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

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[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

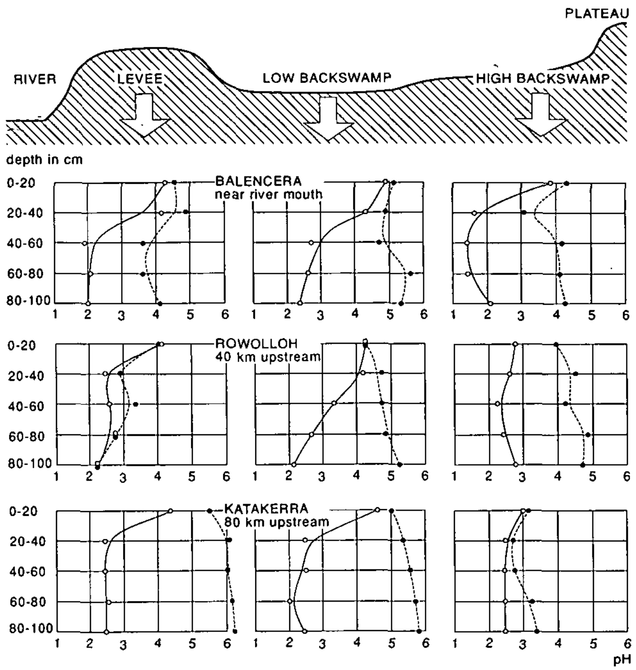


Figure 1 pH of the fresh soil (pecked lines) and pH after incubation (solid lines) along transects at each of the three sites

