ACID SULPHATE SOILS OF THE MANGROVE AREA OF SENEGAL AND GAMBIA

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1 Summary

The mangrove area of Senegal and Gambia consists of intratidal flats with riverain mangrove forest and 'tannes', e.i. saline marshes partly with bare surfaces. Their soils are acid sulphate soils, very shallowly developed in peaty sulphidic mud clays and sands and subject to tidal flooding. The mangrove area covers a total of 500,000 ha and is concentrated in the estuaries of the Casamance, Gambia and the Saloum. At present mangrove forests are absent in the delta of the Senegal River. Tides are saline throughout the year in the Casamance and Saloum estuaries. In the Gambia and Senegal the river flow pushes back the saline tides during the short rainy season from June/July to September/October. Mean annual rainfall prior to 1972 ranged from 400 mm in the North (Senegal estuary) to 1550 mm in the South (Casamance) but since 1972 decreased to less than 250 and 1200 mm respectively. Over the same period soil salinity and acidity have increased and the tanne areas have expanded at the expense of the mangrove forest.

Soil studies have been conducted since 1960 and have been intensified since about 1967 when acidification problems in newly constructed polders became acute.

Traditional small-scale reclamation involved shallow drainage and controlled flooding with saline water to prevent drying of subsoils during dry seasons. Rice was grown on raised beds constructed with top soil only. The beds were desalinized seasonally with the first rains. Salinity used to be a more serious hazard than acidity in traditional

rice fields.

Modern, large-scale polders were designed to enable total exclusion of saline tides and desalinization of soils by deep drainage and leaching with fresh water stored in upstream reservoirs. This reclamation practice invoked an acidification of the soil that, with the available facilities for water management, could not be kept under control.

The diminishing fresh water supply since 1972 increased both salinity and acidity problems in traditional and modern rice polders. In part of the empoldered areas productivity might be restored by combining controlled saline flooding and cultivation on raised beds with a new system *of fresh water management aimed at shallow desalinization and flooding.*

2 Introduction

In Senegal and Gambia the mangroves are concentrated in the estuaries of the Saloum, Gambia and Casamance. The mangrove forests along banks and beaches make place inland for 'tannes' e.i. areas without or with only low herbaceous vegetation. Both areas occur on the same tidal flat. The tannes were originally also covered with mangrove forest, much the same as mangrove areas cleared for paddy and salt production. All together they are referred to in Senegal and Gambia as 'the mangrove' and as such cover a total surface of about 500,000 ha (Figure 1).

This includes the estuary of the Senegal River, where mangrove forests and tannes as such have disappeared, but where their sub-recent existence is evident from their remains in the soil.

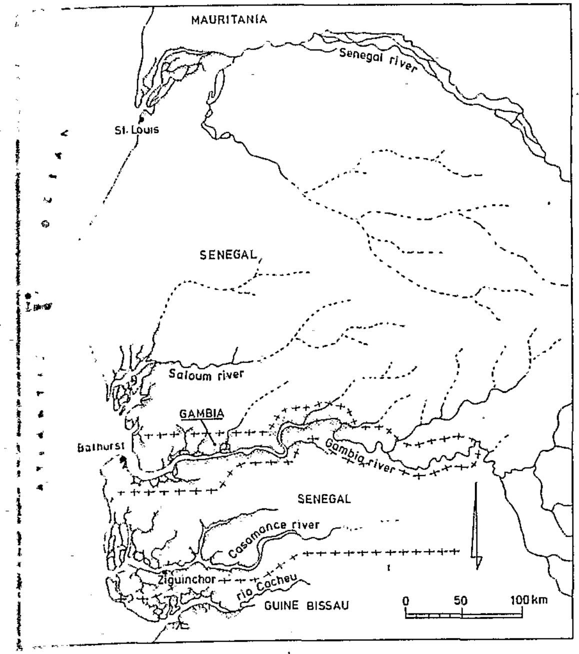

Figure 1. Mangrove area of Senegal and Gambia

The soils of the mangrove area have been studied since the early sixties, mainly in their physiographic context (Bonfils and Faure 1961, Cadillac 1965, Giglioli and Thornton 1965, Charreau et al. 1966, Gaucher 1967, Durand 1967). They were recognized to be predominantly saline acid sulphate soils after acute acidity problems developed in reclamation projects. These problems led to specific studies of the genesis (Vieillefon 1968ab, 1969, 1970a, 1971ab, 1972ab, 1973, 1974, Vieillefon et al. 1973) and the amelioration of these soils (Beye 1972, 1973abcd, Beye et al. 1968, 1975, 1979, Touré 1981, Khouma and Touré 1981). Systematic soil surveys have been conducted since 1972 and at present soil maps on scales 1/50,000 and 1/100,000 and relevant physiographic background information are available for the Casamance (Bodhisane 1974, Marius 1975, Vieillefon 1975, 1977), the Saloum (Marius 1975, Diop 1978), the Gambia (Marius 1976, Dent and Raiswell 1981, Thomas and Varley 1981) and the Senegal (Sedagri 1973, Marius 1975). Detailed maps (scale 1/20,000) have been made for specific reclamation projects (Brouwers 1980, Marius and Aubrun 1980, Daffé and Toujan 1979, Marius 1979, 1980).

The quaternary geology has been studied in detail by Kalck (1978). The dynamic character of the acid sulphate soils has become especially apparent since 1972 when the climate became drier. The concomitant changes in vegetation and soils have been followed by the author from 1973 to 1978. In this paper the main results of these latter studies and of the soil surveys are summarized.

3 Environment

Located between the latitudes 12° and 16° N, the mangroves of Senegal and Gambia are the most northern mangroves of Atlantic type on the West coast of Africa. They extend over about 500,000 ha, half of which are in the estuary of the Casamance and the remainder in the estuaries of the Gambia and the Saloum (Figure 1).

3.1 Climate

The climate is tropical with a long dry season of 7 to 9 months (October/November to May/June) contrasting with a short rainy season of 3 to 5 months (June/July to September/October). Mean annual rainfall (1931-1960) varies from more than 1500 mm in the Casamance (humid-tropical) to 800-1000 mm in The Gambia and Saloum (dry-tropical) to less than 400 mm in the Senegal (semi-arid-tropical). A climatic change toward aridity has taken place in the Sahelian zone since 1968, and has also affected the coastal areas (Table 1).

Table 1. Mean annual rainfall before 1960 and after 1968 (mm) in different deltas

Delta:	Casamance	Gambia	Saloum	Senegal
1931 - 1960	1546	1067	807	373
1968 - 1977	1182	680	605	247

3.2 Vegetation

The dominant tree species in the intertidal zone are characteristic for the West African mangroves: Rhizophora racemosa, Rhizophora mangle, Avicennia africana, Languncularia racemosa and Conocarpus erectus. Among herbaceous plants, mainly the supratidal and marshy 'tannes', the dominant species are Sesuvium portulacastrum, Philoxerus vermicularis, Paspalum vaginatum, Eleocharus mutata and E. Carribea.
Compared to the mangrove vegetation of the more humid coastal areas of Guinea and Sierra Leone, Avicennia nitida is scarce and the 'tanne' areas are larger and more frequently characterised by hyper salinity and the occurrence of bare flats with salt crusts.
A typical sequence of vegetation from river bank to central 'tannes' or to higher upland terraces is as follows (Vieillefon 1969) (Figure 8):

- a thin strip of Rhizophora racemosa;
- Rh. mangle forest;
- Avicennia africana mixed with Rh. mangle;
- a bare flat without any vegetation due to hyper saline conditions, locally called 'tanne vif' and here further on indicated as bare 'tanne';
- a herbaceous marshy flat, locally called 'tanne herbacé' and here: 'herbaceous tanne'.

