Saline acid sulphate soils in Senegal

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Abstract

The tannes region of the Sine Saloum basin in Senegal exhibits a variety of soils related to pyrite oxidation, topographic position, and hydrology. Tanne is the local name for salt-affected coastal flats. Strong salinization and progressive formation of acid sulphate soils has taken place since 1971 caused by the severe drought.

Soils on low terraces, subject to tidal flooding, have oxidized, leading to jarosite formation. Soils on the higher terraces show not only complete oxidation of pyrite to jarosite but, also, hydrolysis of jarosite to goethite and dehydration of goethite to hematite. These processes seem to be extremely rapid compared to the situation in other acid sulphate soil regions, for instance in Southeast Asia. Possibly, in the supersaline conditions, hydrolysis of jarosite to goethite might be stimulated by neutralization of acid, and hygroscopic free salts might accelerate the dehydration of goethite to hematite during the dry season.

Introduction

Twenty years of severe drought, from 1971 onwards, have caused dramatic changes in the fragile ecosystems of the Sahelian coastal area. The main consequences have been extreme salinization and soil acidification. Supersalinization has affected all soils, from the low marine terraces up to the colluvial fringes bordering the higher land, locally known as the 'glacis de raccordement'. The salinization was caused by (i) an upward flux of salts from the soil solution and shallow groundwaters, (ii) inundation by saline water from creeks and rivers, having salt concentrations 2 to 3 times that of seawater and (iii) aeolian deposition of salts.

The drought has also affected the hydrology of the area. Groundwater tables away from the tidal influence of rivers and creeks have dropped considerably, causing oxidation of pyrite and, thereby, strong acidification. Soil acidification, rare before 1971, has become widespread. This paper highlights the soil distribution and the soil forming processes following salinization and acidification in the estuary of the Sine Saloum river (Figure 1).

Climate

The annual rainfall of 600 to 900 mm falls in a single rainy season from May through October. During the last twenty years, rainfall has decreased to less than 600 mm per year (Figure 1) and the rainy season shortened to the period from July through September.
Landscape units

Field description and levelling have permitted the identification of the following landscape units (Michel 1973, Sadio 1989):
- Saline mudflats (tannes) with mangrove vegetation;
- Low terraces, 4-4.5 m above mean sea level, situated close to rivers and creeks, mainly barren;
- Mid-terraces, 4.5-5.0 m above MSL, some vegetated and some bare;
- High terraces, 5-6 m above MSL, completely or locally vegetated;
- Colluvial slope (French equivalent: glacis de raccordement), more than 6 m above MSL, transitional between the terraces and the adjacent uplands.

Soil characteristics and distribution

Unripe saline sulphidic soils
These are potential acid sulphate soils found under mangrove vegetation immediately alongside the tidal creeks. Parent materials are complex, with a succession of sand and unripe clay layers, making up the tannes and the low marine terrace. Under Rhizophora, the profiles are very dark grey (10YR 3/1, 2.5Y or N 4/0) and rich in fibrous organic matter. In the low terrace, the upper part of the profile is grey (5Y 6/1). pH in situ is 6.0-7.3, Eh -130 to -240 mV, total S between 1 and 4 per cent (more than 80 per cent is pyrite), and total iron 1 - 9 per cent. Salinity varies strongly with the season, conductivity ranges from about 15 mS cm⁻¹ in a 1:5 soil:water extract in the rainy season (August – September) to as much as 80 mS cm⁻¹ at the end of the dry season in June.
Saline acid sulphate soils
These soils are differentiated according to the colour of the mottles in the profile, but all are saline.

Soils with pale yellow jarosite
These raw, evidently very young acid sulphate soils are found in the low and mid-terraces. They consist of sandy or half ripe fine loamy material, and have a poor drainage. The land is inundated during the rainy season, and may be inundated by spring tides in the dry season. The profile is characterized by a Gj horizon with pale yellow 2.5Y 8/4 to yellow 2.5Y 7/8 mottles within 50 cm depth. pH is between 3.0 and 4.5 in the top 50 cm; water soluble sulphates are high, between 170 to 420 mmol(+) kg⁻¹; and the EC of a 1:5 extract is very high at 10-50 mS cm⁻¹ during the dry season.