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

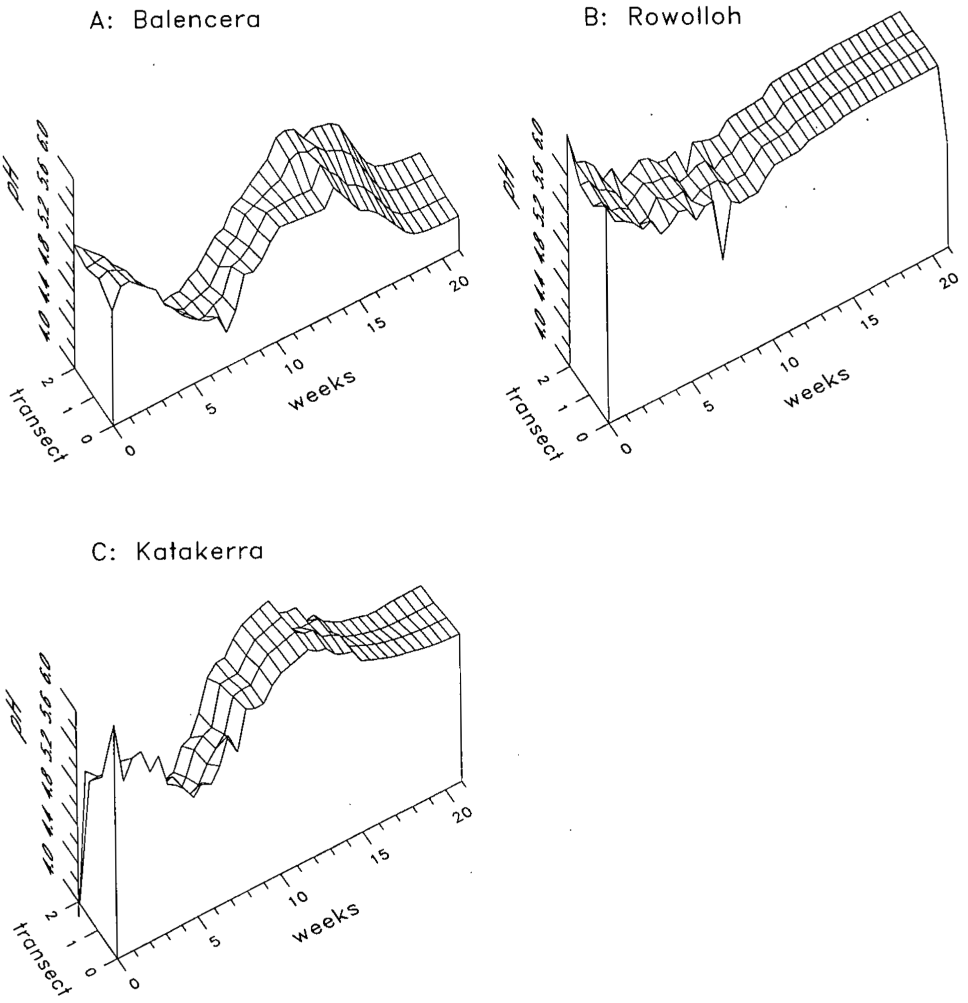


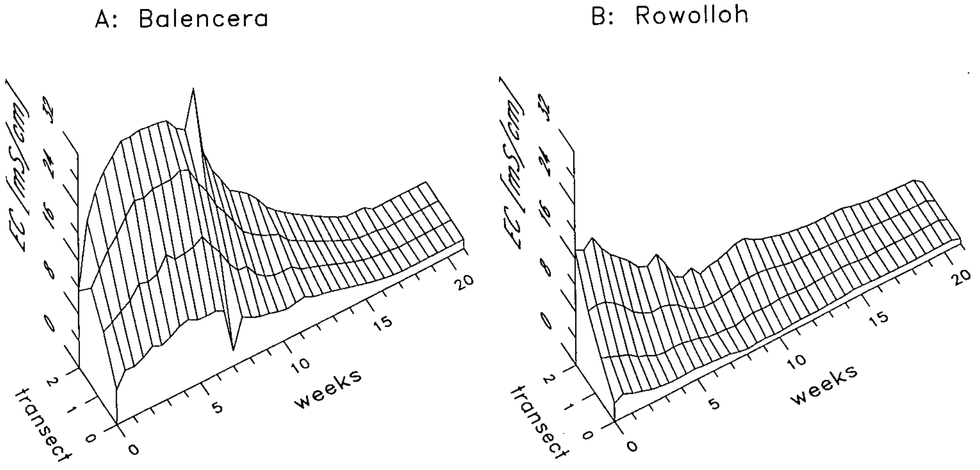
Figure 2 Temporal and spatial variability of pH of the soil solution at 0-25 cm depth in each of the three sites. Along each transect, 0 refers to the river levee, 1 to the low backswamp, and 2 to the high backswamp. Time is weeks after the start of monitoring

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> or = T4> T3> T2> or = T1>T0.



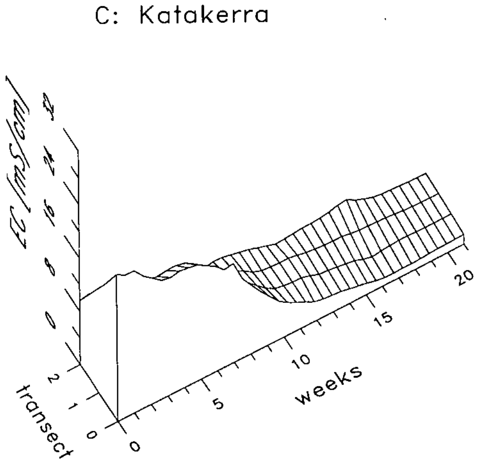


Figure 3 Temporal and spatial variability of salinity (expressed as electrical conductivity) of the soil solution sampled at 0-25 cm depth in each of the three sites. For explanation see Figure 2

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.