The presence of fibrous roots of Rhizophora in the soil throughout the sequence indicates that the Avicennia forest and the tanne have replaced the Rhizophora forest. The vegetation sequence therefore has been described as a chronosequence by Vieillefon (1969). In this sequence the boundary between the tanne and the mangrove forest coincided, at the time of description, with the limit of the daily tidal inundations. In the bare 'tanne', only highest tides flooded the surface.
In this latter supratidal zone the salinity of groundwater and soil was the highest of the sequence. The mangrove forest-tanne limit was associated with a steep gradient in the soil salinity but not with any conspicuous drop in soil pH. Although the soils are potential acid sulphate soils, in the natural conditions prior to the recent climatic drying trend, the field pH of soils always exceeded 4.8 in the central tanne and 5.5 at the boundary of mangrove forest and tanne.

3.3 Hydrological patterns

Sedimentary and geomorphic characteristics in the mangrove areas of the Casamance, Gambia and Saloum are largely determined by the tidal currents and to a lesser extent by discharge of the rivers. In the Senegal delta continental influences e.g. wind blown sands, and fluviatile deposits dominate and tidal currents enter only during the dry season. Tidal currents are felt up to 526 km from the mouth of the Gambia, up to 217 km from the mouth of the Casamance. At present the Saloum is only an arm of the sea without appreciable fresh water discharge from the land. Mean tidal amplitudes are of the order of 1 to 1.5 meters, with spring tide amplitudes of maximally 2.5 meters. Storm floods do not occur, though winds and wave-action become forceful during rain storms and cause abrasion of windward banks and beaches. Undercutting of banks by tidal currents and accretion in quiet water are common phenomena. Currents permanently carry heavy sedimentary loads and in the main channels and along the coast mud banks shift regularly. On wind-exposed banks and beaches sand is sorted out and thrown up as beach ridges by the surf and subsequently is blown up to form dunes.
Tidal flats with mangrove forest build up to slightly below mean high tide level with sediments consisting mainly of heavy clay, except in the Saloum estuary where clay contents are lower and very fine sand predominates.
The Gambia River has an important catchment basin (Figure 1) and a fresh water flow which pushes back the salinity frontier to near the river mouth in the rainy season and dilutes the saline tides in the dry season (Table 2). The Gambia has a main channel that widens regularly towards the ocean, taking up consequently all the affluents of its lower reaches. The mangrove flats line the creek and river banks over a width of a few kilometers and rarely extend to form minor and isolated deltas of islands and networks of channels.

Table 2. Salinity (mS/cm) of main channels (E.C sea water: 46 mS/cm)

	Saloum 1978 35 km upstream	Casamance 1978 60 km upstream	Gambia 1975 130 km upstream
Dry season	115.5	88.7	22.1
Rainy season	68.8	44.7	0.4

The Casamance River (Figure 1, Table 2) has a very small catchment basin and even in the rainy season its flow of fresh water is hardly able to dilute the saline tides. In the dry season the salinity in its main channel is higher than that of sea water. The mangrove areas of the upper tidal reaches are riverain flats of several kilometers width, extending towards the lower reaches to form deltas with islands and reticulate creek patterns and flats over tens of kilometers.
The Saloum estuary (Figure 1, Table 2) consists of large mangrove flats intersected by an intricate network of tidal channels, hardly influenced by river water even during the rainy season. Salinity of the waters exceeds that of sea water throughout the year.
Hydrological conditions in the Senegal estuary are marked by contrasting seasonal alternations of saline tidal regimes and fresh water flooding. Original clayey tidal flats are presently overrun by continental dunes and partly reworked by braiding river courses. Large areas have become land-locked and cut off from tidal influences. Ground waters, however, remain saline.

3.4 Geology

Figure 2 illustrates the typical relations between continental terminal and marine and fluvio-marine deposits of the mangrove area, according to Kalck (1978). In the mangrove area the continental bedrock, mainly sandstone, occurs under unconsolidated mud clays and sands with a depth up to 20 meters. The chemical composition of the muds varies little among the estuaries apart from their SiO_2 content, which is related to varying amounts of quartz (Table 3). The muds are relatively poor in Ca, K and most trace elements.

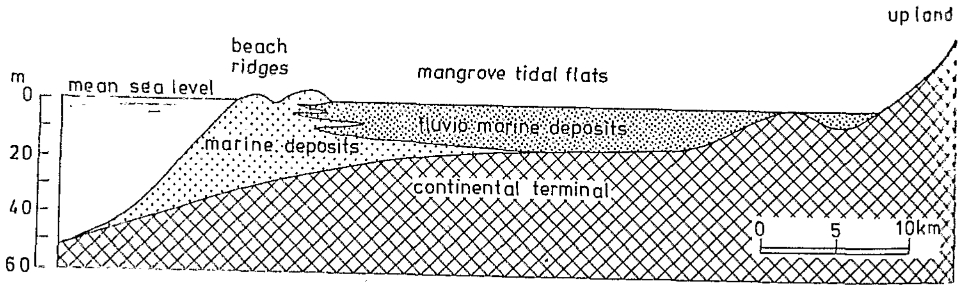

Figure 2. Schematic cross section of the Casamance estuary

Table 3. Mean chemical composition of mud samples

	Samples from mangrove flats			Marine deposits not influenced by mangrove vegetation	
	Casamance 67 samples (%)	Gambia 23 samples (%)	Senegal 15 samples (%)	Casamance 20 samples (%)	Saloum 11 samples (%)
SiO_2	57.7	58.7	64.4	80.2	74.5
Al_2O_3	14.7	15.0	11.1	6.8	7.5
MgO	1.12	0.93	1.30	0.75	0.87
CaO	0.27	0.29	0.78	0.80	2.34
Fe_2O_3	4.67	5,78	5.83	3.03	3.32
Mn_3O_4	0.036	0.101	0,059	0.019	0.015
TiO_2	0.93	1.02	0,63	0.50	0.57
Na_2O	2.53	1.16	2.38	1.15	1.99
K_2O	0.66	0.74	1.23	0.51	0.64
C	2.52	2.27	1.54	0.79	0.55
loss on ignition	16.2	12.6	10.6	6.0	7.9
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Sr	110	116	113	161	271
Ba	95	173	245	60	115
V	85	120	104	68	74
Ni	51	50	50	36	35
Co	21	31	22	17	16
Cr	146	149	154	110	114
B	96	85	81	97	88
Zn	39	60	32	23	19
Ga	22	24	15	15	16
Cu	26	26	37	22	24
Pb	31	36	24	30	26
Sn	34	38	26	20	14

The clay fraction of 0.1-0.5 µm is composed mainly of kaolinite and smectite. The kaolinite is derived from the upland sandstones and the smectite is of marine origin. The relative proportion of these clay minerals in mud samples from all the estuaries enabled the reconstruction of the paleogeographical evolution of the mangrove area (Kalck 1978).