Soils with yellowish mottles
These soils are found in the mid-terraces which are inundated during the rainy season. Their profiles are characterized by a Bj horizon with yellow or pale brown mottles (10YR 7-8/4-8) within the first 50 cm, and a pH of 3.5 to 4.5 in the mottled horizon. The mottles consist of a mixture of jarosite and goethite. The electrical conductivity (1:5 soil:water extract) is between 5 and 50 mS cm⁻¹ in the dry season.

Soils with yellowish red mottles
These soils are formed in mid-terraces and high terraces covered locally with a herbaceous vegetation. Their profiles are characterized by a Bg horizon with reddish yellow and yellowish red (7.5YR-5YR 5-6/6-8) goethite mottles within 50 first cm depth. The profiles are better drained and ripened than those with yellowish mottles. They are also less saline with an electrical conductivity (1:5 extract) between 4 and 8 mS cm⁻¹ in the dry season.

Soils with red mottles
These soils are found in the high terraces and the colluvial slopes. The profiles are characterized by a Bg horizon with red (2.5YR 5/8 or 10R 5/8) mottles within 50 cm depth. The mottles consist of goethite and hematite. Some have dark reddish brown concretions (2.5YR 3-4/4) in the topsoil. The pH is generally 3.5-4.5 within the first 50 cm. The electrical conductivity of a 1:5 extract is between 6 and 40 mS cm⁻¹.

Pedogenetic processes

Pyrite oxidation into jarosite
Acidification was not widespread in Sine Saloum before 1971. It spread upon the start of the catastrophic drought of the seventies (Marius 1979, Sadio 1989). Falling water-tables due to the rainfall deficit have led to pyrite oxidation and formation of acid sulphate soils.

Hydrolysis of jarosite
This process is characterized by change of colour and mineralogy of jarosite with time.
Jarosite is hydrolysed into goethite, according to the following reaction (van Breemen 1976)

\[ \text{KFe}_3(\text{SO}_4)_2(\text{OH})_6 \rightarrow 3\text{FeOOH} + 2\text{SO}_4^{2-} + \text{K}^+ + 3\text{H}^+ \]

Jarosite Goethite

The process can be accelerated by removal of one of the soluble products. This can happen in supersaline conditions by neutralization of acid and, thus, accelerate hydrolysis of jarosite. The soils with yellowish or yellowish red mottles have probably undergone this process.

**Dehydration of goethite**

Desiccation of goethite leads to the formation of red-coloured hematite (van Breemen 1976) according to

\[ 2\text{FeOOH} \rightarrow \text{Fe}_2\text{O}_3 + \text{H}_2\text{O} \]

Goethite Hematite

Hematite occurrence was confirmed by X-ray diffraction although only very small peaks could be observed. Transformation of goethite to hematite is very slow (Langmuir 1971), and must have an intermediate step because of the totally different mineral structures. Schwertmann (1988) postulates ferrihydrate as the intermediate product, but this mineral was not detected in acid sulphate soils in Thailand (van Breemen 1976) or Vietnam. The extreme drought of the seventies and the abundance of hygroscopic salts will have created the strong desiccation for hematite formation.

**Aluminium removal**

Raw acid sulphate soils are usually characterized by much soluble and exchangeable aluminum. However, in supersaline conditions in Sine Saloum, even very young acid sulphate soils with pale yellow jarosite have very low extractable aluminium, often less than 10 mmol(+) kg\(^{-1}\) soil, although the pH is low (<4). Potential acid sulphate soils, after drying, show extractable aluminium between 30 and 110 mmol(+) kg\(^{-1}\) soil. The low extractable aluminium is probably due to the high salt concentration which leads to replacement of Al at the exchange complex and to removal by the tides. In Vietnam, van Mensvoort et al. (1991) pointed out that in acid sulphate soils Al\(^{3+}\) can be substituted by Na\(^+\) and Mg\(^{2+}\) in salt or brackish water.

