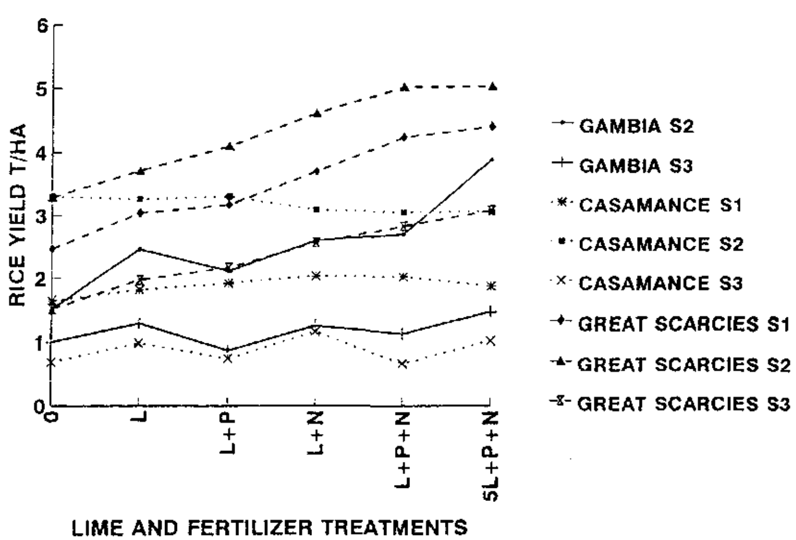


Figure 5: Rice grain yields along the Gambia (Gambia), the Casamance (Senegal) and the Great Scarcies (Sierra Leone) under different fertilizer applications. O is the control, L is 2t of lime, N is 80 kg of N-urea and P is 250 kg ha^{-1}. The trials were implemented during the 1991 rainy season.

Locations	Treatments	Flag leave chemical content							
		K mmol kg^{-1}	Na mmol kg^{-1}	Ca mmol kg^{-1}	Mg mmol kg^{-1}	Fe mmol kg^{-1}	Molar ratio Fe:Ca+Mg %	N mg kg^{-1}	K:Na ratio
GAMBIA Jenol (82)	T0	451	620	10	152	13.86	8.55	nd	0.73
	T1	604	1310	14	237	16.03	6.38	nd	0.46
	T2	461	960	10	179	13.64	7.22	nd	0.48
	T3	431	735	9	176	12.93	6.99	nd	0.59
	T4	421	606	9	170	13.03	7.28	nd	0.69
CASAMANCE Kagnoutt (91)	T0	303	117	238	125	4.85 c	1.34	1493	2.59
	T1	335	191	260	132	4.87 c	1.24	1579	1.75
	T2	323	115	252	111	5.16 b	1.42	1764	2.81
	T3	316	116	260	139	5.63 a	1.41	1831	2.72
	T4	316	115	274	125	5.69 a	1.43	1949	2.75
Fanda (82)	T0	348	94	221	72	7.14	2.44	1544 b	3.70
	T1	341	72	267	73	12.21	3.59	1554 b	4.74
	T2	339	103	315	88	8.15	2.02	1515 b	3.29
	T3	341	125	246	81	7.54	2.31	1853 a	2.73
	T4	366	101	270	82	9.90	2.81	1842 a	3.62
Adeane (83)	T0	348	605	157	321	12.30	2.57	1977	0.58
	T1	336	522	180	330	12.78	2.51	2006	0.65
	T2	359	356	184	351	11.57	2.16	1886	1.01
	T3	369	410	198	357	11.10	2.00	2049	0.90
	T4	346	411	186	314	11.69	2.34	2072	0.85
GREAT SCARCIES Balencera (91)	T0	298	181	10	70	5.41	6.76	nd	1.65
	T1	263	190	8	79	7.05	8.11	nd	1.38
	T2	310	185	10	75	5.75	6.76	nd	1.68
	T3	290	182	11	73	5.87	6.99	nd	1.59
	T4	262	189	8	70	6.41	8.22	nd	1.39
Rovollov (92)	T0	502	304	0.9 c	49	4.53	9.08	nd	1.65
	T1	514	370	1.1 b	53	5.19	9.60	nd	1.39
	T2	510	237	1.1 b	48	4.83	9.85	nd	2.15
	T3	545	277	1.3 a	56	4.39	7.66	nd	1.97
	T4	550	283	1.3 a	54	4.64	8.39	nd	1.94
Katakera (93)	T0	340	165	1.82 c	45	5.43	11.59	nd	2.06
	T1	344	160	2.14 bc	42	4.93	11.16	nd	2.15
	T2	350	175	2.74 ab	42	5.37	12.01	nd	2.00
	T3	369	160	3.39 a	42	5.10	11.24	nd	2.31
	T4	384	163	2.89 a	44	5.44	11.61	nd	2.36

Table 6: Treatment effect on nutrient contents in rice flag leaves at panicle initiation on 1992 trials in the mangrove environment of Gambia, Casamance and Great Scarcies. The treatments are: a control plot, 2 t lime, 2t lime and 250 kg rock-P, 2t lime and 80 kg of N-urea, and 2t lime and 250 kg and 80 kg ha^{-1} N-urea.

Low rice yields (less than 1 t/ha) to complete crop failure and little to no response to liming and fertilizer treatments were observed at the river mouth of the Gambia and at the upstream site of the Casamance river. These can be attributed to high soil salinity. In 1991 no significant treatment effect was observed at any site along the Casamance river and at S3 site along the Gambia river. The effect of lime alone to increase rice yield was statistically significant ($P < 0.05$) at S2 in the Gambia river and all sites along the Great Scarcies river. Additional application of rock-P to limed plots gave a significant yield increase only at S2 and S3 along the Great Scarcies river. Yield was increased more by lime and N than by lime and rock-P along the Gambia river (S2), and at all sites along the Great Scarcies river. Heavy application of lime (10t/ha) with additional N and rock-P fertilizers did not outperform the moderate lime dressing (2 t/ha) except at S3 along the Great Scarcies river basin. In 1992, treatment effects were observed at all sites, except at S3 along the Casamance river where salinity was very high. An effect of lime alone was confirmed for the sites along the Great Scarcies river. Additional application of rock-P to limed plots did not increase rice yield significantly in general probably because of the limited amount used in these possibly strongly P-fixing soils, confirming the results obtained in 1991. Application of N to limed plots increased yield significantly and was not significantly different from the combined lime, rock-P and N, except at S3 along the Great Scarcies river. These findings implied that there was little or no response to rock-P (250 kg/ha) in the acid sulphate soil of the study area. In general, fertilizer and lime application influenced the yield components (tiller count, grain weight and panicle number) and plant height. Plant height was influenced by N application during early growth and to a lesser extent at maturity. Tiller number was not influenced by N at 15 DAT but a significant effect was observed at 30 DAT for most sites. In general, liming alone and with additional application of N and or rock-P increased panicle number per m^2 in most sites. However effects on panicle number of additional application of P did not differ significantly from the application of lime alone. Grain weight (1000 grains weight) differed significantly between the wet and dry environments (30 to 39 g in wet environment and 24 to 26 g for the dry environment). Within catena's, rice yield was generally affected by landscape position (Table 7). In the dry environments, low yields to complete crop failure were observed on levees, except at S2 along the Casamance river. By contrast high rice yields were obtained on the levees along the Great Scarcies river. In general the low backswamp zones gave stable yields. Yield limitations at the high backswamp and its proximate low backswamp were observed at the site S3 along the Great Scarcies river. The effect of liming, combined with rock-P and N at each landscape unit is plotted in fig. 3. A positive effect of lime alone was observed at different landscape units: near the levee (along the Gambia river at site S3 and along the Great Scarcies river at S1 and S2); at the low backswamp 1 (along the Gambia river at S3 and S1, and along the Great Scarcies river at S2); and at the high backswamp (all sites along the Great Scarcies river) (Fig. 6). Additional application of rock-P was generally not effective, and even depressed yield in few landscape units (at low backswamp at S2 and S3 along the Gambia river and the Casamance river). Lime combined with N did increase rice yield almost at all landscape units with few exceptions e.g. at low backswamp 1, in site S2 along the Casamance river. Heavy application of lime combined with rock-P and N was not necessarily better than moderate liming, and in some cases also depressed rice yield e.g. along the Casamance river at site S2 at low backswamp 1 and along the Great Scarcies river at S2 near levee and at low backswamp1.

Table 7: Mean rice yields (kg ha^{-1}) during the 1991 field trials along the Gambia (Gambia), the Casamance (Senegal) and the Great Scarcies (Sierra Leone) at four landscape units along the low-lying part of the floodplains.

Landscape units	Yiear 1991								
	Grain yields in kg ha^{-1}								
	Gambia			Casamance			Great Scarcies		
	Mouth (S1)	Midstream (S2)	Upstream (S3)	Mouth (S1)	Midstream (S2)	Upstream (S3)	Mouth (S1)	Midstream (S2)	Upstream (S3)
Levee	0	0 b	1133 a	0 c	3201 a	711 b	4199 a	4367 ab	3541 a
Low backswamp1	--	2428 a	1210 a	2193 a	3026 a	674 b	3732 b	3991 c	2721 b
Low backswamp2	--	--	--	1574 b	2627 a	1260 a	3029 c	4574 a	1100 d
High backswamp	0	--	--	--	3870 a	0	3053 c	4245 b	2061 c
CV %	--	27	39	23	31	45	9.03	4.72	6.7

--= trails not implemented or no existing landscape units

Mean followed by the same letter are not different at level 0.05 (Duncan's test) within site.

Figure 6: Rice grain yields in different landscape units at different sites along the Gambia (6a-b), the Casamance (6c-e), and the Great Scarcies (6f-h) under different soil fertilizer application. O is the control, L is 2t of lime, N is 80 kg of N-urea and P is 250 kg ha^{-1}. The trials were implemented during the 1991 growing season.