4.1 Profile development

In the Casamance and Gambia estuaries the parent material consists mainly of peaty, sulfidic mud clay; in the Saloum area peaty, sulfidic very fine sandy muds predominate. Total sulphur content is normally above 5%. Pure peat layers are common. The peat consists mainly of fibrous root remains of Rhizophora species. In the sandy muds of Saloum, shell fragments may occur at 80 cm below the present surface.
Profile development (Figure 3) is predominantly shallow and determined by frequent inundations of saline tides, by predominantly shallow ground watertables which exceed 50 cm depth only for short periods, and seasonal acid sulphate soil formation. Physical ripening of the parent material muds is incomplete even in most top soils and structural peds hardly develop. The more conspicuous morphometric differentiation in the profiles pertains to mottling, decomposition of organic matter, activity of living roots and animals and seasonal fluctuations in salinity and acidity. As tidal influence decreases, profile differentiation extends to a greater depth and has a more permanent character due to increased seasonal fluctuations of the ground watertables through precipitation and evapotranspiration. This results in a regular sequence of soil profiles from creek banks inland, concurrent with vegetation sequences which are determined by the same gradient of tidal influences (Figure 3). In the Senegal estuary, soil profile development in the fluvio-marine clays is much more advanced due to large seasonal ground water fluctuations and exclusion of tidal influences.

4.2 Physical characteristics (Table 4 a,b)

The bulk of the soil material in the Casamance and the Gambia estuaries is made up of heavy clay with many inclusions of fibrous Rhizophora roots and of coarser woody material. The mineral fraction contains more than 50% clay. Bulk densities of 0.3 to 0.6 are common and water contents are normally above 100%. As a result of a high macroporosity, lateral and vertical permeability is high and tidal waves pervade soil bodies up to several hundreds of meters from the creek banks.

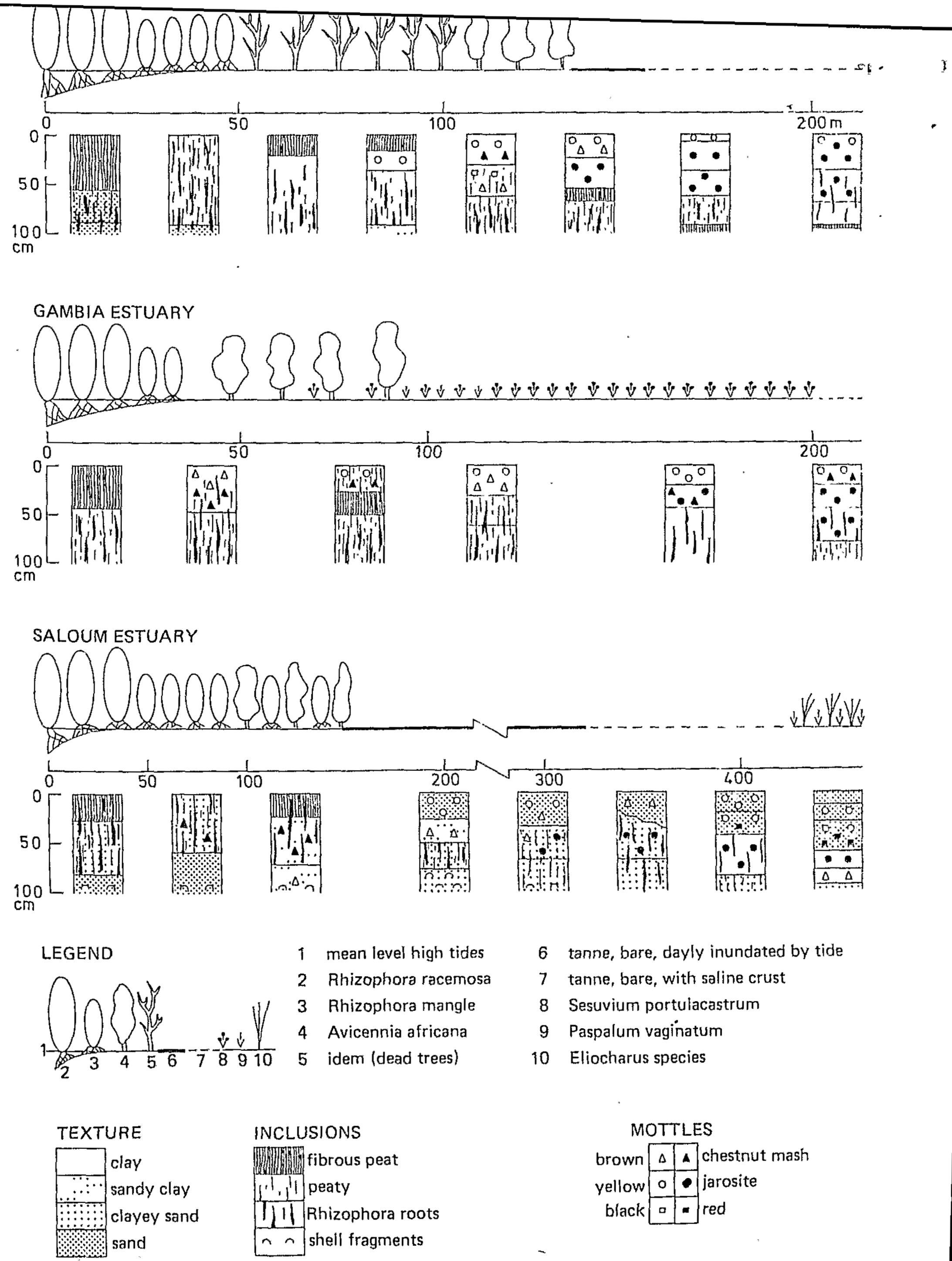

Figure 3. Soil profile development and vegetation sequence

Table 4a. Analytical data of some potentially acid sulphate soils

	Depth cm	Clay %	Silt %	Sand %	Moisture Content %	Bulk density	Eh mV	Soil pH Fresh	Soil pH Air-dried	C‰	N‰	C/N	Fulvic acid. C‰	Humic acid. C‰	Total S %	Saturated extract EC mS/cm	pH	Fe_2O_3 mg/l	Al_2O_3 mg/l
	HALIC SULFIHEMISTS																		
CASAMANCE	0- 20	69.3	23.	1.0	285	0.3	-160	7.	3.	151	4.6	26.	17.2	1.6	4.6	40	4.4		
	50- 70	66.6	29.5	1.1	155	0.4	-180	7.	2.7	97	2.2	16.6	18.7	3.6	4.1	155	2.4	5250	4800
	100-120	64.6	25.3	1.1	139	0.5	-200	6.6	2.7	57	1.7	9.8	20.7	2.2	6.1	160	2.2	2950	3280
GAMBIA	0- 20	54.8	40.8	4.4	320	0.21	-170	7.1	2.1	86	2.7	31.7			5.6				
	50- 70	58.6	37.2	4.2	138	0.43	-190	7.	2.4	44.4	1.6	28.1			5.9	85	3.4		
	80-100	62.1	32.7	5.1	150	0.38	-120	7.2	3.2	28.	1.2	23.1			4.1	61	2.6	785	780
	HALIC SULFAQUENTS																		
CASAMANCE	0- 20	70	27.2	2.8	130	0.56	-170	6.9	3.4	47.8	2.	23.9	2.68	1.88	3.1				
	20- 40	66.8	29.1	4.1			-180	6.6	2.5	47	1.5	31.1	3	2.36	8.8	260	2.6	2950	190
	60- 80	69.6	28.1	2.3	123	0.56	-180	6.6	2.3	25.4	1.	24.7	1.88	1.8	6.2	325	2.4	2300	190
	80-110	72	25.2	2.4			-180	6.6	2.6	22.6	1.	23.3	3.08	0.52	6.6				
GAMBIA	0- 20	64.6	31.2	4.0	85	0.59	-160	6.1	3.6	46.4	2.	22.5	2	1.9	2.6	64	3.7		
	20- 40	66.8	31.9	1.3	170	0.39	-200	6.1	2.5	78	2.8	27.8	4.	2.2	2.8	113	2.7		
	40- 60	66.5	31.7	1.8	173	0.39	-180	6.2	2.7	96	2.6	36.1	4.1	3.	6.0	118	2.5		
	80-100	66.8	32.5	0.7	180	0.38	-180	6.3	2.2	37	1.7	21.4	3.6	4.1	3.1	123	2.9		
SALOUM	0- 20	23	20	56.5	22	–		7.	3.5	18.2	1.27	14.3			2.1	70			
	20- 40	24	29	47.5	77			7.2	2.	24.2	1.52	15.9			3.2	70			
	60- 80	36.5	25.5	37	77			7.3	2.1	40.6	2.02	20.1			3.7	130			
	80-100	38.6	25	36	123			7.2	2.	52.6	2.75	19.1			3.3	130			
	SULFIC HALAQUENTS																		
SALOUM	0- 20	29.7	7	63.5	127	0.6		6.4	3.5	53.4	1.5	35.6	5.8	2.2	2.1	169	2.6		
	40- 60	27.3	8.4	64.3	108	0.7		6.4	2.7	29.6	0.8	36.4	3.6	1.6	1.9	107	7.7		
	80-100	34	14	52	25	1.5		6.3	6.5	11.7	0.4	31.6	1.08	0.3	0.7	41	7.1		