The soils of the high terraces and colluvial fringe, which are less saline, have much higher exchangeable aluminium than the younger soils.

**References**


The development of an acid sulphate area in former mangroves in Merbok, Kedah, Malaysia

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Abstract

The Merbok area was reclaimed from mangrove swamp in 1964. In 1974, about 40 percent of the reclaimed land was left uncultivated and the best paddy yields were only about 1.4 t ha⁻¹. Also, a few hundred ha of rice fields outside the scheme were abandoned after reclamation started. In 1991, about 85 percent of the land was cultivated and yields have increased dramatically to some 4 t ha⁻¹.

It is shown that the presently productive parts in the Merbok Scheme Area were formerly high tidal mangrove flats, flooded by less than 20 percent of high tides. These soils were already oxidized to a depth of 30 to 40 cm, prior to reclamation. The application of low amounts of lime (2 t ha⁻¹ yr⁻¹) and other inputs such as fertilizers, pesticides, land levelling, and direct seeding have improved paddy yields. However, the area which was reclaimed from regularly flooded lower mangrove flats, with pyrite in the topsoil, is still idle.

Introduction

Acid sulphate soils are problem soils which, however, are suitable for various crops under controlled water management that keeps the sulphidic horizon reduced, preventing the oxidation of pyrite (Dent 1986, 1992). Under some favorable hydrologic conditions it may be possible to prevent oxidation of pyrite near the surface, as was reported in The Gambia (Dent 1986) but, in other areas, traditional methods of rice growing have been developed that have adapted to acid soil conditions.

In Kalimantan, Indonesia, farmers practise repeated transplantation of rice so as to allow rice development in deep water, which is no longer acid (Driessen and Ismangun 1973, Sarwani et al. 1992). In Vietnam, the technique is modified, using short-duration rice varieties (Xuan et al. 1982). Another way of avoiding acidity is to accelerate the oxidation of pyrite in raised beds, followed by leaching of acids and aluminium into ditches. Variations of this technique are use in West Africa, Vietnam and, also, by Javanese transmigrants in Kalimantan. In Malaysia, the introduction of irrigation and double cropping was reported to alleviate acid sulphate problems in the Muda Scheme (Zahari et al. 1982).

Most of the successful approaches towards the use of acid sulphate soils are located in fresh water environments. Reclamation failures predominate, however, in originally
saline environments where potential acid sulphate soils are reclaimed from mangrove swamp. Reclamation failures in a salt water environment have been reported from Sierra Leone (Hart 1959), Thailand (Van Breemen et al. 1973) and Guyana (Brinkman 1982). Therefore, it is generally recommended that these sulphidic soils be not converted to rice growing. Moreover, mangroves in their virgin state are important as a breeding ground for fish and prawns and a source of firewood (Brinkman 1982, Dent 1986). Nonetheless, highly pyritic soils under mangroves have been reclaimed, although information on the long term fate of the reclaimed land is scanty.

In this paper, we report a decrease of abandoned land as well as an increased rice production in a former mangrove area which was reclaimed in 1964. The causes of these improvements and also the adverse side effects of reclamation for adjacent rice fields, are discussed.

Physical field description

The Merbok estuary (Figure 1) is located in Kedah, south of Alor Star. In 1964, the Merbok Scheme area of about 1000 ha was reclaimed from an estuarine mangrove swamp with potential acid sulphate conditions. A bund was constructed to prevent intrusion of saline water. Four outlets were constructed for draining the Scheme and its hinterland, which consists of a marine terrace (Figure 1). The terrace consists of sediments of an open accreting coast type which do not develop acid sulphate soils upon drainage (Die-mont and van Wijngaarden 1974). The annual rainfall is 2155 mm, with a pronounced dry period from December to March when evapotranspiration exceeds rainfall.

Aerial photographs of the Merbok area before reclamation show that the mangrove vegetation of the reclaimed area was not different from the remaining mangroves,
which have predominantly Rhizophora species. This indicates an estuarine sedimentation pattern and pyritic (> 1 per cent pyrite-S) soils (Diemont and van Wijngaarden 1974). Two vegetation types, relevant to the present study, can be distinguished:
- Backswamps with Rhizophora species, flooded by 60 to 90 percent of all high tides;
- Backswamps with mixed stands of Rhizophora and Bruguiera species and Exocaricia agallocha, flooded by less than 30 percent of all high tides. There are abundant lobstermounds which form, after reclamation, an oxidized surface layer up to 40 cm thick.