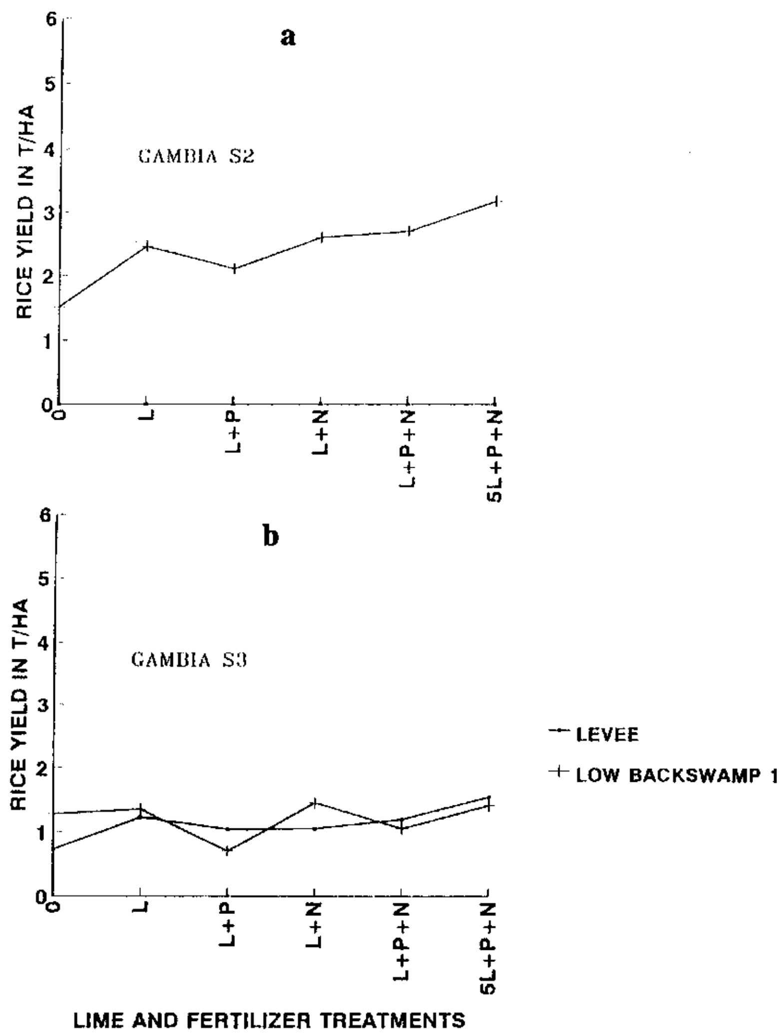
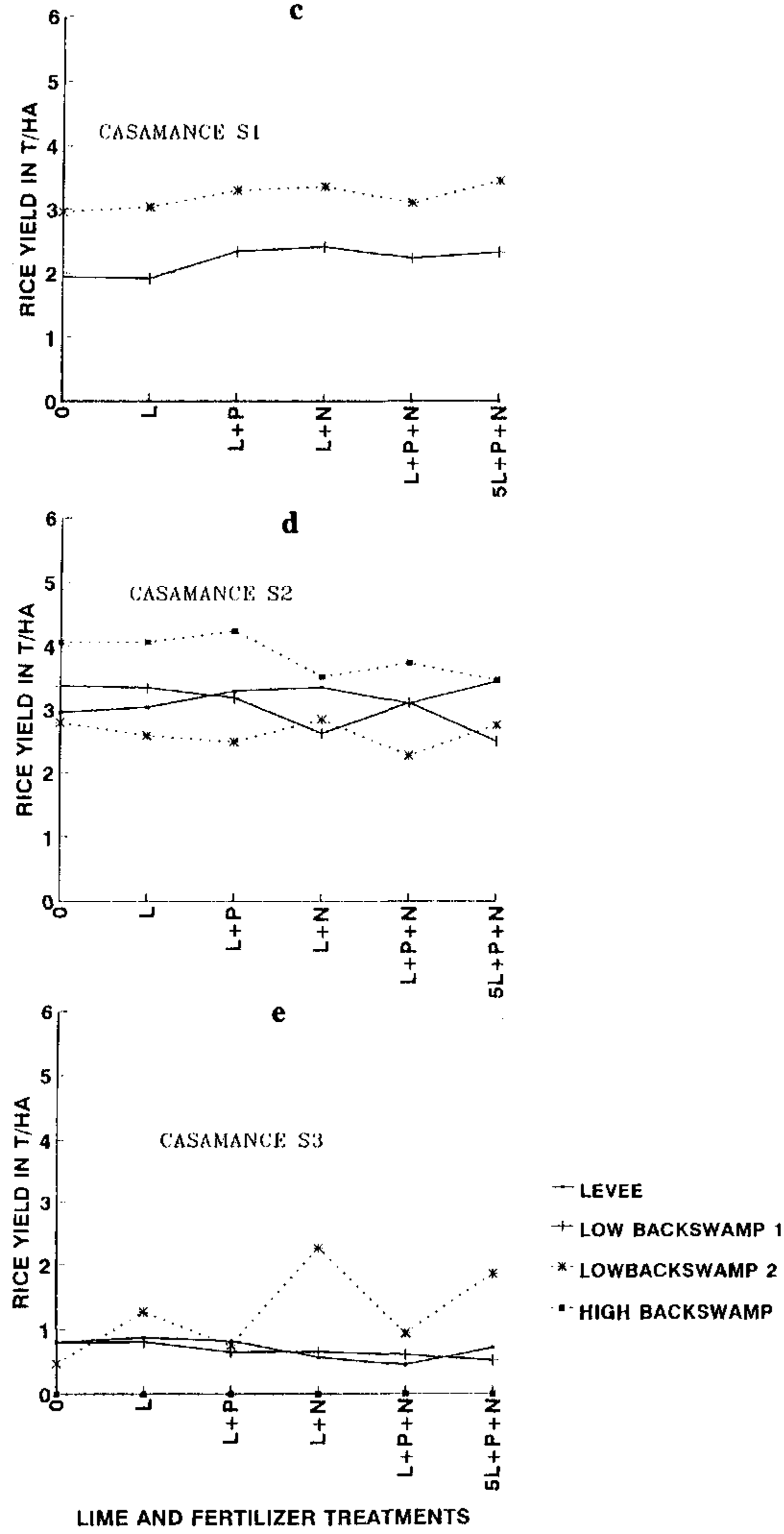
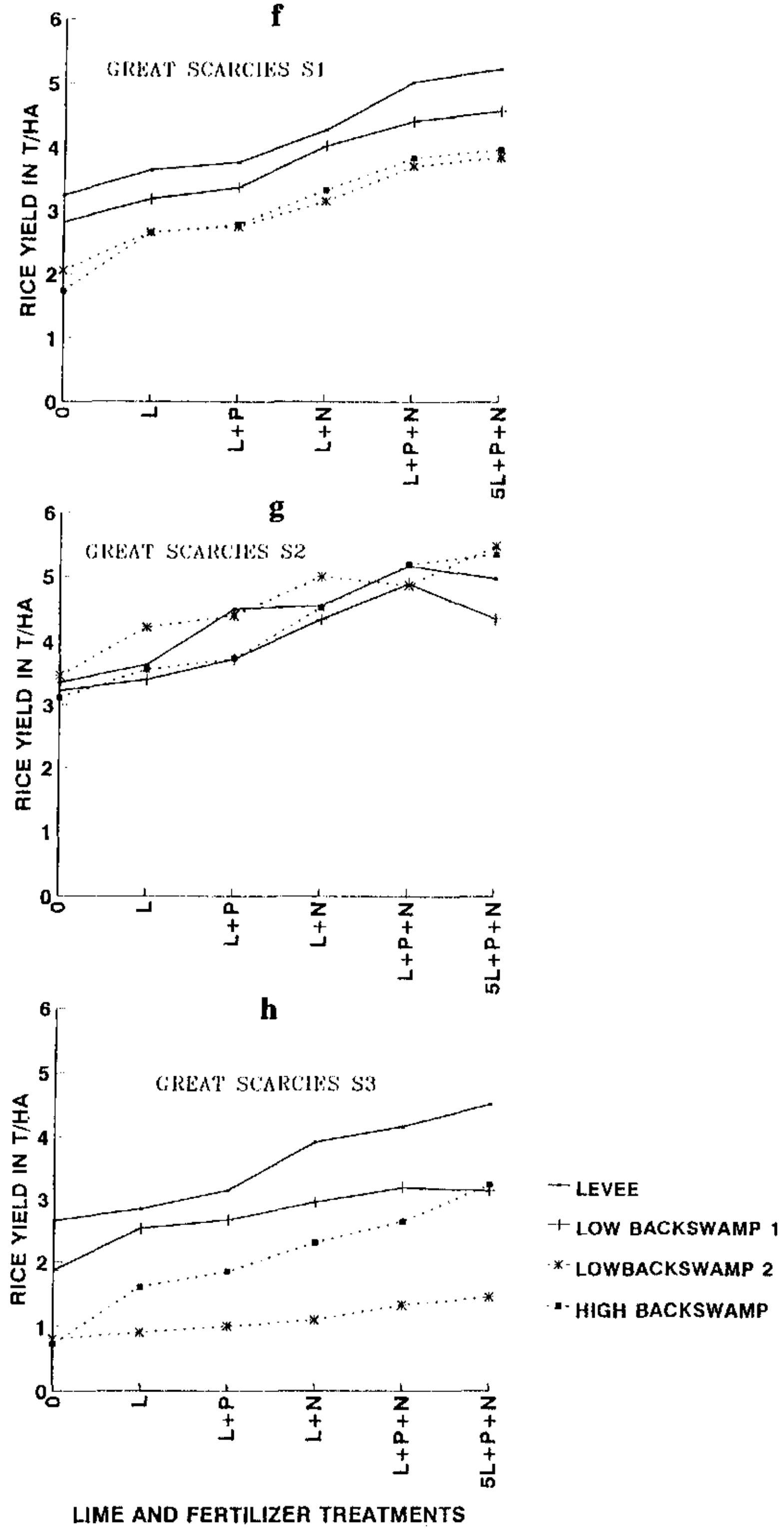


Figure 6: Rice grain yields in different landscape units at different sites along the Gambia (6a-b), the Casamance (6c-e), and the Great Scarcies (6f-h) under different soil fertilizer application. O is the control, L is 2t of lime, N is 80 kg of N-urea and P is 250 kg ha^{-1}. The trials were implemented during the 1991 growing season.




f
GREAT SCARCIES S1
RICE YIELD IN T/HA
0
1
2
3
4
5
6
0
L
L+P
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L+P+N
5L+P+N
g
GREAT SCARCIES S2
RICE YIELD IN T/HA
0
1
2
3
4
5
6
0
L
L+P
L+N
L+P+N
5L+P+N
h
GREAT SCARCIES S3
RICE YIELD IN T/HA
0
1
2
3
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5
6
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L+P
L+N
L+P+N
5L+P+N
LEVEE
LOW BACKSWAMP 1
LOWBACKSWAMP 2
HIGH BACKSWAMP
LIME AND FERTILIZER TREATMENTS

Residual effect of lime and rock-P on rice

Table 8 gives the means of rice grain yield along the Great Scarcies river at four landscape units with the different residual treatments. A highly significant residual effect of lime was observed in all sites along the Great Scarcies river and nowhere along the Casamance river. A residual effect of rock-P and N was observed only at the upstream site along the Great Scarcies river.

