Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils

Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils

Ho Chi Minh City, Viet Nam, March 1992

Edited by
D.L. Dent and M.E.F. van Mensvoort

Publication 53

International Institute for Land Reclamation and Improvement,
P.O. Box 45, 6700 AA Wageningen, The Netherlands, 1993

ISBN 90 70754 312

Printed in The Netherlands

Preface

Acid Sulphate Research and Management: Moving the Goalposts

For 20 years now, workers on acid sulphate soils have met to discuss their key findings and, to a large extent, direct their future research at international symposia held in Wageningen (1972), Bangkok (1981), Dakar (1986) and, in March 1992, Ho Chi Minh City. The symposia have served the needs of communication between our far-flung, increasingly inter-disciplinary community in a way that papers scattered in journals cannot serve.

The aims of the first symposium were 'to summarise all available information and to present recent advances on, and management of acid sulphate soils'. The upsurge of research and the accelerating development of tropical wetlands makes the first of these tasks, now, a daunting one. But, thanks to recent reviews, the Ho Chi Minh City symposium has been able to concentrate on current problems, recent advances and, it should also be said, setbacks.

Uniquely, acid sulphate soils and the problems they bring are the products of land reclamation. The first goal of land reclamation remains what it has always been: production. Now other, equally vital, goals have forced themselves on our consciousness: the goals of economic viability, sustainability and environmental protection. For the first time, farming systems, modelling of processes and environmental management have been addressed by specific sessions of the symposium.

The selected papers are arranged here in broad themes:
- Looking at the landscape;
- Identifying problems and seeking solutions:
  - The farmers' way;
  - By experimental work on fertility and management;
  - By attempts at land evaluation;
  - By modelling;
- Environmental management.

Two encouraging aspects of the symposium have been, first, the many multinational, multi-disciplinary papers that do not really fit neatly into even these broad compartments and, secondly, the many teams introducing ambitious work that is just beginning. These new projects were the subject of lively interplay of ideas and comment. We look forward to their results in the next symposium.

Linkages between different aspects of research have become more and more apparent. Soil survey is still the essential basis for soil management, as is shown by the simple but effective use of survey data in managing river water quality in Finland (Palko and Yli-Halla), and the difficulty of effective management of the water quality without it (Callinan et al.). Again, perceptive observations and measurement of the reduction in dissolved oxygen contents of acidified streamwaters in Australia link with the second stage of oxidation of Fe^{2+} released by partial oxydation of pyrite in acid sulphate soils. This, with reports of very high hydraulic conductivities measured in some sulphidic soils in Kalimantan (Hamming and van den Eelaart) and the presence there of brown horizons without the characteristic mottling patterns (Andriesse, Diemont et al.) set us thinking anew about long distance transport of acidity and its likely environmental effects (van Breemen).

Little by little, use is being made of the painfully-accumulated knowledge in the management of acid sulphate soils. The old models have proved useful, even though advice in land development based on them may have been conservative. The new mathematical models (Bronswijk and Groenenberg, van Wijk et al., Eriksson), much more detailed and requiring advanced equipment, will now start to play an increasingly important role.

The Mekong delta provides several examples of success through adaptive research; for example with better design and construction of raised beds for leaching and drainage (inter alia Le Quang Tri et al.), and the successful transfer to acid sulphate soils of the alternate rice-shrimp cropping system (Vo-Tong Xuan). But management problems have more often been attacked by simply throwing people at them. Failures go unrecorded and, so long as the sole goal has been production, social and environmental impact of development have been ignored.

It is time to move the goalposts. Much has been learned since the first symposium. We know that:

1. Acid sulphate soils can be reclaimed;
2. Acid sulphate soils can be improved;
3. The economic returns from investment in acid sulphate soils vary as much as acid sulphate soils do, but are never so good as from investment in other kinds of soil in the same environment;
4. Development of acid sulphate soils has wholly bad effects on other people's water, therefore on other people's livelihood, and on all kinds of wetland habitat.

It is a reasonable prediction that, in the near future, large areas of acid sulphate soils will become wasteland as a result of rising costs of production relative to better soils and diminishing water resources as these are needed elsewhere. This bleak scenario can be mitigated by managing landscapes as a whole, rather than considering acid sulphate soils in isolation; and changing the direction of research. We will have to move away from the fire brigade work to solve present problems to more foreward-looking work to design sustainable, environment-friendly systems of using acid sulphate land. In this way we have avoid more problems arising in future.

It was impossible to include all material presented at the symposium in this book. There was a limit to the number of pages. Some of the work included large, detailed colour maps which cannot be reproduced here. Others reported on work only just started, only of local importance, or too far beyond the goals of the symposium. The ISSS working group on acid sulphate soils intends to report on most of the remaining material in its newsletter.

The Editors.

Contents

Acid sulphate soils: Diagnosing the illness

W. Andriesse

The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen, The Netherlands

Abstract

Diagnosing the occurrence, extent and severity of acid sulphate soil conditions, both potential and actual, is the first step in land use planning for areas in which such conditions may exist. Soil surveyors' craftsmanship, so far, has been unable to cope sufficiently with the specific intricacies of these soils. They have a high spatial variability and, particularly in their natural state, they are poorly accessible. Also, their dynamic nature frustrates proper characterization and interpretation.

Identification in the field remains problematic; quantification of the danger of acidification upon drainage, or the negative effects on the environment and/or crop production in already-acidified conditions, more so. Field characteristics are hard to match with chemical data. In an elaborate research project in southern Kalimantan, Indonesia, such relationships could only be established between a limited number of field characteristics and the relationships found are mostly area-specific.

New technologies have been applied with different degrees of success: computerized interpretation of digital remotely sensed data, geostatistics and geographic information systems. As yet, operational application of computer classification of remotely sensed imagery is much hampered, in the humid tropics in particular, by limited availability of good quality images and insufficient facilities. Also, the quickly and frequently changing use of the land renders this technique of restricted operational value. Additionally, where strict relationships between vegetation/land use and soil conditions do not always exist, the images do not necessarily reflect acid or potentially acid soil conditions.

Some applications of geostatistics appear promising. For example, Kriging showed that within a range of map scales between 1:10 000 and 1:30 000, map accuracy is not affected by the density of observations. Consequently, considerable savings can be achieved in terms of time and money spent on soil surveys.

Attempts to better characterize acid sulphate soils include the development of a completely new classification system (ILRI) as well as proposals to revise the USDA Soil Taxonomy.

Introduction

Acid sulphate soils are problem soils, not least because their diagnosis in the field is difficult. Their occurrence in waterlogged, tidally-flooded, coastal lowlands, their low bearing capacity and, perhaps worst of all, their dense natural vegetation (mangrove and nipa forest) makes them inaccessible. Soil survey under these conditions is slow and, thus, costly.

Another inherent problem is that pyrite, the very source of acidification, due to its formation in association with the roots of mangroves, nipa or reed, has a very heterogeneous distribution, both vertically and laterally, and at the micro level as well as at the meso level. Micro-level differences refer to variations within distances of some centimeters, i.e. within the pedon; meso-level differences refer to variations within some tens to some hundreds of meters, i.e. within landscape units. This high spatial variability makes it difficult to map acid sulphate soils at a high level of reliability.

Also, laboratory techniques to quantify the danger of acidification or to estimate the adverse effects of already-acidified conditions on the environment and/or on crop production are time-consuming and require well-equipped laboratories. More often than not, this means that surveyors have to send samples from the field to places some hundreds, or even thousands, of kilometers away. In the case of potentially acid soil material, this is not an attractive option as samples will always acidify to some extent during transport and pre-treatment so analytical results will be affected. Cutting back on the number of analyses to be carried out seems desirable, but only if easily-recognizable field characteristics can be matched with chemical data.

Lastly, the dynamic nature of the properties of acid sulphate soils largely frustrates their proper characterization and interpretation. Such dynamics act at daily level (the tides), at annual level (the seasons) and at the longer term (drainage systems that initiate aeration, ripening and acidification).

Over the last few years, several attempts have been made to complement soil surveyors' craftsmanship with new tools and techniques. These new methods comprise computerized interpretation of digital, remotely-sensed data; geostatistics; and geographic information systems. The following examples provide a state-of-the-art account of their use in areas with acid sulphate soils.

As in soil mapping, grouping of soils with similar characteristics remains an essential step for land evaluation and land use planning, new developments in soil classification will also be dealt with.

Methods of analysis

Verification

Verification of acid sulphate conditions remains dependent on laboratory analyses and the shortage of reliable, sophisticated and fast laboratory facilities slows down the progress of soil surveys. Also, the high costs of conventional laboratory analyses may affect the quality of surveys. Therefore, the development and application of field tests, or tests that can be performed in simple field laboratories, is an attractive option. Lists of useful field tests, compiled by Dent (1986) and Langenhoff (1986), are presently being adapted by Janssen et al. (1992). A rapid titration method, the so-called TPA/TAA method (Konsten et al. 1988) has been used in several places, including Indonesia (Konsten and Muhrizal Sarwani 1990, Janssen et al. 1990) and Sierra Leone (EDAFOS 1989, Sylla et al. 1993).

Laboratory methods to characterize acid sulphate soils include:

- Determination of sulphur fractions;
- Incubation of moist soil samples;
- Titration of actual and potential acidity (TPA/TAA method).

Each of these methods has its specific merits and drawbacks (Table 1).

Table 1 Comparison of laboratory methods for the identification of sulphate acidity in soils (Janssen et al. 1993)

	Sulphur determinations	TPA/TAA method	Incubation method
accuracy	high (quantitative)	moderate (semi-quantitative)	low (qualitative)
applicability	universal	local	universal
practicability	professional laboratory	field laboratory	anywhere
proficiency level	laboratory analysts	laboratory technicians	laboratory technicians
equipment required	advanced equipment: AAS, X-ray apparatus, freeze drier, fume cupboard	simple equipment: pH meter, waterbath, shaker, burettes	very simple equipment: pH meter or pH paper
costs involved	high	low	very low
time required	some weeks	some days	2-3 months
pre-treatment required	freeze-drying	TAA: none (fresh samples) TPA: H_2O_2 oxidation	none (fresh samples)
hazard	great (HF-digestion !!)*	moderate (H_2O_2-oxidation !)*	none

* waste and acid disposals required

Sulphur fractions

No single method for the determination of the various sulphur compounds in potential acid sulphate soils has gained general acceptance. Begheijn et al. (1978) present wet chemical methods for the determination of (water-soluble + adsorbed)-S, jarosite-S, (pyrite + organic + elemental)-S, pyrite-S, elemental-S and total-S. They found an excellent correlation between total-S and the sum of the sulphur fractions. According to the authors, the determination of either pyrite-S or oxidizable-S (i.e. (pyrite + organic + elemental)-S) provides better information about potential acidity than the determination of total-S. This is due to the variable contribution of (water-soluble + adsorbed)-S and jarosite-S to total-S.

In most potential acid sulphate soils, almost all sulphur occurs as pyrite, even in soils with relatively high contents of organic carbon. Therefore, the determination of pyrite-S or oxidizable-S only, rather than the determination of total-S, suffices for the characterization of potential acid sulphate conditions.

Wet chemical analysis is accurate but costly. Moreover, as sophisticated equipment is required, its application is restricted to professional, operational laboratories. More rapid methods of total-S determination include X-ray fluorescence and the induction furnace method. The results obtained with X-ray fluorescence do not differ greatly from wet chemical analysis, although the X-ray results tend to be slightly higher. The suitability of the Leco induction furnace combustion method with automatic titration has been reported variously (Tabatabai 1982) but it may be useful as a simple and rapid method in support of field surveys. A description of procedures is included in Janssen et al. (1992).

The TPA/TAA method

The field laboratory method introduced by Konsten et al. (1988) is a semi-quantitative method to estimate total actual and potential acidity relatively quickly, without the use of sophisticated equipment or expensive chemicals. It can be applied in a field laboratory to large numbers of soil samples at a time (Muhrizal et al. 1990).

- **Total Potential Acidity (TPA)** is the acidity that may develop in the soil upon complete oxidation of all reduced sulphur species. TPA is defined as the amount of titratable acidity at pH 5.5 of a fresh soil sample in a 1 mol/l NaCl suspension (soil/water ratio 1:2.5) after complete, forced oxidation with hydrogen peroxide.
- **Total Actual Acidity (TAA)** is defined as the amount of titratible acidity that is actually present in a soil sample. The actual acidity is titrated up to pH 5.5 in a 1 mol/l NaCl suspension (soil/water ratio 1:2.5). In the determination of TAA no oxidation with hydrogen peroxide takes place.
- **Total Sulphidic Acidity (TSA)** is defined as the difference between TPA and TAA. TSA represents all reduced sulphur fractions in the soil. TSA is, therefore, a measure of the acidity that may be generated by the oxidation of the sulphur fractions.

The relationship between TPA and/or TSA on the one hand, and pyrite-S and/or total-S content on the other, is not always consistent. If such a relationship exists, it is area-dependent. This is caused by a number of factors (Janssen et al. 1993; Konsten and Muhrizal Sarwani 1990), including:

- The lack of precision of the TPA/TAA-method, in particular at low contents of pyrite (i.e. less than 1-1.5 per cent FeS_2);
- The effect of the neutralizing capacity of the soil, which is incorporated in the result of the TPA/TAA determination but not incorporated in the analyses of the sulphur fractions;
- The critical role of organic matter: TPA and TAA do not determine the same variables: in the TAA determination, the contribution of organic acids to the total acidity is included. In the TPA determination, however, these organic acids are destroyed upon proper oxidation with H_2O_2 so they do not contribute to the acidity measured.

Incubation

Incubation is a simple but protracted method to identify potential sulphate acidity. Incubation of moist soil samples simulates the oxidation of pyrite under natural conditions. The soil samples are oxidized by storing them in open, thin-walled polythene bags, at air temperature (20-30 °C), keeping them moist by occasional re-wetting.

A pH-drop to values below 3.5 (Van Breemen 1982) or 4 (Dent 1980) is enough to diagnose the soil as potentially acid. If samples are large (some 500 cm^3), the pH may continue to drop for at least one year if the samples are kept moist (Dent 1986). In Pulau Petak, soil samples of about 1000 cm^3 reached maximum acidification after 65 to 85 weeks of incubation (Konsten and Muhrizal Sarwani 1990).

Both the critical pH upon incubation as well as the length of the incubation period itself have been subject of much discussion. Brinkman and Pons (1973) suggested a critical limit of pH 3.0-3.5 (H_2O 1:1) for the identification of potential acidity upon incubation during 'a few weeks to six months', Van Breemen (1982) proposed pH 3.5, Dent (1980) and Thomas and Varley (1982) pH 4.0 and Sutrisno et al. (1990) pH 3.7. Dent's plea (Dent 1986) to apply an incubation period of three months 'for the sake of standardization' is, soon, to be honoured (partly) in Soil Taxonomy (Fanning and Witty 1993).

Relationships between field characteristics and analytical data

The efficiency and, also, the quality of soil surveys would be much increased if acid sulphate soils could be readily recognized in the field and if field characteristics could be readily related to chemical parameters. This would enable the surveyor in the field to quantify the danger of acidification upon artificial drainage of potential acid sulphate soils or the negative effects on the environment or on crop production in already-acidified conditions. However, field characteristics of these soils, are hard to match with chemical data. The reason lies, partly, in the heterogeneity of the main characteristics of acid sulphate soils, as well as in their instability. The short-range variation may be countered by multiple sampling within small areas, whereas the use of unstable soil characteristics is just to be avoided.

Ironically, the most conspicuous characteristic of acid sulphate soils, the pH, is extremely unstable and, therefore, hardly applicable as a differentiating characteristic in soil mapping. Instead, Burrough et al. (1988) identified 'depth to jarosite' as a reasonably reliable criterion for soil surveys at scales between 1:20000 and 1:100000 in the Mekong Delta, Vietnam where they were able to establish a reasonable correlation between properties associated with relief (e.g. elevation, depth to jarosite, depth to pyrite, groundwater table, depth to C horizon, drainage class). Unfortunately, these correlations have no universal validity, as was shown in an elaborate research project in southern Kalimantan (Janssen et al. 1990). Here, relationships could be established only between a limited number of field characteristics and (potential) acidity of the soil. Also, the relationships found are mostly area-specific. Table 2 summarizes the results of the Kalimantan study. It shows that soil matrix colour, colours of mottles and (iron) coatings, ripeness and reaction with hydrogen peroxide are correlated with Total Actual Acidity and/or Total Sulphidic Acidity. Also, relationships exist between, on the one hand, the depth to pyrite and, on the other hand, altitude, physiography, (specific kinds of) vegetation, (absence of) flooding, and the occurrence of certain horizons in the soil profile (Table 3).

In this study, possible quantitative relationships between field characteristics and goal variables (in this case TPA, TSA and 'depth to pyrite') were investigated, initially, by plotting in graphs and calculating regressions. Even though an enormous amount of data was thus scrutinized (2500 observation sites, 3-4 samples were taken per site and for each sample at least 7 chemical parameters were determined!), no clear relations could be established in terms of regression equations. As, however, some local clustering was observed in the graphs, the values of each of the goal variables were combined into two classes.

A good relationship was assumed to exist if at least 80 percent of the values of the field characteristic matched with one of the two classes of the goal variable. In applying such an approach, it is important to set relevant and practical limits between the classes of the various goal variables. In the case of Pulau Petak, these limits were set at: TSA = 32 mmol H^+/100g soil, TAA = 26 mmol H^+/100g soil and depth to pyrite = 50 cm. It should be noted that most of the relationships found in this

Table 2 Field characteristics and their relationships with Total Actual Acidity (TAA), Total Sulphidic Acidity (TSA) and Depth to Pyrite (Janssen et al. 1990)

Field characteristic soil horizon	TAA*	TSA**	Field characteristic (profile/site)	Pyrite within 50 cm***
Matrix colour:			Altitude	+
– stability	–	+	Topography	–
– colour	+	+	Landform	+
Mottling:			Position of site	–
– colour	+	+	Micro relief	–
– black specks/mottles	–	–	Land use	–
– abundance	–	–	Vegetation	+
Iron coatings	–	+	Flooding	+
Root remnants:			Thickness peat layer	–
– abundance	–	–	Thickness brown layer	–
– kind	–	–	Depth to grey layer	+
– size	–	–	Groundwater:	
Wood remnants	–	–	– level (measured daily)	–
Ripeness	–	+	– EC (field)	–
Texture	–	–	– pH (field)	–
Smell of H_2S	–	–	Shear strength	–
Reaction with peroxide:				
– Time lapse to reaction	–	+		
– Intensity	–	+		
– pH of foam	–	+		
– colour of foam	–	+		
Soil solution:				
– EC (field)	–	–		
– pH (paper; field)	+	–		
– EC (laboratory)	–	–		
– pH (H_2O; laboratory)	+	–		
Organic matter	–	–		
Water content	–	+		

+ refers to a partial relationship
– indicates that no relation exists
* The limit between sulfuric and non-sulfuric horizons has been set at TAA = 26 mmol H^+/100 g soil
** The limit between pyritic and non-pyritic layers has been set at TSA = 32 mmol H^+/100 g soil
*** Potential acid sulphate soils have a pyritic layer within 50 cm from the mineral surface

study are valid only within certain ranges: some grey colours do indicate a high potential for acidification, but not in all horizons; ripeness is an indication of low actual acidity, but the reverse is not true: unripeness is not an exclusive identifier of high potential acidity (see Table 3).

Still, even these partial relationships can help in distinguishing map units with different potential sulphate acidity. They are particularly useful if applied in combinations. In Pulau Petak, for example, reliable field differentiation of actual and potential acid sulphate soils is possible using matrix colour, reaction with H_2O_2, and landform as criteria. Landform can be used to broadly distinguish between non-potentially acid and potentially acid conditions: in Pulau Petak, levees and coastal ridges do not have pyritic layers within 50 cm of the mineral soil surface. In the lower-lying remainder

Table 3 Summary of relationships between field characteristics and chemical parameters of acid sulphate soils in Pulau Petak (Janssen et al. 1992)

Field characteristic (layer)	TAA*	TSA**	Description
Matrix colour:			
– stability	–	+	If matrix colours are stable (greyish) brown (hues 7.5YR and 10YR, chroma > 1): TSA < 32 mmol; for all grey colours (hues 10YR/chroma 1, and hues 2.5Y, 5Y, 5GY and N) and for unstable (greyish) brown colours: TSA ≥ 32 mmol.
– Colour	+	–	If dominant hue N or sub-dominant hue 5GY: TAA < 26 mmol.
Mottles colour	+	+	If hue 5YR: TSA < 32 mmol; if hue 5GY or N: TSA ≥ 32 mmol; jarosite-like mottles indicate horizons with most active oxidation of pyrite: TAA 'relatively high'
Iron coatings	–	+	If (reddish brown) iron coatings occur on ped faces: TSA < 32 mmol
Reaction with peroxide:			
– Time lapse	–	+	If time lapse till reaction ≤ 15 seconds: TSA ≥ 32 mmol If time lapse till reaction ≥ 99 seconds: TSA < 32 mmol
– Intensity	–	+	If no reaction: TSA < 32 mmol; if strong reaction: TSA ≥ 32 mmol
– pH of foam	–	+	If pH of foam ≥ 4.0: TSA < 32 mmol
– Colour of foam	–	+	For specified colours of foam: TSA ≥ 32 mmol
pH (paper: field)	+	–	If pH (field) < 3.6: TAA ≥ 26 mmol

Field characteristic (profile/site)	DPYR***	Description
Altitude	+	Altitude is a very rough indicator only for DPYR
Landform	+	In levees and coastal ridges: DPYR ≥ 50 cm; in alluvio-marine plains and old river beds: DPYR may be < 50 cm
Vegetation	+	In Nipa-Piai complex (*Nipa fruticans* and *Achrosticum aureum*): DPYR < 50 cm and TAA < 26 mmol; in Alang Alang (*Imperata cylindrica*) DPYR ≥ 50 cm
Flooding	+	If no flooding: DPYR ≥ 50 cm
Thickness of brown layer	+	Pyritic layer generally starts below or at the base of the brown layer (hues 1.5YR and 10YR; chroma > 1)
Depth to grey layer	+	Pyritic layer generally starts above or at the top of the grey layer (hue 10YR; chroma 1 and hues 2.5Y, 5Y, N and 5GY)

\+ refers to a (partial) relationship
– indicates that no relation exists
* The limit between sulfuric and non-sulfuric horizons has been set at TAA = 26 mmol H^+/100 g soil
** The limit between pyritic and non-pyritic layers has been set at TSA = 32 mmol H^+/100 g soil
*** Potential acid sulphate soils have a pyritic layer within 50 cm from the mineral surface

of the area (the alluvio-marine plains and old river beds) depth to pyrite is highly variable, and both potential and actual acid sulphate soils occur.

The hydrogen peroxide test, however much it may be affected by the influence of organic matter, is a 'quick and reliable qualitative field test to determine the depth of the pyritic substratum' (NEDECO/Euroconsult/BIEC 1984). Strong to violent effervescence within a few seconds and a yellowish colour of the foam indicate high TSA (Table 3). The pH drop resulting from the peroxide treatment could not be correlated significantly with high potential acidity. This is contrary to findings in other parts of the world where a pH $\leq$ 2.5 or 3 after H_2O_2 treatment would indicate severe sulphate acidity (Brinkman et al. 1984, Dent 1986).

Geostatistics

General

Geostatistical methods are finding increasing application in soil surveys, particularly in detailed and semi-detailed studies (Webster and Oliver 1990). Over the past few years, such techniques have been applied in areas with acid sulphate soils to better describe their specific and inherent variability and to determine the best observation density for soil mapping.

Observation density

Burrough et al. (1988) in a study from Vietnam aimed at determining the optimum observation density in soil surveys, used nested sampling and nested analysis of variance. They concluded that spatial variability studies helped in determining the sizes of the main scales of the soil patterns in the area. This enabled selection of the scale at which a reliable soil map could be made. As was discussed in Section 3, depth to jarosite also came out as a reasonably reliable criterion for surveys at scales between 1:20000 to 1:100000. The short-range variation of jarosite could be anticipated by using average values of multiple sampling within small areas.

In southern Kalimantan, Bregt et al. (1990 and 1992a) studied the effect of observation density on prediction accuracy for the variable 'depth to pyrite'. Using information from a regular grid of 820 observation points, different observation densities were simulated and the effect on prediction accuracy was evaluated. Four spatial prediction techniques were applied: global mean, local mean, inverse distance and kriging. The remarkable conclusion was that, within a scale range of the map between 1:10000 and 1:30000, map accuracy remains substantially the same whether the observation density is 200 or 22 km^{-2} (Figure 1). In other words, costs of soil mapping could be considerably reduced while maintaining the quality. In this case, the total costs of the survey at scale 1:30000 were calculated to be some 80 percent less than at scale 1:10000. The total costs of the survey included costs of fieldwork (time spent by survey teams and transportation costs), laboratory analyses and a certain amount of fixed costs (preparations, basemaps, data processing, reporting). Another outcome of this study is that, for the area concerned, the conceptually and operationally complicated kriging technique did not perform better than the much simpler prediction techniques of inverse distance and local mean. Both results can be explained by the high short-range variability of the soil characteristic concerned, the depth to pyrite.

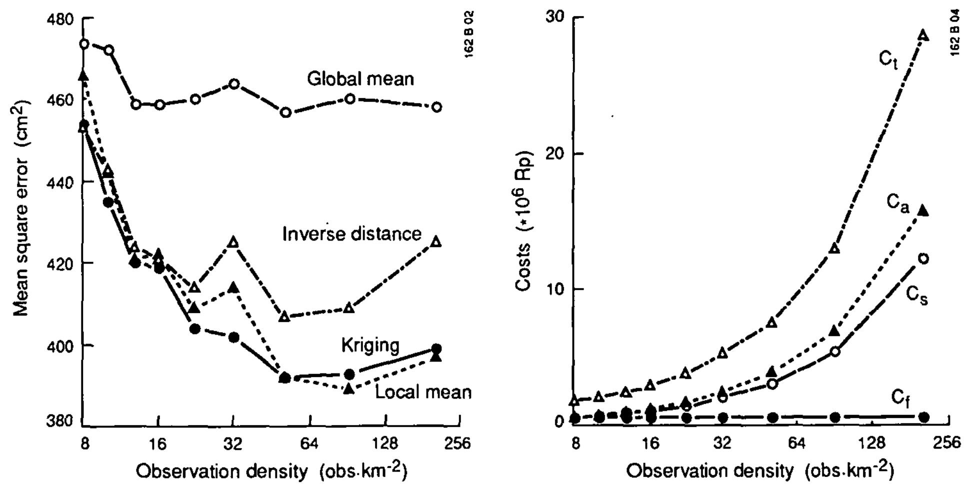


Figure 1 Accuracy of four different prediction techniques (left) and costs of soil mapping (right) versus observation density in Pulau Petak, Indonesia. Cf: Fixed costs; Cs: Survey costs; Ca: Analysis costs and Ct: Total costs (Bregt et al. 1993)

Map presentation

Spatial prediction techniques, like those mentioned above, can be used to predict values of selected variables at sites that are not visited. In addition to these predicted values, also estimates can be made of the prediction error, expressed as the standard deviation. The kriging technique produces these standard deviations automatically. They can be used to calculate confidence intervals for each grid point. Having calculated the predicted values as well as predicted uncertainty of these values (i.e. the standard deviation), the probability that a selected threshold value of the variable concerned is exceeded can also be calculated. These probabilities can be mapped (Bregt et al. 1993). In Figure 2a the variable 'depth to pyrite' is shown in the conventional way. In Figure 2b, the probability is represented that pyrite occurs deeper than 50 cm from the soil surface. Probability class intervals of 10 percent are used. Darker grey tones indicate higher probabilities, i.e. safer conditions.

Since depth to pyrite has a high spatial variability, the boundaries on the conventional map, showing its predicted values, are not very reliable. Mapping this variable in the form of conditional probabilities gives a much better picture of its real nature. Maps like these are useful for land use planning. They enable planners to build in safety margins, much like the application of reliability intervals of rainfall or other climatic variables.

Remote sensing

Under the difficult and, often, unpleasant conditions in tropical coastal lowlands, progress of fieldwork in soil surveys is slow and the value of remote sensing techniques is obvious. Remote sensing, whether by means of aerial photographs or through satellite imagery, not only serves to speed-up the progress of work but it, also, helps in understanding the landscape. There are limitations, however, in its use both from a practical point of view and in a technical sense. Advantages and disadvantages of three different techniques of remote sensing are discussed below: interpretation of aerial photographs, manual interpretation of hard copies of satellite imagery, and computerized processing of digital satellite imagery. A summary is provided in Table 4.

Air photo interpretation

Air photo interpretation, either using black and white or false colour photographs, has proved to be an extremely useful tool in soil surveys. It derives its strength from the relationships between landforms and soil conditions which allow a tentative interpretation of soil conditions based on delineations of landform units on the photos. In areas of clear relief, a great asset of air photos is their stereoscopy, which permits delineations on the basis of slope and relief.

Coastal lowlands, however, have little relief. In the humid tropics, in particular, sediment units are little pronounced, restricted in their height ranges by the relatively small differences between river discharges in the drier and wetter parts of the year. Delineation of landform units, therefore, relies on secondary interpretation using vegetation, land use and drainage as indicators. This poses problems: vegetation does not always reflect soil conditions uniquely; land use may change quickly and, thus, the land use at the time of exposure of the photo may not be the same as observed during the survey; land use, in itself, may cause changes in soil properties (oxidation of pyrite!) and natural drainage is much altered by drainage canals and ditches.