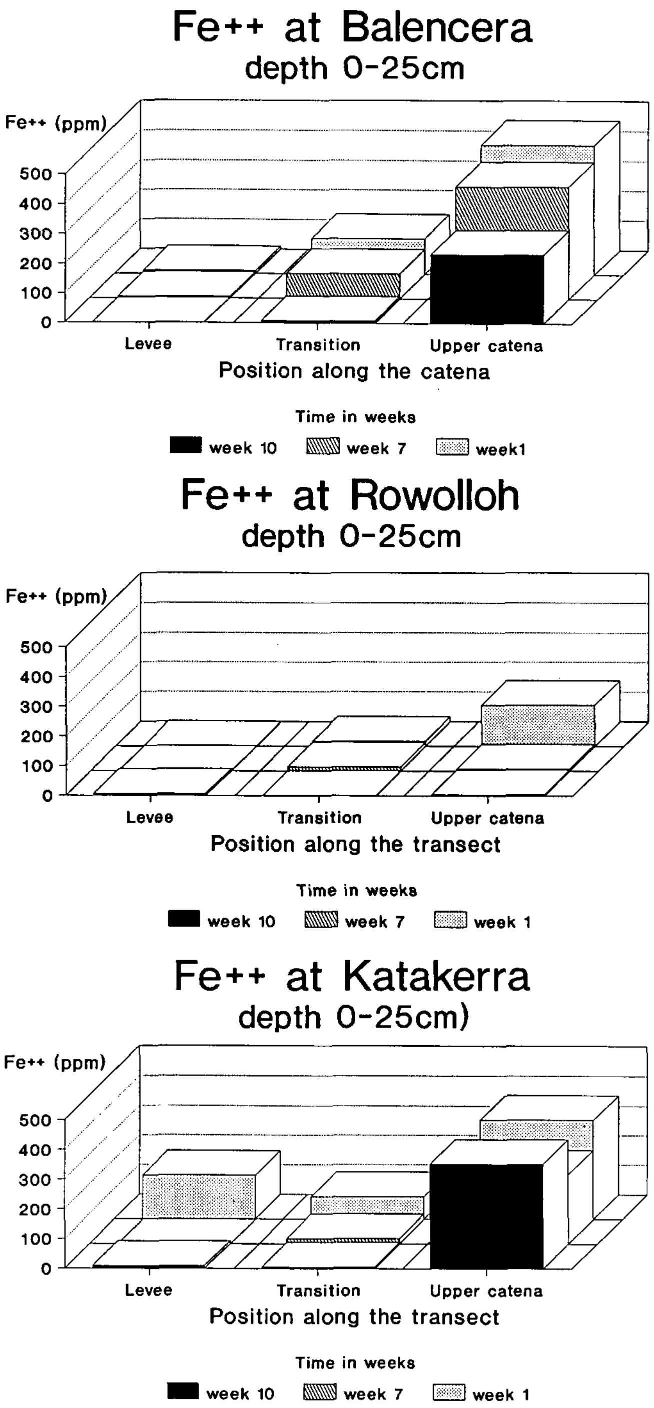
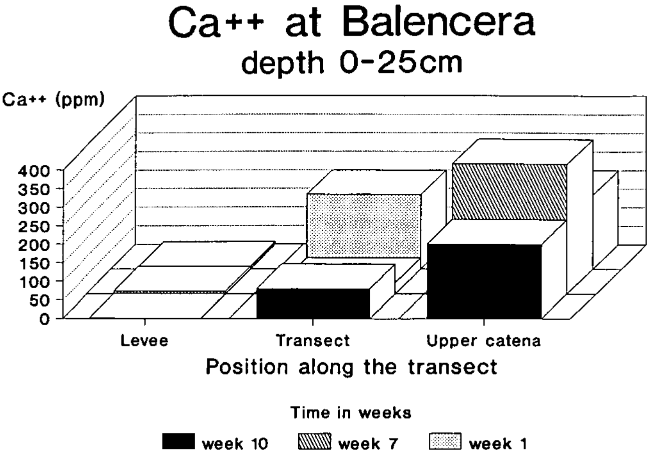
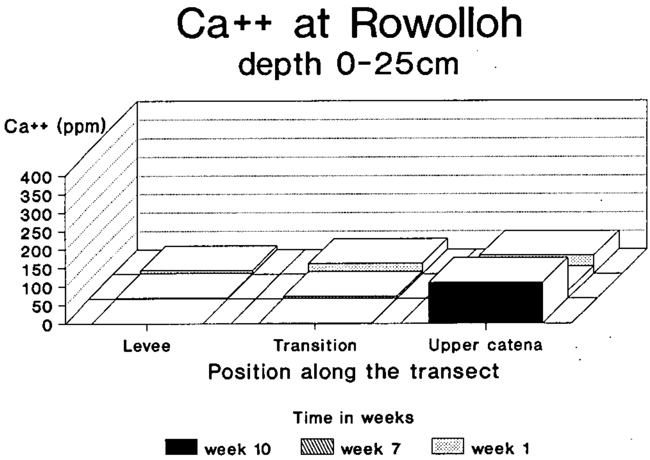


Figure 4 Concentrations of dissolved Fe^{2+} at 0-25 cm depth in each of the three sites, as a function of position in catena, at 1, 7 and 10 weeks after the start of monitoring