Table 8: Residual effect of lime and rock-P in the year after the treatments at 3 sites along the Great Scarcies river basin (Sierra Leone). Treatment were: T0 = control plot, T1 = 2 t lime, T2 = 2t lime and 250 kg rock-P, T3 = 2t lime and 80 kg of N-urea, T4 = 2t lime and 250 kg and 80 kg ha^{-1} N-urea and T5 = 10 t lime plus 250 kg rock-P and 80 kg ha^{-1} N-urea.

Locations	Treatments	Yield (kg ha^{-1})	Lanscape units	Yield (kg ha^{-1})	CV %
Balencera	To	3563 d	Levee	4966 a	
	T1	3820 c			
	T2	4227 b	Low backswamp1	3953 b	
	T3	3859 c			
	T4	4275 b	Low backswamp2	3604 c	
	T5	4527 a			
			High backswamp	3656 c	
					8.70
Rowollow	To	3670 b	Levee	3911 a	
	T1	3835 ab			
	T2	3900 ab	Low backswamp1	3914 a	
	T3	4011 a			
	T4	3977 a	Low backswamp2	3873 a	
	T5	4008 a			
			High backswamp	3904 a	
					8.22
Katakera	To	1651 e	Levee	3438 a	
	T1	1957 d			
	T2	2973 b	Low backswamp1	miss	
	T3	2677 c			
	T4	3203 ab	Low backswamp2	2547 b	
	T5	3460 a			
			High backswamp	1976 c	
					13.43

DISCUSSION

In the Gambia and Casamance river basins salinity stress clearly was the dominant factor limiting rice production. Above a critical level (EC of soil solution of about 12 dS /m), rice yields were low or the crop failed completely. In the wet environment of the Great Scarcies river, soil salinity did not limit rice production, even though soil salinity was high during the dry season (Sylla et al. 1994a). Along the Great Scarcies river, salt leaching by rain and fresh water runoff can be used to obtain essentially non-saline conditions. By contrast, in the highly saline and dry environments, the short duration and low intensity of the wet season often do not allow for a sufficiently long salt-free growing season.
Besides salinity, acidity stress was observed in some aeric Sulfaquents or young Sulfaquepts (Soil Survey Staff 1990), particularly on slightly elevated grounds. In this study the effect of lime on the rice crop varied greatly. Positive effects of liming were observed on non saline acid sulphate soils along the Great Scarcies river. As expected, liming was ineffective at high salinity. However, in the drier environments (e.g. Casamance) the effect of lime was still not significant on acid sulphate soils, even after reaching notably low salt levels by leaching before transplanting. Toure (1982) and Ottow et al. (1983) reported similar findings in Sulfaquepts, sulfic Tropaquepts and aeric Sulfaquents along the Casamance river. The effect of lime on rice in acid sulphate soils may have to be related to the availability of Ca and Mg (Moore & Patrick 1989b). The chemical analyses of rice flag leaves as well as of the soil solution indicated that available Ca and Mg was sufficient along the Casamance river, but too low along the Great Scarcies river. This may explain why liming was effective along the Great Scarcies river but not along the Casamance river.

Ottow et al. (1983) claim that dissolved Ca and Mg play an important role in modifying the toxic effects of high concentrations of dissolved iron, and attribute iron toxicity to a multiple stress rather than to high concentrations of dissolved iron persé. Recently Moore & Patrick (1989 a) and Moore et al. (1990) related Fe uptake by rice on acid sulphate soils to the activity ratio of Fe^{2+} to other divalent cations Ca, Mg and Mn. In their study of 134 flooded rice fields in Thailand, they also demonstrated that the concentrations of Ca and Mg in the soil solution were in equilibrium with Ca and Mg on the cation exchangeable complex. These findings may help to interpret the divergent effects of liming in the wet and in the dry environments observed in our studie. Apparently, the positive effect of lime along the Great Scarcies river, where soil contents of Ca and Mg are low, can be attributed to a depressed Fe toxicity by increased Ca availability and a lowering of the Fe to Ca + Mg activity ratio. The absence of bronzing in spite of high leaf-Fe contents and the low response to liming along the Casamance river basin, must be attributed to sufficient divalent cations brought in during the dry season by sea water, and sorption of these cations on the exchange complex. Probably, assessment of iron toxicity by means of leaf analyses should be related to relative concentration of Fe to the divalent cations rather than to an absolute Fe-leaf concentration. In the site (Great Scarcies S3) showing severe leaf bronzing typical of iron toxicity, the Fe to (Ca+Mg) molar ratio in leaves was indeed highest (> 10).

In dry environments, rice yield was well correlated with the spatial variability of soil salinity at all scales. Soil salinity was reflected by the Na-content of the leaves. Applying lime to saline soil tended to increase Na-contents in leaves, an effect observed earlier by Moormann (1961) in Vietnam.

Our results for limed and unlimed acid sulphate soils in West Africa corroborate the conclusion of Moore and coworkers that metal availability should be evaluated by considering activity or charge fractions in soil solution and plant tissue. In addition, multiple correlation analysis between yield, yield components, element concentrations in flag leaves and in the soil solution proved to be a good tool for assessing physiological disorders in rice plants. Such an approach can help to identify the appropriate reclamation techniques.

CONCLUSIONS

When trying to improve rice production in West African mangrove ecosystem, spatial variability of soil attributes is clearly a major factor to be considered. Two complementary approaches were applied: (1) the characterization of relationships between rice yield and the chemical status of the soil at different scales, and (2) the evaluation of relationships between nutrient availability, soil solution chemical composition, rice yield and yield components. We found that the West African Mangrove agro-ecosystem comprises two main environments, one with salinity, and one with actual and potential acidity as the dominant factors limiting rice growth. In the dry environment with highly saline acid sulphate soils, salinity must be depressed by leaching with fresh water before rice can be grown succesfully. Where sufficient water is available to do so, rice does not seem to suffer greatly from acidity. Due to high levels of divalent cations in the soil solution brought by the aridity of the climate iron toxicity was depressed, and liming had little or no effect. In acid sulphate soils in the wet environment, concentration of dissolved Ca and Mg are low, and here iron toxicity can be alleviated with a fairly small lime dressing which causes a decreased divalent charge fraction of Fe^{2+}. Such liming had a residual effect. Application of rock-P was not very efficient.

Also within single river basins and catenas, consideration of the variability of soil attributes at different scales is important for determining the best rice improvement technique. Application of multiple correlation analysis involving soil chemical properties, plant tissue, yield and yield components can help to diagnose physiological disorders related to a given soil environment, or treatment effect on rice yield.

REFERENCES

ANDRIESSE, W.(1993). Acid sulphate soils: Diagnosing the illness. In *Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils* (Eds D.L. Dent & M.E.F. van Mensvoort), pp. 11-29. ILRI Publ.No 53. Wageningen, The Netherlands.

BENCKISER, G., OTTOW J.C.G., WATANABE I., & SANTIAGO S. (1984). The mechanism of excessive iron-uptake (iron toxicity) of wetland rice. *J. Plant Nutr.* **7**, 177-185.

BEYE, G., TOURÉ, M. & ARIAL, G. (1975). Acid sulfate soils of West Africa: Problems of their management for agriculture use. *Internal Rice Research Conference*. Los Banos, Philippines.

BLOOMFIELD, G. & COULTER, J.K. (1973). Genesis and management of acid sulfate soils.

Advance in Agronomy p. 266-319.

BREEMEN, N. van (1976). Genesis and soil solution chemistry of acid sulfate soil in Thailand. *Agr. Res. Rep.* 848. PUDOC, Wageningen, The Netherlands.

BREEMEN, N. van (1993). Environmental aspects of acid sulphate soils. In *Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils* (Eds D.L. Dent & M.E.F. van Mensvoort), pp. 391-402. ILRI Publ.No 53. Wageningen, The Netherlands.

BREEMEN, N. van & MOORMANN, F.R. (1978). Iron toxic soils. In *Soils and Rice* pp. 781-800 (Ed International Rice Research Institute), Los Banos, Phlippines.

DENT, D. (1986). *Acid sulphate soils: The baseline for research and development.* ILRI. publ. No. 44. Wageningen, The Netherlands.

DENT, D. (1992). Reclamation of acid sulphate soils. *Adv. Soil Science* **17**, 79-122.

DENT, D.L. & MENSVOORT, M.E.F. van (Eds) (1993). *Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils.* ILRI Publ.No 53. Wageningen, The Netherlands.

DETURCK, P., WEERASINGHE, K.D.N., GUNARATHNA, D.A.B.N, LEXA, J.P. & VLASSAK, K. (1993). Rice production on acid sulphate soils of Sri Lanka. In *Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils* (Eds D.L. Dent & M.E.F. van Mensvoort), pp. 137-145. ILRI Publ.No 53. Wageningen, The Netherlands.

DO THI THANH REN, VO THI GUONG, NGUYEN MY HOA, VO QUANG MINH & TRAN THANH LAP (1993). Fertilization of nitrogen, phosphorus, potassium and lime for rice on acid sulphate soils in the Meckong delta, Vietnam. In *Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils* (Eds D.L. Dent & M.E.F. van Mens voort), pp. 147-159. ILRI Publ.No 53. Wageningen, The Netherlands.

GENT, P.A.M. van & UKKERMAN, R. (1993). The Balanta rice farming system in Guinea Bissau. In *Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils* (Eds D.L. Dent & M.E.F. van Mensvoort), pp. 103-111. ILRI Publ.No 53. Wageningen, The Netherlands.

HOWELER, R.H. (1973). Iron-induced oranging disease of rice in relation to physico -chemical changes in a flooded oxisol. *Soil Sci. Soc. Am. Proc.* **37**, 898-901.