Table 4b. Analytical data of some acid sulphate soils

	Depth cm	Clay %	Silt %	Sand %	Moisture content %	Bulk density	Eh mV	Soil pH Fresh	Soil pH Air-dried	C‰	N‰	C/N	Fulvic acid. C‰	Humic acid. C‰	Total S %	Saturated extract EC mS/cm	pH	Fe_2O_3 mg/l	Al_2O_3 mg/l
	HALIC SULFAQUEPTS																		
CASAMANCE	0- 20	65	29	4.3	67	0.86	380	3.5	3.6	9.8	0.52	18.8	0.6	0.14	2.6	100	3.9		33
	20- 40	63	28	2.9	42	0.91	430	3.2	3.4	13	0.65	20	1.95	1.38	3.8	185	3.4	15	70
	50- 70	62	33.2	2.7	129	0.51	290	3.6	2.6	30.2	1.	29	4.	3.5	3.9	245	2.7	510	1780
	90-110	66	31.2	2.6			210	3.7	2.8	22.2	0.86	25.8	2.36	1.5	4.9	260	2.3		2970
GAMBIA	0- 15	77.4	19.2	3.5	36	0.89	480	3.7	3.5	16	0.9	28.2			0.5	82.1	3.6	31.2	11
	20- 40	77.6	17.8	4.5	71	0.65	580	3.5	3.	8.4	0.5	15.8			2.0	80.	3.4	56.6	18
	50- 70	72.7	23.7	1.6	128	0.47	480	3.6	3.1	10	0.4	22.7			1.1				
	80-100	72	25	4.3	137	0.45	280	3.5	3.1	13.6	0.7	20			0.7				
SALOUM	0- 20	8.9	5.5	82.7				4.	3.6	1.72	0.1	17.2				299	3.5	50	21
	40- 60	32.5	9.8	56.6	51	0.97		3.5	3.6	7.9	0.27	29.3	5.2	4.6	3.9	281	3.1	1200	125
	60- 80	45.4	13.2	41.4	93	0.7		3.6	2.1	26.5	0.64	41.4	4.6	2.5	4.4	365	1.5	2000	1220
	80-100	26.3	15.9	7.8	26	1.3		3.5	2.3	3.1	0.25	12.4	4.3	1.4	2.4	275	1.7	3500	2400
	SULFIC HALAQUEPTS																		
CASAMANCE	0- 20						80	5.5	5.4	23	1.3	17.3	1.08	1.08	0.4	27	5.6		
	20- 40				60	0.96	200	5.2	5.3	13.4	0.76	17.6	0.9	1.56	0.6	35	5.4		
	45- 65				81	0.67	250	4.5	2.9	30.2	1.16	26	2.8	3.6	3.2	180	3.1	390	872
	80-100				81	0.67	- 50	4.7	2.6	37.4	1.25	29.9	1.5	2.3	4.5	225	2.6	760	2430
GAMBIA	0- 20	54.6	24.4	21	92	0.62	230	5.6	5.4	34.8	1.7	21	1.7	0.53	0.3	55	7.1		
	20- 40	61.8	25.1	13.1	95	0.63	280	5.7	5.3	30	1.1	27	1.75	0.3	0.5	70	6.5		
	40- 60	67.4	29	3.7	146	0.45	- 10	6.	2.3	70	2.3	30.3	4.	1.27	4.6	142	2.7	276	265
	80-100	52.3	33.8	13.3	148	0.44	-180	6.2	2.1	58	1.8	32	3.95	0.9	6.1	163	2.6	252	645
SALOUM	0- 20	11.6	8.5	77.5					5.	1.6	0.12	13.7	2.85	0.35		150.4	5.8		
	20- 40	28.1	12	68.6	25	1.4		4.4	3.7	8.6	0.32	26.9	4.95	3.32		219	3.6		
	60- 80	32	12	56.2	66	0.9		4.3	2.7	14.4	0.43	33.5	5.2	1.8		274	2.2		
	100-120	43.1	9.7	51.7	75	0.8		5.2	2.4	19.8	0.63	31.4	2.36	0.6		320	2.2		

Physical ripening in this latter zone does not proceed beyond the nearly unripe and half ripe stages (N values 1.0 to 2.0). Deeper inland, in the 'tanne' areas, ripening in the upper 40 cm may reach the nearly ripe stage (N value 0.7 to 1.0), bulk densities, however, remain below 1.0.

The water content of clayey top soils in the 'tanne' areas may fall below 40% and salt crusts may be formed on the surface, but no significant cracking occurs and the structure remains massive with many pores. Soil colours do change with ripening. Matrix colours of the unripe clay are normally dark grey (10 YR 3/1 - 4/1 or N 3/0 - 4/0) and these turn to brownish grey (10 YR 4/2 - 5/2) in the half ripe and nearly ripe horizons. At the same time brown and yellow and, rarely, red mottles appear. Typical is the pale yellow jarosite, initially associated with root remains.
In the Saloum estuary and locally near the mouth of the Casamance River, the patchy occurrence of very fine sandy soil material causes irregular patterns of ripening, water content and bulk density. Textures vary widely among horizons and ripe surface soils and sandy subsoil layers may occur together with half ripe peaty sandy clay horizons. Structure and mottling of top soils of these sandier soils are similar to those of heavy clay soils.

4.3 Chemical characteristics (Table 4 a,b)

Acidity

Nearly all of the soils of the mangrove area contain potential acid sulphate material within 40 cm of the surface, with total sulphur content exceeding 5% for heavy clay and 2% for sandy mud. Only in the deepest developed profiles potential acidity has about disappeared from the upper 40 cm. In some sandy subsoils potential acidity (pyrite) is exceeded by potential alkalinity (shell fragments). Except for these sediment layers rich in shells, all soil horizons acidify strongly on drying and as a rule air-dried samples give pH values of 2.0-3.5. Prior to the decrease in annual rainfall since 1972, field pH reached such low levels only in polders and, temporally, in subsoils in the centre of 'tannes' during exceptionally pronounced dry seasons.