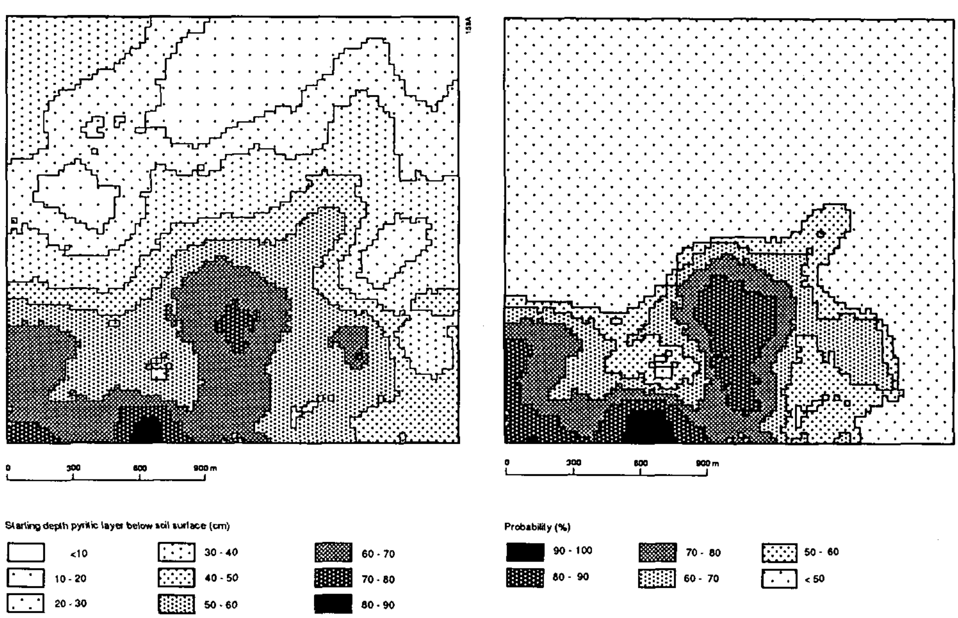


Figure 2 Depth to pyrite in the Belawang area, Pulau Petak, Indonesia (Bregt et al. 1993)
2a: Depth to pyrite (in cm); prediction by kriging
2b: Probability (in %) that depth to pyrite exceeds 50 cm

Table 4 Comparison of different remote sensing techniques (Janssen et al. 1993)

	Scale range	Resolution*	Costs of acquisition	Advantages	Disadvantages
Infra red, black and white airphotography	1:10 000-1:100 000	na	low	easy to handle and interpret; good basemap for field use; infra red additionally useful for vegetation/crop interpretation	security restrictions; difficult to overview, large number of prints to handle; scale distortion; cloud cover
False colour airphotography	1:10 000-1:100 000	na	low-moderate	as for black and white	as for black and white; colour offers no great additional advantage
Satellite imagery (hard copies)	1:50 000-1:1 000 000	na	low-moderate	relatively easy to interpret; good overview; choice of spectral bands; temporal possibility	cloud cover
Satellite imagery (digital copies)	na	LS MSS: 80x80m TM: 30x30m SP MSS: 20x20m PAN: 10x10m	moderate-high	excellent ortho-image basemaps; automated classification and fit on existing basemaps; choice of spectral bands; geographical correction; GIS compatible; temporal possibility; 'unlimited' scale range of output	sophisticated equipment required for processing (off-site); high costs of processing; difficult orientation with screen images; cloud cover

* LS: Landsat (Multi-Spectral Scanner/Thematic Mapper); SP: SPOT (Multi-Spectral Scanner/Panchromatic); na: not applicable

Traditional air photo interpretation appears to be best applicable in soil surveys at semi-detailed scales, i.e. between 1:25 000 and 1:100 000. Black and white, panchromatic air photos at scale 1:50 000 very clearly showed the main landform units in Pulau Petak (alluvio-marine plains, river levees, beach ridges, old riverbeds and low peat domes) as well as the (semi) permanent vegetation (mangrove and nipa swamps, freshwater swamps, rubber and coconut plantations, etc.). Other features that could be distinguished easily were the main drainage canals and new settlements.

Dent (1986) recommends infra red photography (either black and white or false colour) for soil surveys in wetland areas as it provides greater contrast. Water and wet soil absorb infrared radiation strongly, so they appear very dark on the picture. Also, there is more contrast between different plant species and crops suffering from stress or diseases commonly show very clearly.

In quite a number of countries, a practical limitation to the use of aerial photography is their restricted availability due to elaborate administrative and security procedures. If these problems are overcome, costs of existing photography are low. In Indonesia, for example, prints of existing panchromatic b&w photos (1:50 000) cost (officially) Rp. 8000 per sheet (1988; Rp. 1700 = 1 U.S.$). Full coverage of Pulau Petak (approximately 2100 km^2) required some 180 sheets: U.S.$ 0.40 km^{-2}. Colour photography at scale 1:80 000 would have cost U.S.$ 0.60 km^{-2}.

Manual interpretation of satellite imagery

False colour Landsat MSS prints (spectral bands 5, 6 and 7, scale 1:250 000, 1987) were found useful in southern Kalimantan in the general delineation of landforms. Subsequently, detailed information on soils, drainage, vegetation and land use, gathered in the field could be extrapolated using these images. The comparison between images of the wet and the dry season (May and October respectively) proved particularly useful for the identification of peat domes and peat covers overlying the mineral soils. Both band 5 and 7 enhance the wetter conditions prevailing in peats. Cloud cover on the selected images was virtually nil although, generally, clouds restrict operational application, particularly in the humid tropics.

The costs were U.S.$ 350 per sheet, two sheets covered the study area. Therefore, costs per unit area are comparable to (false) colour aerial photography: U.S.$ 0.65 km^{-2}. The large scale difference, however, should be noted. Short-term temporal comparison of aerial photography is not an option, though. It should be noted that prices of Landsat MSS imagery (hard copies) have doubled since.

Computerized interpretation of digital satellite imagery

SPOT panchromatic digital imagery, having a resolution of 10 × 10 m is excellently suited for the production of geometrically corrected ortho-image maps at scales up to 1:20 000 (Reijneveld et al. 1991). Base maps thus produced for Pulau Petak showed intricate detail of drainage systems and individual fields. The costs involved are certainly not prohibitive if compared to ordinary field surveying. In this case, the study area covering some 2100 km^2, U.S.$ 10 000 was spent mainly on computer time and photographic processing, in addition to the costs of SPOT tapes (U.S.$ 2500 per panchromatic tape; 2 tapes were necessary for full coverage of the area; total costs U.S.$ 2.40 km^{-2}). The base maps were produced as transparencies enabling unlimited diazo reproduction.

In the same area, SPOT multispectral digital imagery (resolution 20 × 20 m) was used for automated classification of vegetation and land use. The result, however, had insufficient legend detail and little relevance for soil mapping. The main problem was the intricacy of the cropping systems which cause a strongly varied reflection on the imagery, which is hard to classify. The cultivation systems in the area are mostly complexly intercropped. Only locally rice, rubber and coconut are grown as single crops. Moreover, land use in Pulau Petak changes rapidly, both in the geographical sense as farmers tend to shift their (rice) fields within a few years after reclamation, and in terms of crops grown (Muhrizal Sarwani et al. 1993).

Operational problems were encountered too. Automated classification requires sophisticated and expensive computer equipment which was not available near the survey area. In the Pulau Petak study, the classification was performed in the Netherlands as a research project and classified images were sent to Indonesia to establish ground truth. For each class of vegetation or land use distinguished on these screen images, several sample areas were located and visited. Finding the actual location of these sample areas proved to be very difficult as the images showed too little infrastructure to enable easy location. Also, the screen-images were of various and somewhat inaccurate scale. Here, the ortho-image base maps came in very useful.

Costs involved in this study consisted of the multispectral SPOT tapes (U.S.$ 1750 per tape; two tapes were required for full coverage of the area; total costs U.S.$ 1.65 km^{-2}) and computer plus operator time amounting to U.S.$ 15 000 for classification of three selected sub-areas of 105, 875 and 450 km^2 respectively.

Soil classification

The grouping of soils with similar characteristics is essential for the purpose of land evaluation and land use planning. To be of practical value, this grouping should be based on soil characteristics that are relevant to specified land uses and that are measurable either directly in the field or in a laboratory (Dent 1986). For acid sulphate soils, such characteristics include potential acidity, depth of the pyritic or acidified layer, ripeness, texture, salinity, depth and fluctuation of the watertable, and depth and duration of flooding. In the following sections, aspects of three major classification systems are being discussed. The ILRI classification system (Dent 1986) has been developed specifically for acid sulphate soils. The other two, Soil Taxonomy (Soil Survey Staff 1990) and the FAO Legend of the Soil Map of the World (FAO 1974) cater for all soils.

The ILRI system

In the ILRI classification system, the first five characteristics mentioned above have been incorporated. Watertable and flooding are excluded from the classification proper, presumably because of their dynamic nature and manageability. Their effect on suitability thus remains to be assessed in the process of land evaluation.

Based on the composition of the soil, three major categories are distinguished: organic soils (O), sandy soils (S) and clays (C) (Table 5).

Across these categories further distinction is made into potential ('sulphidic') and ac-

	Organic soils		Sandy soils	Clayey soils			
Undrained not potentially acid	Unripe peat and muck		(Saline) sand	Unripe (saline) clay			
Potential acid sulphate soils	Unripe sulphidic peat and muck		Sulphidic sand	Unripe saline sulphidic clay			
Acid sulphate soils	Raw acid sulphate peat and muck	Ripe acid sulphate peat and muck	Raw acid sulphate sand Acid sulphate sand	Raw saline acid sulphate clay	Ripe acid sulphate clay with raw subsoil	Ripe acid sulphate clay	
Associated non acid sulphate soils	Peat and muck with unripe subsoil	Ripe peat and muck	Sand		Ripe clay with unripe subsoil	Ripe clay	Ripe acid aluminium clay

Table 5 Major categories of potential and actual acid sulphate soils (Dent 1986)

tual acid sulphate soils, the latter group being split into 'raw' and 'ripe' units. 'Raw' implies the presence of a reserve of pyrite that will cause a drop in pH of at least 0.2 units upon incubation, to a value below pH 4. Ripe acid sulphate soils are ripe indeed: $n < 0.7$ and they have $pH < 4$, with or without jarosite. Further practical differentiation may be made according to the depths at which actual (a) or potential acidity (p), salinity (s) and unripe material (w) occur. The general correlation between the ILRI system and Soil Taxonomy is shown in Table 6.

Soil Taxonomy

Although widely used as an international soil classification system, Soil Taxonomy has shortcomings for survey and interpretation of acid sulphate soils:

Sulfidic materials

In the current definition of sulfidic materials, the inherent acid-neutralizing capacity of the soil (i.e. the sum of CEC and bases released by slowly-weathering clay minerals) is implicitly taken as being equivalent to 0.75 percent S at the most. Although this is probably reasonable for many heavy-textured soils, the actual buffering capacity can vary considerably, depending on texture and mineralogy. Many authors have proposed to incorporate the effects of these properties in the definition of sulfidic materials. The essence of their suggestions is that it is better to let the soil 'speak for itself' by allowing it to oxidize by incubation (Dent 1986). Proposals are presented in this symposium to revise the present definition of sulfidic material accordingly (Fanning and Witty 1993).

The term 'waterlogged' in the definition of sulfidic materials implies, under field conditions, a pH near neutrality. In southern Kalimantan, Indonesia, many young and waterlogged acid sulphate soils occur that have a pH of less than 4.0 or even less than 3.5. Most of these soils have a high pyrite content ($S > 0.75$ percent) within 50 cm from the surface (these soils are raw acid sulphate clays in the ILRI classification). They neither show jarosite mottling nor are they physically ripe. The acidity of these soils is caused by lateral inflow of acids from nearby sources, a very common phenomon in the area (Hoyer and Hobma 1989, De Wit 1990).

Soil Taxonomy	Profile Form				ILRI nomenclature	Principal soil groups
Sulfihemists	p_1 p_2 p_3	O		w_2 w_3	unripe sulphidic peat	Potential acid sulphate soils
		O/C C/O O/S S/O			unripe sulphidic muck	
Sulfaquents	p_1 p_2	S	s_1 s_2		saline sulphidic sand	
		C	s_1 s_2	w_2 w_3	unripe saline sulphidic clay	
Sulfic Hydraquents	p_3					
Sulfic Fluvaquents and Sulfic Haplaquents	p_3	S	s_2		sand with saline sulphidic subsoil	
		C	s_2	w_1	ripe clay with saline sulphidic subsoil	
Sulfohemists	a_1 a_2	O	s_1 s_2	w_2 w_3	raw saline acid sulphate peat	Raw acid sulphate soils
			s_2	w_1	peat with raw subsoil	
		O/C C/O	s_1 s_2	w_2 w_3	raw saline acid sulphate muck	
		O/S S/O	s_2	w_1	muck with raw subsoil	
		O			acid sulphate peat	
		O/C C/O O/S S/O			acid sulphate muck	
Sulfaquepts	a_1 a_2	S	s_1 s_2		raw saline acid sulphate sand	
		C	s_1 s_2	w_2 w_3	raw saline acid sulphate clay	
			s_2	w_1	acid sulphate clay with raw subsoil	
					ripe acid sulphate clay	Ripe acid sulphate soils
Sulfic Haplaquepts and Sulfic Tropaquepts	a_3	S			sand with acid sulphate subsoil	
		C	s_2	w_1	ripe clay with raw acid sulphate subsoil	
					ripe clay with acid sulphate subsoil	
					ripe acid aluminium clay	Acid aluminium soils

Table 6 Approximate correlation between Soil Taxonomy and the ILRI classification of acid sulphate soils (Dent 1986; for explanation of symbols, see text)

Currently in Soil Taxonomy, these soils classify as Typic Sulfaquents as they have sulfidic material within 50 cm of the mineral soil surface. However limiting for their agricultural use possibilities, the actual acidity of these soils is not reflected in this classification. This should be amended and, therefore, it is suggested to define a lower limit for the pH permitted in sulfidic materials. At the same time, this limit should be the upper limit of the sulfuric horizon, making the definitions of sulfidic materials and sulfuric horizon mutually exclusive. For the conditions in southern Kalimantan this limit should be pH 3.7 (Sutrisno et al. 1990).

The Sulfuric horizon

The present definition of the sulfuric horizon in Soil Taxonomy raises several problems as it requires the occurrence of both a pH $<$ 3.5 and jarosite mottles. There is no thickness criterion for this horizon. The pH criterion, in itself, is being criticized (Gopinathan and Joseph 1977, Dent 1986, Sutrisno et al. 1990) and the requirement of the jarosite mottles poses problems, since jarosite is not always present in sulphuric horizons, as has been observed in many areas (Van Breemen 1982, Marius 1985, Van Mensvoort and Le Quang Tri 1988, Sutrisno et al. 1990).

Actually, only very few soils are known that have a pH $<$ 3.5 and that are not influenced by sulphuric acid (van Breemen 1982). As it is necessary to have evidence that the acidity is caused by sulphuric acid the criterion should be broadened so as to include: the presence of jarosite, the presence of water-soluble sulphates, underlying sulphidic materials or lateral influx of sulphuric acid.

Ripeness and n-value

The stage of physical ripening of the soil can be characterized by the n-value, which is calculated using an empirical formula which relates water content, texture and organic matter (Pons and Zonneveld, 1965)

$$n = (A - 0.2R)/(L + 3H)$$

The factor A in this formula is the water content of the soil under field conditions, R is the content in silt plus sand, L is the clay content and H is the organic matter content. All factors are expressed in weight percentage oven dry soil. This formula was developed in the Netherlands where illite clays are dominant. Also, the correction factor for organic matter (here: 3) was established for well-humified material. Where humification of organic matter has not occurred, a larger multiplier should be used. Soil Taxonomy, even though recognizing this need, does not specify this. In the absence of such specifications, the hand-squeezing test is appropriate to assess ripeness of the soil. It should be noted though that comparison of calculated n-values with ripeness classes as determined by hand squeezing for soil materials from different parts of the world shows consistently lower n-values in the Mekong Delta (Table 7).

Currently in Soil Taxonomy, soils that have a sulfuric horizon but are physically unripe are classified as Entisols. Such soils cannot enter the Inceptisols due to the ripeness requirement of the latter: Inceptisols should have an n-value $\leq$ 0.7 between 20 and 50 cm from the surface. By complying with this requirement, soils with a diagnostic horizon (the sulfuric horizon) are being classified in an order of soils (the Entisols) that should not have a diagnostic horizon. Moreover, the acidified status of these

Table 7 Ripeness classes and n-values of clays in Vietnam, Indonesia and The Netherlands (Janssen et al. 1993)

Ripeness class (determined by hand squeezing)	n-value (calculated)*		
	Mekong Delta	Pulau Petak	The Netherlands
Ripe	<0.6	<0.7	<0.7
Nearly ripe	0.6-0.8	0.7-1.0	0.7-1.0
Half ripe	0.8-1.1	1.0-1.3	1.0-1.4
Practically unripe	1.1-1.6	>1.3	1.4-2.0
Unripe	>1.6		>2.0

* The multiplier for organic matter is 3

soils is neglected in their classification names. Fanning and Witty (1993) now propose to classify these soils as Inceptisols, irrespective of their unripeness.

Subgroups
Pons et al. (1989) proposed the introduction of a number of subgroups in order to cater for soils with histic, umbric or mollic epipedons (Histic and Humic Subgroups) and for soils with sulfidic materials or sulfuric horizons at different depths (Sulfidic and Sulfic subgroups). Partly in addition to these subgroups, Sutrisno et al. (1990) proposed the introduction of Haplic, Sulfidic, Sulfic, Sulfuric and Aeric subgroups for Sulfaquents, Hydraquents and Fluvaquents, Sulfaquepts and Tropaquepts.

The FAO system
In the Legend of the FAO/Unesco Soil Map of the World (FAO 1974) all actual and potential acid sulphate soils are classified as Thionic Fluvisols, regardless of the degree of development and acidity. No further subdivision is made. Thionic Fluvisols are defined as Fluvisols (i.e. soils developed from recent alluvial deposits) having a sulfuric horizon or sulfidic material, or both, at less than 125 cm from the surface. The sulfuric horizon and sulfidic material are defined as in Soil Taxonomy, except for the lower limit set for the pH permitted in sulfidic materials ($pH > 3.5$). At the 'Third Reunion of the Committee for Correlation of the West African Soils', held in Dakar, Senegal, in 1975, the introduction of two sub units was proposed: Sulfuric-Thionic Fluvisols (actual acid sulphate soils) and Sulfidic-Thionic Fluvisols (potential acid sulphate soils) but these proposals have not been incorporated in the recently revised legend (FAO/Unesco/ISRIC 1990). Instead, FAO now advises to add the qualifier Proto- for soils with sulfidic materials: Proto-Thionic Fluvisols (FAO 1991).

References

Begheijn, L.T., N. van Breemen and E.J. Velthorst 1978. Analysis of sulphur compounds in acid sulphate soils and other recent marine soils. Soil Science and Plant Analysis IX (9), 203-211

Breemen, N. van 1982. Genesis, morphology and classification of acid sulfate soils in coastal plains. In: Acid sulfate weathering. SSSA Special Publication 10, 66-130. Soil Science Society of America, Madison Wisconsin

Bregt, A.K., J.A.M. Janssen, J.S. van de Griendt, W. Andriesse and Alkasuma 1993. Optimum observation

density for mapping acid sulphate soils in Conoco, Indonesia: Accuracy and costs. Soil Use and Management, (in press)
Bregt, A.K., H.J. Gesink and Alkasuma 1993. Mapping the conditional probability of soil variables. Geoderma, (in press)
Bregt, A.K., Alkasuma, J.A.M. Janssen, J.S. van der Griendt and W. Andriesse 1990. Optimum observation density for mapping the starting depth of the pyritic layer in Conoco. In: AARD/LAWOO Papers Workshop on Acid Sulphate Soils in the Humid Tropics. Bogor, November 1990, 62-70. AARD, Bogor
Brinkman, R., M.E.F. van Mensvoort and L.J. Pons 1984. Report of a mission to Vietnam, February-March 1984. VH 10 Project. Mission Report No. 10. Dept. of Soil Science and Geology. Wageningen Agricultural University, Wageningen
Brinkman, R. and L.J. Pons 1973. Recognition and prediction of acid sulphate soil conditions. In: H. Dost (editor): Acid sulphate soils. Proceedings of the International Symposium on Acid Sulphate Soils. August 1972, Wageningen. International Institute for Land Reclamation and Improvement Publication No. 18, Vol. I, 169-203, Wageningen
Burrough, P.A., M.E.F. van Mensvoort and J. Bos 1988. Spatial analysis as a reconnaissance survey technique: an example from acid sulphate soil regions of the Mekong Delta, Vietnam. In: H. Dost (editor): Selected papers of the Dakar symposium on acid sulphate soils. January 1986, Dakar. International Institute for Land Reclamation and Improvement Publication No. 44, 68-69, Wageningen
Dent, D.L. 1980. Acid sulphate soils: morphology and prediction. J. Soil Science 31(1), 87-99
Dent, D.L. 1986. Acid sulphate soils: a baseline for research and development. International Institute for Land Reclamation and Improvement Publication No. 39, Wageningen
De Wit, P.A.J.W. 1990. Hydrological research in Unit Tatas. LAWOO/AARD Scientific Report no. 25, Research Program on Acid Sulphate Soils in the Humid Tropics. LAWOO, Wageningen
EDAFOS 1989. Soil survey of three inland valleys of the Rhombe swamp, Sierra Leone. Rhombe Swamp Irrigation Project, Freetown
Fanning, D.S. and J.E. Witty 1993. Revisions of Soil Taxonomy for Acid Sulphate Soils. In: D.L. Dent and M.E.F. van Mensvoort (editors). Selected Papers of the Ho Chi Minh City symposium on acid sulphate soils. International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen
FAO 1974. FAO-Unesco Soil Map of the World (1 : 5 000 000). Vol. I: Legend. Unesco, Paris
FAO/Unesco/ISRIC 1990. FAO-Unesco Soil Map of the World (1 : 5 000 000). Revised Legend. FAO World Soil Resources Report 60, Rome
FAO 1991. FAO-Unesco Soil Map of the World (1 : 5 000 000). Guidelines for distinguishing soil subunits in the FAO/Unesco/ISRIC revised legend. FAO World Soil Resources Report 60 (Annex 1), Rome
Gopinathan, B. and K.T. Joseph 1977. Anomalies in the US Soil Taxonomy classification of pyrite-containing alluvial soils. In: Clamatrops: Conference on classification and management of tropical soils. Paper No. 17. August 1977, Kuala Lumpur. Malaysian Society of Soil Science, Kuala Lumpur
Hoyer, A. and T.W. Hobma 1989. Results on water management experiments in Unit Tatas. LAWOO/AARD Scientific Report No. 12. Research Program on Acid Sulphate Soils in the Humid Tropics. LAWOO, Wageningen
Janssen, J.A.M., Hendro Prasetyo and Alkasuma 1990. Acid sulphate soils; field characteristics and mapping. In: AARD/LAWOO Papers Workshop on Acid Sulphate Soils in the Humid Tropics. November 1990, Bogor, 51-61. AARD, Bogor
Janssen, J.A.M., W. Andriesse, Hendro Prasetyo and A.K. Bregt 1992. Guidelines for soil surveys in acid sulphate soils in the humid tropics; the main problems considered. AARD/LAWOO Research Program on Acid Sulphate Soils in the Humid Tropics. AARD, Bogor. (In preparation)
Konsten, C.J.M. and Muhrizal Sarwani 1990. Actual and potential acidity and related chemical characteristics of acid sulphate soils in Pulau Petak, Indonesia. In: AARD/LAWOO Papers Workshop on Acid Sulphate Soils in the Humid Tropics. November 1990, Bogor, 30-50. AARD, Bogor
Konsten, C.J.M., W. Andriesse and R. Brinkman 1988. A field laboratory method to determine total potential and actual acidity in acid sulphate soils. In: H. Dost (editor): Selected Papers of the Dakar Symposium on Acid Sulphate Soils. January 1986, Dakar. International Institute for Land Reclamation and Improvement Publication No. 44, 106-134, Wageningen
Langenhoff, R. 1986. Distribution, mapping, classification and use of acid sulphate soils. A literature study. STIBOKA Internal Communications No. 74. The Netherlands Soil Survey Institute, Wageningen
Marius, C. 1985. Mangroves du Senegal et de la Gambie; Ecologie, Pédologie, Géochimie, Mise en Valeur et Aménagement. Coll. Travaux et Documents No. 193. Editions de l'ORSTOM, Paris

Mensvoort, M.E.F. van and Le Quang Tri 1988. Morphology and genesis of actual acid sulphate soils without jarosite in the Ha Tien Plain, Mekong Delta, Vietnam. In: H. Dost (editor). Selected papers of the Dakar symposium on acid sulphate soils, 11-15. International Institute for Land Reclamation and Improvement Publication No. 44, Wageningen

Muhrizal Sarwani, Mansur Lande and W. Andriesse 1993. Farmers' experiences in cultivating acid sulphate soils. In: D.L. Dent and M.E.F. van Mensvoort (editors). Selected Papers of the Ho Chi Minh City symposium on acid sulphate soils. International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen

Muhrizal Sarwani, Hairunsyah and J.A.M. Janssen 1990. Management aspects of a field laboratory in support of soil surveys; an experience from Pulau Petak, Indonesia. LAWOO/AARD Scientific Report No. 31. Research Program on Acid Sulphate Soils in the Humid Tropics. LAWOO, Wageningen

NEDECO/Euroconsult/BIEC 1984. Nationwide study of coastal and near-coastal swampland in Sumatra, Kalimantan and Irian Jaya. Tidal Swampland Development Project (P4S), Final Report Vol. 1. Directorate General of Water Resources Development, Ministry of Public Works, Jakarta

Pons, L.J., M.E.F. van Mensvoort and Le Quang Tri 1989. A proposal for the classification of mineral Vietnamese acid sulphate soils according to Soil Taxonomy. Acid Sulphate Soils Newletter (2) 5-9, ISSS, Wageningen

Pons, L.J. and I.S. Zonneveld 1965. Soil ripening and soil classification. Initial soil formation in alluvial deposits and a classification of the resulting soils. International Institute for Land Reclamation and Improvement, Publication no. 13, Wageningen

Reijneveld, A., B. Pengel and W. Andriesse 1990. Application of digital image processing techniques in a land cover survey of Pulau Petak, Southern Kalimantan, Indonesia. LAWOO/AARD Research Programme on Acid Sulphate Soils in the Humid Tropics, Scientific Report No. 32. LAWOO, Wageningen

Soil Survey Staff 1990. Keys to Soil Taxonomy (Fourth Edition). SMSS Technical Monograph No. 19. Conell University, Ithaca

Sutrisno, J.A.M. Janssen and Alkasuma 1990. Classification of acid sulphate soils; a proposal for improvements of the Soil Taxonomy system. In: AARD/LAWOO Papers Workshop on Acid Sulphate Soils in the Humid Tropics. November 1990, Bogor, 71-80, AARD, Bogor

Sylla, M., N. van Breemen, L.O. Fresco and C. Dixon, 1992. Temporal and spatial variability of soil constraints in relation to rice production in mangrove soils along the Great Scarcies River (Sierra Leone). In: D.L. Dent and M.E.F. van Mensvoort (editors). Acid sulphate soils. Selected papers from the Ho Chi Minh City symposium. International Institute for Land Reclamation and Improvement, Publication no. 53, Wageningen

Tabatabai, M.A. 1982. Sulphur. In: A.L. Page, R.H. Miller and D.R. Keeney (editors): Methods of Analysis, Part 2. American Society of Agronomy Series., No. 9 (2nd Edition) 504-506. American Soc. Agron., Madison, Wisconsin

Thomas, P. and J.A. Varley 1982. Soil survey of tidal sulphidic soils in the tropics: a case study. In: H. Dost and Van Breemen (editors): Proceedings of the Bangkok Symposium on Acid Sulphate Soils. January, 1981. Bangkok. International Institute for Land Reclamation and Improvement Publication No. 31, 52-72, Wageningen

Webster, R. and M.A. Oliver 1990. Statistical methods in soil and land resources survey. Oxford University Press, New York

Amelioration of potential acid sulphate soil by pyrite removal: Micalo Island, New South Wales, Australia

G.M. Bowman

CSIRO Division of Soils, GPO Box 639, Canberra 2601, Australia

Abstract

Potential acid sulphate soils are found extensively on the estuarine floodplains of the east coast of Australia. Within the estuary of the Clarence River in northern New South Wales, a proposed resort development on Micalo Island, former sugarcane farmland was considered environmentally undesirable because of the presence of acid sulphate soil adjacent to drainage channels and potential acid sulphate soil underlying most of the island. The latter is a thick stratum of grey silty sand, with a low proportion of fines and a variable but low proportion of marine shell debris. The pH of the subsurface sediments was predominantly about 6.5, but the pH was as low as 2.5 in the oxidized materials on the ground surface.

Particle size distributions indicated that the sediments consist of well-sorted sand, with generally less than 10 per cent by mass finer than 20 microns. The acidity buffering capacity of the sediments is low, with the neutralization potential of the coarse shell content unlikely to be effective at the microscale. Dispersed subsamples were separated into 6 size fractions and the sulphate content of each was analyzed by ion chromatography to determine water extractable and hydrogen peroxide oxidizable sulphur. The results indicate that in nearly all samples the bulk of oxidizable sulphur is contained in the < 20 micron size fraction and that a much smaller secondary concentration occurs in the 75-125 micron range.

To ameliorate the soil problems on Micalo Island, it is proposed that the nearsurface acid sulphate soil should be chemically neutralized, but that simple hydraulic separation techniques commonly used in mineral sand mining would be adequate to separate the finer pyritic sediment (say < 75 microns), which could then be chemically neutralized or returned beneath the permanent watertable.

For high value commercial developments on coarse-textured acid sulphate soils, this separation and neutralization procedure should be an environmentally acceptable and cost-effective alternative to existing treatment options.