JEFFERY, J.W.O. (1963). Fertilizer trials on Sierra Leone swamp rice soil. *Agron. Trop.* **18**, 806-810.

KONSTEN, C.J.M., W. ANDRIESSE, W. & BRINKMAN, R. (1988). A field laboratory method to determine total potential and actual acidity in acid sulphate soils. In *Selected papers of the Dakar Symposium on acid sulphate soils* (Ed H. Dost) pp. 106-134. ILRI Publ. No. 44, ILRI Wageningen, The Netherlands.

KSELIK, R.A.L. (1990). Water management on acid sulphate soils at Pulau Petak, Kalimantan. In *Papers Workshop on acid sulphate soils in the humid tropics* (Ed AARD/LAWOO) pp. 249-276. Bogor November 1990.

KSELIK, R., SMILDE,K.W., RITZEMA, H.P., KASDI SUBAGYONO, SARAGIH, S., MAULIANA DAMANIK & SUWARDJO, H. (1993). Integrated research on water management, soil fertility and cropping systems on acid sulphate soils in South Kalimantan, Indonesia. 177-194.

MOORE, P.A. Jr., ATTANANDANA, T. & PATRICK, W.H.Jr. (1990). Factors affecting rice growth on acid sulfate soils. *Soil Sci. Soc. Am. J.* **54**, 1651-1656.

MOORE, P.A. & PATRICK, W.H.Jr. (1989 a). Iron availability and uptake by rice in acid sulfate soils. *Soil Sci. Soc. Am. J.* **53**, 471-476.

MOORE, P.A. & PATRICK, W.H.Jr. (1989 b). Calcium and magnesium availability and uptake by rice in acid sulfate soils. *Soil Sci. Soc. Am. J.* **53**, 816-822.

MOORMANN, F.R. (1961). Acid sulphate soils (cat clays) of the Tropics. Ministry of Rural Affairs. National Directorate of Agriculture, Directorate of Studies and Research in Agriculture, Forestry and Animal Husbandry, Vietnam.

MUHRIZAL SARWANI, MANSUR LANDE & ANDRIESSE, W. (1993). Farmers' experiences in using acid sulphate soils: some examples from tidal swampland of southern Kali mantan, Indonesia. In *Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils* (Eds D.L. Dent & M.E.F. van Mensvoort), pp. 113-121. ILRI Publ.No 53. Wageningen, The Netherlands.

OTTOW, J.C.G., BENCKISER, G., WATANABE, I. & SANTIAGO, S. (1983). Multiple nutritional stress as the prerequisite for iron toxicity of wetland rice (Oriza sativa L.). *Tropical Agriculturist. (Trinidad)* **60**, 02-106.

OTTOW, J.C.G., PRADE, K., BEERTENBREITER, W. & JACQ, V.A. (1991). Strategies to alleviate iron toxicity of wetland rice on acid sulphate soils. In *Rice production on acid soils of the tropics* (Eds P. Deturk & F.N Ponnamperuma) pp. 205-211. *Institute of Fundamental Studies*, Kandy, Sri Lanka.

PONNAMPERUMA, F.N. & SOLIVAS, J.L. (1982). Field amelioration of acid sulphate soil for rice with manganese dioxide and lime. In *Proceedings of the Bangkok symposium on acid sulphate soils* (Eds H. Dost & N. van Breemen) pp. 219-301. ILRI publ. No. 31, Wageningen, The Netherlands.

PONS, L.J. & BREEMEN, N. van (1982). Factors influencing the formation of potential acidity in tidal swamps. In *Proceedings of the Bangkok symposium on acid sulphate soils* (Eds H. Doşt & N. van Breemen) pp. 37-51. ILRI publ. No. 31, Wageningen, The Netherlands.

PRADE, K., OTTOW, J.C.G. & JACQ, V. (1988). Excessive iron uptake (iron toxicity) by wetland rice (*Oriza sativa L.*) on acid sulphate soils in the Casamance, Senegal. In *Selected papers of the Dakar Symposium on acid sulphate soils* (Ed H. Dost) pp. 150-162. ILRI Publ. No. 44, ILRI Wageningen, The Netherlands.

RORISON, I.H. (1972). The effect of extreme soil acidity on the uptake and physiology of plants. In Dost, H. (ed) *Acid sulphate soils. Proceedings of the first International Symposium* (Ed H. Dost) pp.223-254. ILRI publ. No. 18 vol. 1. Wageningen, The Netherlands.

SOIL SURVEY STAFF (1990). Keys to soil taxonomy, fourth edition. *SMSS Technical Monograph* No. 6. Virginia Polytechnic Institute and State University, Blacksburg. USA.

SYLLA, M., BREEMEN, N. van, FRESCO, L.O., DIXON, C. & STEIN, A. (1993). Temporal and spatial variability of soil constraints affecting rice production along the Great Scarcies mangrove swamps, Sierra Leone. In *Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils* (Eds D.L. Dent & M.E.F. van Mensvoort), pp. 247-259. ILRI Publ.No 53. Wageningen, The Netherlands.

SYLLA, M., STEIN, A., BREEMEN, N. van & FRESCO, L.O. (1994 a). Spatial variability of soil salinity in the mangrove rice agro-ecosystem in West Africa. Paper submitted to *Agric. Ecosystems and Environment.*

SYLLA, M., STEIN, A., MENSVOORT, M.E.F. & BREEMEN, N. van (1994 b). Causes of spatial variability of soil actual and potential acidity in mangrove agro-ecosystem of West Africa. Paper submitted to *Soil Sci. Soc. of Am.*

TANAKA, A. & YOSHIDA, S. (1970). Nutritional disorders of the rice plant in Asia. In: *IRRI tech. Bull.* 10. IRRI, Los Banos, Phillipines.

TING CHAONG CHAANG, ROHANI BT. SAARI, DIEMONT, W.H. & AMINUDDIN BIN YUSOFF (1993). The development of an acid sulphate area in former mangroves in Merbok, Kedah, Malaysia. In *Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils* (Eds D.L. Dent & M.E.F. van Mensvoort), pp. 95-101. ILRI Publ.No 53. Wageningen, The Netherlands.

TOURÉ, M. (1982). Improvement of acid sulphate soils: effects of lime, wood ash, green manure and preflooding. In *Proceedings of the Bangkok symposium on acid sulphate soils* (Eds H. Dost & N. van Breemen) pp. 223-236. ILRI publ. No. 31, Wageningen, The Netherlands.

TURNER, J.M. (1980). *The response to nitrogen fertilizer of mangrove swamp rice in Sierra Leone.* Unpublished MSc thesis. The University of Reading, U.K.

WARDA (1983). Annual Report. Regional Mangrove Swamp Rice Reseach Station, Rockupr. Sierra Leone.

WATSON, G.A. & WILLIS, M. (1985). Farmers' local and traditional rice crop protection techniques: some examples from coastal swamplands, Kalimantan, Indonesia. *IARD Journal* (7) 1 & 2:25-30.

WILLIAMS, C.N. (1980). Effects of lime, drainage, manganese dioxide, and seedling condition on rice in acid sulphate soil in Brunei. *Expt. Agriculture* **16**, 313-320.

CHAPTER 7

RICE VARIETAL RESPONSE TO SOIL SALINITY AND ACIDITY IN MANGROVE ENVIRONMENT.

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Rice Varietal Response to Soil Salinity and Acidity in Mangrove Environments.

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ABSTRACT

Soil salinity and acidity are the main obstacles to high rice yields in mangrove environments in West Africa. Rice varieties tolerant to these soil stresses is the most practical techniques for the farmers that cannot access to high input agriculture. One of the best approach for selecting rice variety for stress environment is by raising yield potential through the different yield components. This study was aiming to test the behavior of 4 rice varieties of different tolerance levels in saline and moderately saline acid sulfate soils. We found that panicle number did not seem to be a pertinent parameter for selecting the high yielding variety. In stress environment, the percentage of filled grain, the 1000 grain weight and the number of spikelets was found highly correlated with grain yield. The application of multiple correlation techniques between nutrient concentrations in flag leaf, rice yield and yield components may channel to the best variety to be use and maybe to promising breeding for stress environments.

INTRODUCTION

There have been outstanding achievements in rice (*Oryza sativa L.*) breeding in the past 20 years by National and International Agricultural Reseach Institutes. The amount of literature pertaining to the subject is huge (Blum, 1988). Workers in the field of stress physiology have made significant progress in understanding how physical and chemical constraints reduce plant development and crop yield and what plant modifications may be considered. At the same time, in spite of the extensive efforts in soil classification and mapping, soil scientists agree that it is impossible to predict all plant nutritional responses from soil type. Dudal (1976), van Wambeke (1976) and Clark (1982) gave an appreciation of potential problems that can be formulated based on soil classification. However, proper experimentation and testing is essential to determine varietal adaptability to the target soil environment (Blum, 1988). In mangrove environments, soil salinity and acidity have been reported as the main soil limitations for rice growth (Dent, 1986, 1992). Salinity is a main obstacle to high rice yields on millions of hectares of flat land in deltas, estuaries, and coastal fringes. Rice is salt-tolerant during germination but sensitive after the 1- to 2-leaf stage. Tolerance increases during tillering stage, then decreases from panicle formation to flowering. Maturation of fertilized florets is apparently less affected (Iwaki and Ota, 1953; Iwaki, 1956; Pearson, 1959; and IRRI, 1968). Many workers pointed out that grain yield of rice is more affected than vegetative characters (Pearson, 1959; Kaddah and Fakhry, 1961; Kaddah, 1963; IRRI, 1968; Narale et al., 1969; Barakat et al., 1971; Akbar et al., 1972 and Datta, 1972). In acid soils, iron toxicity can be a nutritional disorder of wetland rice (Ponnamperuma et al., 1955; Tanaka and Yoshida, 1970). In acid sulfate soils, iron toxicity is associated often with salinity, phosphorus deficiency, and low base status. The critical iron content leading to iron toxicity symptoms differs according to variety and other factors (Tanaka et al., 1966; Virmani, 1977). Ikehashi and Ponnamperuma (1978) reviewed the varietal tolerance of rice for adverse soils. The objective of this study was to test rice varietal response under soil stresses in mangrove environments where salinity and acidity together may affect rice.