The soils under both vegetation types are pyritic (1 to 2 per cent pyrite-S) to a depth of approximately 1.5 m. However, in the lobstermounds under the mixed stands, oxidation and loss of pyrite is already under way. In the lobstermounds, jarosite can be observed and the pH in the lower part of the mound decreases from 7 to 2.5. Simultaneously, the pyrite content drops to between 0.1 and 0.5 percent pyrite-S (Table 1).

Methods

In 1973, the number of farmers and the rice yields in the Scheme area were assessed and abandoned fields were mapped. In 1991, the same procedure was repeated. In 1974, the pH wet (1:2.5) and pH dry (after 2 months of repeated drying and rewetting) were measured in both the Scheme area and in the adjacent old paddy area. Bulk samples from various depths in two fields (M and L) were taken in 1974 and, again, in 1991 to compare pyrite contents, which were calculated from total sulphates after correction of 2 N HCl soluble sulphates. Agronomic data were obtained from the regional office of the Department of Agriculture in Sungai Petani, Kedah.

Results

Soil characteristics

The presence of potential acid sulphate soils in the Merbok Scheme area was confirmed by a significant drop of the pH after drying and rewetting (Figure 2), whereas in the so-called ‘old paddy area’ on a marine terrace the pH drop after drying and rewetting is negligible. In the reclaimed area, the field pH of the soil as well as the pH of the water in the ditches was as low as 2.5 in the dry season. Upon flooding in the wet season, a pH of 5 to 6 is encountered, which is commonly explained by microbial activity.

Table 1 A lobstermound soil profile

<table>
<thead>
<tr>
<th></th>
<th>Total S %</th>
<th>Pyrite S %</th>
<th>Total acidity mmol kg⁻¹</th>
<th>pH fresh</th>
<th>pH dry</th>
<th>EC mS cm⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh mud</td>
<td>1.1</td>
<td>0.8</td>
<td>6</td>
<td>6.5</td>
<td>3.2</td>
<td>2.8</td>
</tr>
<tr>
<td>Jarosite horizon</td>
<td>0.7</td>
<td>0.1</td>
<td>146</td>
<td>2.0</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Brownish horizon</td>
<td>0.2</td>
<td>0.1</td>
<td>5</td>
<td>5.9</td>
<td>5.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Subsoil</td>
<td>1.5</td>
<td>1.3</td>
<td>6</td>
<td>6.4</td>
<td>3.6</td>
<td>3.4</td>
</tr>
</tbody>
</table>
reduction of iron oxides in the presence of metabolizable organic matter.

Acidification of the soil as a result of oxidation of pyrite is normally reflected in the soil profile by straw-yellow mottles of jarosite but jarosite was not encountered in the Scheme area. Outside the scheme, north of block A (Figure 1) mangroves were reclaimed by local farmers prior to the inception of the scheme but, at that time, enough fresh water was available to prevent serious acidification. After construction of the bund, the potential acid sulphate soils developed into acid sulphate soils with a pronounced jarosite layer within 30 cm of the surface.

Table 2, which compares the total S and pyrite-S in 1974 with the situation in 1991, shows a decrease of pyrite in the subsoil over this period, which is presumably caused by oxidation. The absence of jarosite is probably due to a low redox potential, which promotes oxidation of pyrite to ferrous sulphate but not to jarosite (Van Mensvoort and Le Quang Tri 1988).