Introduction

The extensive occurrence of acid sulphate soils within the major estuaries of eastern Australia is being increasingly recognized as low-lying, swampy land is subject to pressure from urban and agricultural expansion and from new commercial resort developments (Walker 1963, 1972; Willett and Bowman 1990). At the same time, community concern is increasing as a result of reports that disturbance and drainage of these soils is causing major environmental damage, typified by massive fish kills in rivers, a decline in coastal fishery resources, degradation of estuarine ecosystems and a decrease in the productivity of agricultural land (Veness 1990).

Although conventional ameliorative techniques for acid sulphate soils are often prohibitively expensive for current agricultural land uses, large commercial developments can usually afford to apply innovative solutions to reduce the potential environmental consequences of disturbing these soils. It is proposed to develop a residential resort / golf course / educational complex on 400 hectares of land on Micalo Island, near Yamba, on the lower Clarence River in northern New South Wales (29°27′S, 153°19′E).

The island consists of a low-lying floodplain, primarily composed of estuarine sediments showing a strong marine influence. Much of the island has been drained by a series of ditches and channels to allow sugar cane production, while towards the southern end (outside the area of the proposed development) large aquaculture ponds have been constructed.

A preliminary investigation of Micalo Island failed to recognize the presence of acid sulphate materials (Coffey Partners International 1991), but a subsequent study indicated that both potential and actual acid sulphate soils are widely distributed across the island (Warren 1991). This paper confirms the occurrence of acid sulphate soils within the development area, presents the results of particle size analyses of the pyritic sediments, and examines the possibility that the pyrite in the sediments is sufficiently concentrated in the finer size fractions that it can be separated from the coarse fractions and dealt with in an environmentally benign way.

Methods

Field survey

During a period of wet weather in May 1991, a large tracked excavator was used to dig temporary pits over 3 meters deep at six sites on Micalo Island (Figure 1).

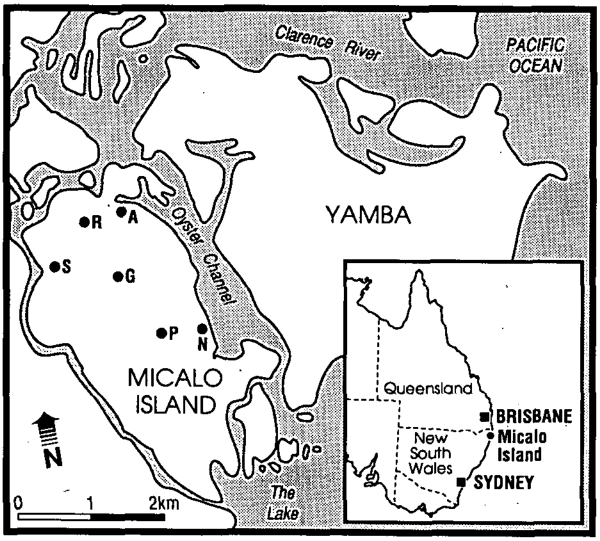


Figure 1 Location map of Micalo Island, showing soil sampling sites A, G, N, P, R & S.

Four of the sites (A, G, N and P) were located adjacent to sites previously sampled by Warren (1991). The additional two pits were located towards the northern and western sides of the island (respectively, sites R and S, Figure 1). Sediment/soil samples were obtained from the sides of each excavation before slumping of the wet sediments occurred, and placed in labelled click-seal plastic bags.

Measurements of *in situ* soil pH were also made with a portable digital pH meter, using a gel-filled combination electrode which was field calibrated and pressed directly into the saturated sediments of the pit wall. Surface water and ground water pH measurements were also recorded. Field pH measurements are presented in Table 1. Addi-

Table 1 Micalo Island samples: description and field pH

Site	Depth (m)	Description	pH
A	surface	rainwater on ground	7.0
	surface	dark brown organic sandy clay	6.2
	0.25	mottled brown organic sandy clay	5.9
	1.0	medium grey sand, little mud	5.8
	3.0	medium grey sand, little mud	6.1
G	surface	rainwater on ground	6.4
	surface	excavated drain spoil	4.6
	0.3	mottled organic muddy sand, shell	7.3
	0.5	dark grey organic muddy sand	7.4
	1.0	dark grey muddy sand, v. shelly	–
	3.0	uniform dark grey muddy sand	–
N	surface	rainwater on ground	5.5
	surface	brown swamp water	5.3
	surface	friable organic rich sand	6.3
	0.45	pale grey silty sand, jarositic	6.8
	0.5	dark grey clayey/silty sand	6.5
	1.2	medium grey muddy sand, sulphide	6.7
	3.0	medium grey muddy sand, shelly	6.5
	3.0	groundwater flowing into pit	2.4
P	surface	excavated drain spoil	3.6
	0.4	grey silty sand, part oxidized	5.5
	0.6	orange mottled grey muddy sand	6.3
	1.0	medium grey slightly muddy sand	6.6
	2.0	medium grey slightly muddy sand	6.2
R	0.5	compact dark organic clay, dry	–
	1.0	indurated fine sand, podzolised	–
	3.0	uniform medium grey muddy sand	–
S	surface	rainwater on ground	6.3
	surface	brown swamp water	5.0
	surface	organic peaty material	3.7
	surface	jarositic drain spoil	2.5
	0.3	jarositic mottled organic clay	4.1
	0.6	pale sand, very little fined	6.6
	0.8	uniform dark grey muddy sand	6.3
	1.0	uniform dark grey muddy sand	6.6
	1.7	uniform dark grey muddy sand	6.7
	3.5	uniform dark grey muddy sand	–

tional observations and sampling of surface materials were carried out along selected drainage ditches.

Because of a lack of refrigerated transport, all samples were oven-dried at 60 °C on the day of sampling, before resealing and shipment to the laboratory. Although oven-drying did severely reduce the potential for biological activity in the sediments and hence restrict acidification, two samples did show marked differences between field and laboratory pH values (see below).

Laboratory analyses

On the basis of field observations, two sites were selected (G and P) as representative of the acid sulphate soil conditions observed on Micalo Island. The four depth samples from each site were subjected to the following laboratory analyses.

Particle size distributions were determined on dispersed subsamples of the sediment by a combination of pipette analyses, high speed centrifugation and dry sieving (Walker and Hutka 1979), yielding the percentage mass of total sediment in the size ranges <2, 2-20, 20-45, 45-75, 75-125, 125-250, 250-500, 500-1000, 1000-2000, and >2000 microns. The results of the particle size analyses for the samples from sites G and P are shown as cumulative mass plots (per cent finer than) in Figures 2 and 3 respectively. As an indication of the acidity generated in the bulk samples during drying, transport and storage, pH was measured on subsamples after 2 hours as a 1:5 soil:water suspension. Another subsample was digested for 72 hours with excess hydrogen peroxide, gently heated to 60 °C for 2 hours, cooled and the pH measured. These pH values are included in Table 2.

To determine the marine carbonate (shell) content of each bulk sample, a dry 10 g subsample was digested with excess HCl (32 per cent w/w) for 72 hours, by which time CO_2 evolution had ceased. The washed sample was then dried and weighed, and the percentage mass loss determined. The results are included in Table 2. A dispersed subsample of known mass from each of the 8 bulk samples was carefully separated into 6 size fractions (<20, 20-45, 45-75, 75-125, 125-250, >250 microns) using sedimentation techniques, flocculation and repeated decanting where necessary, and wet sieving of the coarse fractions.

To determine oxidizable sulphur in each size fraction, subsamples of known mass and moisture content were digested in H_2O_2 using the method of Willett and Walker (1982). The digested solution was diluted to volume and an aliquot of the filtered supernatant was analyzed for sulphate by ion chromatography. Water-extractable sulphate was determined on a 1:5 water extract and oxidizable S was calculated by difference. The results of these analyses are reported as oxidizable S (mg g^{-1}) in Table 2. After correction for the mass of sediment in each size fraction (using the aggregated results of the particle size analyses), oxidizable S in each size fraction in the sample was calculated and expressed as % S (Table 2).

Results

Field observations and measurements

Jarositic mottles on and in oxidized spoil heaps adjacent to drains confirmed the earlier reports of the occurrence of acid sulphate soils on Micalo Island (Warren 1991). Mea-

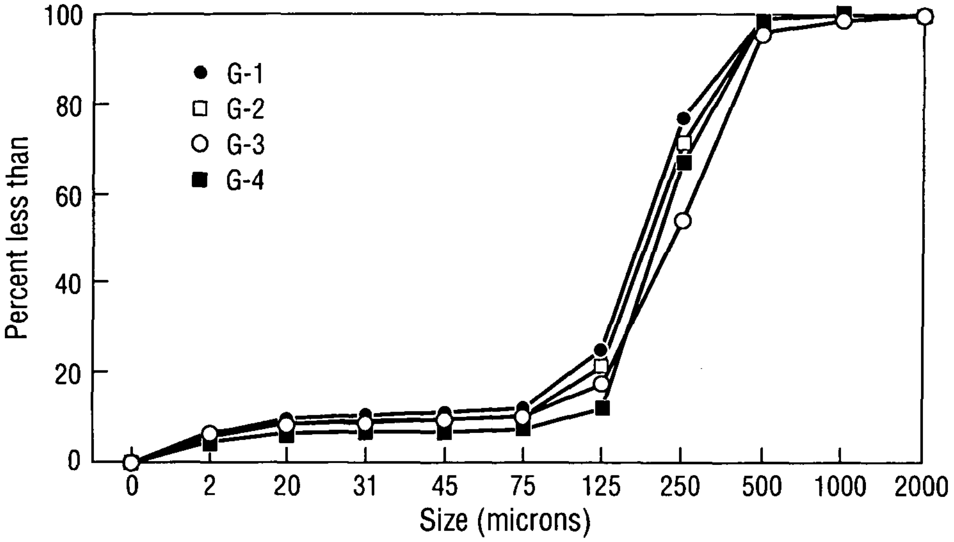


Figure 2 Results of particle size analyses of samples from Micalo Island Site G

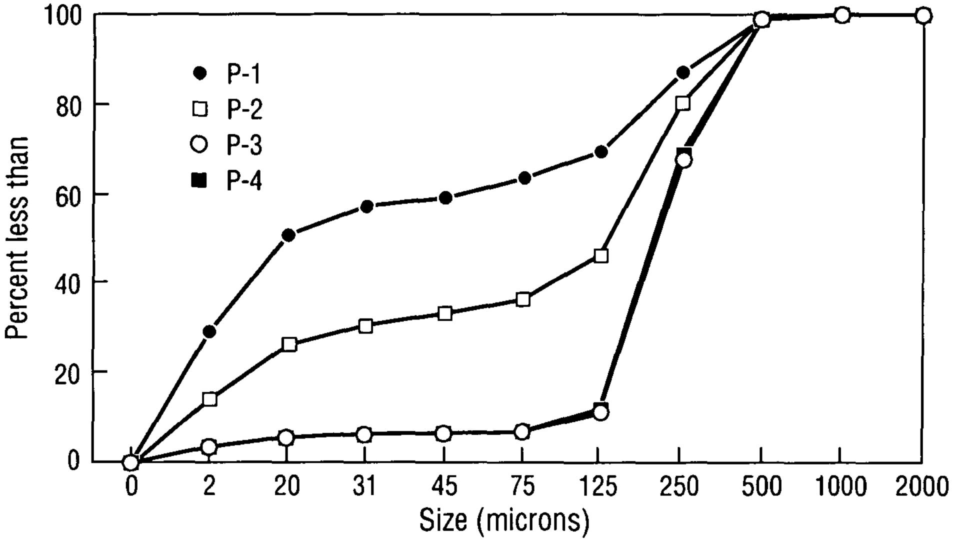


Figure 3 Results of particle size analyses of samples form Micalo Island Site P

surements of the pH of these oxidized spoil heaps (Table 1) substantiated this conclusion, although pH readings for some surface water tended to be near neutral as the measurements were made after a prolonged period of rain.

The pH of the subsurface materials (below 0.5 m) were nearly all between 6.0 and 7.0, consistent with potential acid sulphate conditions. However, in contrast to the description of the usual sulphidic materials as predominantly very fine organic silts

Table 2 Analytical results for selected acid sulphate soil samples from Micalo Island

Sample no.	Depth (m)	$CaCO_3$ (%)	Lab pH		Size fraction microns	Oxidizable S in fraction mg g^{-1}	Per cent sulphur
			H_2O	H_2O_2			
G-1	0.3	2.2	3.68	2.35	< 20	26.7	0.254
					20-45	13.6	0.020
					45-75	7.44	0.009
					75-125	0.47	0.024
					125-250	0.47	0.010
					> 250	0.24	< 0.001
G-2	0.5	1.3	8.17	6.66	< 20	2.87	0.025
					20-45	0.39	< 0.001
					45-75	0.66	< 0.001
					75-125	0.18	0.009
					125-250	0.10	0.003
					> 250	0.10	< 0.001
G-3	1.0	6.7	7.41	7.58	< 20	28.5	0.246
					20-45	10.9	0.012
					45-75	12.3	0.008
					75-125	0.74	0.027
					125-250	0.24	0.010
					> 250	0.10	< 0.001
G-4	3.0	1.7	6.62	3.31	< 20	4.73	0.030
					20-45	14.1	0.008
					45-75	7.97	0.004
					75-125	0.98	0.005
					125-250	0.16	0.005
					> 250	0.12	< 0.001
P-1	0.4	4.9	5.34	3.7	< 20	2.33	0.120
					20-45	2.14	0.018
					45-75	3.24	0.013
					75-125	0.27	0.005
					125-250	0.23	0.003
					> 250	0.15	< 0.001
P-2	0.6	1.9	6.74	5.99	< 20	0.36	0.009
					20-45	0.20	0.001
					45-75	0.36	0.001
					75-125	0.07	0.002
					125-250	0.08	0.001
					> 250	0.02	< 0.001
P-3	1.0	1.2	6.60	5.34	< 20	0.55	0.003
					20-45	2.15	0.002
					45-75	0.65	< 0.001
					75-125	0.10	0.006
					125-250	0.04	0.001
					> 250	0.03	< 0.001
P-4	2.0	1.4	4.30	3.09	< 20	4.31	0.025
					20-45	4.36	0.004
					45-75	3.98	0.002
					75-125	0.27	0.016
					125-250	0.07	0.002
					> 250	0.03	< 0.001

and clays (muds) with relict mangrove traces (Dent 1986), the underlying sediments at Micalo consisted of well-sorted sands with a low proportion of fines.

Laboratory pH and carbonate measurements

As indicated in Table 2, some of the samples from sites G and P showed a significant drop in pH from the *in situ* field reading to that measured in 1:5 soil:water in the laboratory. This probably indicates some oxidation of the sample prior to its complete oven-drying or on re-wetting, although the discrepancy could be due in part to differences in the soil:water ratio for the two readings.

After hydrogen peroxide digestion, nearly all samples gave substantially lower pH readings, probably indicating oxidation of pyrite. However, only samples G-2, G-4, P-1 and P-4 gave pH values after peroxide oxidation that were less than 4.0, the value set by Dent (1986) as the critical level for acid sulphate soils in which the neutralizing capacity of the material is exceeded by the acidity produced. Overall, the pH falls tended to reflect the total % S in the samples (Table 2). The notable exception was G-3, which gave a slight pH rise after the peroxide treatment, but had a high oxidizable S content. However, this sample had by far the highest shell carbonate content of all the samples measured (6.7 per cent) and it is likely that this influenced the result.

It should be noted that the pH falls measured in this investigation are somewhat smaller than those observed by Warren (1991), who reported post-peroxide pH values of 2.0 to 2.5. It seems probable that this was due to different sample pretreatments.

Particle size results

Consideration was given to correcting the <45 micron figures for differential sedimentation caused by the high specific gravity of pyrite. However, calculations indicated that the required correction would be small, and as the results were to be used to assess the possibility of hydraulic separation of pyrite in specific sediment size fractions, it was considered preferable to present the unaltered particle size data.

The plots for Site G (Figure 2) show a predominantly sandy sediment with a relatively low and uniform content of fines (mostly 10 per cent <45 microns). In contrast, the two near-surface samples from Site P (Figure 3) contain a very high proportion of fine material, although much of this is organic colloid which could not be removed by the usual oxidation pretreatments without affecting the pyrite content. The two deeper samples have a near-identical particle size distribution (they overlap on the graph) which is very similar to the four samples from site G. Thus, with the exception of the two organic rich samples from Site P, the samples all consist of well-sorted sand with a low fines component.

Potential acidity

The results presented in Table 2 for total oxidizable S in the Micalo Island samples are in good agreement with those contained in Table 2 of Warren (1991), although they do not apply to the same sites. Total oxidizable sulphur ranges from 0.254 per cent in the upper sample at Site G, to effectively nil in the 1.0 meter depth sample at Site P. At both sites the highest values occur near the surface, with levels generally decreasing rapidly with depth (Table 2). In terms of commonly cited critical levels for Australian acid sulphate soils (Simmond, Bristow 1991), samples G-2 and G-3 are the only ones that could be classed as having a high acid sulphate potential (>0.2

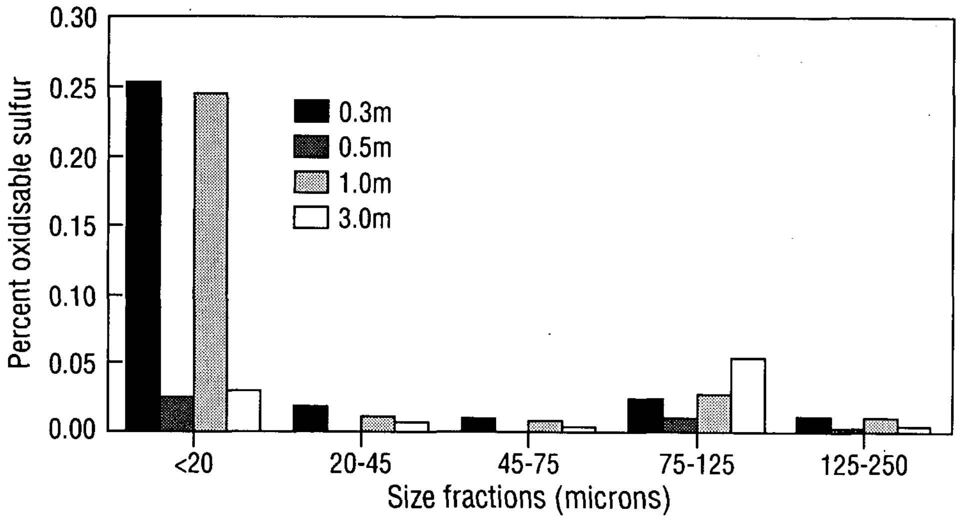


Figure 4 Plot of distribution of oxidizable S in particle size fractions of depth samples from Site G at Micalo Island

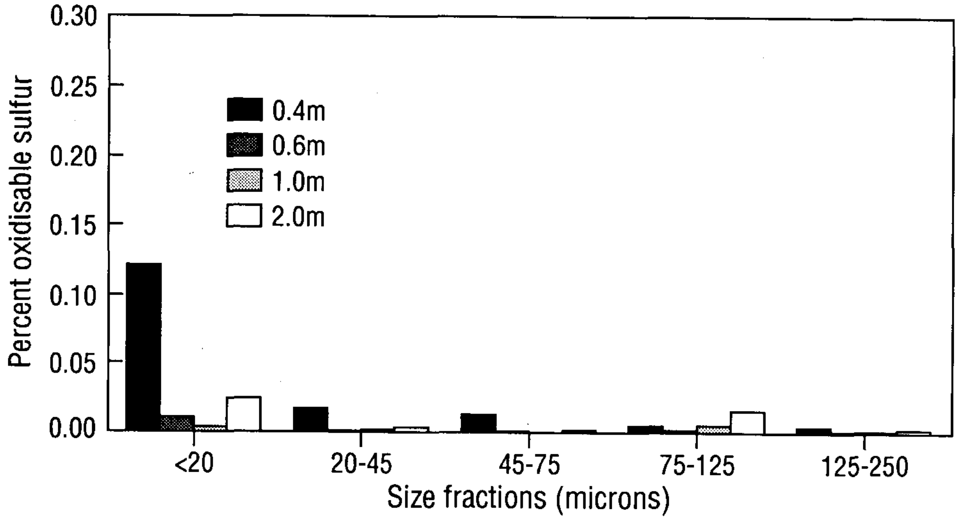


Figure 5 Plot of distribution of oxidizable S in particle size fractions of depth samples from Site P at Micalo Island

per cent S), sample P-1 could be classed as of moderate potential acidity (>0.1 per cent <0.2 per cent S) and the remainder could be regarded as having a low acid sulphate potential (<0.1 per cent S). These values reflect the coarse texture of these sediments and their low inherent acid buffering capacity. Figures 4 and 5 show the distribution of oxidizable sulphur in the various particle size fractions in the samples from

Sites G and P, respectively. Note that for each particle size class, the samples are plotted in order of increasing depth.

It is apparent from the plots that the < 20 micron fraction contains the bulk of the oxidizable S (and hence pyrite) in all samples, but that the absolute levels of oxidizable S are generally greater in the Site G samples. However, it is not so obvious that for nearly all samples there is a small secondary peak of oxidizable S in the 75-125 micron range. In one case (G-4), this peak is actually greater than that for the < 20 micron fraction, although both values are considered low-moderate.

Overall, for most samples, the pyritic material is contained predominantly in the finest fraction and it is only in one sample that the level of oxidizable S rises significantly in the > 75 micron fraction.

Discussion

On the basis of the particle size and chemical data, it is proposed that the most effective method for ameliorating the acid sulphate characteristics of the Micalo Island site will be to mechanically remove the acid sulphate topsoil material and to chemically treat this where necessary using appropriate neutralizing agents (eg. agricultural lime) in a pugmill.

The underlying sulphidic sediment will then be excavated by a dredge (floating on an artificially created pond) using a submersible rotary cutting/suction mechanism coupled with an hydraulic pump to move the sediment onshore, where it will be split into two size fractions by hydraulic techniques. The fine fraction will contain as much as possible of the pyrite and the coarse fraction as little as possible. The pyritic fine sediment will be immediately returned to permanent anoxic storage on the bed of the newly created water feature (part of the planned development) while the coarse fraction will be bunded, allowed to dry and will be consolidated for use as fill material.

This separation procedure has several advantages: wet dredging is usually the most economic earthmoving procedure in coastal areas; pyrite remains wet and will not acidify during the brief treatment time involved nor once it is returned to permanent

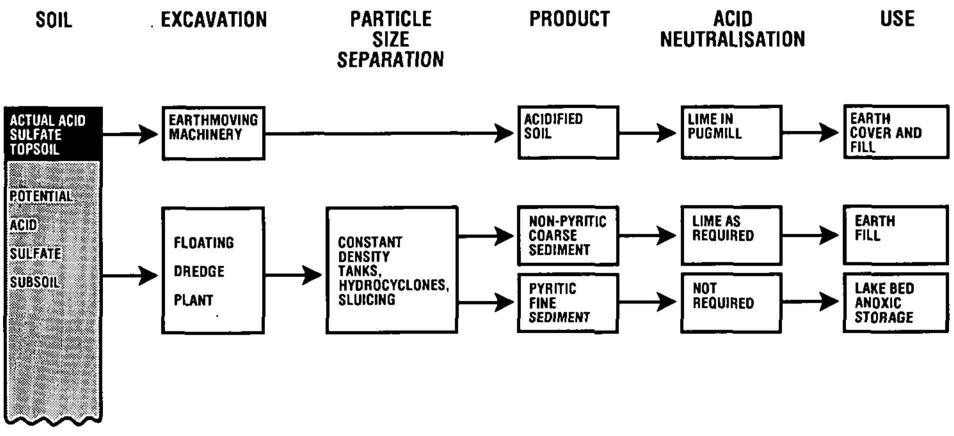


Figure 6 Schematic presentation of proposed acid sulphate treatment procedure

storage beneath water; the volume of pyritic sediment will be much less than that of the original material and therefore easier to handle; and the coarse fraction will be essentially cleaned by the treatment and will be suitable for use as fill as required by the development.

The size separation will be achieved by pumping sediment through wet sieves, constant density tanks and hydrocyclones, and possibly even by just hand sluicing at the discharge point (Figure 6). This technology is extensively used for mineral separation in the heavy mineral sands mining industry in Australia (Kisochosa Kogyo 1991).

The use of hydrocyclones will depend on the efficiency of the other separation techniques, for while they allow the most precise size splits and can be tuned to a specific application, their capacity is generally limited by economic considerations related to attainable pumping pressures and rates of throughput (Trawinski 1976). However with high value projects such as the Micalo Island development (the estimated cost ranges from (AUS) \$48M to \$140M, P. Thorpe, pers. comm. 1991), the use of hydrocyclones is unlikely to be prohibitively uneconomic if environmental considerations dictate a residual pyrite content in the coarse fraction that is unattainable by the cheaper alternative techniques (Svarovsky 1984; Wood 1987).

In addition, as dredging is the preferred sediment handling technique for the 2 million cubic meters of excavation to be carried out at Micalo Island, the additional procedures for removing pyrite will not significantly increase the estimated cost of (AUS) \$3.50 (approx US\$ 2.50) per cubic meter of material.

If 100 per cent separation of the size fractions at 75 microns is achieved, the chemical data indicate that a very slight acidity potential will probably remain because of pyrite in the 75-125 micron size range. However, this should be relatively easily neutralized by the addition of fine lime during handling. It is probable that severe hydraulic agitation will disaggregate any composite pyritic particles > 75 microns, in which case they will move with the fine fraction and not contaminate the coarse. As the analytical results indicate a somewhat different situation in terms of acid sulphate potential at sites G and P, a more comprehensive investigation will be carried out to determine the spatial variability of the acid sulphate conditions at Micalo Island. In addition, the government has directed that a pilot plant should be established to prove the concept of hydraulic separation of the pyrite size fraction, to demonstrate the developer's capability to completely neutralize any residual potential acidity in the coarse fraction, and to show that the pyritic fines can be safely stored.

Acknowledgements

Financial support for this investigation was provided by Kisochosa Kogyo Co. Ltd, Sapporo, Japan. Mr Peter Thorpe provided information on hydraulic separation techniques and Mr L. Walker assisted with fieldwork. Laboratory analyses were carried out by Mr H. Beatty, Mrs E. Thompson and Mr J. Hutka. Mr J. Gibson assisted with interpretation of the results.

References

Coffey Partners International 1991. Report on preliminary geotechnical studies, proposed development at Micalo Island, Yamba, N.S.W. Report B15488/1-A in Volume 2, Technical Appendices accompanying Statement of Environmental Effects, Micalo Island Development Proposal, Kisochosa Kogyo Co. Ltd & Cosmos Resort Co. Ltd, Lismore

Dent D.L. 1986. Acid sulphate soils: a baseline for research and development. ILRI pub.39, Wageningen

Kisochosa Kogyo 1991. Statement of Environmental Effects, Micalo Island Development Proposal, Kisochosa Kogyo Co. Ltd & Cosmos Resort Co. Ltd, Lismore

Simmonds, Bristow 1991. Acid Sulphate Potentials. Report to Planners North P.L., Ref No. 17393B, 5th April 1991

Svarovsky L. 1984. Hydrocyclones. Holt, Rinehart & Winston, London

Trawinski H. 1976. Theory, applications, and practical operation of hydrocyclones. Engineering & Mining Journal 177, 115-127

Veness R. 1990. Acid Sulphate Soils. Soilnote 22/90, N.S.W. Soil Conservation Service

Walker P.H. 1963. A reconnaissance of soils in the Kempsey district, N.S.W. Soil and Land use Series no. 44, CSIRO

Walker P.H. 1972. Seasonal and stratigraphic controls in coastal floodplain soils. Australian Journal of Soil Research, 10, 127-142

Walker P.H. and J. Hutka. 1979. Size characteristics of soils and sediments with special reference to clay fractions. Australian Journal of Soil Research, 17, 383-404

Warren J. 1991. Investigation and assessment of acid sulphate soils at a proposed resort development Micalo Island, Yamba, N.S.W. Report by James Warren, Biological and Environmental Consultant in Volume 2, Technical Appendices accompanying Statement of Environmental Effects, Micalo Island Development Proposal, Kisochosa Kogyo Co. Ltd & Cosmos Resort Co. Ltd, Lismore

Willett I.R. and G.M. Bowman 1990. Acid sulphate soil conditions near flood mitigation drains of the lower Macleay River. Report prepared for Kempsey Shire Council, CSIRO Division of Soils, Canberra

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

Wood P.A. 1987. Proceedings of 3rd International Conference on Hydrocyclones, Oxford. Elsevier, London

Survey strategies for acid sulphate soils

A.K. Bregt[1], J.A.M. Janssen[1], Alkasuma[2]

[1] DLO-Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen, The Netherlands
[2] Centre for Soil and Agroclimate Research, Bogor, Indonesia

Abstract

To survey acid sulphate soil areas, land systems survey, free survey and probability sampling may be used. Advantages and disadvantages of these different approaches have been examined. Selection of the most appropriate method depends on the user's requirements and soil conditions.

In an acid sulphate soil area in Kalimantan, Indonesia, the short-range variation in the depth to the pyritic layer meant that increasing the intensity of survey beyond 22 observations per square km did not yield more accurate maps.

For mapping acid sulphate soils, a combination of land systems or free survey with probability sampling is proposed. This procedure is flexible and provides detailed quantitative data for the most interesting parts of the survey area.

Introduction

The purpose of soil survey is to obtain information on the soil conditions in an area. The amount of soil information to be collected depends on the intended use of this information. Specific purposes need more specific and, usually, more detailed data. For general questions, generalized data are sufficient. It is a challenge for the soil surveyor to provide the right amount of information. Providing more information than needed leads to overkill, which hampers proper use; whereas insufficient information may lead to wrong decisions. So it is important to select the soil survey strategy which yields the required information at the lowest cost. Choice of method depends on the user's requirements and also the specific soil conditions. Terms of reference can then be drawn up describing, for example, which soil attributes need to be collected, what survey or sampling method will be used, how many observations will be made and what equipment and staff is required.