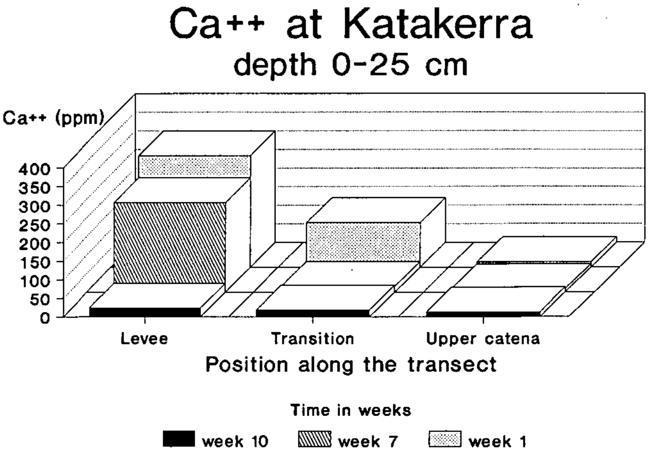


Figure 5 Concentrations of dissolved Ca^{2+} at 0-25 cm depth in each of the three sites, as a function of position in catena, at 1, 7 and 10 weeks after the start of monitoring

Table 2 Soil treatments and environmental effects on rice yield

Locations	Treat-ments*	Yield t/ha	Landscape position	Yield** t/ha	cv %
Balancera (near river mouth)	T0	2.47 d	levee	4.20 a	
	T1	3.04 c			
	T2	3.17 c	low backswamp 1	3.73 b	
	T3	3.70 b			
	T4	4.24 a	low backswamp 2	3.05 c	
	T5	4.40 a			9.03
			high backswamp	3.73 b	
Rowolloh (transition)	T0	3.29 e	levee	4.57 a	
	T1	3.71 d			
	T2	4.10 c	low backswamp 1	4.37 ab	
	T3	4.61 b			
	T4	5.03 a	low backswamp 2	4.24 b	
	T5	5.03 a			4.72
			high backswamp	3.99 c	
Katakera (upstream)	T0	1.51 f	levee	3.54 a	
	T1	1.97 e			
	T2	2.17 d	low backswamp 1	2.72 b	
	T3	2.57 c			
	T4	2.83 b	low backswamp 2	2.06 c	
	T5	3.09 a			6.71
			high backswamp	1.10 d	

* for an explanation of treatments see text

** within location means followed by the same letter are not different at level 0.05 (Ducan'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.

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Effect of fluoride on aluminium tocixity in rice

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Abstract

Anionic complexation of aluminum reduces Al^{3+} activity in solution. The reduction of Al toxicity in rice by addition of fluoride anions in the nutrient solution also results in an increase in available phosphate and pH.

Fluoride addition in nutrient solutions with high Al^{3+} concentration (20 ppm) induces an increase in nutrient absorption and dry matter of rice plants. High F^- concentrations (15 ppm) do not reduce root growth and development and increase the Al toxicity threshold to Al^{3+} concentrations up to 15-20 ppm.

The results show possibilities of improving crop production in acid soils by small fluoride applications in the form of fluoroapatite.

Introduction

Decreasing Al toxicity in acid soils by addition of organic and phosphate anions is well known. Studying the correction of Al toxicity by fluoride was suggested by the fact that F is present in fertilizers currently used in agriculture, in particular as hydroxy fluorapatite. Phosphate fertilizers used in Vietnam currently contain 1.3 to 3.6 per cent fluoride.

Material and methods

Research was carried out using whole rice plants, variety IR 13240-10-1 (NN9A), in experimental conditions described by Tang Van Hai et al. (1989). The nutrient solution had the following composition, in ppm $(NH_4)_2SO_4$ = 10; $CaCl_2.2H_2O$ = 10; $MgSO_4.7H_2O$ = 1; KCl = 10; KH_2PO_4 = 1; Fe-EDTANa = 1. For one litre of solution, 1 ml of Hoagland's trace elements solution was added.