Land use changes
The land reclaimed by local farmers produced rice yields of about 2 t ha⁻¹ previous to construction of the bund in 1964. But this area was abandoned due to severe acidity which developed after a lowering of the watertable caused by the construction of the

Table 2 Comparison of the percentages total-S and pyrite-S in two fields of the Merbok Scheme sampled in 1974 and 1991

<table>
<thead>
<tr>
<th>Field number</th>
<th>Depth cm</th>
<th>Total-S %</th>
<th></th>
<th>Pyrite-S %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>0-15</td>
<td>0.09</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>0.53</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>80-100</td>
<td>1.35</td>
<td>0.66</td>
<td>1.20</td>
</tr>
<tr>
<td>L</td>
<td>0-15</td>
<td>0.13</td>
<td>0.12</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>50-80</td>
<td>0.66</td>
<td>0.69</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>80-100</td>
<td>1.65</td>
<td>1.06</td>
<td>1.57</td>
</tr>
</tbody>
</table>
Table 3 Numbers of farmers in the Merbok Scheme area in different years

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of farmers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966</td>
<td>437</td>
</tr>
<tr>
<td>1974</td>
<td>199</td>
</tr>
<tr>
<td>1991</td>
<td>278</td>
</tr>
</tbody>
</table>

bund. Within the scheme area, also, the initial situation was alarming. Nearly half of the farmers left between 1966 and 1974 (Table 3). Nearly half (394 ha) of the arable land was abandoned, most in block C and D (Figure 3), due to severe acidity.

In 1991 the overall situation had improved. Farmers were resettled (Table 3) and only 15 percent (147 ha) was left idle. The situation in block D, however, had become worse (Figure 3).

Figure 3 Merbok Scheme, changes in land use between 1973 and 1991. Blackened areas abandoned.
Table 4 Paddy yields in cultivated land in the Merbok Scheme area (after 1974, only limed fields included)

<table>
<thead>
<tr>
<th>Year</th>
<th>Paddy t/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>1.2-1.4</td>
</tr>
<tr>
<td>1984</td>
<td>3.0</td>
</tr>
<tr>
<td>1985-87</td>
<td>3.4</td>
</tr>
<tr>
<td>1988-89</td>
<td>4.2</td>
</tr>
<tr>
<td>1990</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Rice yields
The best rice yields in the Scheme area in 1974 were about 1.4 t ha⁻¹ (Table 4). In the adjacent older rice fields, on non-sulphidic marine terraces, yields were reported to have decreased after construction of the bund due to water shortage. Yields in 1974 on these older terraces were less than 1.2 t ha⁻¹, while land previously reclaimed from mangroves was even abandoned. Since 1987, lime has been supplied by government agencies upon request by farmers. Lime is applied at 2 t ha⁻¹ yr⁻¹. Yields in limed rice fields have improved tremendously, up to 4.5 t ha⁻¹ in 1990 (Table 4), but not all farmers applied for lime, for reasons which will be discussed below. In 1991, some 370 ha were double cropped, mostly in areas A and B.

Discussion and conclusions

Paddy yields in the Merbok Scheme quadrupled following moderate applications of lime, sufficient fertilizers and pesticides. At the same time, the abandoned land area decreased from over 40 per cent to 15 per cent.

However, no improvement has been observed in block D, where even more land was abandoned in 1991 than in 1974 (Figure 3). This is because the soil in block D was reclaimed from the Type I vegetation where the soil has 1 to 2 per cent pyrite-S present in the topsoil, as can be observed in the remaining mangroves outwith the bund in block D.

The soil under the now successful cultivation was already improved by lobsters. After reclamation and some years of leaching, the topsoil is in a state in which the crop can respond to modest applications of lime and fertilizer.

A solution to the problem of the land reclaimed by the farmers prior to the scheme but, subsequently, abandoned is, basically, to manage the groundwater level, which may only involve the construction of a gate in the main canal.

This case study suggests that there is hope for growing rice in some pyritic mangrove areas. However, it should be recognized that farmers in the Merbok area are only part-time farmers and most of their income is from off-farm activities. Furthermore, even with free lime and fertilizers, only some farmers are using these inputs, because too much work is involved to spread the lime. Even if the work load were reduced by improving the roads, the farmers' plots of about 1.5 ha are too small to yield a reasonable income. One option is to accept part-time farming; another is to increase the land holding per farmer; a third option is to introduce prawn culture but the risks for smallholders of prawn culture are high.
References