Survey and sampling methods

Beckett (1968) distinguished three main survey methods: physiographic survey, free survey and grid survey. They differ in the extent to which the mapped boundaries are based on obervations at sampling points, rather than on surface appearance of soil attributes as perceived on the ground, by remote sensing, or on topographic or geological maps. Over the past twenty years, probability sampling has been used more and more to obtain accurate information. The probability sampling can be in the form of a grid or an other sampling scheme.

Physiographic survey
In physiographic survey, the mapped soil boundaries are based on external features of the soil and the landscape perceived by interpretation of air photos or other remote sensing images. Field observations are made, not to locate boundaries, but to describe the soil within each map unit and the survey costs per km^2 are relatively low.

Free survey
Free survey is the most widely used survey method. According to this method, the soil surveyor uses known or observed relationships between soil attributes and features of the landscape that can be seen in the field or on air photos. In this way, the surveyor builds a conceptual model about the soil behaviour. Using the model, he selects each observation point where it is likely to yield the most useful information (Dent and Young 1981). Soil boundaries are delineated during field work, and in contrast with physiographic survey, the mapping model is refined with each successive field observation.

A free survey yields a soil map and descriptions of soil profiles at points. Each mapping unit is characterized by a representative profile and sometimes an estimate of variation within units which is used for the interpretation of the soil map.

More detailed information is obtained by increasing the survey intensity which goes hand in hand with a narrower definition of the mapping units.

Soil attributes are recorded, usually, on a nominal scale (that is by grouping into classes) or on an ordinal scale (semi-quantitative rating). Survey costs per km^2 are higher than for physiographic survey and they rise steeply with increase in intensity (or scale) of survey.

Probability sampling
An essential feature of probability sampling is that the sampling locations are determined by a random procedure so that statistical theory can be used for an unbiased estimation of, for instance, means and variances of attributes. There is a great diversity of possible sampling schemes but three basic kinds can be distinguished (Ripley 1981, Webster and Oliver 1990):

- Random
  The sampling locations are chosen completely random. Disadvantages are that, firstly, the total number of observations needed to obtain a certain precision in the statements is relatively high and, secondly, clustering of samples can lead to over- or undersampled areas;
- Systematic
  An even coverage of an area can be obtained by locating samples at regular intervals on a grid. The location of one grid point must be chosen at random. Systematic sampling is easy to perform. If, however, there are periodicities in the soil population, the results can be biased;
- Stratified
  The area is divided into different strata. Within the different strata sample locations can be chosen according to a random (stratified random) or a systematic (stratified systematic) procedure.

To select the best sampling scheme, it is important to know the questions to be ans-

wered. Most probability sampling schemes concentrate on estimating means and variances of an attribute for an area. When we are interested in predicting attribute values at point locations, the scheme will be quite different. Using the geostatistical model for answering this question, sampling must be done in order to:
- Estimate the spatial structure of the attribute. This is usually expressed in a semivariogram;
- Make predictions for specific locations.

Sampling schemes for estimating the semivariogram are proposed by Russo (1984), Warrick and Myers (1987) and Pettitt and McBratney (1992). All three proposed procedures attempt to obtain short-range information as well as information over larger distances. Sampling schemes for spatial prediction by means of kriging use a systematic grid (McBratney et al. 1981, McBratney and Webster 1981).

Example strategies

At present, information about acid sulphate soil areas to support national planning, resource inventory and general orientation can be obtained by exploratory and reconnaissance survey and published maps. For purposes such as regional land use planning and project feasibility studies, more detailed information is required. This information is produced by a survey at semi-detailed level, that is at scales of 1 : 50 000 to 1 : 100 000. Large acid sulphate soil areas still need to be surveyed at this level. For agricultural advisory work and project planning, detailed survey, that is at 1 : 25 000 or larger scales, is most suitable.

The following discussion relates to surveys for project feasibility and regional planning, and for project planning where the main survey effect will be in future. Table 1 summarizes the kind of information needed.

For project feasibility and regional planning, physiographic survey or free survey is employed, depending on the scale of operations. Both methods are cheap and yield the information needed. The procedure is well described by Dent and Young (1981). It involves prior study of existing information, interpretation of satellite imagery and/

Table 1 Information needed for regional or for project planning

	Project feasibility and regional planning	Project Planning
Purpose	Identification of areas that are potentially useful, or not	Decisions on kind and location of specific developments
Information needed	Broad range of attributes over a large area	Broad range of attributes over a limited area, quantitive data and thematic maps of some single attributes needed
Knowledge of the level of accuracy	Not essential	Very important

Table 2 General procedure for combined free survey and probability sampling

Procedure
- Study existing soil information of the area;
- Carry out air photo interpretation in order to delineate major physiographic units based on landscape, vegetation, hydrological features and existing data;
- Characterize units by a few soil observations in the area;
- Select units which seem to be interesting for further investigation;
- Carry out grid sampling within the selected units. The location of the grid is determined by a random procedure. In order to obtain information about the 'short range' variability near some grid points, additional observations must be made;
- Use the data from the grid sampling to:
  - Calculate mean and variance of a variable in the units;
  - Calculate spatial structure (semivariogram) within the units;
  - Make spatial predictions of a variable in the units;
- Report results.

Requirements
- Staff with high level expertise in soil science;
- Staff with expertise in data processing;
- Computer equipment and processing software;
- Field and laboratory equipment.

or air photos to delineate mapping units followed by fieldwork for sampling and, if necessary, revision of boundaries. Staff with a high level of experience in soil science is essential.

For project planning, more detailed, quantitative information is needed. Free survey has been the most widely used procedure for acid sulphate soils (Dent 1986) but is effective only where clear relations have been established between landscape features and soil conditions. In acid sulphate areas, these relationships are often only present at a rather general level.

Probability sampling is being used increasingly to provide data for quantitative statements about the soil attributes in acid sulphate areas. The general procedure involves: determination of locations for sampling points, sampling at these locations, and the use of spatial prediction procedures to predict attributes for unvisited locations. In comparison with free survey, it requires staff with less expertise in soil science but staff with expertise in data processing, computing equipment and software.

Not surprisingly, probability sampling is not popular with experienced soil surveyors who feel that valuable information about soil-landscape relationships remains unused.

Combination of free survey and probability sampling

As far as we know, a combination of free survey and probability sampling has not yet been applied to acid sulphate soil areas. The procedure is summarized in Table 2. According to this procedure, first, a free survey must be used to identify larger physiographic units, such as backswamps, levees and ridges. Interpretation of air photos and satellite imagery forms the basis for the delineation of the units. Some field observations must be made in these units to get a general idea of their composition. In the second phase, probability sampling must be applied within the distinguished units. It is not necessary to sample all the units. We can limit our activities to those units that are of main interest for our survey purpose. For example, if we are conducting a survey for the location of new settlement sites in an acid sulphate soil area, it is sensible to concentrate the activities in those units that seem to be suitable according to the first phase. The result is that more accurate data have been obtained for the area of interest.

A combination of free survey and probability sampling yields accuracy of information and is flexible. The requirements in terms of expertise and equipment are larger than for either technique used alone, but the costs can be lower than for an overall free survey or probability sampling.

Pulau Petak: experience and survey strategy

Pulau Petak is an acid sulphate soil area of about 2000 km^2 located in Southern Kalimantan, Indonesia, between the rivers Barito and Kapuas Murung. Details are reported by Alkasuma et al. (1990), Bregt et al. (1990), Bregt et al. (1992), Janssen et al. (1992), and Bregt et al. (in press). In these studies, the main focus was on the attribute depth to the pyritic layer, as it is an attribute of major importance for the use of these soils.

Field characteristics

Based on extensive literature and field research, Janssen et al. (1992) concluded that the identification of potential and actual acid sulphate soils by only landscape and soil profile characteristics is problematic. No universal relationships can be established between, for instance, profile characteristics and the starting depth of the pyritic layer. For a proper identification of acid sulphate soil characteristics, laboratory analysis of soil samples is necessary.

Spatial variability

Depth to the pyritic layer shows a high short-range variation. This is indicated by a high nugget effect in the semivariogram (Figure 1). A similar high short-range variation in the attribute depth to the pyritic layer has been observed in the Mekong Delta, Vietnam by Bos and Van Mensvoort (1984).

In Vietnam as in Indonesia, nugget effects of about 300 cm^2 are found. In the study reported by Bos and Van Mensvoort (1984), the minimum sampling spacing is 30 m. Bregt et al. (1990) used a minimum sampling spacing of 1 m. In order to reveal more spatial structure in the starting depth of the pyritic layer, Bos and Van Mensvoort suggested sampling at shorter distance. It is doubtful if this would reveal more structure. An illustration of the high short-range variation in the starting depth of the pyritic layer is presented in Figure 2. Differences of more than 50 cm in the depth of the pyritic layer are found in Pulau Petak within 25 m. A high-short range variation in the starting depth of the pyritic layer seems to be quite common for acid sulphate soils.

An effect of this large short-range variation is that the starting depth of the pyritic layer cannot be predicted with a high accuracy.

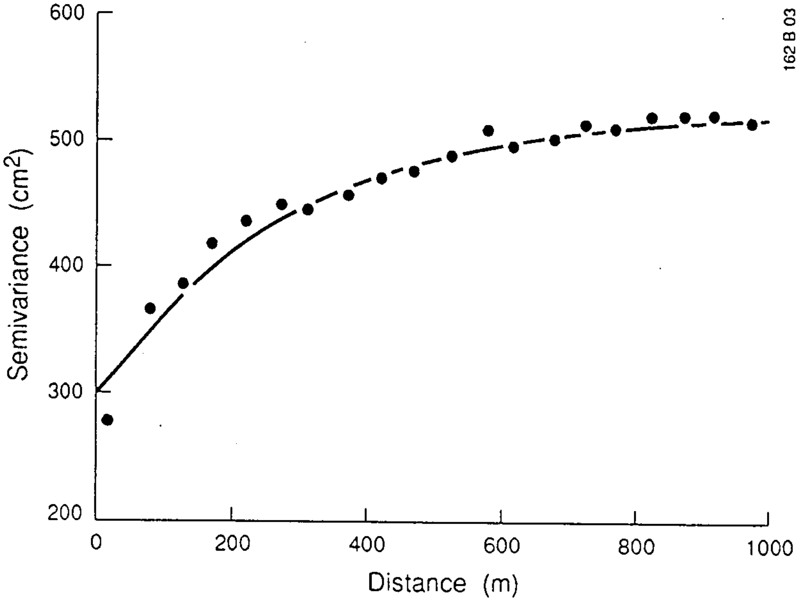


Figure 1 Semivariogram of the depth to the pyritic layer in Pulau Petak

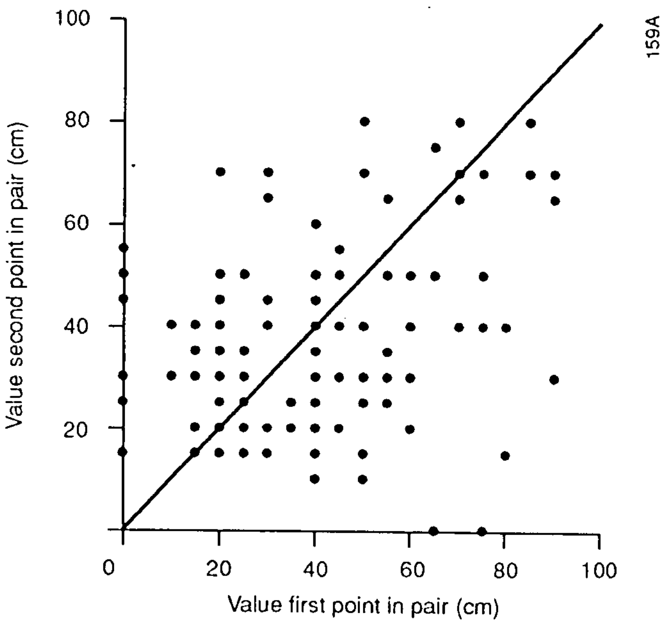


Figure 2 Scatter diagram of the depth to the pyritic layer in Pulau Petak for pairs of observation points with a mutual distance of less than 25 m

Observation density

In Pulau Petak the effect of observation density on mapping acid sulphate soils was investigated (Bregt et al. 1992). In a study area of 410 ha, 820 observation points were made in a regular grid. In addition, 75 test observations were made. To determine an optimum observation density in terms of prediction accuracy and costs, the variable depth to the pyritic layer was used. The number of observations was reduced step-wise by a random procedure in order to obtain lower observation densities. Predictions were made for the test observations using the global mean (the average of all the observations in the test area); the inverse distance; the local mean of the nearest observation points; and kriging based on the semi-variogram. Prediction errors were calculated for all the step-wise reduced observation densities. Results are presented in Figure 3.

No significant differences exist between kriging, local mean and inverse distance. A density of 22 observations per square kilometer was selected as the optimum for the conditions in the Conoco grid area. This density is equivalent to a map scale of 1:30 000.

Survey strategy

Based on the findings in Pulau Petak a combination of free survey and probability sampling seems to be the most appropriate strategy for this area. Following the general outline procedure shown in Table 2, we recommend the following steps:

- Produce physiographic map of the region at a scale of 1:200 000 by interpreting air photos, and hydrological and landscape conditions;
- Sample profiles in the units and determine potential and actual acidity of the soil;
- Select units for further investigation;

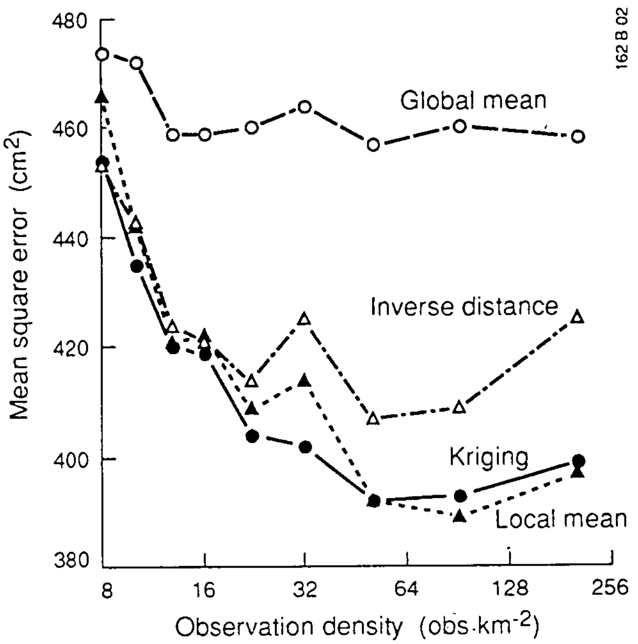


Figure 3 The Mean Square Error of four prediction techniques versus observation density in a 410 ha study area in Pulau Petak

- Carry out grid sampling in the selected units. An observation density of about 20 observations per km^2 is recommended. A grid spacing of 300 m can be used and near some grid point observations need to be made at closer intervals. It is also possible to start with a wider grid e.g. 500 m spacing and add points later. If 10 per cent of Pulau Petak area is of potential interest, about 4000 observations need to be made;
- Use the collected data to calculate:
  - Spatial structure within the units (semivariogram). If the semivariogram shows a pure nugget effect (a flat variogram) then the unit can be considered as spatially homogeneous. From the point of view of the minimum management, no further sub-division of the unit is necessary;
  - Mean and standard deviation of the attributes in the units;
- An interesting option is to make spatial prediction (to map) with e.g. kriging in the units (presenting information in the form of conditional probabilities (Bregt et al. 1992));
- Report results.

References

Alkasuma, Hendro Praseyto, A.K. Bregt and J.A.M. Janssen 1990. Observation density and map scale for survey of acid sulphate soils: A Case Study in Pulau Petak, Southern Kalimantan. AARD & LAWOO, ILRI, Wageningen, The Netherlands

Beckett, P.H.T. 1968. Methods and scale of land resource surveys in relation to precision and cost. In: G.A. Stewart (editor), Land evaluation. Macmillan of Australia, Victoria, pp. 53-63

Bos, J. and M.E.F. van Mensvoort 1984. Spatial variability of potential and actual acid sulphate soils in the Mekong Delta, Vietnam. Dept. of Soil Science and Geology, Agric. Univ., Wageningen

Bregt, A.K., Alkasuma, J.A.M. Janssen, J.S. van de Griendt and W. Andriesse 1990. Optimum observation density for mapping the starting depth of the pyritic layer in Conoco. In: Proceedings Workshop Acid Sulphate Soils in the Humid Tropics. AARD & LAWOO, Bogor, Indonesia

Bregt, A.K., H.J. Gesink and Alkasuma 1992. Mapping the conditional probability of soil variables. Geoderma, vol. 53, no 1/2 pp. 15-29

Bregt, A.K., J.A.M. Janssen, J.S. van de Griendt, W. Andriesse and Alkasuma. Optimum observation density for mapping acid sulphate soils in Conoco, Inonesia: accuracy and costs. Soil Use and Management (in press)

Dent, D.L. 1986. Acid sulphate soils: a baseline for research and development. Publication 39, ILRI, Wageningen, The Netherlands

Dent, D.L. and A. Young 1981. Soil survey and land evaluation. George Allen and Unwin, London

Janssen, J.A.M., W. Andriesse, Hendro Praseyto and A.K. Bregt 1992. Guidelines for soil surveys in acid sulphate soils in the humid tropics; the main problems considered. AARD & LAWOO, ILRI, Wageningen, The Netherlands

McBratney, A.B., R. Webster and T.M. Burgess 1981. The design of optimal sampling schemes for local estimation and mapping of regionalized variables. I. Theory and method. Computers & Geosciences 7: 331-334

McBratney, A.B. and R. Webster 1981. The design of optimal sampling schemes for local estimation and mapping of regionalized variables. II. Program and examples. Computers and Geosciences 7: 335-365

Pettitt, A.N. and A.B. McBratney 1992. Sampling designs for estimating spatial variance components. Applied statistics (in press).

Ripley, B.D. 1981. Spatial statistics. John Wiley & Sons, New York

Russo, D. 1984. Design of an optimal sampling network for estimating the variogram. Soil Science Society of America Journal 48: 708-716

Warrick, A.W. and D.E Myers. 1987. Optimization of sampling locations for variogram calculations. Water Resources Research 23: 496-500

Webster, R. and M.A. Oliver 1990. Statistical methods in soil and land resource survey. Oxford University Press, Oxford

Standard profiles of acid sulphate soils

W.H. Diemont[1], L.J. Pons[2] and D.L. Dent[3]

[1] Institute for Forestry and Nature Research P.O. Box 9201, 6800 HB Arnhem
[2] Department of Soil Science and Geology, Agricultural University Wageningen, P.O. Box 37, 6700 AA Wageningen
[3] School of Environmental Sciences, University of East Anglia Norwich NR 4 7TJ

Abstract

Regional differences in acid sulphate soil profiles are caused by the wide range of environmental conditions, both during pyrite accumulation and during post-marine developments.

Standard profiles are described for the dry tropics and wet tropics. The differences in profile form reflect differences in land suitability.

Introduction

Acid sulphate soils, both potential and actual, exhibit a wide range of profile forms. Regional differences may be caused by differences in climate and associated vegetation types but, in the initial phase of pyrite accumulation, any effects of climate are overridden by different rates of sedimentation, especially between slow rates in estuaries and faster rates along open coasts. Other factors that may contribute to the initial, intertidal profile are the tidal regime, drainage conditions and sediment sources.

Divergence between profiles may be increased by subsequent changes to a fresh-water environment leading to peat accumulation or superposition of fresh-water sediments. These latter developments, which may be triggered by changes in relative sea level, may start at any stage of the saltwater sedimentation sequence, arresting pyrite accumulation. These uncompleted profiles add further variety to the range of acid sulphate soil profiles.

Several local studies have provided results which may be extrapolated to other areas. For example, the seminal study of the chemistry of acid sulphate soils in Thailand by Van Breemen (1976) has provided knowledge of the process of the oxidation of pyrite; the general conditions for the formation of pyrite in tidal areas were deduced from a few case studies in Surinam and Malaysia (Pons et al. 1982). This paper focusses, first, on similarities in the sequence of sedimentation during pyrite accumulation under a range of climate and geomorphic conditions. These enable us to postulate 'Standard Profiles' for the wet tropics and dry tropics. Divergences from the standard profiles in the post-marine stage are then discussed, with emphasis on the role of sea level changes. No attempt is made to discuss local varieties in profile form.

The examples reflect the availability of analytical data. Field tests for pyrite are not entirely reliable and the semi-quantitative test for potential acidity (Konsten et al. 1988) does not give detailed information on pyrite. Pyrite and 'free' iron oxides were determined according the method described by Begheijn et al. (1978). Horizon designations follow Dent (1986) with an additional distinction for reduced horizons

Table 1 Horizons designations for clayey acid sulphate soils

Horizons of unripe saline clay soils under natural conditions	
G	undifferentiated, unripe surface layer
Grp	practically unripe or half ripe, permanently reduced and containing primary pyrite (< 1 per cent pyrite-S)
Grs	as Grp, but accumulating secondary pyrite (> 1 per cent pyrite-S)
Gro	half ripe, partly oxidized with iron pipes and ped coatings
Go	nearly ripe, oxidized with mottles, nodules, pipes and coatings of iron oxide; not potentially acid; no pyrite
Gj	severely acid; yellow mottles of jarosite; practically unripe or half ripe; reserve of pyrite present
Horizons developing after drainage	
Gj	severely acid; black, dark grey or pinkish brown, with pale yellow jarosite mottles; practically unripe or half ripe; reserve of pyrite present
GBj	severely acid; grey with pale yellow jarosite mottles; nearly ripe
Bj	severely acid; strongly mottled grey with reddish iron oxide and yellow jarosite mottles, ripe
Bg	not severely acid; strongly mottled grey with reddish iron oxide mottles and nodules; ripe
Hj	severely acid peat or severely acid, organic-rich soil without jarosite; reserve of pyrite present
A	surface mineral soil, oxidized, not severely acid

with primary pyrite deposited along with the rest of the sediment and those with additional, secondary pyrite (Table 1).

Standard profile characteristics

Most marine sediments contain small amounts of pyrite, less than 1 per cent pyrite S by mass, which may be called 'primary pyrite' (Pons 1963, 1973). These layers are dubbed Grp in Table 1. Pyrite formed in situ, in the sediment, associated particularly with root remains, may be called 'secondary' pyrite. Its accumulation leads to sulphidic horizons with more than 1 per cent pyrite S, dubbed Grs. Gr horizons may be covered by a thin layer of recent sediment, not yet pyritized, which is conveniently labelled a G horizon.

The emergence of tidal vegetation is crucial to the accumulation of pyrite for several reasons. First, the vegetation is a source of metabolizable organic matter for sulphate reduction. It also facilitates the transport of oxygen which, in combination with sulphides, produces sulphur or polysulphides in the Grs horizon. Besides, a well rooted soil has also a lower pH, which improves the solubility of iron oxides, probably accelerating pyrite formation (van Breemen 1976). As much as 90 per cent of 'free iron', which is the source of pyrite-Fe, may be converted (Diemont and Van Wijngaarden, unpublished).

Thus, the depth at which formation of pyrite starts in the tidal zone depends on the level at which the tidal flat is colonized by vegetation. This is determined by climatic conditions and water salinity (Figure 1). In arctic climates, tidal flats become vegetated

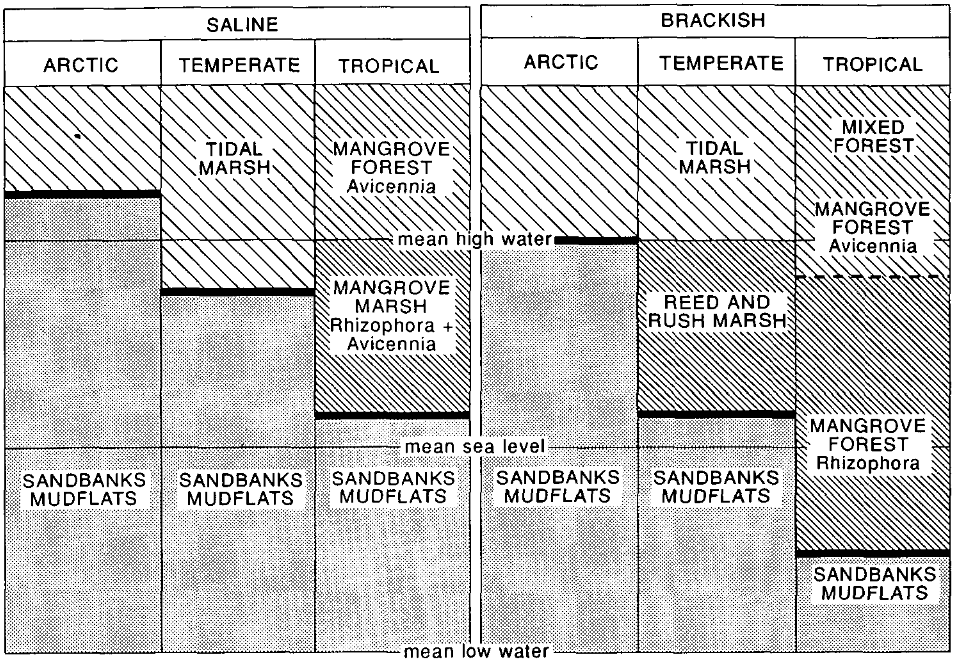


Figure 1 Tidal vegetation in humid climates along arctic, temperate and tropical coasts (after Pons et al. 1982)

only near Mean High Water (MHW), where oxidation prevails over reduction. Also in a desert climate, vegetation is inhibited and, therefore, pyrite does not accumulate. Under temperate brackish water conditions, colonization by a tidal reed marsh (*Phragmites*) starts near Mean Sea Level (MSL), whereas in salt water, colonization by species such as the rush (*Scirpus maritima*) in Northwestern Europe is between MHW and MSL. In this part of the tidal range, reducing conditions in the subsoil encourage the accumulation of pyrite. In the tropics, mangrove vegetation may colonize mudflats even below MSL in brackish water. In the Malaysian-Indonesian region, this zone is dominated by the Nipa palm. Again, colonization in a salt water environment starts higher, with either *Rhizophora* in estuaries or *Avicennia* on open coasts.

Although the presence of vegetation under reduced soil conditions and regular tidal flooding are prerequisites for the accumulation of secondary pyrite in tidal deposits, not all such sediments will build up high concentrations of pyrite. The ultimate concentration will depend upon the rate of sedimentation. High concentrations of secondary pyrite are observed in slowly-sedimenting estuarine systems where sediment accumulation is about 1 or 2 mm yr^{-1} but not in open coast systems with a rapid sedimentation of a cm or more per year (Diemont and van Wijngaarden 1974, van Breemen 1976, Pons et al. 1982). Representative examples of the distribution of pyrite for different geomorphological conditions in tidal soils are similar for both wet tropical conditions in S.E. Asia (Table 2) and dry tropical in West Africa (Table 3). Where the sequence of sedimentation is not yet complete, no differences are observed between the wet and dry tropics.

Table 2 Pyrite S, organic matter and field pH in sulphidic soils and a non sulphidic soil in the wet tropics. A1 is from a saline estuarine system under *Rhizophora* in peninsular Malaysia; A2 a brackish estuary with *Nipa* in Kalimantan; B from an open, accreting coast under *Avicennia-Bruguiera* in peninsular Malaysia. Al profiles are flooded by 90 per cent of all high tides (Diemont unpublished; Diemont and van Wijngaarden 1974)

A1					A2			B				
Horizon	Depth cm	Pyrite S %	OM %	pH	Depth cm	Pyrite S %	OM %	Horizon	Depth cm	Pyrite S %	OM %	pH
Grs	10-30	1.7	22	6.2	20-50	1.5	25	G	0-10	0.0	6	7.4
Grs	60-80	2.1	15	5.9	100-150	1.2	6	Grp	10-15	0.5	5	7.5
Grs	120-140	1.6	5		150-200	1.4	4	Grp	50-65	0.6	5	7.8
Grp	160-180	0.5	3		250-300	0.9	2					

Table 3 Pyrite S in a sulphidic soil (A) and a non-sulphidic soil (B) in a dry tropical climate. A is under *Rhizophora* in the Sine Saloum estuary, Senegal; B under *Avicennia* in an open, accreting coast in Guinea Bissau. Both profiles are flooded by 90 per cent of all high tides

A				B			
Horizon	Depth cm	Pyrite S %	pH	Horizon	Depth cm	Pyrite S %	pH
Grs	0-50	1.4	6.9	G	0-30	0.0	7.6
Grs	50-80	2.2	7.0	Grp	40-70	0.2	7.9
Grs	100-130	2.3	7.1	Grp	150-180	0.6	8.3
Grs	150-180	2.1	6.9	Grp	300-330	0.3	8.1
Grp	200-230	1.3	7.5				

There are certain field relationships between vegetation, the rate of sedimentation and the presence of sulphidic horizons, but the interpretation of soil conditions from the vegetation is not straightforward. With regard to mangroves, observations can be summarized as follows. In estuaries where sediment is accumulating relatively slowly *Rhizophora* species or *Nipa* are predominant in a salt-water and brackish-water environment, respectively (Table 2). Along open coasts with a rapid sedimentation rate, *Avicennia* is the pioneer, succeeded by *Bruguiera* species. There is no confusion with regard to the indicative value of *Nipa* and *Rhizophora*, both species indicate highly pyritic environments. But *Avicennia* species are also found in highly pyritic soils where the original *Rhizophora* species has been cut. Besides, *Avicennia* replaces *Rhizophora* under hypersaline conditions in a dry tropical climate and, at the sub-tropical limits of mangrove vegetation where *Avicennia* occupies both pyritic and less pyritic soils (Dent 1980).

At the final stages of tidal sedimentation, where floods occur only at the highest tides, pyritization ceases and inland species take over. These changes occur at a similar level in different climates (Figure 1) but distinct differences in soil horizons are observed between the wet and dry tropics. Under dry tropical conditions, such as in Senegal, jarosite develops in the topsoil in the so-called 'tannes'. In the example given in Table 4, the jarosite horizon (Gj) is still shallow, but it may reach a depth of 30 to 40 cm (Marius 1985).