Five rice seedlings were transplanted 15 days after germination into holes in a 7 cm lucide disc and held in place by cotton plugs. 12 discs were placed in 15 *l* containers, receiving a fresh nutrient solution every two days. After 30 days, each disk was placed in polyethylene containers with 1.3 *l* of solution which was refreshed every day. The composition of this second nutrient solution varied according to Al^{3+}, PO_4^{3+} and F^- concentrations, i.e. the elements of which are being investigated. Mg^{2+} concentration was 10 ppm; Al^{3+} was added in the form $Al_2(SO_4)_3.18\ H_2O$. K^+, Ca^{2+}, Mg^{2+} and PO_4^{3-} concentrations were determined by ICPES, and of F^- and Al^{3+} activities by an Orion 960900 ion-selective electrode. The equilibrium constant values proposed by Lindsay (1979) were used to determine the activities of the various ion species and the Al^{3+} complexation by F^- in the nutrient solution.

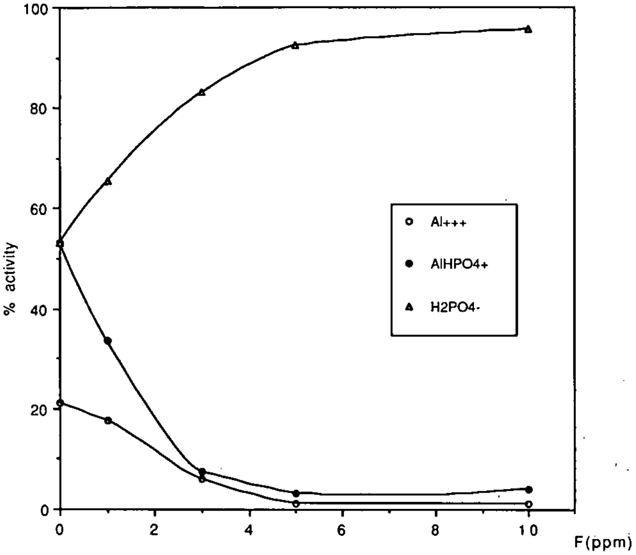

Figure 1 Evolution of relative activities (%) of Al^{3+}, $AlHPO_4^+$ and $H_2PO_4^-$ as a function of F^-concentration in nutrient solution with 5 ppm Al.

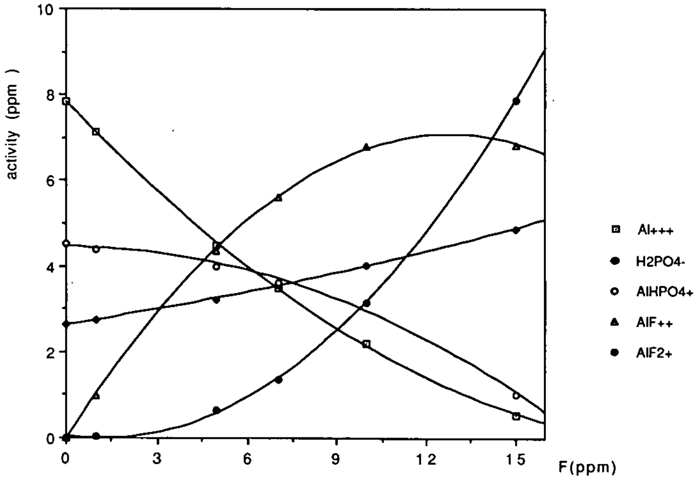

Figure 2 Evolution of the activities (ppm) of Al^{3+}, $H_2PO_4^-$, $AlHPO_4^+$, AlF^{2+} and AlF_2^+ as a function of F concentration in nutrient solution with 20 ppm Al.

Results and discussion

Figure 1 shows that increasing F^- concentration drastically modifies Al^{3+} activity in the nutrient solution. By complexing Al, F^- directly rules the $H_2PO_4^-$ activity which increases with decreasing Al^{3+} activity, by removing phosphate from the $AlHPO_4^+$ complex.