MATERIAL AND METHODS

On-station trials

During the rainy season of 1993, two trials were implemented at the Senegalese Institute for Agricultural Research Station at Djibelor (Senegal). Two soil types were selected to host the trials: a saline acid Sulfaquepts and a non-saline acid Sulfic Tropaquepts (Soil Survey Staff, 1990). The trials were designed as split-plot experiments replicated 3 times at two locations. The main plots were treated with or without 10 t ha^{-1} lime and the subplots were planted with 4 rice varieties of different sensitivity to salinity: IR 64 (International check), IR 31785-58-22 (susceptible to salinity but well adapted to arid conditions), IR 4630 (tolerant to salinity) and Rok5 (high yielding variety bred for mangrove ecosystem). All plots received 120 kg ha^{-1} N_urea, 60 kg ha^{-1} P_2O_5, (triple superphosphate) and 40 kg ha^{-1} K_2O (KcL). Lime, P and K were applied during land preparation, and N_urea was broadcast in split doses (2/3 at 20 DAT and 1/3 at 40 DAT). Land preparation was done by ridging to mimic farmer's practices in saline soil conditions (Dent, 1986). The ridges were about 50 cm high and 50 cm large with furrows of about 30 cm large. Thirty days old seedlings were transplanted on the ridges with a 25 x 25 cm spacing. Weeds, insect pests and blast (*Pyricularia oryzae Cav.*) were controlled chemically. Agronomic monitoring was done every 15 days after transplanting on plant height and numbers of tillers and panicles. At the flowering stage, flag leaves were sampled, washed with deionized water and dried for further laboratory analyses. All yield components were measured according to IRRI standards. Harvesting was done by hand, the grain threshed, winnowed and sun-dried. Grains were weighed and samples taken for grain moisture content and the 1000 grain weight taken. Yields were corrected to 14% moisture. The numbers of spikelets per panicle were measured on basis of 4 hills. Soil monitoring for salinity and acidity was done by direct soil sampling using a gauge auger at depths 0 to 20 cm and 20 to 40 cm at transplanting, panicle initiation, flowering and at harvesting stages. Flood water was also sampled for pH and EC measurements at the different growth stages.

Chemical analyses

Soil samples were air-dried, ground to pass a 2 mm sieve. pH and EC were measured in a 1:2.5 and 1:5 soil-water suspension respectively. Exchangeable Ca and Mg were measured by Atomic Absorption Spectrophotometer (AAS) using an air-acetylene flame after adding $LaCl_3$. Exchangeable Al was measured by AAS with a nitrous oxide-acetylene flame. Na and K were measured by flame photometry (AES) using an air-acetylene flame after adding CsCl. Total nitrogen was measured after digestion (Kjeldahl) in a mixture of sulfuric acid and Selenium by Auto Analyzer. Available P was analyzed by the Olsen method.

Plant samples were oven-dried (70 to 80°C) overnight and digested in a mixture of sulfuric and salicylic acids. Na, K and Ca were measured by AES and AAS and N as for the soil samples. Surface water samples were analyzed for pH and EC.

Statistical Procedures

ANOVA and F-test were computed to compare treatments. Multiple regression techniques were used to analyse yield, yield components and, leaf chemical contents at panicle initiation as a diagnostic tool in assessing physiological disorders.

RESULTS

Results from the soil monitoring for salinity and acidity are summarized in fig 1. The analysis of surface water showed very low pH in the saline acid zone (pH ranging from 3.1 to 3.58) throughout the growing season while the flood water pH increased from 3.8 to 5.26 in the less saline acid zone.

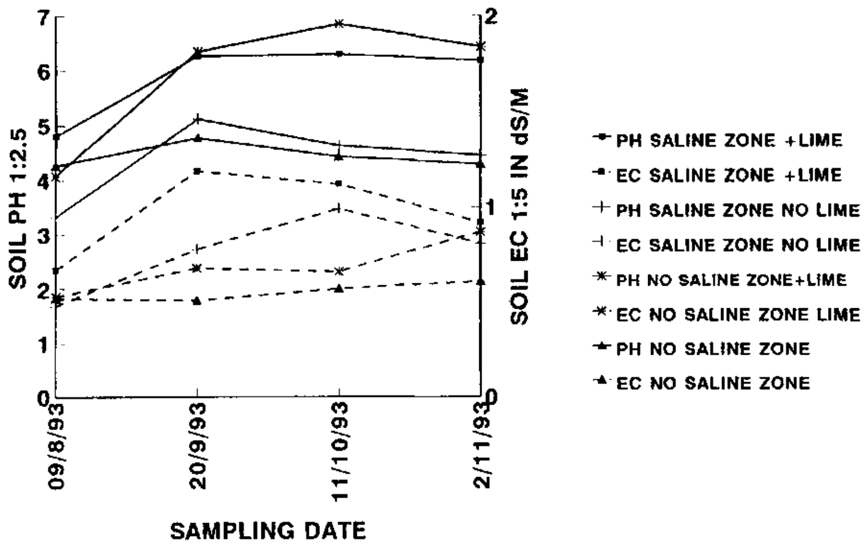

Figure 1: Rice plant height of four rice varieties at different days after transplanting in saline (a) and less saline (b) acid sulfate soils with or without lime application. Rice trials were implemented during the 1993 growing season at Djibelor Rice Research Station.

Plant height was affected by lime application in both saline and less saline acid soils (fig. 2a, b). Salinity restricted plant height mainly at the early growth stage. Varietal differences in their yield and yield components as well as the nutrient content of their flag leaves are summarized at table 1. The panicle number per m^2 was highest in the saline and acid soil. The susceptible variety (V2) showed the highest panicle number. In general, liming increased the panicle number per m^2 (except for the tolerant varieties V3 and V4 in the less saline and acid soil). The percentage of filled grain was not affected by the location. However, significant reduction of the percentage of filled grain was observed for the susceptible variety (V2) in the saline zone. In the saline and acid soil, Rok5 (V4) exhibited the highest percentage of filled grain. For the different varieties, the grain weight (1000 grains weight) was significantly affected by salinity and lime applications. After

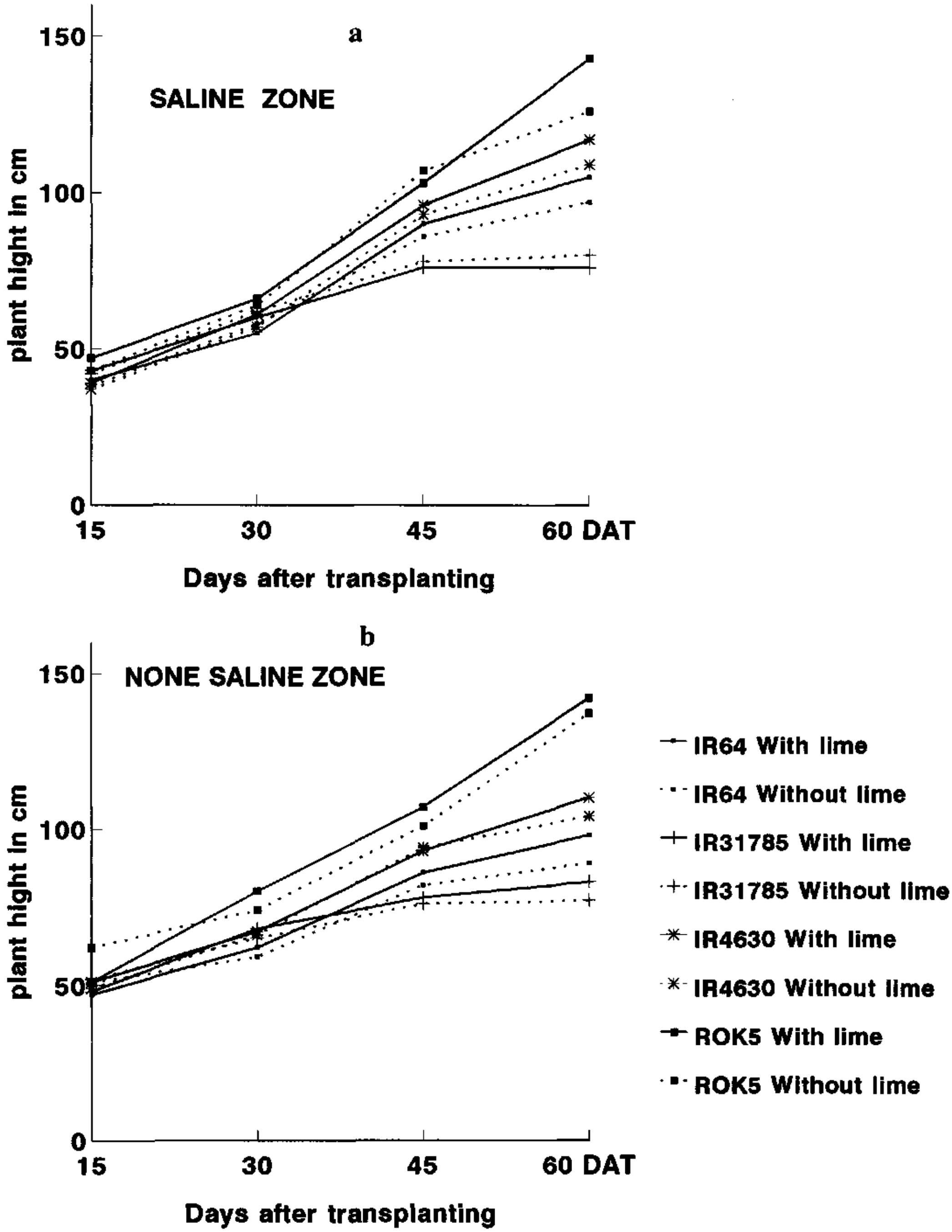

Figure 2: Soil salinity and acidity variation at different periods during the rice growing season of 1993 in saline and less saline acid sulfate soil treated or not with 10t ha^{-1} lime at Djibelor Rice Research Station.