Table 4 Completed profile development under estuarine conditions in a wet tropical climate (C1) and a dry tropical climate (C2). C1 is an estuarine backswamp with lobster mounds in peninsular Malaysia; C2 a tanne backswamp in Senegal. Both sites are flooded by less than 10 per cent of all high tides.

C1					C2			
Horizon	Depth cm	Pyrite S %	Free Fe %	pH	Horizon	Depth cm	Pyrite S %	pH
G	0-10	1.0	0.5	5.2	Gj	0-10	0.2	5.5
Gj	30-50	0.5	1.7	2.9	Grs	20-50	2.0	6.7
Go	80-100	0.1	1.2	3.9	Grs	100-180	2.2	7.1
Grs	100-250	1.4	0.8	6.9	Grp	200-230	1.3	7.5
Grp	250-280	0.5	1.7	7.1				

In the wet tropics, even soils which are flooded by only 10 per cent of all high tides are still reduced, but oxidation is triggered by the activity of lobsters. In the lobster mounds, an inverted soil profile develops, where the fresh soil material brought up by the lobsters (G horizon) has still a relatively high pyrite content, whereas pyrite in the longer-exposed subsoil is nearly zero (Table 4).

The divergence between conditions in the wet tropics and the dry tropics is illustrated by the Standard profiles (Figure 2) that have developed by the end of the tidal sedimentation.

Profile characteristics based on changes under fresh-water conditions

The period of time during which salt-water conditions prevail depends on the rate of sedimentation in relation to the magnitude of the tidal range, progression of the coast, and changes in relative sea level. With regard to sea level, different localities have different histories. In Surinam, a slowly rising sea level kept pace with the sedi-

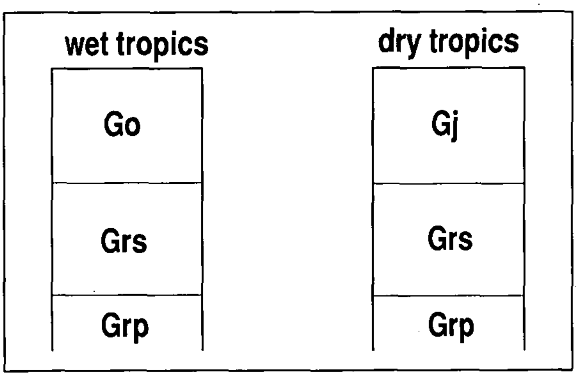


Figure 2 Standard profiles of acid sulphate soils at the completion of tidal sedimentation in the wet tropics and in the dry tropics. In the wet tropics, an acid sulphate horizon (Gj) does not occur but jarosite (and acidity) is present in a transitional stage in lobster mounds (Table 4)

mentation rate, producing sulphidic muds of at least 4 m thick (Brinkman and Pons 1968). The more limited depth of secondary pyrite in S.E. Asia and in West Africa indicates that secondary pyritization in the mangrove belt started close to the present sea level, although there is evidence from the west coast of peninsular Malaysia that mangroves started to grow some 1500 years B.P. at a slightly (0.5 to 1 m) lower sea level (Diemont and Van Wijngaarden in prep.). In The Netherlands and the English Fenlands, subsidence led to sulphidic materials becoming covered by peat and now occurring below present sea level. In contrast, sulphidic materials derived from the bottom sediments of the brackish Littorina Sea, predecessor of the Baltic, have been uplifted (Pons et al. 1982). Slightly elevated marine terraces have been reported in both West Africa (Michel 1973) and South-East Asia (Tjia 1970; Diemont and Supardi in press).

Well developed acid sulphate soils with a Bg Bj Grs Grp profile on terraces in West Africa reflect an estuarine origin, but in S.E. Asia these 'old' ripe acid sulphate soils are found only where there is a marked dry season, such as in Thailand, and in the north of peninsular Malaysia.

Acid sulphate soils on terraces in Indonesia are covered by ombrogenous peat. These peats began to develop on former mangrove deposits and shallow sea floors following uplift of 1 to 2 m some 4000 to 5000 years B.P. (Diemont and Supardi in press). The mineral deposits under the peat were always unripe, but represent a wide range of former saline or brackish environments and include both sulphidic and non-sulphidic materials (Table 5).

Not all coastal areas in Indonesia have been subjected to a relative fall in sea level. In South Kalimantan, near Banjarmasin, eutrophic (clayey) peats occur, which reflect regular flooding by river water. Underneath the peat there is a brown mineral layer which is absent under ombrogenous peats. The brown layer is very low in iron oxides, but is on top of pyritic material (Table 6). The presence of a brown layer poor in

Table 5 Distribution of pyrite below peat in former estuarine mangrove swamp in W. Kalimantan (A), an open accreting coastline in Riau (B), and a former sea floor in W. Kalimantan (C).

	A			B			C		
	Depth m	Pyrite S %	pH	Depth m	Pyrite S %	pH	Depth m	Pyrite S %	pH
Peat	0.0-1.7	–	3.0	0.0-1.3	–	3.0	0.0-0.7	<0.1	–
Mineral	2.0-2.3	2.1	4.2	1.4-1.7	0.9	4.6	7.1-7.3	0.2	6.1
Soil	2.7-3.0	1.5	4.7	2.2-2.5	0.4	3.8	8.2-8.8	0.2	7.1
	3.5-4.0	1.0	6.4	3.6-3.9	0.2	3.9			

Table 6 Distribution of pyrite, iron oxides, and pH in the Barito floodplain in East Kalimantan

Depth	Horizon	Pyrite S %	Fe-oxides %	pH
0.1 – 0.4	Eg	0	0.7	3.6
0.5 – 1.0	2 Gj	2.6	3.6	3.8
2.0 – 2.5	2 Grp	0.8	4.0	5.2
3.0 – 3.5	2 Grp	0.7	3.7	5.5
3.5 – 4.0	2 Grp	0.9	2.7	6.0
5.5 – 6.0	2 Grp	0.8	3.6	6.0

Table 7 Distribution of pyrite in the delta of the Mahakam river in South Kalimantan

Depth, m	Horizon	Pyrite S %	Fe-oxides %	pH
A. Nipa with some fresh water species; lobster mounds present				
0 –0.1	Go	<0.1	2.3	4.9
0.1–0.6	Grp	0.6	1.0	5.2
0.6–1.0	Grp	0.8	0.9	5.7
1.0–1.5	2 Grs	1.3	0.6	5.7
1.5–2.0	2 Grs	2.8	0.6	5.5
2.0–3.0	2 Grs	2.5	0.3	5.7
B. Fresh water forest with some Nipa. Lobster mounds				
0 –0.7	Go	0.9	1.0	5.6
0.7–1.0	2 Grs	1.6	1.2	5.8
1.0–1.5	2 Grs	1.6	0.7	5.4
2.0–2.5	2 Grs	2.8	0.4	5.6

iron is not yet explained in detail. However, iron-depleted sediments alternating with eutrophic peat have also been shown to be present in the inner (fresh-water) floodplain of the Mahakam in East Kalimantan over a thickness of some 4 m (Diemont and Pons in press). It seems likely that depletion of iron in mineral layers is a gleying phenomenon (Eg horizon) typical of fresh-water flood plains.

In the delta of Mahakam river, there is no peat but most of the delta is, at present, under fresh water swamp forest. The presence of lobster mounds and some Nipa palms indicate a previous brackish water environment and this is reflected by the soil profile. The topsoil to a depth of 0.7 m has iron oxide mottles, whereas there is a lot of pyrite in the reduced subsoil (Table 7B). The low amount of primary pyrite in the topsoil indicates that the surface sediments originate from marine sources but, probably, deposited under fresh water conditions which do not favour the formation of secondary pyrite (Diemont and Pons in press).

The contrast between the wet tropics and areas with a strong dry season is, again, shown by the above examples of soils developed on marine terraces. Where there is a pronounced dry season, sulphidic materials have developed into ripe acid sulphate soils with pronounced jarosite horizons, as seen in Senegal, Thailand and the northern part of peninsular Malaysia. Under the very wet conditions of Sumatra, Kalimantan and Sarawak, terraces have been covered by ombrogenous peat that has arrested further soil development (Figure 3).

Areas not subject to changes in relative sea level have developed other kinds of soil profiles, of the general form illustrated in Figure 4.

Conclusions

Regional differences in profile form can be attributed to climatic differences. Most striking is the absence of distinct jarositic horizons in the wet tropics. In the perennially wet tropics, the development of acid sulphate soils from sulphidic materials is arrested by the development of a cover of ombrogenous peat. Earlier reports from Indonesia

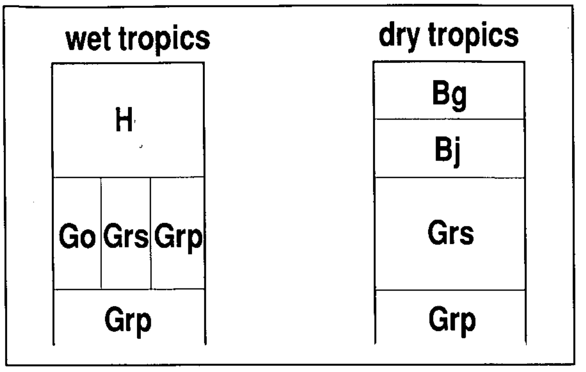


Figure 3 Contrasting standard profile soils developed on marine terraces in the wet tropics and in the dry tropics

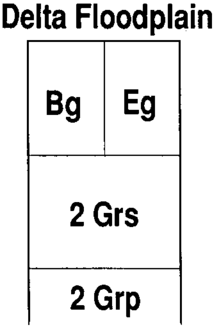


Figure 4 Standard profile under fresh water conditions succeeding salt or brackish tidal conditions

assumed that the horizons below the peat were, typically, rich in pyrite. Our examples show that this is not always the case, but for several different reasons.

Of course, acid sulphate soils with jarosite may still develop with enforced drainage but the formation of iron II sulphate upon partial oxidation and the common absence of jarosite reported from Vietnam (Van Mensvoort and Le Quang Tri 1988) may be far more widespread in the wet tropics.

Without further systematic local surveys, some of these conclusions must remain tentative. Even so, some practical conclusions may be drawn:

- Modelling studies of the fate of acidity during oxidation (for example Bronswijk and Groenenberg 1993) should take account of the local environment;
- Differences in soil profile mark differences in land suitability. There is still a great need to study the successes and failures of reclamation of acid sulphate soils in relation to their specific environmental conditions. In this respect, circumstantial evidence suggests that reclamation of sulphidic soils where the sulphidic layer is at the surface should not be attempted, but that is feasible with other profile forms, particularly where tidal sedimentation has been completed (Dent 1991, Ting et al. 1993);

- The variability of profile form may be a criterion for selecting areas for habitat conservation, as differences in the profile may well reflect differences in biodiversity.

References

Begheijn, L.T., N. van Breemen and E.J. Velthorst 1978. Analysis of sulphur compounds in acid sulphate soils and other recent marine soils. Soil Science and Plant Analysis IX (9). 203-211

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

Brinkman, R. and L.J. Pons 1968. A pedo-geomorphological classification and map of the Holocene sediments in the coastal plain of the three Guyanas. Soil Survey Papers no. 4, Netherlands Soil Survey Institute, Wageningen

Bronswijk, J.J.B. and J.E. Groenenberg 1993. A simulation model for acid sulphate soils, I Basic Principles. In: D.L. Dent and M.E.F. van Mensvoort (editors): Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils. ILRI Publ. 53 International Institute for Land Reclamation and Improvement, Wageningen

Dent, D.L. 1980. Acid sulphate soils: morphology and prediction. J. Soil Science 31, 1, 87-99

Dent, D.L. 1986. Acid sulphate soils: a baseline for research and development. Publ. 39, International Institute for Land Reclamation and Improvement, Wageningen

Dent, D.L. 1991. Reclamation of acid sulphate soils. In: R. Lal and R.B.Stewart (editors). Soil Restoration. Advances in Soil Science 17, 79-122. Springer Verlag, New York

Diemont, W.H. and L.J. Pons 1986. Conservation et gestion de mangroves de Guinee-Bissau. RIN contributions to research on management of natural resources. 1986-4. Research Institute for Nature Management, Arnhem

Diemont, W.H. and L.J. Pons (in press). A preliminary note on peat formation and gleying in the Mahakam inland floodplain, East Kalimantan, Indonesia. Proceedings international symposium on tropical peat land, 6-10 May 1991, Kuching, Sarawak, Malaysia

Diemont, W.H. and Supardi. Forest in Peat in Indonesia on former sea beds. Proceedings IPS symposium on tropical peat and peatlands for development, Yogyakarta (in press)

Diemont, W.H. and W. van Wijngaarden 1974. Sedimentation patterns, soils, mangrove vegetation and land use in the tidal areas of W. Malaysia. In: G. Walsh, S.E. Snadeker, and H.J. Teas (editors): International symposium on biology and management of mangroves. 513-518. East-West Centre, Honolulu

Dost, H. (editor) 1988. Selected papers of the Dakar symposium on acid sulphate soils. Publication 44, International Institute for Land Reclamation and Improvement, Wageningen

Konsten, C.J.M., W. Andriesse and R. Brinkman 1988. A field laboratory method to determine total potential and actual acidity in acid sulphate soils. In: Dost (1988) 106-134

Marius, C. 1985. Mangroves de Sénégal et de la Gambie. ORSTOM Traveaux et Documents 193, Paris

Van Mensvoort, M.E.F. and Le Quang Tri 1988. Morphology and genesis of actual acid sulphate soils without jarosite in the Ha Tien Plain, Mekong Delta, Viet Nam. In: Dost (1988) 11-23

Michel, P. 1973. Les bassins des fleuves Sénégal et Gambie. Etude geomorphologique. Mémoires ORSTOM 63. 752 pp

Pons, L.J. 1963. Pyrites as a factor controlling chemical 'ripening' and formation of cat-clay with special reference to the coastal plain of Surinam. Proceedings Congr. Agr. Res. Guyanas, Paramaribo 1963. Bull. 82; 141-162

Pons, L.J. 1973. Outline of the genesis, characteristics, classification and improvement of acid sulphate soils. In: H. Dost (editor): Acid sulphate soils: proceedings of the International Symposium, 13-20 August 1972, Wageningen. International Institute for Land Reclamation and Improvement. Publ. 18, Vol. 1, 3-22, Wageningen

Pons, L.J., N. van Breemen and P.M. Driessen 1982. Physiography of coastal sediments and development of potential soil acidity. In: J.A. Kittrick, D.S. Fanning and L.R. Hossner (editors). Acid sulphate weathering. Special Publication 10, 1-18, Soil Sci. Soc. Am., Madison, Wsc.

Ting, C.C., R.Bt. Saari, W.H. Diemont and A Bin Yusoff 1993. The development of an acid sulphate area in former mangroves in Merbok, Kedah, Malaysia. In: D.L. Dent and M.E.F. van Mensvoort (editors): Selected papers of the Ho Chi Minh City symposium on acid sulphate soils. ILRI Publ. 53, International Institute for Land Reclamation and Improvement, Wageningen

Tjia, H.D. 1970. Quaternary shorelines of the Sunda Land Southeast Asia. Geologie en Mijnbouw. 49(2) 135-144

Revisions of Soil Taxonomy for acid sulphate soils

D.S. Fanning[1] and J.E. Witty[2]

[1] Dep. of Agronomy, University of Maryland, College Park (UMCP), MD 20742 U.S.A
[2] USDA Soil Conservation Service, National Soil Survey Center, Federal building 100, Centennial Mall North, Lincoln, NE 68508-3866 U.S.A

Abstract

Proposed amendments to 'Soil Taxonomy' for acid sulphate soils for inclusion into a new 'Keys to Soil Taxonomy' include:

- A new definition of the sulfuric horizon, defining pH as $\leq$ 3.5 (1:1 by weight in water), not requiring the presence of jarosite but accepting other evidence that the low pH is from oxidation of sulfidic material and adding a 15 cm or more thickness requirement;
- A new definition of sulfidic materials, based on a pH drop on incubation (of at least 0.5 units) to a pH of < 4.0 within 8 weeks.

If there is a sulfuric horizon within 1.5 m of the mineral soil surface, the soil will be classified in Inceptisols regardless of the physical ripeness or other characteristics of the underlying materials.

A subgroup of Salorthidic Sulfaquepts is provided for soils with both a salic horizon within 75 cm of the surface and a sulfuric horizon within 50 cm of the surface. A subgroup of Hydraquentic Sulfaquepts will be recognized if all subhorizons of a Sulfaquept between depths of 20 and 50 cm have an n-value > 0.7.

Sulfic subgroups of Tropaquepts and Haplaquepts are redefined based on the presence, within a depth of 1.5 m, of either a sulfuric horizon, or like a sulfuric horizon except that its pH is between 3.5 and 4.0, or sulfidic materials (for these Aquepts that don't qualify for Sulfaquepts). A similarly defined subgroup of Sulfic Cryaquepts is provided for Cryaquepts.

A great group of Sulfochrepts is provided for mineral soils with a sulfuric horizon within 50 cm of their surface that don't have an aquic moisture regime and that are not artificially drained, such as certain soils in mine spoil.

Mineral soils with sulfidic materials at depths of less than 50 cm but no sulfuric horizon are expected to go into Sulfaquents. Typic Sulfaquents have an n-value > 0.7 and at least 8 percent clay in all subhorizons between a depth of 20 and 50 cm. Other Sulfaquents without a histic epipedon that would cause placement into a Histic subgroup regardless of n-values) and lower n-values will be recognized as Haplic Sulfaquents. Criteria for Sulfic subgroups of Fluvaquents and Haplaquents are also revised.

All organic acid sulphate soils will not be forced into Hemists as previously. Sulf great groups will be recognized in Saprists as well.

[1] Joint contribution from Maryland Agric. Expt. Sta (MAES) and USDA, SCS. Contribution No. 8478 and Sci. Art. No. A6307 of MAES, UMCP, Dept. of Agronomy

Introduction

It has been recognized for many years that revisions of Soil Taxonomy for acid sulphate soils are needed (inter alia van Breemen 1982, Pons 1988, Pons et al. 1989, Janssen et al. 1990, Fanning and Witty 1991). Following discussions during the 4th international symposium on acid sulphate soils held in Vietnam, the following revisions have been prepared for inclusion in Keys to Soil Taxonomy, to supercede the present version (Soil Survey Staff 1990). Copies of the proposals are available from D.S. Fanning.

Definition of the sulfuric horizon

The present definition is:

> The sulfuric (L. *sulfur*) horizon is composed either of mineral or organic soil material that has both a pH less than 3.5 (1:1 in water) and jarosite mottles (the color of fresh straw that has a hue of 2.5Y or yellower and chroma of 6 or more).
>
> A sulfuric horizon forms as a result of artificial drainage and oxidation of sulfide-rich mineral or organic materials. Such a horizon is highly toxic to plants and virtually free of living roots.

We suggest that this be changed to:

> The sulfuric (L. *sulfur*) horizon is 15 cm or more thick and is composed of either mineral or organic material that has a pH $\leq$ 3.5 (1:1 by weight in water, or in a minimum of water to permit measurement) under field conditions and evidence that the low pH is caused by sulfuric acid. The evidence is one or more of the following: a) jarosite mottles, b) immediately subjacent sulfidic materials, or c) 0.05 percent or more watersoluble sulphate.

A sulfuric horizon forms as a result of drainage, most commonly artificial, and oxidation of sulfide-rich mineral or organic materials. Such a horizon is highly toxic to most plants. It may also form in places where sulfidic materials have been exposed as a result of surface mining, road construction, dredging or other earth-moving operations.

These changes are, essentially, those suggested by Van Breemen (1982). The reasons for the changes are many. First, the range of color of jarosite previously stipulated was too restrictive. Jarosite with a chroma of 3 to 4 and values as low as 5 has been documented in what we consider to be Sulfaquepts dredged from Baltimore Harbor (Fanning and Fanning 1989, Fanning et al. 1992). We prefer to not set color criteria for jarosite in the sulfuric horizon definition, although the color should be discussed in accompanying text of the complete version of Soil Taxonomy.

Several authors have reported acid sulphate soils without jarosite (inter alia Van Mensvoort and Le Quang Tri 1988, Sutrisno et al. 1990). Thus other evidences that the low pH comes from active sulfuricization have been sought. Van Breemen (1982) proposed the soluble sulphate criterion; Fanning and Witty (1986) proposed the presence of subjacent sulfidic materials. Sutrisno et al. (1990) argue that, sometimes, the original layer of sulfidic materials that gave rise to the suspected sulfuric horizon was so thin that it has entirely oxidized away, or that acidity may have moved laterally from its source. These authors suggest that the horizon 'be underlain by sulfidic material or physiographically and hydrologically related to nearby areas with sulfidic material'. The latter suggestion cannot be accepted because it violates the principle that the basis for the classification of a soil should be found within the soil itself.

The upper pH limit of the sulfuric horizon has been difficult to resolve. The present proposal is only a slight change from < 3.5 to ≤ 3.5, measured in water, 1:1 by weight. The value of 3.5 is retained because we feel that this limit distinguishes horizons in which pyrite is still present and actively oxidizing, whereas a higher value would permit the inclusion of materials as sulfuric horizons in which pyrite is no longer present and sulfuric acid may only be produced by processes, such as the hydrolysis of jarosite, which are thought to be slow processes and not as severe as the active oxidation of pyrite.

Soil Taxonomy recognizes acid sulphate soils with pH (1:1 in H_2O) between 3.5 and 4 in the upper 50 cm and that, presumably, do not have pyrite remaining in this depth range, as Sulfic subgroups of other Aquepts (e.g. Sulfic Tropaquepts). By leaving the upper pH limit of the sulfuric horizon at 3.5, the soils with sulfuric horizons within 50 cm of the surface, Sulfaquepts and Sulfochrepts, may more closely approximate what Dent (1986) refers to as raw acid sulphate soils.

The proposed minimum thickness of 15 cm is arbitrary. Pons et al. (1989) have suggested 20 cm. For plants, 15 cm of a pH $\leq$ 3.5 would be expected to be very restrictive. The previous sulfuric horizon definition had no thickness requirement. Most knowledgeable soil scientists feel there should be one. Perhaps, lateral continuity of the horizon, or an occurrence in half or more of the lateral extent of a pedon, should be stipulated but new work is needed to develop this criterion.

Pons (1988) argued that there should also be a physical ripeness requirement for the sulfuric horizon, and suggested that it be ripe (n-value $\leq$ 0.7). If the horizon was not ripe, but had the other characteristics of a sulfuric horizon, he would recognize the zone in a soil profile with these characteristics as a sulfuric material. However, we feel that having both sulfuric horizons and sulfuric materials would overly complicate Soil Taxonomy.

Sulfuric horizons will vary considerably in their physical ripeness if only the sulfuric horizon (and no sulfuric materials, as suggested by Pons) are recognized. This variation will be used to recognize those soils with a sulfuric horizon within 50 cm of the soil surface and high n-values in the zone from 20 to 50 cm as Hydraquentic Sulfaquepts (see later section on subgroups). However, in our opinion, the formation of a sulfuric horizon is a dramatic step in soil genesis, a 'big bang' (Fanning 1991), and this should carry a soil into Inceptisols even if the soil is not fully ripe to a depth of 50 cm.

Definition of sulfidic materials

The present definition of sulfidic materials (Soil Survey Staff 1990, p. 36) is:

> Sulfidic materials are waterlogged mineral or organic soil materials that contain 0.75 percent or more S (dry weight), mostly in the form of sulfides, and that have less than three times as much carbonate ($CaCO_3$ equivalent) as S.

We propose instead:

> Sulfidic materials contain oxidizable S compounds, and are mineral or organic soil materials with a pH of more than 3.5 that, if incubated as a 1 cm thick layer under moist (field capacity), aerobic conditions at room temperature, show a drop in pH of at least 0.5 units to a pH of less than 4.0 (1:1 by weight in water, or in a minimum of water as required to read the pH with a pH meter) within 8 weeks.

Other revised information on how sulfidic materials accumulate, occur, etc. to appear with the definition in Keys to Soil Taxonomy, is given by Fanning and Witty (1989).

The revised definition is preferred because the present definition requires sulfidic materials to be waterlogged, and the ratio of S to $CaCO_3$ is not easy to obtain and may not always be a good indicator of the ability of a material to form a sulfuric horizon. Dense (low porosity) upland, sulfide-bearing materials that give rise to the formation of sulfuric horizons upon exposure to oxidizing conditions often do not have a waterlogged appearance. Incubating, to see if the pH drops sufficiently, is a more reliable way of knowing if significant acidity will form upon exposure to aerobic conditions, and this can be done under field conditions, so that laboratory analyses for S and $CaCO_3$ are not required. Dent (1986) indicates that 'the best criterion of potential acidity is a fall of pH to less than 4 during three months of moist incubation'.

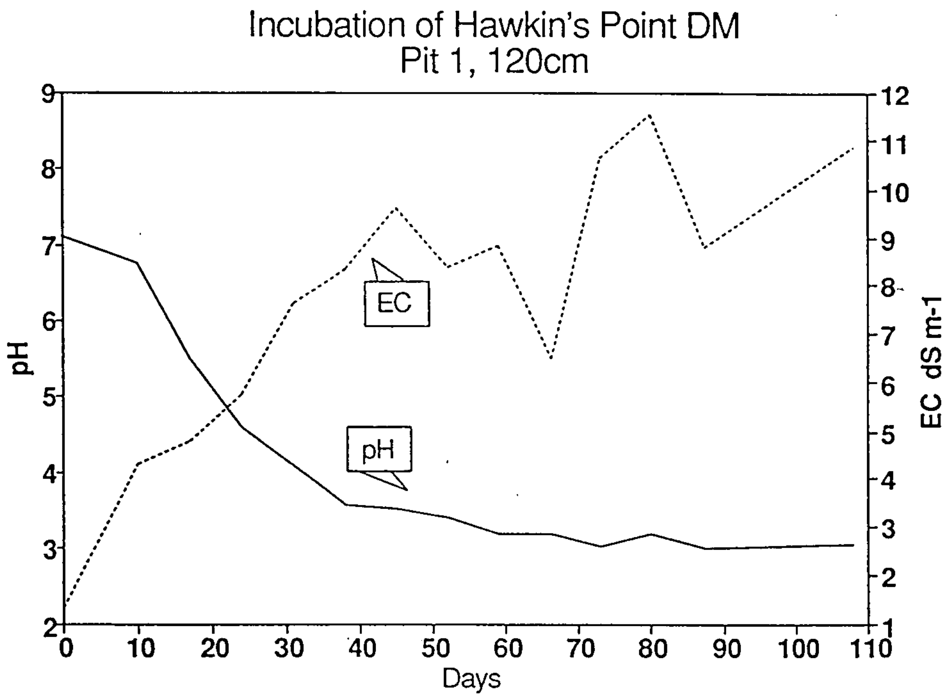


Figure 1 pH and electrical conductivity for 1:2 (dry soil:water) by weight dilution of a suspected sulfidic material (Hawkins Pt., Baltimore Harbor, MD, dredged materials) as a function of incubation time. Incubating material was wetted daily except weekends, and kept in a glass dish on a laboratory bench. After Fanning (1992).

This also agrees with the pH of < 4.0 required for Sulfic subgroups of Aquepts and makes it easier for a material to qualify as sulfidic than requiring a pH of 3.5 or less as will be required for a sulfuric horizon.

The length of the incubation proposed by different workers varies. It seems reasonable to continue the incubation until the pH either drops to < 4.0, if before 8 weeks, or until it levels out to a nearly constant value, if still dropping significantly after 8 weeks (Figure 1).

It would be good to have more rapid methods to identify sulfidic materials. Konsten and Sarwani (1990) found good correlation between pyrite content and potential acidity estimated by titration of soil samples with NaOH in 1 mol/l NaCl after oxidation with H_2O_2 for at least two days. Also H_2O_2 field tests, using such parameters as the time lapse between the addition of the H_2O_2 and the start of the reaction, and the intensity of the reaction, have been found to have some value in identifying sulfidic materials, but were not totally reliable (Dent 1986, Janssen et al. 1990). For materials undergoing active sulphate reduction, for example tidal marsh, the whiff-test based on the intensity of H_2S smell emananting from a soil (Darmody et al. 1977) may be a useful field test.

Placement into soil orders

Entisols versus Inceptisols

At present, soils with sulfuric horizons near the surface are placed in Entisols if there are sulfidic materials within 50 cm, or if the n-value is > 0.7 in all subhorizons between 20 and 50 cm. We propose this be changed to bring all mineral soils with sulfuric horizons within 1.5 m of the mineral soil surface into Inceptisols, as already argued. Earlier versions of Soil Taxonomy, such as 'Selected Chapters' in 1970, placed soils with sulfuric horizons within 50 cm of the surface into Inceptisols regardless of (the presence of) sulfidic materials or the n-value in this depth range. We prefer to return to this approach. If a soil has ripened enough to have a sulfuric horizon, it should be an Inceptisol.

The soil described in Fanning and Fanning (1989 p. 306-311, and Plate 2D) is a case in point. It had a 34 cm thick sulfuric horizon (with pH from 3.3 to 3.5), underlain by sulfidic materials, and was half-ripe (n-value of 1.01 at 8-18 cm; and 1.62 at 34-50 cm). It was possible to drive over such soils with a pick-up truck in summer months and to plant crops using light equipment, such as a hand operated rototiller. The sulfuric horizon caused extreme chemical problems for crops which would not be recognized by strict application of present Soil Taxonomy classifying the soil as a Sulfaquent. By our new proposals, it would be a Sulfaquept but placed in a Hydraquentic subgroup to show its relatively low bearing capacity.