At present the field pH in soils of bare tannes with salt crusts, varies between 3.0 and 3.7 down to 100 cm, except for a temporary rise to pH 5 to 6 in the surface soil, shortly after rainstorms or spring tide inundations. In the daily inundated tidal flats field pH varies at present between 5 and 6 against formerly (before 1972) 6 and 7. Along the creek banks field pH values have not changed. Depending on the composition of the creek water, they range from 6.0 to 6.5 for weakly brackish and up to 7.3 for hypersaline tides.

Organic matter

In the soils under Rhizophora forest and in the reduced subsoils of 'tannes', fibrous root remains of Rhizophora are common and often are the most conspicuous constituant of the soil. Organic matter content expressed as C-content of these layers often exceeds 5% and may reach up to 15%. C/N ratios range between 20 and 40 indicating a low degree of decomposition. Fulvic acids normally predominate over humic acids.
In the partly ripened and oxidized top soils of the tannes, considerable decomposition of fibrous root remains has taken place as can be deduced from abundant open pinholes in the massive clay. C-contents in these horizons fall below 3% and C/N ratios below 20.

Sulphur

Sulphur contents of parent materials range from 1 to 4% for mud sands and 3-10% for mud clays. Most of the sulphur comes from micro crystalline clusters of pyrite embedded in organic matter, especially in fibrous root remains of Rhizophora. In the tanne zones, soil horizons with jarosite mottles have lower sulphur contents. The lowest S-contents (below 0.5%) are found in the half ripe or nearly ripe top soils without jarosite mottles. In the jarosite horizons sulphur comes mainly from the jarosite and near the surface from water soluble sulphates and gypsum. In the Saloum estuary gypsum crystals also occur deeper in the profile. Elsewhere conspicuous gypsum crystals are found in the powdery saline crusts of bare tannes. In the Casamance, recently with increasing climatal aridity, at the basis of the powdery crust a thin gypsum bed is formed.

Soluble salts and salinity

All soils of the mangrove area are more or less saline in natural conditions. During the prolonged dry season losses by evapotranspiration are largely balanced by saline tidal water from the creeks. As a result ground waterlevels rarely fall below 50 cm under the surface except in the areas far from the creeks where tidal waves dampen and subsurface lateral influx of saline ground water only partially compensates evapotranspiration losses. Salinity of the ground water increases from the creek banks inward to a level several times that of sea water (Tables 5 and 6). Desalinization during the short rainy season proceeds only superficially in the modal vegetation and soil sequence (Table 5).

Table 5. Electrical conductivity (mS/cm) of saturation extracts of soil sampled at the end of the rainy season

	Mangrove forest		Bare tanne	
	Rhizophora species	Avicennia africana	Inundated daily	With salt crust
Casamance				
0- 20 cm	41	27	45	100
40- 60 cm	155	180	105	185
80-100 cm	160	225	175	260
Gambia				
0- 20 cm	61	45	80	84
50- 70 cm	85	72	82	247
Saloum				
0- 20 cm	169		151	281
40- 60 cm	108	-	219	299
80-100 cm	41		321	365

Table 6. Analytical data of creek and groundwater in typical vegetation
and soil sequences
[illegible] = creek, M = mangrove forest with Rhizophora (r) or Avicennia (a),
[illegible] = tanne, daily inundated (i) or with saline surface crust (s)

Sequence	pH	EC mS/cm	Cl^-	$\frac{1}{2}SO_4^{2-}$	HCO_3^-	$\frac{1}{2}Ca^{2+}$ (mmol/liter)	$\frac{1}{2}Mg^+$	K^+	Na^+	SiO_2
[illegible]ance [illegible] 1978										
[illegible]	7.2	45.9	600	105	2.35	23.0	118.4	10.5	510	0.064
[illegible]	6.2	66.7	920	104	2.11	36.8	192.0	16.4	780	0.100
[illegible]	6.4	84.0	1260	128	1.66	42.8	262.4	22.0	1080	0.160
[illegible]	6.6	77.5	1120	122	1.55	44.8	233.6	19.6	940	0.136
[illegible]	4.3	86.2	1300	127	–	33.6	275.2	22.2	1090	1.060
[illegible]	3.6	103.1	1690	230	–	35.2	451.2	18.6	1430	1.340
[illegible]ia [illegible] 1978										
[illegible]	7.6	43.7	360	51.4	0.9	11.6	72	10.5	340	0.18
[illegible]	7.9	40.1	344	42.9	2.0	11.2	72	9.6	310	0.19
[illegible]	7.9	45.3	400	60.0	1.5	13.2	112	11.9	350	0.12
[illegible]	8.0	49.7	424	51.4	1.6	13.6	84	12.8	380	0.60
[illegible]	3.5	75.0	676	85.7	–	28.4	148	16	590	1.06
[illegible]	2.8	107.8	1000	128.6	–	44.0	224	24	820	1.33
[illegible] [illegible] 1978										
[illegible]	8.0	88.1	800	80.6	2.6	29.2	176	14.2	665	0.03
[illegible]	8.0	97.0	800	92.3	2.6	29.6	184	15.4	665	
[illegible]	8.0	127.0	1160	128.6	3.7	39.8	272	21.0	1000	0.20
[illegible]	7.5	197.2	1760	171.4	1.2	41.8	416	34	1500	0.42
[illegible]	4.3	212.3	1860	162.8	–	37.6	428	38	1600	0.70
[illegible]	3.5	283.0	2600	214.3	–	41.2	536	52	2300	1.09

Table 6 demonstrates that both highest salinity and acidity occur in the bare tannes with salt crusts at the surface e.i. in the zone where, during the dry season, evapotranspiration exceeds replenishment by tidal water and where the pyritic subsoil is liable to be exposed to the atmosphere to greater depth.
The increase in dissolved sulphate during the formation of hyper saline ground water is less than the increase in chloride, even though considerable amounts of sulphate must be liberated during pyrite oxidation under these conditions (Table 6). Sulphate concentrations are probably kept relatively low by precipitation of gypsum and jarosite, which are very conspicuous in these soils.
Dissolved SiO_2 in the ground water increases both absolutely and proportionally (to Cl^-) when going from creek banks to tanne centres. In view of the presence of silicified Rhizophora roots in bare tannes (Marius 1976) its concentration probably exceeds the amorphous silica solubility (2 mmol/l) at times. In the very acid tanne centres dissolution of silicates (clay minerals) is probably the source of dissolved silica.
In aqueous extracts of subsoil samples, which turn extremely acid (pH 2.5-3) in the laboratory, soluble iron and aluminum may reach contents of up to 3.5 g Fe or 2.5 g Al per litre. Under natural conditions in the field, the pH normally does not fall below 3.2 and concentrations will probably not rise above about 700 mg Fe/litre and 50 mg Al/litre. However, introduction of drainage systems might cause much more extreme acidification in the field, with concomitant higher levels of soluble Fe and Al.

4.4 Soil classification

The regular soil sequence between creek banks and tanne centres comprises potential and actual acid sulphate soils and sometimes para acid sulphate soils that are strongly saline and locally hypersaline. Soil samples from the whole profile under the mangrove forest and from depths below 40 cm in tanne areas usually have sulphur contents exceeding 0.75%, N values over 1.0 and a pH of the air-dried soil below 3.5. Soils in tannes may have jarosite mottles in the upper horizons. In terms of

Soil Taxonomy these acid sulphate soils are Halic Sulfaquepts and the potentially acid soils are Halic Sulfaquents. Where fibrous peaty sulfidic clays under Rhizophora have more than 30% organic matter over more than half of the profile depth, soils are classified as Halic Sulfihemists.