Soil type	Treatments	Varieties	Yield components				Yield ($kg\ ha^{-1}$)	Chemical flag leaf content				
			Panicle / m^2	% filled grain	1000 grains weight	Spikelets per panicle		Na mmol kg^{-1}	K mmol kg^{-1}	Ca mmol kg^{-1}	N %	K:Na molar ratio
Saline acid soil	Lime (2t ha^{-1})	V1	232	86	25	110	4120	96	423	122	3.41	4.41
		V2	323	76	22	59	1240	121	294	147	3.31	2.43
		V3	168	86	26	116	4687	90	422	116	3.11	4.69
		V4	139	93	31	133	4813	87	508	101	3.38	5.84
	Mean plot		216	85	26	105	3715	99	412	122	3.30	4.16
	Without lime	V1	195	84	23	99	2953	62	296	92	2.60	4.77
		V2	289	74	21	78	1080	64	265	125	2.63	4.14
		V3	166	88	26	125	3307	65	338	93	2.35	5.20
		V4	107	92	29	119	3073	58	372	66	2.29	6.40
	Mean plot		189	85	25	105	2603	62	318	94	2.47	5.13
Mean of saline soil			203	85	25.5	105	3159	81	365	108	2.89	4.51
Less saline acid soil	Lime (2t ha^{-1})	V1	208	87	26	103	4580	47	392	97	1.70	8.34
		V2	232	86	22	76	3180	50	359	128	1.49	7.18
		V3	139	89	28	129	4633	57	497	106	1.93	8.72
		V4	112	86	32	126	4173	56	518	101	2.18	9.25
	Mean plot		173	87	27	109	4142	53	442	108	1.83	8.34
	Without lime	V1	198	89	25	88	3573	87	481	91	2.33	5.53
		V2	235	85	23	96	2313	85	315	97	2.09	3.71
		V3	112	86	25	110	3980	60	387	80	1.97	6.45
		V4	131	87	31	131	3720	72	438	75	1.65	6.08
	Mean plot		169	87	26	106	3397	76	405	86	2.01	5.33
Mean of less saline soil			171	87	26.5	107	3769	64	424	97	1.92	5.23
CV % over soil type			15.82	8.38	6.20	15.86	17.30	24	15	15.6	15.5	----

Table 1: Rice grain yields, yield components and nutrient content on flag leaves at panicle initiation from the 1993 varietal trials implemented in saline acid sulfate soil and moderately saline acid sulfate soil at Djibelor Rice Research Station (Senegal).

liming the effect of salinity on grain weight was less. The susceptible variety (V2) had always the lowest 1000-grain weight and V4 (Rok5) had the largest. The number of spikelets per panicle did not differ significantly in response to the treatments. But significant differences were observed between varieties. The number of spikelets per panicle was lowest for V2.

In general, rice yield decreased significantly with salinity and increased with liming. In saline acid environment Rok5 (V4) performed better with lime than the check variety (V1) and the tolerant V3. In less saline acid conditions or without lime, V3 performed better. In all cases the susceptible variety (V2) yielded less.

Yield components	Chemical leaf contents					Statistics
	Na	K	Ca	N	K/Na	Adjusted R^2
Panicle per m^2	0.506	-0.655	0.780	0.310	-0.643	0.851
% filled grain	-0.275	0.667	-0.642	-0.195	0.519	0.547
1000 grains weight	-0.190	0.836	-0.539	-0.086	0.586	0.756
Spikelets per panicle	-0.304	0.718	-0.620	-0.084	0.507	0.760
Yield	-0.261	0.842	-0.353	-0.099	0.643	0.639

Table 2: Correlation coefficients between grain yields, yield components and nutrient contents in rice flag leaves at panicle initiation from the 1993 trials implemented in saline and moderately saline soils at Djibelor Rice Research Station (Senegal).

In saline conditions, flag leaves had highest contents of Na, Ca and N but low K contents. Liming in saline conditions increased the leaf content of Na, K, Ca and N. In less saline acid condition, liming decreased the Na and N-leaf and increased the concentrations of K and Ca in the leaves. Varietal difference on their leaf-nutrient contents was observed. The susceptible variety V2 tended to have highest flag-leaf Na contents in saline conditions with lime, and lower K contents, giving low K:Na ratios. Rok5 always had the highest K:Na ratio, followed by the tolerant V3 and the international check (V1). The K:Na ratio was found highest in less saline conditions which corresponded to the relatively highest yields.

Multiple correlation between yield components and nutrient concentration in flag leaves at panicle initiation showed that:

- Panicle numbers per m^2 was highly correlated with Ca-leaf contents (r = 0.78) and negatively correlated with K-leaf contents (r = -0.66);

- The % filled grain was positively correlated with K-leaf contents (r = 0.67) and negatively with Ca-leaf contents;

- Grain weight was highly correlated with K-leaf contents (r = 0.84) and negatively correlated with Ca-leaf contents (r=-0.54);

- Spikelet numbers per panicle was highly correlated with K-leaf contents (r = 0.72) and negatively with Ca-leaf contents (r = -0.62).

Multiple correlation between yield and yield components showed a negative correlation between yield and panicle per m^2 (r = -0.67) and a positive correlation with the % filled grain (r = 0.78), grain weight (r = 0.66) and spikelet numbers per panicle (r = 0.74). Table 2 summarizes the different correlations between yield and yield components with the nutrient concentrations of flag leaves.

DISCUSSION

Marked differences exist in rice varietal performance on mangrove soils. Knowledge of nutrient uptake at various levels of soil salinity and acidity and their effect on yield components should point to the best adapted agronomic practices. Attanandana et al. (1982) concluded that liming acid sulfate soils depressed Na and Fe and increased Ca in plants, and found a negative correlation between yield and K plant. Arulandoo (1982) reported that liming at a dose of 2.5t ha^{-1} increased rice yield mainly by increasing the spikelet number and, to a lesser extent, the panicle number and grain weight. Our results showed that in saline and acid conditions, liming increased the panicle number for all varieties and particularly the most susceptible variety. The increase in spikelet number and grain weight with lime was observed for three varieties. In saline conditions, the susceptible variety yielded the smallest spikelet number at liming. Perhaps this is due to an inversely proportional relationship between grain per panicle and panicle number per m^2 (IRRI, 1968). In general for all four cultivars studied, panicle number was highest in the saline environment. Dingkuhn et al. (1992) found that salinity levels did not affect tiller numbers but confirmed our observation on the spikelets sterility and uncomplete grain filling as an effect of salinity level. Flag leaf analyses showed significant differences between zones (saline and less saline environments) as well as between lime treatment and varietal effects. In saline acid conditions rice plant tended to accumulate more N in the flag leaf than in less saline conditions and liming in this conditions increased N-leaf in all varieties. This effect of lime on N-leaf is also reported by Do Thi Thanh Ren et al. (1993). In less saline acid conditions, however, the effect of lime on N-leaf was variety-dependent. Increasing Ca-leaf contents upon liming was observed and reported in many studies (Moormann, 1961 and Dent and van Mensvoort, 1993). For Na and K in rice leaves, Dingkuhn et al. (1992) claim that salinity is partly a nutritional stress, due to the physiological displacement of K (an essential element) by a chemically similar but physiologically functionless Na. They found low K:Na leaf ratio in susceptible rice cultivars and highest in more tolerant ones. Our results confirm that in all conditions the susceptible variety had the lowest K:Na ratio in flag leaves. Liming in saline and acid conditions increased both Na and K in the leaf while in less saline conditions liming generally decreased Na but increased K-leaf contents resulting in highest K:Na ratio as well as the highest rice grain yields. Attanandana et al. (1982) found also a decrease in Na-leaf content and an increase of K with lime application. The unexpected increase of Na in leaves upon liming in saline acid soils may be caused by an increase of dissolved Na by Ca-Na ion exchange in soils having a high Exchangeable Sodium Percentage (ESP in Casamance soils can be as high as 15). Bhumbla and Abrol (1978) report high uptake of Na by rice in the presence of carbonate in the soil. From our results, Rok5 and the international check (IR 64) seem to have the most stable yields in mangrove soils where salinity and acidity are common.The tolerant IR4630 performed similarly if lime was applied.

CONCLUSIONS

Varieties adapted to mangrove ecosystems should combine both a good tolerance of salinity and acidity. The nutrient uptake of different varieties at different management levels indicates among these tolerant varieties which is the best to be used for a given cropping system. This implies that location-specific trials are needed to determine what variety is most adapted for farmers. Furthermore, physiological research will be needed to improve our understanding of metal availability and rice plant uptake.

REFERENCES

Akbar, M., T. Yabuno, and S. Nakao. Breeding for saline-resistant varieties of rice. I. Variability for salt tolerance among rice varieties. Jpn. J. Breed. 22(5):277-284.

Arulandoo, X. and Kam Suan Pheng 1982. Management of acid sulphate soils in the Muda irrigation scheme, Kedah, Peninsular Malaysia. In: Dost, H. and N; van Breemen (ed): Proceedings of the Bangkok symposium on acid sulphate soils. ILRI publ. No. 31, Wageningen, The Netherlands. pp: 195-212.

Attanananda, T., S. Vacharotayan and K. Kyuma 1982. Chemical characteristics and fertility status of acid sulphate soils of Thailand. In: Dost, H. and N; van Breemen (ed): Proceedings of the Bangkok symposium on acid sulphate soils. ILRI publ. No. 31, Wageningen, The Netherlands.pp: 137-156.

Barakat, M.A., M.A. Farah, and S.I. Fakhry. 1971. Relative tolerance in 16 varieties and crosses of rice to salinity of irrigation water. Agric. Res. Rev., U.A.R., 49(2):201-206.

Bhumbla, D.R. and I.P. Abrol 1978. Saline and sodic soils. In: IRRI: Soils and Rice. International Rice Research Institute. Los Banos, Philippines. pp: 719-738.

Blum, A. 1988. Plant breeding for stress environments. CRC Press, Inc. Boca Raton, Florida.

Clark, R.B. 1982. Plant response to mineral element toxicity and deficiency. In: Christiansen and Lewis (eds): Plant breeding for less favorable environments. Wiley-Interscience, New York.pp:71-80.

Datta, S.K. 1972. A study of salt tolerance of twelve varieties of rice. Curr. Sci. 41(12):456-457.

Dent, D.1986. Acid sulphate soils: The baseline for research and development. ILRI. publ. No. 44. Wageningen, The Netherlands.

Dent, D. 1992. Reclamation of acid sulphate soils. Adv. Soil Science 17:79-122.

Dent, D.L. and M.E.F. van Mensvoort (ed) 1993. Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils. ILRI Publ.No 53. Wageningen, The Netherlands.

Dingkuhn, M., F. Asch and K. Miézan 1992. Salt tolerance of rice varieties under irrigated conditions in the Sahel. WARDA annual Report, WARDA, Bouaké, Cote d'Ivoire.