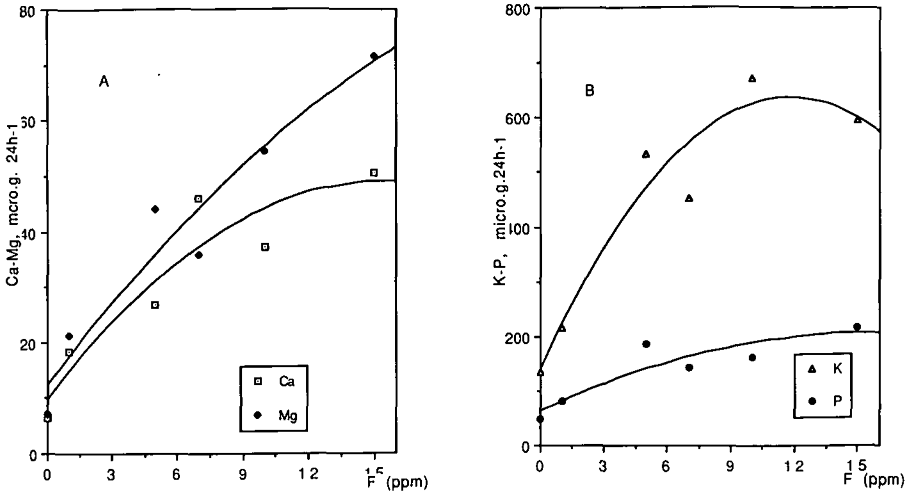

Figure 3 Evolution of the absorption of Ca, Mg (A) and K, P, (B) in µg during 24 hours by 5 plants as a function of F concentration for a nutrient solution with 20 ppm Al.

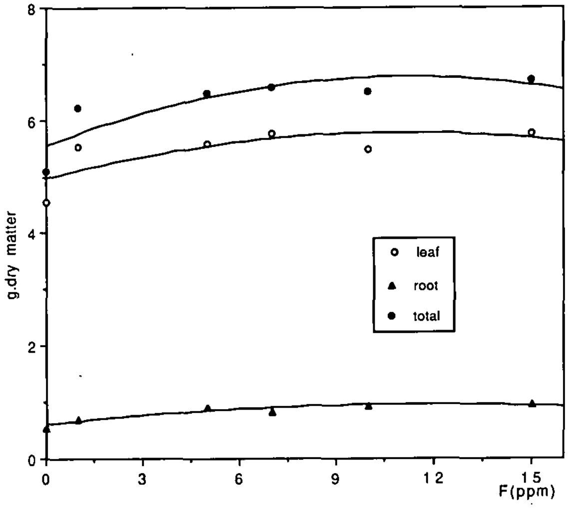

Figure 4 Evolution of dry matter (measured after 50 days) as a function of F^- concentration in nutrient solution with 20 ppm Al.

Figure 2 showing ion activities as a function of F concentration at an Al concentration of 20 ppm, shows that F^- forms stable complexes with Al^{3+}. The relative quantities of the various Al-F complexes depend on the F/Al concentration ratio. The higher the latter, the higher the amount of F^- anions around Al^{3+} cations. With F/Al concentration ratio of 2.0, the amount of free F^- anions is high in the nutrient solution, possibly inducing F^- toxicity, while Al-F complexes do not have any depressive effect on plant growth (Ritchie et al. 1986).

Figures 3A and 3B show that Al^{3+} complexation by F^- reduces the antagonistic effect of Al^{3+} on the absorption of K^+, Ca^{2+} and Mg^{2+} by rice plants. The available $H_2PO_4^-$ pool increases with increasing F^- concentration, promoting P absorption by rice. The effect of increasing F^- concentration on K^+ absorption is much stronger than on P absorption.

Figure 4 shows that high F^- concentrations in the nutrient solution do not hamper root growth and development and do not have any adverse effect on total dry matter, because Al-F complexes do not affect plant growth and nutrient absorption (Figure 3).

Conclusions

F^- strongly complexes Al^{3+} ions in solution. Our results show that Al^{3+} complexation by F^- anions in nutrient solutions induces increased nutrient absorption by rice plants as well as increased dry matter. Addition of F^- in small quantities displaces the Al^{3+} toxicity threshold to Al^{3+} concentrations as high as 15-20 ppm in nutrient solutions. These results confirm previous observations made by Ritchie et al. (1986) and Léon et al. (1986).

Acknowledgements

The research work presented here has been supported by the STD1 and STD2 Program of the Commission of European Communities (DGXII) on the reclamation and management of acid soils in Vietnam. We thank F.N.R.S. for its financial support for our participation at this symposium (ref. C18/5-MB401).

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