In the deepest developed soils the pH of the surface layer may be above 4.0, but decreases with depth to 3.5 at 50 cm below the surface and jarosite mottles are common. These soils are Sulfic Halaquepts.

Desalinized acid sulphate soils with very ripe brown and red mottled surface horizons, jarositic subsurface horizons and with a pH of the air-dried soil between 3.5 and 4.0 within 50 cm depth, occur locally in the Senegal delta and in some valleys of the Casamance (Baila) in older terraces. These soils are about the most developed acid sulphate soils of Senegal and belong to the Sulfic Tropaquepts of the Soil Taxonomy.

In literature on the soils of the mangrove area of Senegal and Gambia, frequently other soil classification systems have been applied. Table 7 presents an attempt to correlate the more commonly used of these systems.

Table 7. Correlation of soil classifications

Soil Taxonomy	FAO	CPCS[1]	ORSTOM[2]
Sulfihemist	Thionic Fluvisol	Sols hydromorphes organiques-tourbeux-eutrophe	Halithiosol organique
Halic Sulfaquent	Thionic Fluvisol	Sols hydromorphes moyennement organiques	Halithiosol halique
		Sols peu évolués non-climatiques-d'apport salés	
		Sols humiques à gley-salés	Halisol sulfuré
Halic Sulfaquept	Gleyic Solontchak	Sols halomorphes à structure non dégradée-salins-acidifiés	Halisulfosol halique
Sulfic Halaquept	Gleyic Solontchak	Sols halomorphes à structure non dégradée-salins-acidifiés	Halisol acidosulfaté
Sulfic Tropaquept	Dystric Gleysol	Sols hydromorphes minéraux -à gley	

[1] Commission de Pédologie et de Cartographie des Sols, Paris, 1967

[2] Office de la Récherche Scientifique et Technique Outre-Mer (Proposal) (Ségalen et al. 1979)

5 Changes in soil conditions as a result of increased climatic aridity

Since 1972 the annual rainfall in Senegal and Gambia has decreased by about 25-40% compared to the long term mean up to that year (Table 1). In the mangrove area changes in vegetation became conspicuous. The author monitored these environmental changes from 1973 through 1978 with special emphasis on a sequence of vegetation and soil in Lower Casamance that had been studied in detail earlier (1967-1971) by Vieillefon (1969, 1972b). The main changes observed will be summarized in the following. They are illustrated by Table 8.

Table 8. Changes in vegetation, pH of soil in situ and salinity of ground water (mS/cm) in the mangrove area of Senegal due to advance of climatal aridity since 1971

May 1971, dry season

Vegetation sequence:	Rhizophora forest		Avicennia africana		Tanne	
	Rh. racemosa	Rh. mangle + Paspalum	+ Scirpus	+ Sesuvium + Philoxerus	Bare saline crust	Herbaceous Eleocharus
pH 10 cm	6.6		6.9		6.7	5.6
pH 50 cm	7.1		5.8		5.8	5.4
pH 90 cm	6.9		5.6		4.9	5.2
Salinity	50		70		90-100	80

May 1974, dry season

Vegetation sequence:	Dead trees		Tanne		
	Bare surface	Patches of Sesuvium Paspalum+Eleocharus	Closed cover of Sesuvium	Bare saline crust	Bare saline crust
pH 10 cm	5.7		5.5	3.3	4.3
pH 50 cm	5.9		3.5	3.0	4.6
pH 90 cm	5.9		4.8	3.4	6.0
Salinity	95		115	130	130

May 1978, dry season

Vegetation sequence:	Bare surface	Tanne		
		Closed cover of Sesuvium + Eleocharus + Conocarpus	Bare saline crust	Bare saline crust
pH 10 cm	5.3	4.1	3.0	5.3
pH 50 cm	5.3	3.6	3.2	3.4
pH 90 cm	6.0	4.1	3.3	4.4
Salinity	150	150	125	105

November 1978, rainy season

Vegetation sequence:	Bare surface	Avicennia africana regrowth	Tanne		
		+ Sesuvium	Eleocharus, Sporobolus + Sesuvium + Bacopa	Bare saline crust	Bare saline crust
pH 10 cm		6.2	5.2	3.5	3.2
pH 50 cm		5.6	4.5	3.4	3.3
pH 90 cm		5.6	4.7	3.4	3.7
Salinity		20	35	115	90

As a result of the drought, evapotranspiration deficits during the dry season increased and in the mangrove area soil salinity increased. On the other hand the tidal effects were damped at closer distance from the creek banks so that groundwater fell to lower levels especially towards the central parts of the tannes.

In the Rhizophora zones along creek banks, the salinity used to be similar to that of the creek water, but tripled after the drought.

In the intermediate zone with Avicennia africana trees and halophitic herbs, both salinity and acidity increased.

The soils along the creek banks did not show conspicuous changes in horizon development, apart from the rise in salinity during the prolonged dry periods and a slight drop in pH. In the centre of the tannes the relative increase in salinity was less, but here lowering of the ground water level brought about further oxidation of sulphidic subsoil resulting in extreme acidification that even affected the top soil. At the same time the profile deepened slightly, and some ripening of subsoils and segregation of brown mottles took place. In the topsoil salt crusts replaced shallow A1 horizons in places where the herbaceous vegetation had died. Gypsum crystals became very conspicuous near and on the surface and white powdered silicified roots, identified as opal-crystobalite, became a normal phenomenon.

The changes in vegetation were much more spectacular. The Rhizophora forest died leaving bare flats that later on were partly colonized by Avicennia africana trees together with herbaceous patches of Sesusivium portulacastrum from the adjacent land inward zone. In the original Avicennia africana zone all trees died and all herbaceous species except Sesuvium disappeared. In the original herbaceous tanne all vegetation died and the surface became encrusted with salts as in the adjacent bare tanne. Some of the herbaceous species later on reappeared in the Avicennia africana zone together with Sesuvium. The general trend was for the forest to disappear and for the bare flats, especially the salt crusted bare tanne, to expand at the cost of the herbaceous tanne (Figures 4, 5, 6, 7, 8 and 9).

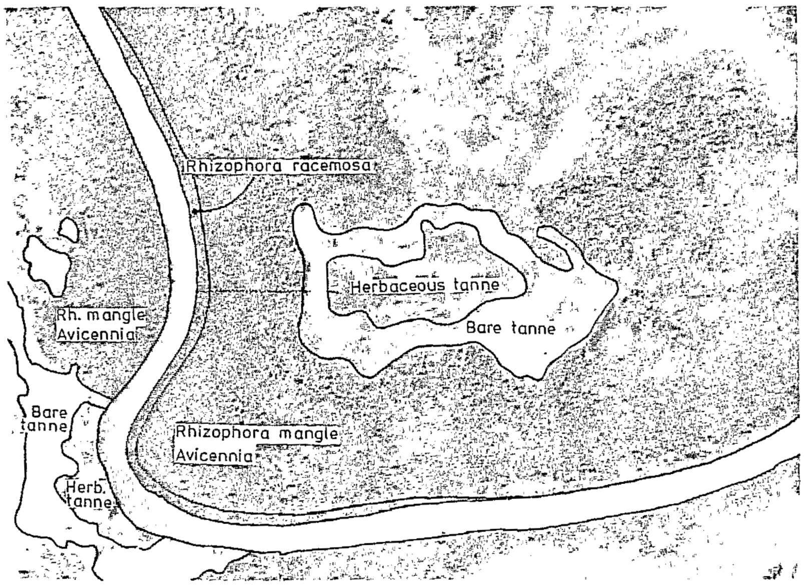

Figure 4. Aerial photograph of mangrove forest and tanne association near Balingoré (Casamance) in 1969