Do Thi Thanh Ren, Vo Thi Guong, Nguyen My Hoa, Vo Quang Minh and Tran Thanh Lap 1993. Fertilization of nitrogen, phosphorus, potassium and lime for rice on acid sulphate soils in the Meckong delta, Vietnam. In: Dent, D.L. and M.E.F. van Mensvoort (ed): Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils. ILRI Publ.No 53. Wageningen, The Netherlands. pp: 147-154.

Dudal, R. 1976. Inventory of major soils of the world with special reference to mineral stress. In: Wright (ed): Plant adaptation to mineral stress in problem soils. Cornell Univ. Agric. Exp. Stn., Ithaca, N.Y. pp: 3-.

Ikehashi, H. and F.N. Ponnamperuma. 1978. Varietal tolerance of rice for adverse soils. In: IRRI (ed): Soils and Rice. The International Rice Research Institute. Los Banos, Laguna, Philippines. pp: 801-823. pp: 801-823.

International Rice Research Institute (IRRI). 1968. Annual report 1968. Los Baños.

Iwaki, S., and K. Ota. 1963. Studies of salt injury in the rice plant. IV. Influence of varying concentration of sodium chloride on growth, heading and ripening of the rice plant. Proc. Crop. Sci. Soc. Jpn. 22:13-14.

Kaddah, M.T. 1963. Salinity effects on growth of rice at the seedling and inflorescence stages of development. Soil Sci. 96:105-111.

Kaddah, M.T., and S.I. Fakhry.1961. Tolerance of Egyptian rice to salt. Soil Sci. 91:113-120.

Moormann, F.R. 1961. Acid sulphate soils (cat clays) of the Tropics. Ministry of Rural Affairs. National Directorate of Agriculture, Directorate of Studies and Research in Agriculture, Forestry and Animal Husbandry, Vietnam.

Narale, R.P., T.K. Subramanyam, and R.K. Mukherjee. 1969. Influence of salinity on germination, vegetative growth and yield of rice (*Oryza sativa* var. Dular). Agron. J. 61:341-344.

Pearson, G.S.1959. Factors influencing salinity of submerged soils and growth of Caloro rice. Soil Sci. 87:198-206.

Ponnamperuma, F.N., R. Bradfield, and M. Peech. 1955. A physiological disease of rice attributed to iron toxicity. Nature 175:265.

Tanaka, A., R. Loe, and S.A. Navasero. 1966. Some mechanisms involved in the development of iron toxicity symptom in the rice plant. Soil Sci. Plant Nutr. 12:32-38.

Tanaka, A. and S. Yoshida 1970. Nutritional disorders of the rice plant in Asia. In: IRRI tech. Bull. 10. IRRI, Los Baños, Phillipines.

Virmani,S.S. 1977. Varietal tolerance of rice to iron toxicity in Liberia. Int. Rice Res. Newsl. 2(1):4-5.

Wambeke, A. van. 1976. Formation, distribution and consequences of acid soils in agricultural development. In: Wright (ed): Plant adaptation to mineral stress in problem soils. Cornell Univ. Agric. Exp. Stn., Ithaca, N.Y. pp: 53.

CHAPTER 8

GENERAL CONCLUSIONS

GENERAL CONCLUSIONS

Ecological conditions vary widely within the mangrove zones of West Africa. Rice is grown in this environment as a staple food and its cultivation is one of the most important land uses. The soils in these coastal lowlands are mostly saline acid sulfate soils. In this thesis, an attempt was made to characterize the mangrove ecosystem based upon a conceptual framework that accounts for the different causal factors involved in the formation of acid sulfate soils (actual or potential). These causal factors were: climate, coastal morphology, hydrology and tidal regime, vegetation and topography. Based on the framework, sites were selected to study the spatial and temporal variability of soil attributes and to set up a network of rice trials for testing the response of rice to different improved agricultural practices in relation to soil characteristics. In this final chapter, the main conclusions are reported and future research challenges are outlined.

1. A number of different environments are distinguished in the coastal mangrove ecosystem of West Africa. The constraints to rice production ranged from excessive soil salinity to high actual or potential acidity. The classification matrix based on the environmental conditions necessary for acid sulfate soil formation provides an outline for detailed classification of mangrove environments outside the geographic scope of this study. Even though the approach needs further field validation, it is shown that mangrove environments in West Africa are variable in their soil properties and such variability may be structured at different scales ranging from macro to micro. The hierarchical structure can provide different levels of information to meet the needs of various decision-makers (government agencies at macro and meso levels and farmers at micro level).

2. The spatial variability of soil salinity was studied in four river basins. The significant effects of causal factors for soil salinization such as climate, distance to the river mouth, and landscape position were tested by nested ANOVA. Two main eco-regions were defined based on their soil salinity conditions at macro level: high salinity in the norther environment of South Sudan Savanna climatic zone and lower salinity in the Guinea Savanna and Equatorial Forest zones. At the meso level (within a river basin), clear differences were observed between "normal" and "inverse" estuaries and associated longitudinal soil salinity patterns. Sub-environments can be defined along each river basin. At micro level (within the catena), the spatial distribution of soil salinity was captured by means of geostatistical methods. The kriged maps illustrated the differences in soil salinity between landscape units. A classification system was matched to the contour maps based on rice salinity tolerance, soil equilibrated with sea water and the lethal salinity levels of mangrove species. The combined nested approach and geostatistical methods yielded a hierarchical classification of soil salinity to assess potential for rice growing.

3. The causes of spatial variability of soil actual and potential acidity were studied at the same locations as for soil salinity. A simple and attractive method for measuring actual and potential soil acidity was adopted. A framework taking account of the processes in acid sulfate soil genesis was applied in parallel with a nested model and geostatistical procedures to determine the contribution of each causal factor and to develop a characterization of rice environments. At the macro level, the same eco-regions defined in chapter 3 emerge: the northern region situated in the drier climatic zone was characterized by a relatively low total sulfidic acidity. The wetter southern region was characterized by high soil total sulfidic acidity. At the meso level, the site position along the river had a highly significant effect on total actual acidity (TAA) and total potential acidity (TPA) of the soil. However, the pattern found in this study did not confirm everywhere the longitudinal variations in potential acidity

reported elsewhere. At the micro level, the kriged maps showed different patterns of soil acidity within catenas and the observed patterns were specific for the eco-regions defined at macro scale. Based upon the different levels and the patterns of variation of TAA and TPA, practical implications were suggested.

4. Spatial and temporal variability of soil salinity and acidity were studied by means of soil solution chemistry, which was related to rice growth in three sites along the Great Scarcies (Sierra Leone). Geostatistical methods were applied to define time windows in which soil salinity and mineral stresses were minimal. These time windows were different between sites and between landscape units along the catena. Iron toxicity of rice plants (bronzing) was specific to the environment with both high dissolved Fe^{+2} and low Ca.

5. The response of rice to different improvement techniques was tested in different environments by determining whether liming and fertilizer application was effective. The results of the field trials used in this study also provide means to characterize rice growing environments. We find that liming was only effective where the molar ratio between Fe and Ca + Mg in the soil solution was high. Such environments were observed in the Equatorial Forest climate zone. Diagnosis of bronzing was better related to the molar ratio of Fe to Ca + Mg in the flag-leaves at panicle initiation than the absolute amount of Fe in the leaf.

6. Rice varietal differences were tested in saline and less saline acid sulfate soils under different lime applications. Varietal differences in yields, yield components and elements in flag-leaf at panicle initiation were affected in different ways by salinity and liming. The susceptible variety (IR 3178-58-22) showed higher of panicle numbers per m^2 in saline conditions but had lower values for the other yield components (% of filled grain, number of spikelets per panicle and the 1000- grain weight) than the tolerant varieties (Rok5 and IR 4630). These differences were reflected in grain yields. Salinity generally affected rice flag-leaves by giving highest contents of Na, Ca and N and lowest contents of K. The molar ratio K:Na was lowest for the susceptible variety in saline soils. Liming in less saline acid condition increased the K:Na ratio in leaves. The application of multiple correlation between yield, yield components and elements contents in flag-leaves showed that panicle numbers per m^2 was better related to Ca in leaf, while other yield components were better correlated with K in the leaf. This was reflected in the relation between yield and yield components, which gave a negative correlation between grain yield and the number of panicles numbers per m^2, and a positive correlation with the other yield components.

FUTURE CHALLENGES:

1. For proper land use planning in West African mangrove environments, a detailed quantitative and qualitative evaluation of land and land use systems is needed. The challenging task of soil scientists and agronomists is to provide information on the opportunities and constraints for the use of mangrove land as a basis of making decisions on land use. These include natural resources conservation as well as rice cultivation. Such information should be integrated with socio-economic data in order to provide practical recommendations to governments and farmers.

2. Crop simulation models can be of great importance to define iso-yield lines for mapping potential and actual rice yields within the mangrove environments. The complexities and the high variability of soil constraints are real challenge to cope with.

3. Combining the results from land and land use evaluation and crop simulation modeling in the mangrove environments with Geographic Information Systems may yield a comprehensive agro-ecological zoning of practical usage.

4. However, these challenging tasks could only be achieved if the available knowledge to do

the job is present. This may be done through fruitful cooperation on training programs between North and South.

ABSTRACT

SAMENVATTING

ABSTRACT

In the mangrove environment of West Africa, high spatial and temporal variability of soil constraints (salinity and acidity) to rice production is a problem for the transfer and adoption of new agronomic techniques, for land use planning, and for soil and water management. Recently, several National and International Agricultural Centers have initiated research programs to characterize environments where their newly developed technologies have to be applied. However, the mangrove agro-ecosystems in West Africa have not been characterized in a detailed way. Most of the soils in this environment are potential or actual saline acid sulfate soils. The spatial and temporal variability of soil salinity and acidity in these coastal lowlands results from complex interactions between climate, coastal morphology, river hydrology, vegetation, landform and tidal flooding. Diagnosing the occurrence of both potential and actual acid sulfate soils is the first step in land use planning for such areas. But to cope with the intricacies of these soils, understanding the processes of soil salinization and acidification at different scales should be formalized to properly characterize mangrove environments.

The main objectives of this thesis were: 1) to give a comprehensive characterization framework for the West African mangrove environments with emphasis on the possibilities of and constraints for rice cultivation; 2) to determine the various causal factors for soil salinization and acidification; 3) to test whether temporal variability of soil chemistry is sufficient to provide a time window of minimum stress during the rice growing period; 4) to relate the response of rice to improved agronomic practices in specific environments and to provide a means to characterize specific rice growing locations, and 5) to test rice varietal responses to saline and acid soils under different agronomic practices and to relate yields and yield components to the nutrient contents in leaves, in order to diagnose physiological disorders.