Soils with salic horizons and sulfuric horizons

In regions with long dry seasons, as in Senegal and Guinea Bissau, there are mineral soils that, at least for parts of some years, have both salic and sulfuric horizons close to their surfaces (Fanning 1992). If salic horizons are recognized, present Soil Taxonomy would place such soils into Aridisols and no taxonomic recognition would be given to their acid sulphate character. We suggest that the key to soil orders (Soil Survey

Staff 1990, section F.1), that gives the criteria for Aridisols with salic horizons be changed to read:
1. Do **not** have an argillic, a natric, or a sulfuric horizon **but**....etc.
This would have the effect of keeping soils with both sulfuric horizons and salic horizons out of Aridisols. More work is needed to test the existence and extent of such soils. One should keep in mind that a new definition of the salic horizon and of Aridisols (and of suborders e.g. Salids) has been proposed by the International Committee on Aridisols. The proposed definition of the salic horizon is:

A salic horizon meets the following requirements:
1. Is 15 cm or more thick, and
2. Has an EC equal to or greater than 30 dS/m in a 1:1 soil:water extract, and
3. Product of EC and thickness is 900 or more, and
4. Conditions 1,2 and 3 prevail for 90 consecutive days or more, in 7 out of 10 years.

The proposed new definition of Aridisols requires an aridic soil moisture regime and this might exclude soils that are active acid sulphate soils in coastal regions from entering Aridisols even if they had a salic horizon.

Addition of Sulfochrepts

A great group of Sulfochrepts is proposed at the top of the key for great groups of Ochrepts (Soil Survey Staff 1990 p. 251) for those Ochrepts with a sulfuric horizon within 50 cm of the soil surface. This would provide a place for soils, such as in sulfide-bearing spoil from surface mining, that have a sulfuric horizon at a shallow depth without an aquic moisture regime or artificial drainage, as described by Witty et al. (1986).

Subgroups

Sulfaquepts
At present, all Sulfaquepts are considered Typic. Fanning and Witty (1989) proposed that Salorthidic Sulfaquepts be recognized for those Sulfaquepts with a salic horizon within 75 cm of the soil surface.

A Hydraquentic subgroup is now proposed for those Sulfaquepts that meet the n-value requirements of Hydraquents (n-value > 0.7 in all subhorizons between a depth of 20 and 50 cm) as suggested above. This should allay the objection of Pons (1988) to soils entering Inceptisols that are not physically ripe. This gives such soils special recognition within Inceptisols, showing them to be transitional to Hydraquents.

Other Sulfaquepts that do not meet the criteria for either the Salorthidic or the Hydraquentic subgroups would be Typic. Pons et al. (1989) proposed a variety of other subgroups of Sulfaquepts based on the depth at which the sulfidic material underlies the sulfuric horizon, the presence of various epipedons other than ochric, and various combinations of these characteristics. These subgroups need further consideration.

Sulfic subgroups of other Aquepts

The present definitions of the Sulfic subgroups of Tropaquepts and Haplaquepts (Soil Survey Staff 1990 p. 249 and 245, respectively) require one or both of the following:

1. Jarosite mottles and a pH between 3.5 and 4.0 (1:1 water, air-dried slowly in shade) in some subhorizon within 50 cm of the soil surface; or
2. Jarosite mottles and a pH of less than 4.0 (1:1 water, air-dried slowly in shade) in some subhorizon between 50 and 150 cm.

We propose changing to:

Tropaquepts (or Haplaquepts) with one or more of the following within a depth of 150 cm:

1. A sulfuric horizon; or
2. A subhorizon 15 cm or more thick with the characteristics of a sulfuric horizon except for a pH between 3.5 and 4.0; or
3. Sulfidic materials.

Similar criteria would be applied to define a subgroup of Sulfic Cryaquepts (not presently recognized). The need for a subgroup of Sulfic Cryaquepts, and some examples of these soils in Sweden have been described by Öborn (1989). Pons et al. (1989) have also proposed that Humaquepts be permitted to occur in tropical regions and that a parallel set of subgroups for acid sulphate conditions be recognized in the Humaquepts, as they suggest for Tropaquepts. At present, soils that would be Humaquepts, except for an isomesic or warmer iso- temperature regime are forced into Tropaquepts. These matters need further consideration. Trop great groups have been eliminated in other parts of Soil Taxonomy (the temperature regime basis for this separation can be indicated at the family level of classification). Eventually Tropaquepts may be eliminated also.

Sulfaquents

At present, only Haplic (that have sulfidic materials at a depth of 30 cm or more and an n-value of less than 1) and Typic (other) Sulfaquents are recognized. We propose Histic (histic epipedon), Haplic (sulfidic materials at a depth of 30 cm or more and an n-value less than 1 in some subhorizon between 20 and 50 cm, and no histic epipedon), and Typic (others) subgroups (Fanning and Witty 1989). Typic Sulfaquents will share the n-value characteristics of Hydraquents.

Other matters

Organic acid sulphate soils have so far received little consideration. The high buffering power of organic soil materials may prevent a low enough pH from being obtained on incubation, according to the proposed new definition of sulfidic materials, for some materials that may qualify under the old definition to qualify under the new. This is another argument for having the pH to be reached on incubation for the identification of sulfidic materials to be < 4.0, as now proposed, rather than ≤ 3.5. More testing of the incubation method for identifying sulfidic materials employing organic soil materials would be worthwhile.

In discussions during this symposium, Rosmarkam, from Indonesia, and Fitzpatrick, from Australia, indicated a need for Sulf great groups of Saprists. There have been previous requests in the United States. At present, all Histosols with sulfuric horizons within 50 cm of the soil surface (Sulfohemists) or with sulfidic materials within 100 cm of the surface (Sulfihemists) are forced into Hemists regardless of the kinds of organic materials. We now propose to eliminate statement 2 in the definition of Hemists (Soil Survey Staff 1990 p. 225) and to set up Sulfo and Sulfi great groups of Saprists parallel to those in Hemists.

We also now propose to change the criteria for Sulfic subgroups of Fluvaquents and Haplaquents, which are presently defined based on the occurrence of sulfidic materials within a depth of 1 m, to include soils with either sulfidic materials, or with a subhorizon 15 cm or more thick with characteristics of a sulfuric horizon except for having a pH between 3,5 and 4.0, within a depth of 1 m.

More information is needed on the colours of both mineral and organic acid sulphate soils (Fanning et al. 1992). Problems such as the unstable-colour brown layer that is relatively high in organic matter and low in iron, as found in Indonesia (Prasetyo et al. 1991), need more investigation.

References

Breemen, N. van 1982. Genesis, morphology, and classification of acid sulphate soils in coastal plains. In: J.A. Kittrick, D.S. Fanning and L.R. Hossner (editors): Acid Sulphate Weathering. Soil Sci. Soc. Am. Spec. Publication No. 10, Soil Sci. Soc. Am., Madison

Darmody, R.G., D.S. Fanning, W.J. Drummond Jr. and J.E. Foss 1977. Determination of total sulfur in tidal marsh soils by X-ray spectroscopy. Soil Sci. Soc. Am. J. 41: 761-765

Dent, D.L. 1986. Acid sulphate soils: A baseline for research and development. International Institute for Land Reclamation and Improvement Publication No. 39, Wageningen

Fanning, D.S. 1991. Big bang theory of soil genesis. Agronomy Abstracts for American Society of Agronomy meetings, p. 311, Denver

Fanning, D.S. 1992. Salinity problems in acid sulphate coastal soils. In: H. Leith and A. Al Massoum (editors): Toward rational use of high salinity tolerant plants. Vol. 1. TVS Vol. Kluwer Academic Publishing, Dordrecht. Submitted for publication

Fanning, D.S. and M.C.B. Fanning 1989. Soil: morphology, genesis, and classification. John Wiley & Sons, New York

Fanning, D.S., M.C. Rabenhorst and J.M. Bigham 1992. Colors of acid sulphate soils. In: J.M. Bigham and E.J. Ciolkosz (editors): Soil color. Soil Sci.Soc. Am. Spec. Publication No. , Soil Sci. Soc. Am., Madison. Accepted for publication

Fanning, D.S. and J.E. Witty 1989. Proposed changes in the classification of acid sulphate soils in 'Soil Taxonomy'. Acid Sulphate Soils Newsletter No. 2 (Nov. 1989), 10-13

Janssen, J.A.M., H. Prasetyo and Alkasuma 1990. Acid sulphate soils: field characteristics and mapping. Papers workshop on acid sulphate soils in the humid tropics, 51-61. AARD & LAWOO, Bogor

Konsten, C.J.M. and M. Sarwani 1990. Actual and potential acidity and related chemical characteristics of acid sulphate soils in Pulau Petak, Kalimantan. Papers workshop on acid sulphate soils in the humid tropics, 30-50. AARD & LAWOO, Bogor

Mensvoort, M.E.F. van and Le Quang Tri 1988. Morphology and genesis of actual acid sulphate soils without jarosite in Ha Tien Plain, Mekong Delta, Vietnam. In: H. Dost (editor): Selected papers of the Dakar symposium on acid sulphate soils, 11-15. International Institute for Land Reclamation and Improvement Publication No. 44, Wageningen

Öborn, I. 1989. Properties and classification of some acid sulphate soils in Sweden. Geoderma 45, 197-219

Pons, L.J. 1988. Should acid sulphate soils be classified among the Inceptisols or the Entisols? In: H. Dost (editor): Selected papers of the Dakar symposium on acid sulphate soils, 90-96. International Institute for Land Reclamation and Improvement Publication No. 44, Wageningen

Pons, L.J., M.E.F. van Mensvoort and Le Quang Tri 1989. A proposal for the classification of mineral Vietnamese acid sulphate soils according to Soil Taxonomy. Acid Sulphate Soils Newsletter No. 2 (Nov. 1989), 6-10

Prasetyo, H.J.M. Janssen and Alkasuma 1990. Landscape and soil genesis in Pulau Petak. Papers workshop on acid sulphate soils in the humid tropics, 18-29. AARD & LAWOO, Bogor

Soil Survey Staff 1990. Keys to Soil Taxonomy. Fourth edition, SMSS, Department of Soil and Crop Environmental Sciences. Virginia Tech, Blacksburg

Sutrisno, J.A.M. Janssen, Alkasuma 1990. Classification of acid sulphate soils: a proposal for the improvement of the Soil Taxonomy system. Papers workshop on acid sulphate soils in the humid tropics, 71-80. AARD & LAWOO, Bogor

Witty, J.E., D.S. Fanning and D.P. Wagner 1986. Status of classification of acid sulphate soils in the U.S. Paper presented at the 3rd International Symposium on Acid Sulphate Soils, Dakar, Senegal

Origin and properties of inland and tidal saline acid sulphate soils in South Australia

R. W. Fitzpatrick[1], W. H. Hudnall[2], P. G. Self[1] and R. Naidu[1]

[1] CSIRO, Division of Soils, Private Bag No. 2, Glen Osmond South Australia, 5064.
[2] Agronomy Department, Louisiana Agricultural Experiment Station, LSU Agricultural Centre, Baton Rouge, LA, 70803, USA.

Abstract

This paper provides a general overview of the transformation of two inland Alfisols to saline sulfidic marsh soils due to rising saline ground waters in a Mediterranean climate in South Australia. A summary of field and laboratory observations relating to the formation of two inland saline sulfidic marsh soils is presented and compared in terms of probable genesis and soil processes with a natural tidal acid sulphate soil. The unaltered pedons represent (i) a Mollic Natraqualf (with recently acquired sulfidic and sodic materials) derived from micaceous schists containing pyrite-rich bands in the Mt Lofty Ranges, (ii) a Petrocalcic Palexeralf (with recently acquired sulfidic and sodic/salic materials) derived from Quaternary strandlines on a plain 55 km inland from the coast of southeast South Australia (Mallee region), and (iii) a Terric Sulfihemist in a coastal mangrove tidal swamp of the St. Vincent Gulf. Based on the information gained in the study of these unique inland and coastal marsh soils, we have developed proposals for the modification of Soil Taxonomy to accept these soils for which no taxa currently exist.

The origin of the primary forms of sulphur is considered to be vastly different for each pedon. In the Mollic Natraqualf (with sulfidic material), the presence of the sulphate is caused by locally rising ground water in a tree-cleared landscape. The sulphate dissolved in the ground water originates primarily from the weathering of iron sulphide bands found in complex fractured rock systems. In both upland and bottom land topographic positions, the dissolved sulphate seeping to the soil surface is transformed to fine grained pyrite framboids by sulphur-reducing bacteria in the presence of organic matter to form an Alfic Sodic Sulfaquent (proposed new subgroup). In the Petrocalcic Palexeralf (with sulfidic materials and salic horizons) a rising regional ground water brings ancient wind blown salt stored in the landscape to the surface horizons in only bottom land topographic positions to form a Petrocalcic Salic Sulfaquent. In the coastal swamp, tidal flushing is the main mechanism of sulphur accumulation. The presence of sapric material indicates that this pedon should be classified as a Terric Sulfisaprist (proposed new subgroup).

Introduction

Several property holders in the central and southern Mt Lofty Ranges areas and the lower Murray Mallee region of South Australia have expressed concern about a rapid increase in waterlogging and salinity, especially over the past 10 years, and believe it is now becoming a serious threat to the productivity of their land and the water quality of streams. Some property holders estimate that as much as 20 per cent of available arable land in some catchments may be susceptible to waterlogging and salinization. Clearly, there are serious economic implications.

Much of the native vegetation in the central and southern Mt Lofty Ranges has been replaced by annual pastures and crops which are relatively inefficient in their use of rainfall, resulting in increased recharge of ground and perched watertables. Consequently, a higher proportion of the soils have become subject to waterlogging both by surface and saline ground water. Impaired drainage and perched water during winter have induced pedogenic processes that differ drastically from those operating before clearing. These induced conditions of soil waterlogging not only lead to salinity but also loss of fertility and soil structure decline, with a resultant decline in both agricultural production and stream water quality. We found acid sulphate-like soils to be associated with several areas subject to waterlogging (Fitzpatrick 1991a,b). Two different sub-catchments, one with soils representing profiles derived from fractured, metamorphosed rocks (mainly mica schists) near Mt. Torrens and the other with soils on alkaline stranded dunes near Cooke Plains, were selected for detailed study. A pedon from a tidal mangrove swamp was included for comparison.

Acid sulphate soils have been identified on several coastal flood plains of Australia, ranging from the tropical northern coast of the Northern Territory (Willett et al. 1992) to the sub-humid coasts of southern New South Wales (Willett and Walker 1982). Despite their wide distribution, little research has been reported on natural acid sulphate soils in Australia and especially in South Australia, probably because of the lack of agricultural or urban development where they occur (Willett et al. 1989).

This paper is part of a series reporting studies involving soil-landscape processes associated with various forms of soil degradation occurring in micro-catchments in southern Australia (Fitzpatrick 1991a,b; Fitzpatrick et al. 1992a,b,c; Naidu et al. 1992a,b). A summary of field and laboratory observations relating to the formation of potential acid sulphate saline soils as a result of land clearing and rising saline groundwater tables is presented. These soil degradation processes lead to hydrogeochemical conditions which are ideal for microbial activity.

The objectives of this paper are to: (i) describe briefly the types of sulfidic materials found in two recently-formed inland saline, sulfidic marsh soils and compare them with tidal mangrove swamp soils along the coastline of the Gulf St. Vincent, and (ii) discuss the implications for soil classification.

Field monitoring and laboratory analyses

Extensive field monitoring and laboratory analyses were carried out on samples from all three sites studied. Field monitoring included piezometry to measure groundwater levels and to collect water for Eh and pH measurements (Naidu et al. 1992a). Laboratory analyses included the measurement of electrical conductivity, Eh, pH, hydrogen peroxide-treated pH, aged pH, and air-dried pH. Chemical composition was determined by a combination of X-ray spectroscopy and inductively coupled plasma emission analyses. In addition, organic C and nitrogen, as well as soluble salts were measured. Mineralogical analysis was carried out by powder X-ray diffraction (XRD), whereas scanning electron (SEM), transmission electron (TEM) and light microscopy were used to examine soil thin sections, soil fragments and dispersed samples. Energy dispersive X-ray analysis (EDX) was used to obtain chemical analyses of individual soil grains. Details of these methods are given in Fitzpatrick et al. (1992b).

Study sites and description of soils

The soils studied represent two inland pedons each from the Herrmanns sub-catchment near Mt. Torrens in the Mt. Lofty Ranges and the Cooke Plains sub-catchment near Tailem Bend in the Mallee region of the lower southeast of South Australia. For comparison, a pedon from the coastal mangrove swamp at St. Kilda 15 km north of Adelaide in the St. Vincent Gulf, South Australia was sampled. All three study sites are subject to a Mediterranean climate but rainfall ranges widely from 420 mm at the coastal site, through 770 mm at Mt Torrens and decreasing again to 380 mm at Cooke Plains.

Herrmanns sub-catchment

The soil in the Herrmanns sub-catchment was a Mollic Natraqualf (Soil Survey Staff 1990) that acquired saline sulfidic materials within the past 5 to 15 years. This newly formed pedon is located in a seepage area on a footslope subject to a rising groundwater table following deforestation (Fitzpatrick 1991a,b). As a result of the recently acquired saline sulfidic characteristics within 100 cm of the surface in this pedon, it cannot be satisfactorily classified amongst the subgroups in Soil Taxonomy (Soil Survey Staff 1990). A detailed profile description for the Herrmanns pedon is given in Fitzpatrick et al. (1992b). The pedon is derived from acid-fractured, metamorphosed rocks that are mainly micaceous schists containing pyrite-rich bands. The soil is part of catenary toposequences on hill slopes where the dominant soils are Typic Palexeralfs in upslope and midslope positions, grading towards wetter Aquic Palexeralfs, Alfic Sodic Sulfaquents (seepage areas) and Mollic Natraqualfs in lower-lying topographic positions with more strongly gleyed argillic horizons. In the natric argillic horizons (Btn) of these soils, distinct yellow-coloured ferruginous mottles occur, and with increasing depth the dominant chroma in the soil matrix is 2.

Cooke Plains sub-catchment

The original soil was a Petrocalcic Palexeralf grading to an Aeric Halaquept (i.e. Siliceous sand over calcrete) in down slope positions and is derived from Quaternary strandlines on a coastal plain at the western margin of the lower Murray Mallee region. As for the Herrmanns soil, this soil has acquired saline sulfidic characteristics within the past 5 to 15 years and as a result does not satisfy existing Soil Taxonomy criteria (Soil Survey Staff 1990).

Generally speaking, the Cooke Plains soil-landscape pattern is variable and complex due, in part, to several cyclic soil formation processes that have taken place over a long period of time. In adjacent landscape positions, deep sandy soils (windblown) containing ancient stored salt are juxtaposed with very shallow soils on calcrete (petrocalcic horizon) and contemporary seasonally waterlogged sulfidic saline soils in the dune swales.

St Kilda

This soil is typical of coastal mangrove tidal swamps and according to Soil Taxonomy (Soil Survey Staff 1990) classifies as a Terric Sulfihemist. The soil is formed in modern intertidal and mangrove swamp deposits and is underlain by unconsolidated Holocene coastal marine sediments (St. Kilda formation) consisting of saturated, light grey, shelly and often silty or clayey sands.

Results and discussion

Herrmanns sub-catchment

Black materials occur in the A1 and E1 horizons and are considered to be typical of potential acid-sulphate soil materials, with high water content, high n-values of > 1.2 (Soil Survey Staff 1990), high soluble salt contents (i.e. have high EC values) and high ESP values (Table 1). These materials have pH values ranging from 6.9-7 9 when measured from a wet sample in a minimal amount of water. Moist samples aged moist for 30 days dropped in pH to values between 2.9 and 3.8. Similar pH reductions were also observed when samples were treated with peroxide (Fitzpatrick et al. 1992b). Such materials are anaerobic and emanate small amounts of hydrogen sulphide gas; particularly so when treated with drops of hydrochloric acid, indicating the presence of monosulphides (Fanning and Fanning 1989). When this sulfidic material is exposed to air and desiccated, the dark organic matter material changes irreversibly to a very dark-grey colour and loses its ability to evolve hydrogen

Table 1 Selected chemical data of acid sulphate soils

Horizon	Depth cm	pH wet	pH oxidized	Organic carbon %	Total S	*ESP
Herrmanns sub-catchment (# Alfic Sodic Sulfaquent)						
A	0-15	7.9	2.9	4.2	0.6	17
E	15-30	6.9	3.8	1.7	0.4	11
Btn1	30-45	5.5	4.2	0.3	0.2	12
Btn2	45-60	5.9	5.0	0.2	0.1	15
Cooke Plains sub-catchment (# Petrocalcic Salic Sulfaquent)						
A	0-15	8.3	3.9	0.9	0.7	23
E	15-30	7.8	7.2	0.5	0.1	19
Btnl	30-45	8.5	8.1	0.1	0.2	18
Ckm	45+					
St Kilda (# Terric Sulfisaprist)						
Oa1	0-12	7.2	2.2	16.1	0.9	49
Oa2	12-32	5.5	1.9	19.8	1.2	39
Oa3	32-48	7.0	1.9	17.1	1.1	31
Oa4	48-55	7.2	2.0	15.5	0.9	25
C	55+	8.0	6.5	7.8	0.3	55

* ESP = Exchangeable Sodium percentage

\# Proposed new subgroups Fitzpatrick et al. (1992a)

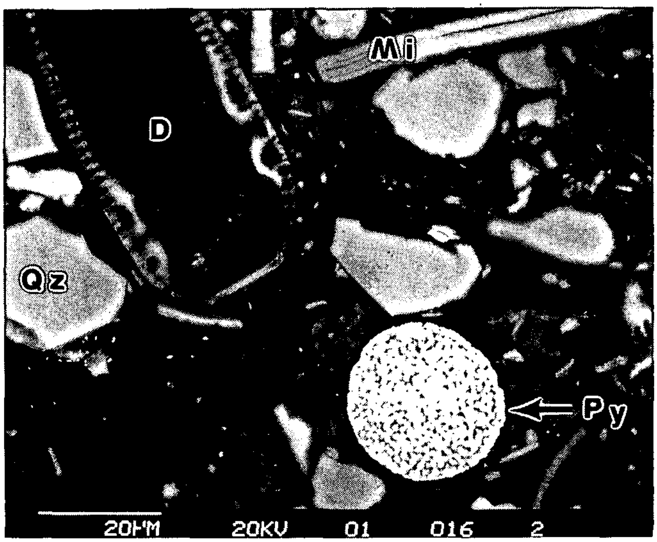


Figure 1 Back scattered electron SEM of polished thin section from the Herrmanns pedon showing a pyrite framboid (Py) embedded in a clay and organic matter-rich matrix together with quartz (Qz), mica (Mi) and diatom fragments (D)

sulphide when treated with to HCl. These properties are indicative of sulfidic materials and, although sulphide was not detected by XRD, some pyrite framboids were detected by SEM (Figure 1). The total sulphur content ranged from only 0.4-0.6 per cent (Table 1).

Fe^{2+} was detected in soilwater only when Eh values were < 100 mV (Naidu et al. 1992a). Interestingly, Fe^{2+} was not detected during most of the summer months in surface horizons. This may be due to oxidation at the surface horizons caused by evaporation and aeration during summer. Mean electrical conductivity (EC) ranged from 6 to 7 dSm^{-1}. Hydrographs (data from piezometers monitoring the groundwater) indicate that in this sub-catchment ground water occurs in complex fractured rock, and sedimentary aquifers, many of which exist as confined aquifers (i.e. the ground water is under pressure). Thus pressure forces water to the surface. These percolated waters are saline, with EC values ranging from 10-13 dSm^{-1}, and contain predominantly Na, Mg, Ca, Cl and SO_4 ions. Concentrations of Mg and Ca are similar but are minor in relation to Na. The pH of surface water ranges from 6.0 to 6.5. Data for ground water measured in deep piezometers suggest that its chemistry remains relatively constant irrespective of wet season rains.

The primary origin of sulphate and iron at Herrmanns is in locally rising ground waters, that dissolve these elements from fractured, porous, partly-weathered mica schists containing thin bands of iron sulphide present deep in the regolith. Once the dissolved sulphate percolates to the surface horizons of these soils it is transformed to very-fine-grained pyrite by sulphate-reducing bacteria in the presence of soil organic matter (Fanning and Fanning 1989).

Cooke Plains sub-catchment

Black materials occur in the sandy A horizons which, like the Herrmanns pedon, are

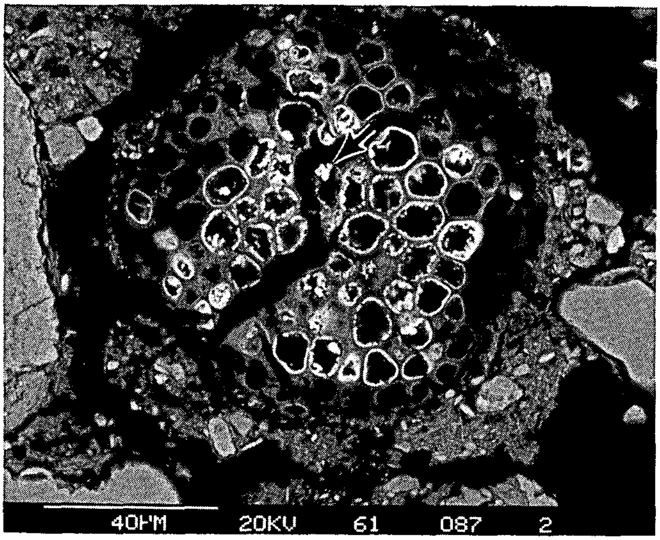


Figure 2 Back scattered electron SEM of polished thin section from the Cooke Plains pedon showing very finely dispersed pyrite (e.g. at arrow) and iron (hydr)oxide crystals in an organic matrix

considered to be typical of potential acid sulphate soil materials, with high water content, n-values > 0.7, very high soluble salt contents and high ESP values (Table 1). These materials at Cooke Plains have pH values ranging from 7.8-8.3 when measured from a wet sample in a minimal amount of water (Table 1). Samples of the A horizon that were aged moist for 30 days had pH values lowered to 3.9. These materials emanate very small amounts of hydrogen sulphide gas when treated with hydrochloric acid and contain very fine grained crystals of pyrite (Figure 2) that are clustered in regions of organic matter (e.g. plant roots). The horizon must clearly be classified as containing sulfidic materials. Furthermore, the A horizon has a salt content of 4.4 per cent and is, therefore, a salic horizon.

Platinum electrodes were installed in these Cooke Plains soils at a depth of 10 cm to monitor Eh. As soil temperature increased, Eh decreased to –400 mV, approaching the stability field of FeS and sulphate reduction. Sufficient organic matter is present (Table 1) for microorganisms to facilitate transformation of sulphate to sulphide which in the presence of reduced iron derived from the weathering of ilmenite grains in the soil, forms iron sulphide (pyrite). During the dry summer months, this pyrite oxidizes and reacts with dissolved calcium to form hydrated calcium sulphate (gypsum). Excess sodium in the presence of a saturated solution of chloride will precipitate to form sodium chloride (halite).

Once dissolved sulphate in the saline ground water (originally stored in the Quaternary strandlines) percolates to the surface horizons of these soils it may transform rapidly to sulphide-containing salts (i.e. very fine grained iron sulphides or pyrite) through the action of sulphur-reducing bacteria in the presence of soil organic matter.

St Kilda site

This estuarine type tidal marsh soil overlies grey sands mixed with shell fragments

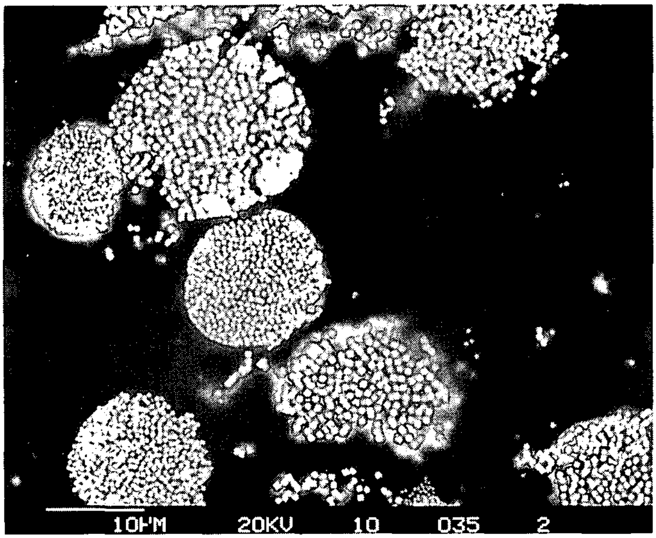


Figure 3 Back scattered electron SEM of polished thin section from the St Kilda pedon showing pyrite framboids in sapric material. Note how some of the framboids are dispersed.

within 50 to 100 cm, and typically has low bulk density and receives inputs of brackish water through daily tidal flushing. The pedon was sampled in dense mangrove woodland and classified as a Terric Sulfihemist (Soil Survey Staff 1990). However, this classification is not totally satisfactory for this soil because all Oa horizons have a small content of fibre (approximately 1/10th) and should be described as sapric material. The pH of the wet Oa horizons ranges from 5.5 to 7.2, decreasing to 1.9 to 2.2 on oxidation (Table 1). Organic carbon (15.5 to 19.8 per cent) and total S (0.9 to 2.2 per cent) contents are considerably higher than in the two inland pedons (Table 1). The St Kilda pedon contains a range of pyrite framboids (in various stages of formation or dispersion) within the sapric material (Figure 3). Despite the presence of a large number of framboids, organic S derived from sea water is the major form of S in this pedon. This is indicative of the ability of sapric material to retain organic S.