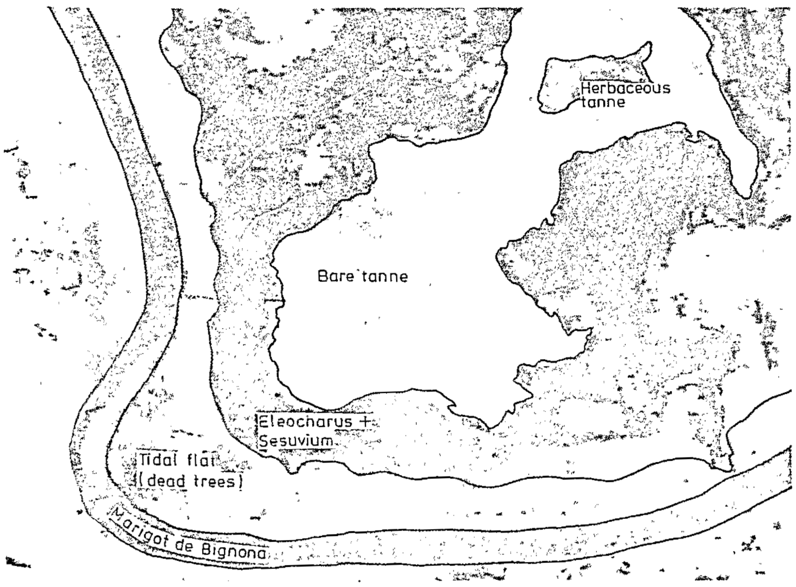

Figure 5. Aerial photograph of same area of Figure 4, but taken in 1978, showing shifts in vegetation boundaries

Figure 6. Changes in vegetation in mangrove area in the Casamance, Situation in 1978. Remains of former Rhizophora mangle and Avicennia africana forest, died since 1972 due to increasing soil salinity and acidity. In the background a narrow strip of surviving Rhizophora racemosa on the very bank of the creek.

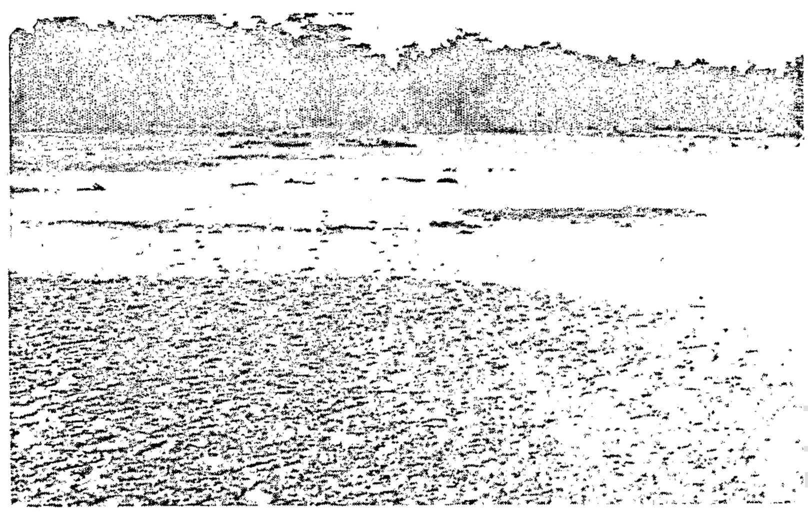

Figure 7. Changes in vegetation in the mangrove area in the Casamance. Situation in 1978. Bare tanne. In the foreground algal remains on saline crust, which appears shiny white in the central section. The darker bare surface along the remaining forest prior to 1972 was covered with mangrove forest (Figure 6) and is daily inundated by the tide.

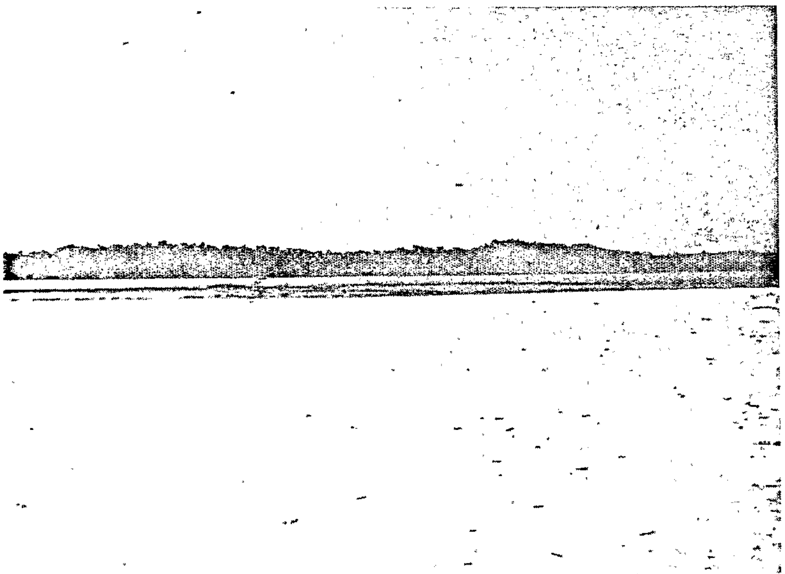

Figure 8. Soil sequence in Saloum estuary: Rh. racemosa, Rh. mangle, bare tanne daily inundated

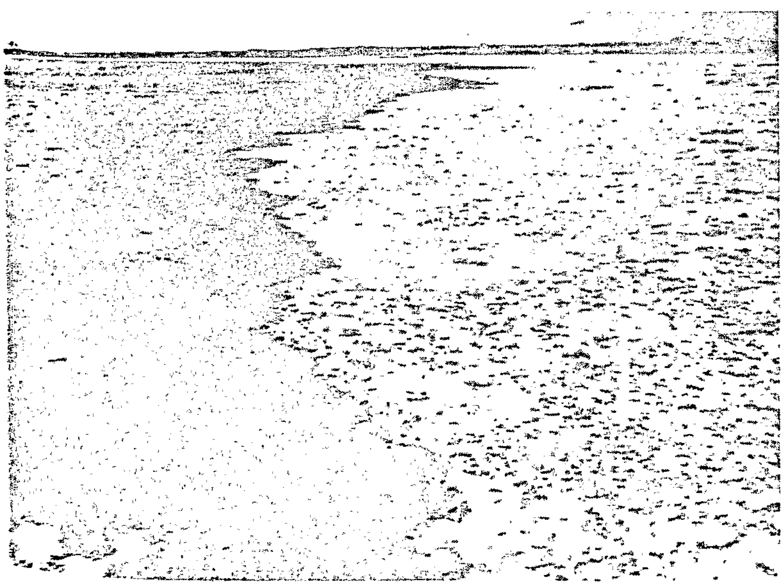

Figure 9. Saloum estuary:
left: bare tanne inundated
right: bare tanne with saline crust

These dramatic changes in vegetation and soil that were triggered off by a sequence of few dry years with annual mean rainfall 25% below that of prior periods, demonstrate the delicate character of the natural ecological equilibrium in the mangrove area. Similar changes have taken place in the past as is indicated by root remains in the soil. Reverse changes, towards less saline and less acid soil conditions and increased tree cover, might also have taken place in periods with either more precipitation or intensified flushing by tides or river water.
A new natural equilibrium of soil and vegetation will probably establish with time. The new salinity level has probably been reached already. Sulfuric acid will continue to be released temporarily as long as residual potential acidity remains in the subsoil horizon that is exposed to the atmosphere during lower ground water levels. Actual soil acidity during dry periods can be expected to decrease when the seasonal release of free acids has decreased to a level that can be balanced by neutralization or immobilization in the soil profile or by removal with floods. Ultimately a pH between 5 and 6 might be reached again.