First, a multi-scale approach was developed involving a range from Macro to Micro level based on the pre-conditions of acid sulfate soil formation. The main factors for classification are climate and coastal morphology at Macro scale; hydrology, physiography and vegetation complexes at Meso level; and topography (catena), vegetation species, tidal flooding and sedimentation rate at Micro level. Information from previous process-based studies on acid sulfate soil formation and data from secondary sources were used. Different environments were then distinguished and their characteristics were summarized by ecological zone. Constraints to rice production and potentials for agricultural development were matched with environmental conservation issues.

To determine the significance of the causal factors developed in the multiple scale approach, 12 sites were selected along 4 river basins in West Africa, vz. from north to south the Gambia, the Casamance (Senegal), the Geba (Guinea Bissau) and the Great Scarcies (Sierra Leone). Along each river basin 3 sites were selected based on distance from the river mouth. Within a site a strip of land perpendicular to the river was selected for intensive grid sampling (40 by 20 m). Soil samples were taken at each grid node during the dry season of 1991. The relation between causal factors and soil salinization and acidification was determined at Macro and Meso levels by nested ANOVA and yielded a classification of the study area in main eco-regions and sub-environments within watershed. At a detailed scale, geostatistics were applied and zones within catena were defined in terms of their main soil characteristics. A nested statistical approach and geostatistics were used complementarily to disentangle the complexity of the causes of soil salinization and acidification.

Temporal variability was studied by monitoring soil solution chemistry at each main

landscape unit within the catena. Since the production of rice critically depends on the lowering of salinity and acidity by natural flooding during rainy season, time windows during which soil limitations are minimal were defined and matched with rice varietal duration.
The response of rice to different improvement techniques were tested by means of a network of trials in the 1991 and 1992 rainy seasons. The residual effects of lime and phosphate rock (applied in 1991) during 1992 was also evaluated. Lime dressing (2 t ha^{-1}) was found effective whenever dissolved Ca and Mg in the soil were low, and had a clear residual effect in the year after application. Application of phosphate rock did not seem to be effective in general. For iron toxicity, the molar fraction of Fe and (Ca + Mg) in soil solution and in flag leaves were found to be more relevant for diagnosing physiological disorders than the absolute Fe content in the soil solution and in rice flag leaves at panicle initiation.
In the 1993 rainy season, rice varietal behavior under different improvement techniques within the main soil limitations in the mangrove environment was tested. Differences in yield and yield components and element contents in flag leaves at panicle initiation were observed between varieties in saline and less saline acid soils. Multiple correlation between rice yields, yield components, element contents in flag leaves at panicle initiation was found to be an effective diagnostic tool for assessing physiological disorders.
The approach used in this study provides a logical framework to describe mangrove environments. The multiple-scale can assist in identifying the information required to cater for the needs of various decision-makers and land use planners. It also provides a key to develop technology packages for intensified and sustainable use. It can be used for the extrapolation of site-specific information to geographically different areas, with similar characteristics.

SAMENVATTING

De belangrijkste bodem-gerelateerde beperkende factoren voor rijstbouw in het mangrove gebied langs de West Afrikaanse kust zijn verzuring en verzouting. Beide vertonen hoge variabiliteit in ruimte en tijd en vormen daardoor een probleem bij het toepassen van agronomische verbeteringsmaatregelen en landgebruiksplanning, en bij bodem en waterbeheer. Recentelijk hebben nationale en internationale onderzoekscentra onderzoek verricht naar meer gedetailleerde methoden ter karakterisering van ecosystemen zodat nieuw ontwikkelde beheersmaatregelen beter toegepast kunnen worden. De mangrove ecosystemen van West Afrika zijn tot nu toe echter slechts in zeer algmene termen beschreven. De meeste gronden in de mangrove gebieden van West Afrika zijn potentiële of actuele kattekleien. De grote variabiliteit in ruimte en tijd van zuur en zout in deze gronden wordt veroorzaakt door complexe interacties van klimaat, kustvorm, rivierhydrologie, vegetatie en getijdewerking. Een goede diagnose van het voorkomen van de potentiële en actuele kattekleien kan een eerste stap zijn naar landgebruiksplanning in dergelijke gebieden (met name ten behoeve van de rijstbouw). Het zal echter nodig zijn om de processen van verzuring en verzouting op verschillende schalen (macro, meso, micro) te beschrijven.

Het doel van dit proefschrift is om (1) een zo volledig mogelijk syteem te ontwerpen voor beschrijving van de West Afrikaanse mangrove-ecosystemen; (2) de oorzaken van verzuring en verzouting te bepalen; (3) te bezien of binnen de jaarlijkse chemische variabiliteit van de gronden een voldoende lange periode zonder of met slechts minimale stress voor rijst voorkomt; (4) een verklaring te geven voor de respons van rijst op teeltkundige maatregelen in specifieke rijst-ecosystemen, en een methode te ontwikkelen voor gedetailleerde beschrijving van deze rijst-ecosystemen, en (5) de respons van diverse rijstvariëteiten te testen in zure en zoute omstandigheden.

Allereerst wordt in het proefschrift een indeling in agro-ecologische zones op verschillende schalen ontwikkeld, gebaseerd op de voorwaarden voor kattekleivorming. Hiervoor is informatie uit eerdere studies naar de vorming en het voorkomen van kattekleien gebruikt.

Op macro-schaal zijn klimaat en kustvorm de belangrijkste bepalende factoren; op meso-schaal zijn dat hydrologie, landschapsfysiografie en vegetatiecomplexen, en op micro-schaal worden hiervoor gebruikt de topografie (binnen catena's), de vegetatie, de getijdewerking en de sedimentatiesnelheid.

De belemmerende factoren voor rijstproduktie en de mogelijkheden voor landbouwontwikkeling zijn getoetst aan de noodzaak tot bescherming van het kwetsbare kustmilieu.

Om de significantie van het onderscheid in gebieden op verschillende schalen te toesten zijn 12 studiegebieden gekozen langs 4 West Afrikaanse rivieren. Van noord naar zuid zijn dit de Gambia rivier (in Gambia), de Casamance (in Senegal), de Geba (in Guinee Bissau) en de Great Scarcies (in Sierra Leone). Langs elke rivier zijn 3 studiegebieden geselecteerd op verschillende afstand tot de riviermond. In elk gebied zijn stroken land loodrecht op de rivier bestudeerd via een intensieve rasterbemonstering (40 bij 20 meter). Op elk punt zijn bodemmonsters genomen, per 20 cm tot 1 meter diepte, gedurende het droge seizoen van 1991. Er is gebruik gemaakt van genestelde variantieanalyse om de significantie van verschillen op macro- en meso-schaal te testen. Dit heeft geresulteerd in een klassificatie in hoofgebieden

en sub-gebieden binnen elk stroomgebied. Op micro-schaal zijn geostatistische methoden toegepast, waardoor via bodemkarakteristieken catena's kunnen worden onderscheiden. Genestelde variantieanalyse en geostatistiek bleken effectief bij het ontrafelen van de complexe verzuring en verzoutingsproblematiek.
Variabiliteit in tijd is bestudeerd aan de hand van de samenstelling van het bodemwater binnen de catena's. Het al of niet mogelijk zijn van rijstbouw hangt sterk af van vermindering van zuur en zout door natuurlijke overstroming met zoet water in het natte seizoen. De lengte van de zuur- en zoutvrije periode bepaalt de keuze van rijstvariëteiten, die verschillen in groeiduur.
De respons van rijst op teeltkundige maatregelen is onderzocht via experimenten in de natte seizoenen van 1991 en 1992. Het naleveringseffect van bekalking en van ruw fosfaat (gegeven in 1991) is eveneens bestudeerd in 1992. Kalkgiften van 2 ton per hectare bleken effectief ingeval van lage hoeveelheden opgelost Ca en Mg in de bodem, en vertoonden dit positieve effect ook nog in het navolgende jaar. Ruw fofaat was in het algemeen niet effectief. Voor het bestuderen van ijzertoxiciteit bleek de molaire fraktie van Fe en (Ca + Mg) in de bodem en de chemische samenstelling van het rijstblad ten tijde van de aarvorming een betere methode om nutrienten problemen te indentificeren dan de absolute hoeveelheid Fe in het bodemvocht en het rijstblad. Gedurende het natte seizoen van 1993 is de reactie getest van rijstvarieteiten op verschillende teeltkundige maatregelen. Verschillen in opbrengst, groeicomponenten en chemische samenstelling van het rijstblad ten tijde van de aarvorming werden gevonden in zoute en minder zoute gronden. Meervoudige correlatie tussen rijstopbrengst, groeicomponenten en chemisch bladsamenstelling bleken effectieve middelen om verschillen in de groei van rijst te verklaren.
Deze studie levert een logisch kader voor het beschrijven van mangrove-ecosystemen. De meerschalige benadering beantwoord aan de behoeften van landgebruiksplanning en beleid op verschillende nivo's. Het helpt bij het maken van een juiste afstemming van nieuwe technologieën voor intensiever, duurzaam landgebruik op de verschillende situaties. Bovendien kan het worden gebruikt voor extrapolatie naar andere gebieden met vergelijkbare geografische eigenschappen.

CURRICULUM VITAE

Mabeye Sylla was born January 10, 1953, in Ndiobène, Sénégal. After his secondary school at the 'Lycée Gaston Berger', Kaolack, where he obtained a 'Baccalauréat serie C: Mathematics and Physics', in 1973, he began his studies in agronomy at the Catholic University of Louvain La Neuve, Belgium. In 1978 he graduated with the degree of 'Ingenieur Agronome Specialiste du Genie Rural' with distinction. From 1978 to 1980, he worked as a consultant at SONED, a Senegalese engineering office in the field of irrigation and drainage design. In 1980, he started a MSc programme in soil science at the North Dakota State University at Fargo, USA, where he graduated in 1983. After his studies, he first worked as a soil scientist and water management engineer with the Senegalese Sugarcane Company in the fields of irrigation, drainage and reclamation of saline sodic soils. Since April 1984, he is employed by the Senegalese Institute for Agricultural Research (ISRA) as theme coordinator of the research team in Natural Resources Management Research Project in Casamance.