Proposed changes to Soil Taxonomy

In this study, we have identified degraded Alfisols in areas severely affected by dry land salinization in which sulfidic materials (i.e. material with a pH value > 3.5 and showing a pH drop of at least half a pH unit upon slow oxidation to a pH of < 4.0) have developed in A and E horizons over the past 50 years or less. These soils are difficult to classify because: (i) they maintain many Alfisol-like characteristics (i.e. argillic and natric horizons), and (ii) the 1990 Keys to Soil Taxonomy (Soil Survey Staff 1990) do not provide categories for aquic soils with sulfidic materials (Sulfaquents) that have within 100 cm of the soil surface either one or more of the following horizons: Argillic, Natric, Petrocalcic or Sodic. In order to be able to recognise both the neo-form (i.e. presence of sulfidic material) and the relict features of these soils it is proposed to add Alfic (presence of argillic horizon) and Sodic (Sodalfic?) as well as Petrocalcic, Salic, and Mollic subgroups to Sulfaquents. Furthermore, the key to soil orders should be changed so that sulfidic material and sulfuric horizons are not permitted in Alfisols. However, in order to accommodate those Alfisols (e.g. Natraqualfs) that have not developed sulfidic materials but do have sulfidic material (i.e. with a pH drop of at least half a pH unit upon slow oxidation to a pH between 4.0 and 4.5) they should key out as Sulfaquentic subgroups (e.g. Sulfaquentic Natraqualfs). Full details of the proposed scheme are given by Fitzpatrick et al. (1992a). Under the proposed scheme soils that have developed sulfidic materials will logically key out as Entisols (Sulfaquents) or Inceptisols (Sulfaquepts) with argillic horizons (i.e. with Alfic sub-groups). Consequently, the two inland soils of this study key out as an Alfic Sodic Sulfaquent (Herrmanns) and a Petrocalcic Salic Sulfaquent (Cooke Plains).

In addition to the above, the mangrove swamp soil highlights another problem with soil classification particularly with respect to the presence of sapric materials in Histosols. To allow for Histosols that contain sapric material (i.e. Saprists) and have either a sulfuric horizon or contain sulfidic material, it is proposed that Sulfosaprist and Sulfisaprist great groups should be added to the Histosol order (Fitzpatrick et al. 1992a). With the addition of these great groups, the St Kilda pedon would classify as a Terric Sulfisaprist.

Bacteria and pyrite morphology

A striking feature of the sulfidic materials in the samples studied was the variation in the morphology of pyrite across the three contrasting sites. At the Herrmanns site, the pedon contained large, well-formed framboids embedded in a clay matrix (Figure 1). This indicates that the conditions (i.e. pH, Eh and S, Fe and organic matter content) in the Herrmanns pedon are well suited to the formation of pyrite. The St Kilda pedon contained pockets of framboids in various stages of formation and dispersal (Figure 3). They are embedded in sapric material. The limiting factor in the formation of pyrite in this pedon is probably the lack of Fe. The dispersal of the framboids is possibly due to wave and tidal action. Framboids were absent from the Cooke Plains pedon and pyrite was present as individual crystals or as clusters of a small number of crystals in close proximity to organic matter (Figure 2). Conditions at Cooke Plains are not suited to framboid formation. This is probably due to a combination of low organic matter content, high pH and saline conditions.

Another striking feature was the presence of highly-conspicuous, red, gelatinous precipitates in the water filled pores and ponds on the soil surface of the Herrmanns pedon. These precipitates consist of ferrihydrite (with minor amounts of goethite) formed by rapid chemical and bacterial (mainly *Gallionella* and *Leptothrix*) oxidation of the Fe^{2+} (Fitzpatrick et al. 1992b). In the dry summer months the precipitates desiccate and form thin iron-rich crusts on the soil surface. These crust contain mainly goethite, ferrihydrite and the recently described iron oxyhydroxysulphate schwertmannite (Bigham et al. 1990).

Conclusions

In several agricultural areas of South Australia, our studies reveal an evolution of inland Alfisols to saline sulfidic marsh soils (Sulfaquents) under a regime of dry land salinization associated with land clearing and consequent rising watertables. This unique type of salting encompasses not only the usual processes of Na^+ and Cl^- ions concentrating in soils but also highly reactive soil processes involving the mobilization and biomineralization of sulphur and iron that rapidly degrades productive soils into saline sulfidic soils.

Based on newly acquired information about these unique soils, we have developed proposals to show how Soil Taxonomy may be modified to accept them where no taxa are currently provided. Relict argillic horizons occur in the Sulfaquents at depths within 100 cm of the soil surface. These are not considered to be buried beneath a deep layer of sulfidic marsh soil and thus the marsh soils, depending on how reactive the sulfidic material is, must either be classified as Alfic Sodic Sulfaquents (i.e. defined sulfidic material is present) or Sulfaquentic Natraqualfs (i.e. sulfidic-like material).

Acknowledgments

The research was funded in part by LWRRDC and NSCP, and we are grateful to members of the Tungkillo Landcare Group for their encouragement and assistance. CSIRO staff who contributed substantially to the study include Alan Bird (light microscope photography), Stuart McClure (SEM), Adrian Beech (chemical analyses), Jim Thompson (thermal analyses) and John Coppi (photography). We also thank Malcolm Wright for critical review of the manuscript.

References

Bigham, J.M., U. Schwertmann, L. Carlson, and E. Murad 1990. A poorly crystallized oxyhydroxysulfate of iron formed by bacterial oxidation of Fe(II) in acid mine waters. Geochimica Cosmochimia Acta, 54, 2743-2758

Fanning, D.S. and M.C.B. Fanning 1989. Soil: Morphology, genesis, and classification. John Wiley and Sons, New York

Fitzpatrick, R.W. 1991a. How rising water-tables cause productive soils to alter to saline mangrove swamp like-soils. CSIRO Div. Soils Tech. Memorandum No. 16/1991. 6 pp.

Fitzpatrick, R.W. 1991b. New methods to tackle soil salinity. Australian Grain, 3, 40-42

Fitzpatrick, R.W., W.H. Hudnall, D.J. Lowe, D.J. Maschmedt, and R.H. Merry 1992a. Proposed changes in the classification of Histosols, Alfisols, Andisols, Aridisols, Inceptisols, Mollisols, Entisols and Spodosols in South Australia. CSIRO Div. Soils Tech Report No. 51/1992. p.17

Fitzpatrick, R.W., R. Naidu and P.G. Self 1992b. Iron deposits and microorganisms occurring in saline sulfidic soils with altered soil water regime in the Mt. Lofty Ranges, South Australia. In: H.C.W. Skinner and R.W. Fitzpatrick (editors) 'Biomineralization Processes of Iron and Manganese – Modern and Ancient Environments'. Catena Supplement No. 21, 263-286

Fitzpatrick, R.W., M.J. Wright, M.A. Wells and R.J. Gilkes 1992c. The formation and identification of iron oxyhydroxides in an Aquic Palexeralf on a hillslope with an altered soil water regime. Proceedings Eighth International Soil Correlation Meeting (J.M. Kimble editor), Louisiana and Texas, U.S.A. (October 7-20, 1990), 123-157

Naidu, R., R.W. Fitzpatrick, and W.H. Hudnall 1993a. Chemistry of saline sulfidic soils with altered soil

water regime in the Mount Lofty ranges, South Australia. Proceedings International Workshop on Salt Affected Soils. Bangkok, Thailand, 17-25 February, 1992. (In Press)
Naidu, R., D.R. Williamson, R.W. Fitzpatrick and I. Hollingsworth 1993b. Effect of landuse on the composition of throughflow water immediately above clayey B horizons in the Warren catchment. Aust. J. Experimental Agric., 33, 239-244
Soil Survey Staff 1990. Keys to soil taxonomy, 4th edition. SMSS Technical Monograph No. 19, Virginia Polytechnic & State University, Blacksburg
Willett, I.R., M.D. Melville and B.N. Noller 1989. Acid sulphate soils research in Australia. Acid Sulphate Soils Newsletter, No 2. 2-3
Willett, I.R. and P.H. Walker 1982. Soil morphology and distribution of iron and sulfur fractions in a coastal flood plain toposequence. Australian Journal of Soil Research 20, 283-294
Willett, I.R., R.H. Crockford and A.R. Milnes 1992. Transformations of iron, manganese and aluminium during oxidation of a sulfidic material from an acid sulfate soil. In: H.C.W. Skinner and R.W. Fitzpatrick (editors) 'Biomineralization Processes of Iron and Manganese – Modern and Ancient Environments'. Catena Supplement No. 21, 287-302

Potential acid sulphate soils developed in marine and high-moor peat materials

L. Giani

Soil Science Division, Carl-von-Ossietzky University, P.O. Box 2503, D-2900 Oldenburg, Germany

Abstract

The saltmarsh seawards of the Sehestedter Außendeichsmoor is built up from marine alluvium and high-moor peat. The soils there are characterized by sulphate depletion, leading to intensive production of methane; by carbonate-depleted profiles and low pH-values, especially in humus-rich parts; and by high amounts of reduced sulphur compounds. These soils are potential acid sulphate soils. According to the German classification they are schwefelreiche Organomarschen.

With respect to further development, properties can be expected similar to those of older Organomarschen, regarded as not having developed under marine conditions. It seems likely that these older Organomarschen initially developed under marine influence. These unique soils are threatened by the present erosion of the high-moor peatland.

Introduction

Most saltings along the North Sea coast are built up from calcareous marine sediments. There is only one small area within the Jadebusen (Figure 1), where saltmarsh soils consist of marine as well as high moor peat material. This is due to high moor peatland named Sehestedter Außendeichsmoor, which is situated outside the dike (Figure 2) and is directly exposed to the sea. This site is now unique, although the contact of marine and high moor peat materials was widespread in the past (Müller et al. 1977).

During storm tides, the Sehestedter Außendeichsmoor becomes flooded and parts of it are eroded. Thus, more than 90 per cent of the peatland has been lost since the construction of the dike in 1725 (Erdmann 1962) and, before long, the remaining 10 ha peatland will disappear. With the outgoing tide, peat is deposited seawards of the moor where marine sediments also settle. These specific conditions govern the properties and development of the soils.

Material and methods

The saltings seaward of the Sehestedter Außendeichsmoor consist of areas dominated by *Puccinellia*, areas with *Spartina* and *Salicornia*, areas without vegetation and pools (Figure 2). Soil sampling was performed using a corer in areas covered by halophytes near areas without vegetation. The sample sites were representative of the very early stages of soil development in this area.

Particle size analysis was performed after HCl and H_2O_2 treatment and dispersing

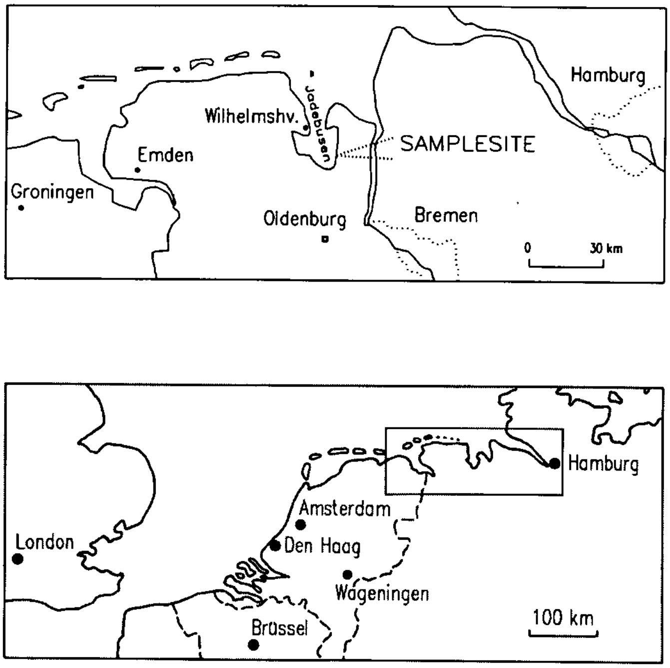


Figure 1 Location of the study area

Figure 2 The Sehestedter Außendeichsmoor: 1 – sampling area; 2 – peatland; 3 – area of pools; 4 – salt marsh area; 5 – dike

particles < 2 mm by shaking in sodium polyphosphate solution. Pore water for the determination of ions was obtained by centrifugation. Salinity was calculated from the sum of soluble ions. For the determination of exchangeable cations, soil samples were shaken three times using 0.1 M $SrCl_2$ solution. Total cation contents were determined after ignition and HNO_3 treatment.

Cations were determined by atomic absorption spectrometry; chloride, potentiometrically; sulphate, according to Grashoff (1976); total sulphur, by HNO_3/HCl treatment (Howarth and Merkel 1984) and sulphate determination; sulphide, after HCl treatment (Giani et al. 1986) according to Pachmayr (1960); elemental sulphur, after Hart (1961) using acetone treatment; carbonate, using the Scheibler apparatus; organic carbon and nitrogen, by HCN analyzer; methane contents by gas chromatography (Giani & Giani 1985); pH and E_H, using a pH/mV-meter.

Results

The particle size composition of profiles 1 and 2 was characterized by extremely low contents of sand and coarse silt (> 23 µm, little more than 1 per cent). In contrast, the contents of middle silt (23-6 µm, 28 per cent) fine silt (6-2 µm, 28 per cent) and clay (< 2 µm, 40 per cent) were high. A similar particle size composition is typical of saltmarsh soils of the North Sea coast. Finer-textured soils such as profile 4 (Table 3), with clay contents of nearly 60 per cent, and coarser soils such as profile 3 (Table 3), with sand contents of more than 60 per cent in the subsoil, may also be found.

Low bulk densities of 0.46 kg dm^{-3} to 0.56 kg dm^{-3}, and large pore spaces of 80 to 83 per cent were found.

Chemical properties are summarized in Tables 1, 2 and 3. Notable are the extremely reduced conditions, with E_H values between +30 and −130 mV. In typical saltmarsh soils comparable in development, similar values may occur but, also, higher redox potentials were found (Table 3), which are mostly restricted to soils of a higher level of development.

The highest S^{2-}-contents were found in the topmost layer and decreased with depth, while the elemental sulphur contents increased with depth from 0.9 to 1.4 mg g^{-1} in profile 1 and from 1.9 to 3.1 mg g^{-1} in profile 2. The contents of total sulphur varied from 1.8 to 30.8 mg g^{-1}, but values from 11 to 15 mg g^{-1} occur frequently. Compared to typical soils at a similar level of development, these contents of total sulphur are very high. More common are the values found in profiles 3 and 4 (Table 3).

Profiles 1 and 2 have organic carbon contents varying between 4 and 13 per cent, much more than in typical saltmarsh soils comparable in development, for example 0.8 per cent in profile 3 and up to 4.4 per cent in profile 4. In profile 1, the highest amount of organic carbon was found at 40 to 60 cm depth, in profile 2 at 50 to 70 cm depth. Here the influence of the peat material was most obvious: pH-values were lower, C/N rations were higher and carbonate contents were lower than in upper and lower soils sections. In profile 1, no carbonate was detectable in this humus-rich section, whereas carbonate was always found in typical saltmarsh soils comparable in development (Table 3; Schröder et al. 1991). Marine sediments at the continental North Sea Coast always contain carbonate. Carbonate depletion is restricted to a few soils on a higher developing level which have been described for the Netherlands

Table 1 Properties of a humus-rich salt marsh soil: Profile 1

Depth cm	Salinity (%)	pH H_2O	Carbonate (%)	E_h (mV)	C_{org} (%)	N mg g^{-1}	C/N*	S_{total}	S^o	S^{2-}	Ca**	Mg**	K**	Na**	Ca***	Mg***	K***	Na***
								mg g^{-1}			(mmol(+) kg^{-1})				mg g^{-1}			
1– 10	2.9	7.6	9.0	30	5.9	4.2	14	11.7	0.9	0.78	95	132	24	563	34.5	3.3	10.5	12.4
10– 20	2.4	7.7	8.7	10	5.7	4.5	13	14.7	0.9	0.46	93	120	24	511	39.4	5.0	10.9	12.2
20– 30	2.0	7.6	6.8	– 10	5.4	4.0	14	15.3	0.7	0.20	90	124	22	511	36.0	4.6	10.7	11.7
30– 40	2.0	7.3	0.0	– 60	10.3	4.2	24	13.2	0.9	0.03	125	198	23	739	16.0	2.4	9.1	16.6
40– 50	2.1	7.2	0.0	– 90	12.7	4.4	29	13.8	1.1	0.32	140	240	24	804	14.5	2.5	8.4	18.1
50– 60	2.0	7.2	0.0	–110	12.7	4.8	27	11.1	1.1	0.02	n.d.	n.d.	n.d.	n.d.	13.5	2.8	8.9	19.5
60– 70	1.9	7.6	7.2	–120	5.8	4.1	14	10.8	1.3	0.32	90	132	22	522	37.5	5.0	10.8	12.5
70– 80	2.0	7.5	6.3	–120	7.0	4.2	16	n.d.	1.2	0.03	95	144	22	543	34.5	4.6	10.9	12.5
80– 90	2.1	7.7	9.2	–120	5.8	4.3	13	8.1	1.3	0.03	98	123	22	478	38.0	4.5	10.6	11.5
90–100	2.2	7.6	7.8	–130	6.3	4.2	15	10.6	1.4	0.07	98	144	22	533	39.0	5.2	10.1	12.1

*: by mass **: exchangeable and soluble cations ***: total cations n.d.: no data

Table 2 Properties of a humus-rich salt marsh soil: Profile 2

Depth cm	Salinity (%)	pH H_2O	Carbonate (%)	E_h (mV)	C_{org} (%)	N mg g^{-1}	C/N*	S_{total}	S^o	S^{2-}	Ca**	Mg**	K**	Na**
								mg g^{-1}			mmol(+) kg^{-1}			
1 – 10	2.6	7.2	11.5	–138	6.3	5.0	12.6	5.9	1.9	1.9	165	264	33	1031
10 – 20	2.1	7.2	11.3	–103	5.6	4.3	12.9	12.5	3.3	1.6	220	216	29	757
20 – 30	2.0	7.3	11.6	–103	6.5	4.9	13.3	14.0	1.6	1.6	231	193	27	685
30 – 40	1.9	7.3	10.9	– 79	5.7	4.2	13.6	14.8	2.0	0.4	209	193	27	664
40 – 50	1.9	7.0	8.0	–103	7.6	4.0	19.1	13.4	1.8	1.8	150	218	26	712
50 – 60	2.8	6.8	5.2	–123	11.5	4.2	27.3	17.9	2.1	1.0	247	359	35	1549
60 – 70	2.7	6.9	7.2	–113	11.4	4.4	25.8	30.8	2.4	0.7	253	351	35	1513
70 – 80	2.3	7.1	7.0	– 63	7.4	4.0	18.4	14.3	2.7	1.0	176	256	29	862
80 – 90	2.4	7.1	9.5	– 83	10.1	5.8	17.4	9.6	3.1	1.8	231	256	31	889

*: by mass **: exchangeable and soluble cations

Table 3 Properties of typical salt marsh soils comparable to those investigated seawards of the Sehestedter Außendeichsmoor: profiles 3 and 4

Prof. Nr.	Depth (cm)	pH H_2O	pH $CaCl_2$	Carbonate (%)	Eh (mV)	C_{org} (%)	N_t mg g^{-1}	C/N***	S_t mg g^{-1}
3.1*	0–0.3	8.0	7.8	7.2	+439	0.8	1.0	8	1.56
3.2	0.3–10	8.1	7.8	5.4	+209	0.8	0.8	10	1.63
3.3	> 10	8.0	7.8	7.0	+ 60	0.8	0.7	11	4.48
4.1**	0–2	8.0	7.9	11.8	+294	4.4	5.7	8	5.18
4.2	>2	7.8	7.7	10.1	− 26	3.6	4.1	9	8.81

* : Profile under *Salicornia* at the Elisabeth-Außengroden, situated opposite to the most eastern island (Figure 1)

** : Profile under *Salicornia* at the western part of the Jadebusen

*** : By mass

and the northern part of the German coast (Beeftink 1977, Brümmer and Schröder 1971).

Upper and lower soil sections, however, are also influenced by the high moor: peat fibres were found throughout the profile, pH-values were lower and the C/N ratios higher (Tables 1 and 2) than in typical saltmarsh soils comparable in development (Table 3, Kooistra 1978, Blume et al. 1986, Brümmer and Finnern 1986; Schröder et al. 1991).

Methane

Microbial activity could be assumed to have been low, due to a low soil temperature of 5°C, during the time of sampling seawards of the Sehestedter Außendeichsmoor. Even so, more than 80 per cent methane was found in gas bubbles forming in water-covered areas near the sample sites. Moreover, the soils were nearly saturated with methane. The methane contents in profile 1 were about 1 mmol kg^{-1}. In profile 2, even 38.4 mmol kg^{-1} was measured (Table 4). Typical saltmarsh soils comparable in development often show methane contents of less than 20 µmol kg^{-1}, but they also might reach higher values, as seen in profile 6 which shows up to 240 µmol/kg methane (Table 5).

Table 4 Methane and sulphate concentrations of humus-rich saltmarsh soils: Profiles 1 and 2

Depth cm	Profiles 1 – 7 CH_4 mmol kg^{-1}	Profiles 1 – 7 SO_4^{2-} kg^{-1}	Profile 2 CH_4 mmol kg^{-1}	Profile 2 SO_4^{2-} mmol kg^{-1}
10	0.8	4.5	1.6	25.0
20	0.8	3.4	2.2	33.0
30	0.7	0.6	2.7	22.8
40	0.8	0.1	10.4	1.5
50	0.9	0.9	38	n.d.
60	0.9	0.5	38.4	1.3
70	1.2	0.3	20.6	2.8
80	1.0	0.4	27.3	1.6
90	0.9	0.7	34.5	1.3
100	0.9	1.5	n.d.	n.d.

Table 5 Methane and sulphate concentrations of typical saltmarsh soils under *Salicornia* in the Jadebusen: Profiles 5 and 6

	Profile 5		Profile 6	
Depth (cm)	CH_4 μmol kg^{-1}	SO_4^{2-} mmol l^{-1}	CH_4 μ mol kg^{-1}	SO_4^{2-} mmol l^{-1}
13	4	20	4	9
26	4	20	4	10
39	4	23	16	13
52	4	22	24	9
65	10	20	24	9
78	8	10	20	6
91	4	21	28	6
104	7	20	28	6
117	7	15	20	6
130	12	14	48	6
143	4	16	32	6
156	5	22	240	5
169	5	23	24	6
182	5	22	36	5

With the exception of the topsoil of profile 2, sulphate concentrations were less than 5 mmol l^{-1} in the pore water of the soils seawards of the Sehestedter Außendeichsmoor. In humus-rich sections, sulphate was often depleted to less than 1 mmol l^{-1}, though the seawater salt concentration of the North Sea amounts to about 20 mmol l^{-1} and these concentrations were reached in typical saltmarsh soils (Table 5).

Discussion

Methanogenesis

Compared with typical saltmarsh soils, methane contents of the soils seawards of the Sehestedter Außendeichsmoor were much higher. Methane production rates from incubated soil samples are similar to those found in rice paddies (Holzapfel-Pschorn et al. 1985), which are considered to be one of the main methane emission sources to the atmosphere (Seiler 1984).

The lesser production of methane in typical marine surface sediments and saltmarsh soils (King and Wiebe 1980, Mountfort et al. 1980, Winfrey et al. 1981) is due to a high sulphate content. Under reduced conditions, sulphate-reducing bacteria and methane-producing bacteria compete for organic matter, especially the main intermediate compounds, acetate and H_2/CO_2. Sulphate-reducers have an advantage and obtain more energy from the transformation of these substrates (Claypool and Kaplan 1974, Kristjannsson et al. 1982). Methanogenesis is restricted to non-competitive substrates, such as amines, methanol and dimethyl-sulphide (King 1984).

If much organic matter is available, then the amount of sulphate is the limiting factor of sulphate reduction. High amounts of organic carbon lead to intensive sulphate reduction until sulphate is depleted. Unused acetate and H_2/CO_2 are then available for the methane producers.

Soil properties and expected further development

The humus-rich soils investigated seawards of the Sehestedter Außendeichsmoor are characterized by high amounts of reduced sulphur compounds throughout their profiles. Drainage produces extreme acidification if the soil contains more than 0.76 per cent sulphur and more sulphur than the threefold amount of carbonate (Dent 1980). Moreover, the carbonate/sulphur ratio will decrease as long as this level of development is maintained. Thus, these soils can be regarded as potential acid sulphate soils.

According to the German soil classification (Bundesanstalt 1982), the soils seawards of the Sehestedter Außendeichsmoor can be regarded as schwefelreiche Roh-Organomarschen (Müller et al. 1977), first described by Giani and Giani (1990). From properties of old schwefelreiche Organomarschen, it was assumed that they had developed under the influence of freshwater or brackish water (Müller et al. 1977). It now seems likely that these older schwefelreiche Organomarschen first developed under marine conditions, all the more since that saltmarshes adjacent to a high-moor peatland were widespread in earlier times (Müller et al. 1977).

Acknowledgements

This work was supported by grants Ge-322/6-1 and Kr-333/23-1 of the Deutsche Forschungsgemeinschaft given to H. Gebhardt and L. Giani and to W.E. Krumbein, respectively. R. Zucht provided the photograph shown as Figure 1.

References

Beeftink, W.G. 1977. The coastal marshes of western and northern Europe: an ecological and physiological approach. In: Ecosystems of the World – Wet coastal ecosystems (V.J. Chapman, editor), Elsevier, Amsterdam

Blume, H.P., G. Brümmer, H. Finnern, J. Lamp and E. Schnug 1986. Landscapes, agriculture and soils of Schleswig-Holstein. Mitt. Dtsch. Bodenk. Ges. 46, 249-261

Brümmer, G. and D. Schröder 1971. Die Marschlandschaft und ihre Böden. Mitt. Dtsch. Bodenk. Ges. 13, 22-33

Brümmer, G.W. and H. Finnern 1986. Marshland soils of Nordfriesland. Mitt. Dtsch. Bodenk. Ges. 51, 43-62

Bundesanstalt für Geowissenschaften und Rohstoffe und der Geologischen Landesämter in der Bundesrepublik Deutschland (editor) 1982. Bodenkundliche Kartieranleitung. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart

Claypool, G.E. and J.R. Kaplan 1974. The origin and distribution of methane in marine sediments. In: Natural gases in marine sediment (I.R. Kaplan, editor). 99-140. Plenum Press, New York

Dent, D. 1980. Acid sulphate soils: morphology and prediction. J. Soil Sci., 31, 87-99

Erdmann, E. 1982. Rund um das Schwimmende Moor. Holzberg, Oldenburg

Giani, L. and D. Giani 1985. Bedeutung der Methanproduktion für die geogene Phase der Marschenentwicklung. Mitt. Dtsch. Bodenk. Ges. 43, 733-738

Giani, L. and D. Giani 1990. Characteristics of a marshland soil developed from marine and peat material. Geoderma 47, 151-157

Giani, L., I. Eden, and H. Gebhardt 1986. Sulfidbestimmung in Böden und Sedimenten. Z. Pflanzenernähr. Bodenk. 149, 354-356

Grashoff, K. 1976. Methods of seawater analysis. Verlag Chemie. Weinheim

Hart, M.G.R. 1961. Turbidimetric method for determining elemental sulphur. Analyst 86, 472-475

Holzapfel-Pschorn, A.R. Conrad and W. Seiler 1985. Production, oxidation and emission of methane in rice paddies. FEMS Microbiol. Ecol. 31, 343-351

Howarth, R.W. and S. Merkel 1984. Pyrite formation and the measurement of sulfate reduction in salt marsh sediments. Limnol. Oceanogr. 29(3), 598-608

King, G.M. 1984. Utilisation of hydrogen, acetate and noncompetitive substrates by methanogenic bacteria in marine sediments. Geomicrobiol. J. 3, 279-306

King, G.M. and W.J. Wiebe 1978. Methane release from soils of Georgia salt marsh. Geochim. Cosmocim. Acta 42, 343-348

Knabke, C. and L. Giani 1991. Ausmaß der Bodenentwicklung in Marschböden des Deichvorlands der niedersächsischen Nordseeküste. Mitt. Dtsch. Bodenk. Ges. 66, 811-815

Kooistra, M.J. 1978. Soil development in recent marine sediments of the intertidal zone in the Osterschelde – The Netherlands. Soil Survey Papers, 14. Netherlands Soil Survey, Wageningen

Kristjansson, J.K., P. Schönheit and R.K. Thauer 1982. Different Ks values for hydrogen of methanogenic bacteria and sulfate reducing bacteria: an explanation for the apparent inhibition of methanogenesis by sulfate. Arch Microbiol. 131, 278-282

Mountfort, D.O., R.A. Ascher, E.L. Mays and J.M. Tiedje 1980. Carbon and electron flow in mud and sandflat intertidal sediments at Delaware Inlet, Nelson, New Zealand. Appl. Environm. Microbiol. 39, 686-694

Müller, W., J.H. Benzler, H. Voigt and J. Tüxen 1977. Bodentypen der Marsch. Genese, Eigenschaften, Nutzung, Meleoration. Mitt. Dtsch. Bodenk. Ges. 24, 15-100

Pachmayr, F. 1960. Vorkommen und Bestimmung von Schwefelverbindungen in Mineralwasser. Dissertation, Universität München

Schönheit, P., J.K. Kristjansson and R.K. Thauer 1982. Kinetic mechanism for the ability of sulfate reducers to out-compete methanogens for acetate. Arch. Microbiol. 132, 285-288

Schröder, H., L. Giani and H. Gebhardt 1991. Initiale Marschbodenentwicklung an zwei Standorten unterschiedlicher Sedimentsbeschaffenheit und Geländemorphologie. Mitt. Dtsch. Ges. 66, 847-851

Seiler, W. 1984. Contribution of biological processes the global budget of CH_4 in the atmosphere. In: Current perspectives in microbial ecology (M.J. Klug & C.A. Reddy, editors), 468-477. American Soc. Microbiol., Washington D.C.

Winfrey, M.R., D.G. Marty, A.J.M. Bianchi and D.M. Ward 1981. Vertical distribution of sulfate reduction, methane production and bacteria in marine sediments. Geomicrobiol. J. 2, 341-362

Saline acid sulphate soils in Senegal

S. Sadio[1] and M.E.F. van Mensvoort[2]

[1] ISRA/ORSTOM, B.P.1386, Dakar, Senegal
[2] Dept. of Soil Science and Geology, Agricultural University, P.O. Box 37, 6700 AA Wageningen, The Netherlands

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.