6 Traditional rice polders and modern reclamation projects in the mangrove area

Seafood, seasalt and rice are the main products of the mangrove area in Senegal and Gambia. The flat relief of the intertidal clay flats and the regularity of tidal amplitudes facilitate the construction of small-scale polders, dikes and canals and the water management in salinas, paddy fields and fishponds. The mangrove forest provides wood for fuel, construction of boats, houses, sluices and implements. Transportation by boat is favoured by the omnipresence of interconnected waterways and the regularity of recurrent winds and tides.
At least 1500 mm of rain is required for a marginal crop of rainfed rice in the saline soils of the mangrove area. In the Senegal and Saloum estuaries the climate is too dry for rice and here fishery is the major traditional basis for subsistence. In the Gambia and the Casamance natural conditions at least were favourable for paddy production. In the Gambia fresh water is supplied by rain and river together, in the Casamance by rain alone. With the decrease of the mean annual

precipitation from 1546 mm prior to 1972 to less than 1200 mm lately, rice production in the Casamance estuary has become risky.

The traditional water management and cultural practice in the Casamance were well adapted to the prevailing conditions. For rice polders Rhizophora forest zones were preferred, the salinity of which used to be the lowest of the normal soil sequence (Table 8, May 1971). Dikes of 1 to 1.5 m high with crests about 20 cm above maximum spring tide level, were built up with clay excavated from a trench along the dike. For sluices hollow tree trunks, preferable of palms, were embedded at various levels in the dike body, allowing maintenance of various water levels in the polder. The lowest sluice was situated below the original surface with its outlet in the trench. For gates fibrous stops impregnated with clay were used and sometimes wooden flap gates.

After closing the dike, clearing was done in the superficially drained polder. The cut wood was transported for use elsewhere, remaining stumps and roots were removed carefully from the soil and locally dried and burned. Then a grid of superficial ditches was dug and the excavated flat topsoil clods were laid on the interjacent surface areas to form raised cambered beds a few square meters each.

Desalinization by alternative flooding and flushing with rain water for one or two rainy seasons was necessary for successful growth of transplanted rice. Thorough drying of the soil during the dry season was prevented by letting in saline water into the superficial ditches, without flooding the beds. Regular annual desalinization of the topsoil could be taken care of by the first heavy rains of the season.

Empoldering normally started at the inland side of the Rhizophora zone and later expanded towards the river bank (Figure 10). In areas with strongly erosive tidal currents the rice polders were protected by a series of peripheral polders the forest of which would not be cut for several years, although initial desalinization would proceed. Moreover, outer dikes were constructed several tens of meters from the banks, leaving a fringe of mangrove forest in the front land.

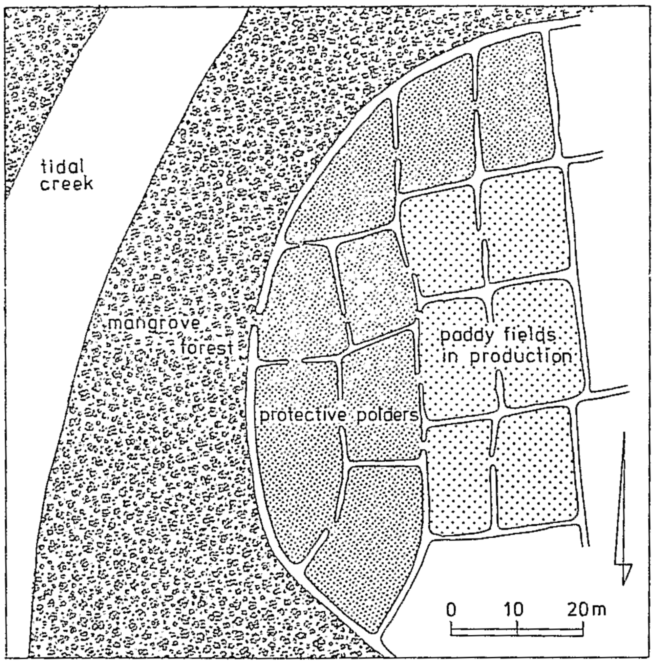

Figure 10. Traditional rice polders in the Casamance estuary (after Pelissier 1966)

This traditional system could not cope effectively with the enhanced salinity after the climatic drying started in 1972. Also the system was not well-suited for modern capital-intensive practices, such as transportation by road, irrigation from reservoirs, etc., which require organizational centralization.

Large-scale reclamation projects for paddy production have been proposed and realized even before 1972. The more important of these are situated in the Lower Casamance where the mangrove flats penetrate into the valleys of tributaries such as the Kamobeul, Guidel, Bignona, Baila and Soungrougrou. Upstream of the tidal area the valleys are dammed to regulate the fresh water supply. Downstreams where the valley widens to the estuary, a concrete dam with wooden gates is constructed in the riverbed to exclude saline tides and increase drainage capacity, for intensive leaching of salts from the upstream mangrove area, now provided with integrated drainage and road systems and cleared and prepared for paddy production. Soil salinity was considered the main problem and potential acidity was underestimated.

The intensive initial leaching and desalinization of the mangrove flats has provoked extreme acidification in several of these reclamation projects. In some polders reclaimed in 1967 the pH of the topsoil dropped as low as 2.7 in 1971 (Beye 1972). Since 1972 decreasing rainfall hampered desalinization and caused increased acidification. Many of the large polders were affected by the climatic change even much more severely than the traditional rainfed paddy fields, where deep drainage was never practised.

In retrospect one might conclude that the over-emphasis on correcting salinity in the polders led to over-drainage, and, like most overdosing of remedies applied to subtle dynamic systems, it resulted in the reverse of the effect aimed at.

In this context some other negative effects of the abrupt exclusion of saline tides should be pointed out. Open waters acidified or polluted otherwise, shrimp and seafood in general became scarce and diseases formerly nearly unknown in the mangrove area, e.g. dysentery, bilharziosis, typhoid fevers, became endemic.

It is evident that many of the rice polders cannot function well on the basis of the original criteria for reclamation, layout and water management. The changes in climate alone require that criteria be adapted to a situation in which less fresh water is available per surface unit and where potential soil acidity is at least as serious a limiting factor as hypersalinity. Increased competition for fresh water is likely to create also the need for organizational adaptation.

From the technical point of view and on the basis of the present knowledge of soils and their dynamics, some recommendations for improvement of the rice polders can be suggested. Improvement measures should involve more efficient use of available fresh water and a more superficial drainage system. These two requirements can be combined by limiting desalinization to the upper soil layers only and by developing and applying cultural practices that decrease the contamination of the topsoil with salts, acids and other toxic constituents from the subsoil. Rice varieties tolerant to the prevailing stresses, and cultural calenders adapted to periodicity of stresses, should also be developed and applied.

Separated irrigation and drainage systems could improve water use efficiency. Moderately saline water can be used to leach salts from more saline soils. Initial leaching of hypersaline subsoils should be done with brackish water or even normal saline seawater rather than with fresh irrigation water. Rainfall should be used as much as possible for leaching of topsoils as is done in the traditional rice polders.

Levels of water in canals and fields and their salinity and acidity should be monitored as measures for control and management. Presence and location and especially the depth of potentially acid pyritic soil layers should be known before reclamation projects are designed.

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