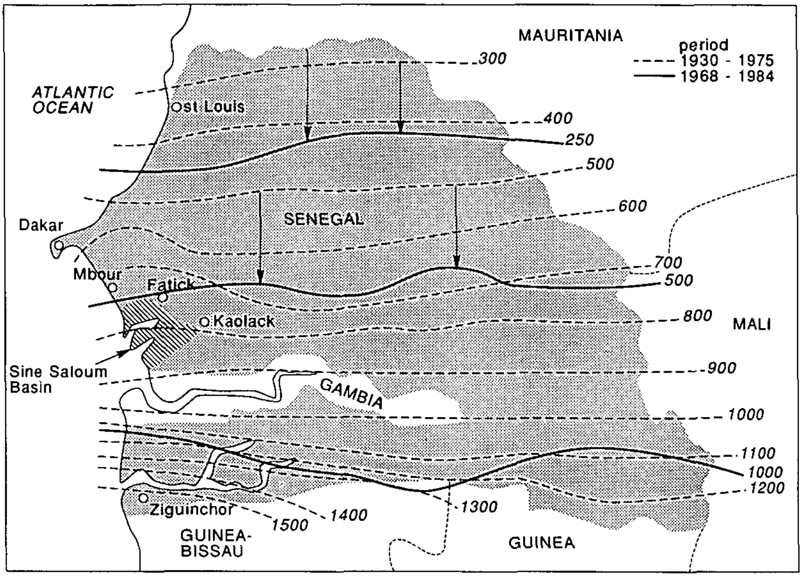


Figure 1 Location of the Sine Soloum Basin, Isohyets showing decreasing rainfall in Senegal

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)

$KFe_3(SO_4)_2(OH)_6 -> 3FeO.OH + 2SO_4^{-2} + K^+ + 3H^+$
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

$2FeO.OH -> Fe_2O_3 + H_2O$
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

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

Langmuir, D. 1971. Particle size effect on the reaction goethite = hemaitite + water. Am. J. Sci. 271: 147-156

Marius, C. 1979. Effets de la sécheresse sur l'évolution des sols de mangroves du Sénégal. ORSTOM/Dakar

Mensvoort, M.E.F. van, Duong Van Ni and J. van der Schans 1991. Improvement of acid sulphate soils by leaching with salt and brackish water. In: P. Deturck and F.N. Ponnamperuma (editors), Rice production on acid soils of the tropics. Institute of Fundamental Studies, Kandy, Sri Lanka

Michel, P. 1973. Les bassins des fleuves Sénégal et Gambie. Etude géomorphologique. Mem. ORSTOM no. 63, 3 tomes, Paris
Sadio, S. 1989. Pédogenese et potentialités forestières des sols sulfatés acides salés des tannes du Sine Saloum, Senegal. PhD Thesis, Agric. University Wageningen.
Schwertmann, U. 1988. Occurrence and formation of iron oxides in various pedoenvironments. In: J.W. Stucki et al. (editors), Iron in soils and clay minerals, Reidel Publishing Company, 267-308

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

Ting Chaong Chaang[1], Rohani Bt. Saari[2], Herbert Diemont[3] and Aminuddin Bin Yusoff[4]

[1] MARDI Acid Sulphate Soils Station, Kuala Linggi, Malaysia
[2] Department of Agriculture, Penang, Malaysia
[3] Institute for Forestry and Nature Research, Arnhem, The Netherlands
[4] MARDI, Serdang, Malaysia

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 (Diemont and van Wijngaarden 1974). The annual rainfall is 2155 mm, with a pronouced 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,

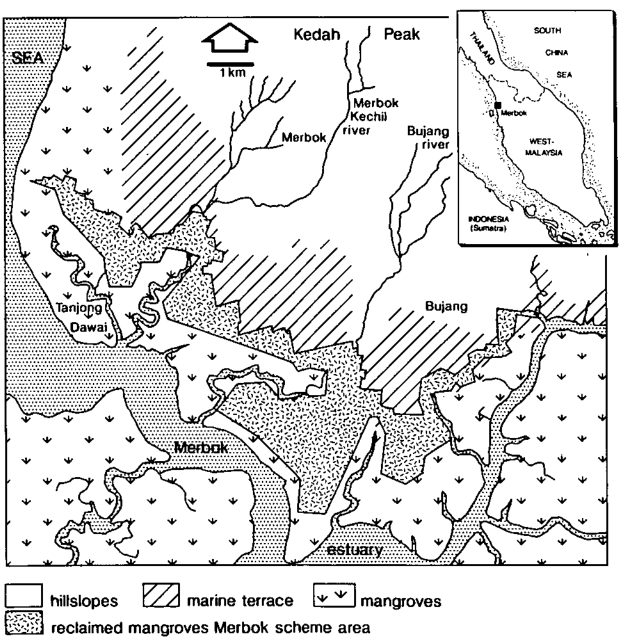


Figure 1 Location of the Merbok area

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 *Rhizophera* and *Bruiguiera* species and *Exoecaria 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

Table 1 A lobstermound soil profile

	Total S %	Pyrite S %	Total acidity mmol kg^{-1}	pH fresh	pH dry	EC mS cm^{-1}
Fresh mud	1.1	0.8	6	6.5	3.2	2.8
Jarosite horizon	0.7	0.1	146	2.0	2.0	1.5
Brownish horizon	0.2	0.1	5	5.9	5.4	2.4
Subsoil	1.5	1.3	6	6.4	3.6	3.4

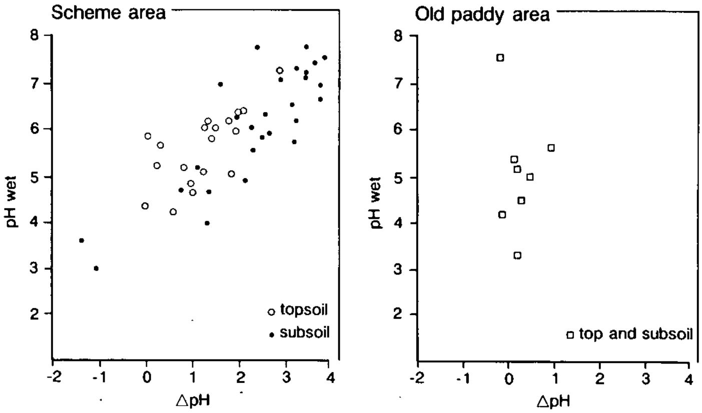


Figure 2 Change in soil pH following drying and rewetting in soils of the Merbok Scheme and the old paddy area on a marine terrace

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

Field number	Depth cm	Total-S %		Pyrite-S %	
		1974	1991	1974	1991
M	0– 15	0.09	0.10	0.06	0.06
	15– 30	0.53	0.17	0.17	0.10
	80–100	1.35	0.66	1.20	0.56
L	0– 15	0.13	0.12	0.10	0.08
	50– 80	0.66	0.69	0.60	0.56
	80–100	1.65	1.06	1.57	0.90

Table 3 Numbers of farmers in the Merbok Scheme area in different years

Year	Number of farmers
1966	437
1974	199
1991	278

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).

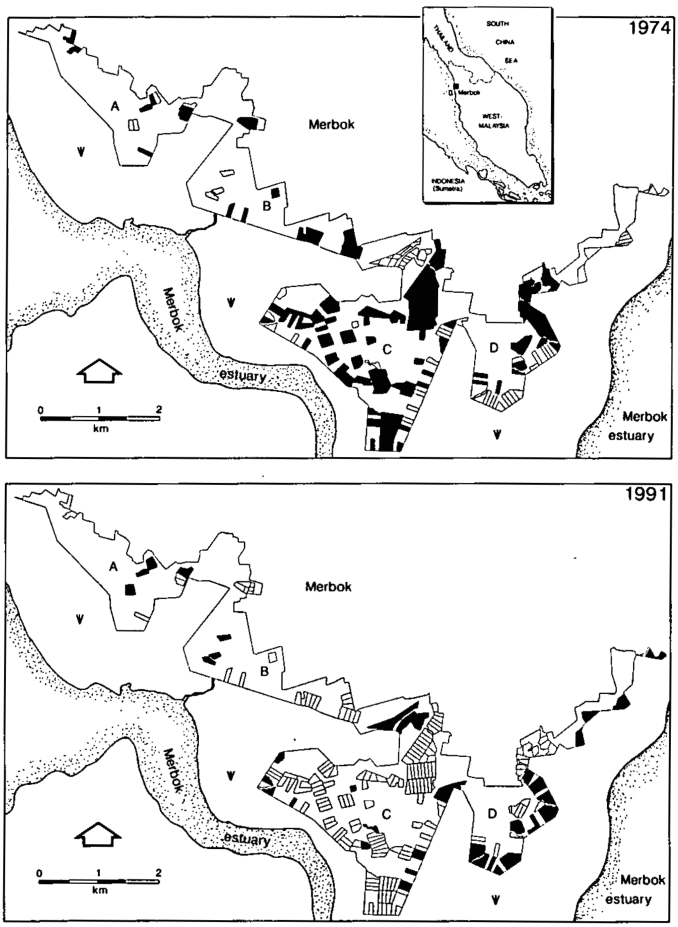


Figure 3 Merbok Scheme, changes in land use between 1973 and 1991. Blackened areas abandoned

Table 4 Paddy yields in cultivated land in the Merbok Scheme area (after 1974, only limed fields included)

Year	Paddy t/ha
1974	1.2–1.4
1984	3.0
1985-87	3.4
1988-89	4.2
1990	4.5

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

Breemen, N. van, M. Tandatemiya and S. Chachareonsook 1973. A detailed survey on the actual and potential soil acidity at the Bang Pakong Land Development Centre, Thailand. In: H. Dost (editor). Acid sulphate soils: Proceedings of the international symposium on acid sulphate soils 13-20 August 1972, Wageningen. International Institute for Land Reclamation and Improvement Publication No. 18, Vol. II, 159-168. Wageningen

Brinkman, R. 1982. Social and economic aspects of the reclamation of acid sulfate soil areas. In: H. Dost and N. van Breemen (editors). Proceedings of the Bangkok symposium on acid sulphate soils, January 18-24, 1981. International Institute for Land Reclamation and Improvement Publication No. 31, 21-36. Wageningen

Dent, D.L. 1986. Acid sulphate soils: a baseline for research and development. International Institute for Land Reclamation and Improvement Publication No. 39, Wageningen

Dent, D.L. 1992. Reclamation of acid sulphate soils. In: R. Lal and R.B. Stewart (editors). Land degradation: Advances in Soil Science 17, 79-122. Springer-Verlag, New York

Diemont, W.H. and W. van Wijngaarden 1974. Sedimentation patterns, soils, mangrove vegetation and land use in the tidal areas of W. Malaysia. In: G. Walsh, S.E. Snedeker and H.J. Teas (editors). International symposium on biology and management of mangroves, 513-528. East-West Center, Honolulu

Driessen, P.M. and Ismangun 1973. Pyrite-containing sediments of Southern Kalimantan, Indonesia. In: H. Dost (editor). Acid sulphate soils: Proceedings of the international symposium on acid sulphate soils. 13-20 August 1972, Wageningen, The Netherlands. International Institute for Land Reclamation and Improvement Publication No. 18, Vol II, 345-358. Wageningen

Hart, M.G.R. 1959. Sulphur oxidation in tidal mangrove soils of Sierra Leone. Plant and Soil, 3, 215-226

Mensvoort, M.E.F. van and Le Quang Tri 1988. Morphology and genesis of actual acid sulphate soils without jarosite in the Ha Tien Plain, Mekong Delta, Vietnam. In H. Dost (editor). Selected papers of the Dakar symposium on acid sulphate soils, Dakar, Senegal, January 1986. International Institute for Land Reclamation and Improvement Publication No. 44, 11-15. Wageningen

Sarwani M., M. Lande and W. Andriesse 1993. Farmers' experiences in using acid sulphate soils: some examples from tidal swampland of southern Kalimantan, Indonesia. In: D.L. Dent and M.E.F. van Mensvoort (editors). Selected papers of the Ho Chi Minh City symposium on acid sulphate soils. International Institute for Land Reclamation and Improvement Publication No. 53, 113-121. Wageningen

Vo-Tong Xuan, Nguyen Kim Quang and Le Quang Tri 1982. Rice cultivation on acid sulphate soils in the Vietnamese Mekong Delta. In: H. Dost and N. van Breemen (editors). Proceedings of the Bangkok symposium on acid sulphate soils. International Institute for Land Reclamation and Improvement Publication No. 31, 251-259. Wageningen

Zahari, A.B., Abd. Wahab Nafis, C.C. Ting and Abd. Rahim Mohamad 1982. Distribution, characterisation and utilization of problems soils in Malaysia – A country report. Tropical Agricultural Research Series No. 15, 41-61. Tropical Agriculture Research Centre. Ministry of Agriculture, Forestry and Fisheries, Tsukuba

The Balanta rice farming system in Guinea-Bissau

P.A.M. van Gent and H.R. Ukkerman

Projet PRIVAT, B.P. 86, Birni N'Konni, Niger

Abstract

Since the beginning of this century, Balanta people in Guinea-Bissau have reclaimed mangrove swamps for rice cultivation. The land is reclaimed in strips: each family has one strip of fields perpendicular to the main creek, in between the village and the creek. These form the basic drainage units. For the first few years, rice is broadcast on the newly-reclaimed land. In the third year, farmers make ridges on which the rice is transplanted. The ridges allow for leaching in the beginning of the rainy season. The size of the ridges varies with the physiographic position of the field and water availability: relatively high-lying fields have low ridges (20cm); ridges in lower-lying fields are over 1 m high.

Based on the physiographic position, soil characteristics and hydrology, a division in 6 different categories of fields has been made, each requiring its own farmers' management.

Nowadays, decreasing rainfall, increased sedimentation and changes in the social structure make the system less resiliant and external inputs are needed.

Introduction

This paper is based on research work carried out by the Rural Engineering Project Phase II, 1983-1988 (Dept. of Rural Engineering and Irrigation 1988). This bilateral project between the Governments of Guinea-Bissau and The Netherlands aimed at a better understanding of the rice production system of the local farmers, in order to develop improvements in the cultivation system to increase labour productivity. Interventions have been made in the fields of water management and soil fertility but alternative crops to replace rice have not been considered.

The project was located in Bissasséma, in the Southern coastal province of Quínara (Figure 1).

The study area

There is a prolonged dry season (November-May) and a rainy season of 5 months (June-October). Since the early '70s, the total amount of rainfall has decreased from over 2000 mm/year to an average of 1600 mm/year (1985-1987). In 1984, the lowest rainfall figure for this area has been observed (1250 mm). With decreasing rainfall, the onset and the end of the rainy season have become less reliable. August to mid-September is the wettest period: a maximum of 300 mm per 10 days has been measured during this period.

A schematic cross-section of the landscape (Figure 2) shows three major elements:

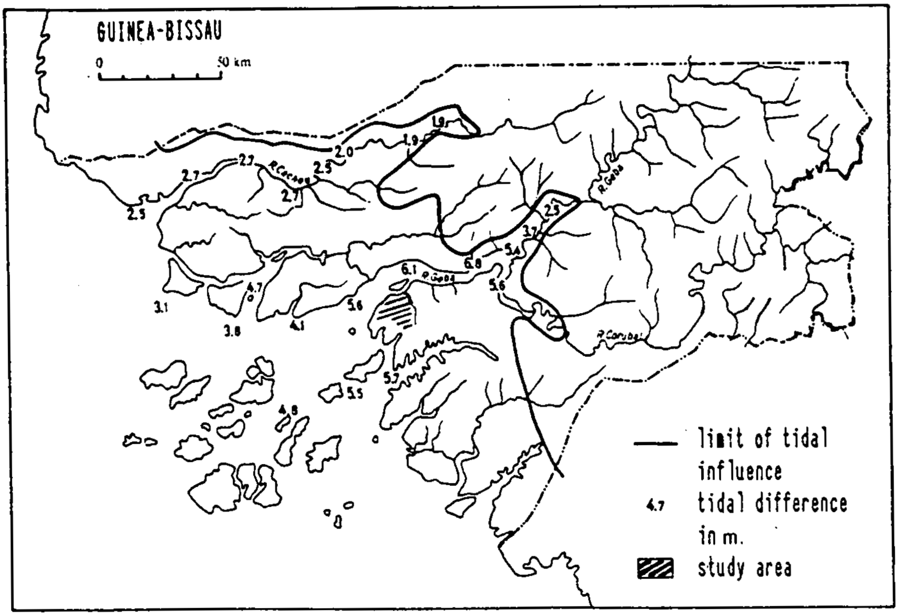


Figure 1 Location of the study area

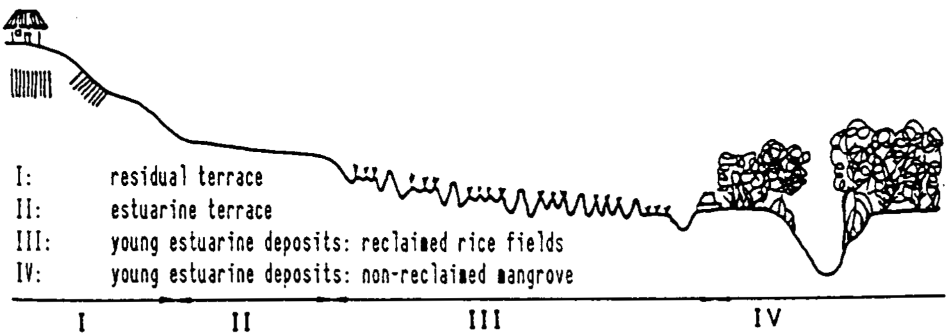


Figure 2 Schematic cross-section of the landscape, showing the three major landscape elements

the so-called residual landscape, the estuarine terrace, and the younger estuarine deposits.

On the flat to undulating residual landscape (maximum 30 m above present mean sea level) villages are situated, surrounded by forests and savanna. The soils are mainly Oxisols, Ultisols and Inceptisols. Drainage varies significantly: under the forest vegetation well drained soils occur, while soils under savanna vegetation are poorly to moderately well drained.

Sulphidic sediments accumulated following land subsidence and sea level rise about 30 000 years ago. In this environment, mangrove (predominantly *Rhizophora*) flourished along the creeks, and barren salt flats were found on the somewhat elevated deposits. These sulphidic soils turned into acid sulfate soils during the sea level fall of 5000-3500 years ago when the estuarine terrace was formed (marine terrace of Nouakchott). Now the terrace is several metres above mean sea level. The soils are classified as Rhodic (Sulfic) Humaquepts (imperfectly drained) and Rhodic (Humic) Sulfaquepts (poorly drained). Nowadays, the terrace is mainly covered by grasses, some cashew and planted cassava.

The sea level fall led to erosion of part of the terrace. During the more recent sea level rise, estuarine clays have been deposited under *Rhizophora* and *Avicennia*. The sulphidic materials have been partially covered by sediments low in pyrite.

In the study area, 75 per cent of these deposits (zero to several metres above present MSL, 1-2 m below the terrace) have been reclaimed. Jarosite has developed at 25-125 cm depth but physical ripening has been limited to the upper 50-75 cm of the profile. In the well drained, usually higher lying areas, Aeric and/or Salic Sulfaquents, Sulfaquepts, Humaquepts and Tropaquepts occur. In the poorly drained, lower-lying areas, Sulfic Tropaquents and Tropaquepts prevail. The reclaimed lands are in use as rice fields or have been abandoned. Soils still under mangrove are Sulfaquents and Aeric (Sulfic) Hydraquents.

The Balanta people

At the end of the last century many Balanta people moved from the northern provinces, close to Bissau, to the southern provinces of Tombali and Quínara. They established villages on the residual landscape, continued their traditional rice cultivation system on the estuarine terrace and started reclaiming lands on the younger estuarine deposits. Rice is their staple crop and fulfills an important role in the animist Balanta society as trade ware, for labour as well as other products, and in ceremonies. Other crops include cassava, sweet potato and maize. Salt mining and wine and liquor production are among the other economic activities. Livestock (cattle) are kept for ceremonial use and as a way to keep savings.

Before the liberation war (1963-1974), in which the Balanta people played a major role, a rice surplus was produced. During the war, many people had to move and abandon their rice fields. Since then rice production has never reached its pre-war level. The society has changed and many young people have left the villages. Although the male village elders still decide on social and agricultural affairs, it is not possible anymore to organize the working groups of young men during the dry season and during land preparation time.

Land reclamation

The Balanta people in Quínara started land reclamation about 80 years ago. In the mangrove area, dikes of 1 m high and 3 m wide were constructed to exclude the tidal water from the lands to be reclaimed. The height of the dikes is about 10 cm above the highest flood level. The construction of the dike is communal village work. One year after reclamation, the dying mangrove is removed. The land is divided amongst the farmers, in strips, 15-30 m wide, perpendicular to the main creek, in between the village and the creek. Consequently, each farmer has a variety of higher as well as lower-lying rice fields, which are called bolanhas.

The second year after reclamation, rice is broadcast on the cleared lands. In the third year, farmers start land preparation with their local spade (arado). Horizontal layers of about 8 cm thick are turned upside down to make ridges and furrows perpendicular to the slope. This work can be done only after the soil has been saturated. The ridges vary in height from 20 cm in the high-lying fields to over 60 cm in the low-lying fields. The latter are prepared first as they are saturated earlier.

The size of the fields within a strip depends on the slope. Sloping strips require smaller fields than flat strips to obtain an optimal water level where all ridges are equally inundated with rainwater. The water level is regulated by opening the bunds between the fields and, finally, by opening the outer dike to the creek.

Fields are not fertilized but, during land preparation, last years' ridge is turned over to become a furrow. The rice stubble ends up at the bottom of last years' furrow, which becomes the new ridge.

Local varieties of rice are sown in seed beds which are prepared on the upland. In the same way as on the rice fields, ridges are made after the first 200 mm of rainfall. They may be fertilized with farmyard manure. The seedlings remain in the seed beds for 3-10 weeks. Transplanting can be done as soon as all fields are prepared, after 650-750 mm of rainfall. Before transplanting the whole field, farmers plant about 10 hills to check whether the seedlings survive. First, the high-lying fields are transplanted, as they will fall dry soon after the rains have stopped. Rice is transplanted on top of the ridges. Most farmers do not remove weeds. Harvest takes place 115-135 days after sowing.

In the period of 1985-1987 a mean yield of 1100 kg paddy/rice field was recorded. A maximum of 3750 kg/ha was recorded in the zero plot of a fertilizer trial.

Per family (5.1 persons), about 2.5 ha is planted each year, which requires about 225 working days from land preparation to threshing. Some 85 per cent of the crop is kept for home consumption and seed. The remainder is used for trade and ceremonies.

Characterization of the different rice fields

During 3 rainy seasons (1985-87), soil characteristics, hydrology, crop-performance and farmers' practises have been monitored along 4 transects in the study area. In between the rainy seasons, soil characteristics have been monitored. Two of the 4 transects represented traditional drainage units, originally being the fields of one family.

Six categories of fields could be distinguished. The major distinction is made between high-lying fields and low-lying fields. High-lying fields are characterized by low ridges (< 20 cm). Land preparation, transplanting and harvesting are carried out early, and early-maturing varieties are used. These high-lying fields are subdivided as follows:

1) Fields with favourable soil properties;
2) Fields neighbouring the terrace;
3) Fields with salinity problems;
4) Fields with limited drainage.

Low-lying fields (part of the present or former drainage system) have higher ridges. Land preparation is done immediately after the rainy season or at the onset of the

rainy season. Late-maturing varieties are transplanted after the water level has reached its peak. These low-lying fields are subdivided into:
5) Fields with sufficient drainage;
6) Fields with limited drainage.

1) High-lying fields with favourable soil characteristics
These fields have favourable soil characteristics (Table 1) so crop yields are determined by total rainfall, rainfall distribution and the farmers' practices. Farmers use these fields almost every year.

During the dry season salinity and acidity increase in the topsoil due to redistribution of salts and acids in the upper 60 cm of the profile. Oxidation does not contribute to the acidity (van den Elshout 1987). When the rainy season starts, the ridges are leached. When bunds in between fields are opened, the leaching water can be flushed to low-lying fields and to the creeks.

Rice is transplanted as early as possible, because water availability at the end of the rainy season is the most limiting factor. Fields fall dry at the end of October or, in somewhat wetter years, by mid November. Fields which have been transplanted late always yield less than the mean yield for fields in this category. In fields where the water availability is limited, irregular crop stands are observed.

2) Fields neighbouring the terrace
These fields, although close to the villages, are not used very often. When fields are not used, the ridges slump which reduces the possibility of leaching. These soils have relatively low pH values, caused by seepage from the terrace. Seepage also brings Fe and Al into the rice fields, making these fields unsuitable for early transplanting. As these fields are also the first ones to fall dry after the rains have stopped, the growing season is too short for rice under the present hydrology regime.

3) High-lying fields suffering from salinity
Fields suffering from salinity are located close to the tidal creeks. During the dry sea-

Table 1a pH (1:2.5) and EC (1:2.5) of the ridges (0–20 cm) and the standing water (not diluted) in the fields of category 1

	pH	EC (mS cm^{-1})
Soil, dry season	4.0	1–6
Soil, planting time	4.6	1–22
Soil, rainy season	4.5–6.0	< 11
Standing water	4.5–6.0	1

Table 1b Some field and yield characteristics of the fields of category 1

Mean height of the ridges (cm)	17
Mean max. water level on top of the ridges (cm)	17
Mean paddy yield (kg ha^{-1}), 32 observations	1220
Min. and max. paddy yield measured (kg ha^{-1})	370–3750

Table 2a pH (1:2.5) and EC (1:2.5) of the ridges (0–20 cm) and the standing water (not diluted) in the fields of category 2

	pH	EC (mS cm^{-1})
Soil, dry season	3.5–4.0	2.5–4
Soil, planting time	4.0	2.4
Soil, rainy season	3.5–5.0	2–4
Standing water	3.5–5.0	< 1

Table 2b Some field and yield characteristics of the fields of category 2

Mean height of the ridges (cm)	10
Mean max. water level on top of the ridges (cm)	15
Paddy yield (kg ha^{-1}), observation	950

son, evaporation of the saline groundwater increases the salinity of the topsoil. This can be reduced at the beginning of the rainy season to a lower but still critical level. During the rainy season, the tidal creeks remain brackish up to 10 km inland. The highest spring tides occur in August and September and, although farmers check the outer dikes very often during this period, only proper maintenance can prevent the dike from breaking. Crops have often been destroyed by saline water intrusion.

The construction of dams to prevent saline water intrusion into the creeks has not proved successful. In the study area, one large creek has been closed by a sluice; this resulted in a drastic lowering of the watertable (1.2 m) and oxidation of the subsoil so that all the fields had to be abandoned (van den Elshout 1987).

As the salinity is increasing rapidly with decreasing water level in the field, the need for early transplanting is greater than in the fields of category 1. Acidity in the topsoil is not a problem, as these fields are reclaimed from levees and raised tidal flats under *Avicennia* that have no pyrite in the topsoil. Only very few fields of this category are in use.

Table 3a pH (1:2.5) and EC (1:2.5) of the ridges (0–20 cm) and the standing water (not diluted) in the fields of category 3

	pH	EC (mS cm^{-1})
Soil, dry season	4.0–5.0	3.5–16.0
Soil, planting time	5.5	3.2
Soil, rainy season	4.5–6.5	1.5–3.0
Standing water	4.0–7.5	1.5–16.0

Table 3b Some field and yield characteristics of the fields of category 3

Mean height of the ridges	12
Mean max. water level on top of the ridges (cm)	20
Mean paddy yield (kg ha^{-1}), 7 observations	340
Min. and max. paddy yield measured (kg ha^{-1})	0–1650

4) High-lying fields with limited drainage

The physiographic position of these fields is comparable to the fields of category 1 but, due to the very limited drainage possibilities of the surrounding low-lying fields, fields of category 4 have too high water levels and limited possibilities for flushing. Salinity is not a problem but pH values are low. With the decreasing water level at the end of the rainy season, the pH decreases rapidly.

Farmers who plant in good time before the peak water level in the fields, may obtain good yields. When rice is planted after the peak water level (end of October), the growing period becomes too short (fields fall dry mid December). Many of these fields are flooded too deeply to consider rice cultivation.

5) Low-lying fields with sufficient drainage

Low fields with sufficient drainage give the highest yields in the study area. Ridges are high, which increases possible rooting depth, the availability of nutrients, and the possibilities for leaching. Because fields in the depression can drain towards a creek, the fields are flushed as well. During the dry season, saline water can be taken in through the outer dike so that the farmers can work the soil during the dry season. This is an advantage since the construction of high ridges is time-consuming and labour is scarce. Unfortunately, the surface area of the category is small.

Van den Elshout (1987) showed that the intake of saline water has no influence on the salinity of the fields in the following growing season. According to the farmers, saline water kills weeds very efficiently.

Water is available in very large quantities and fields remain wet until January. Hence salinity and acidity do not pose problems; apparently sufficient dilution takes place. As the present rice varieties do not grow fast enough to follow the increasing water level at the beginning of the rainy season, rice is transplanted at the end of September, after the peak water level. Harvesting takes place in December-January.

6) Low-lying fields with limited drainage

Intrinsically, the possibilities of these fields should be similar to the former category:

Table 4a pH (1:2.5) and EC (1:2.5) of the ridges (0–20 cm) and the standing water (not diluted) in the fields of category 4

	pH	EC (mS cm^{-1})
Soil, dry season	3.8–4.5	< 2.0
Soil, planting time	4.5	1.2
Soil, rainy season	3.5–5.4	< 1.0
Standing water	4.0–5.0	< 1.0

Table 4b Some field and yield characteristics of the fields of category 4

Mean height of the ridges (cm)	10
Mean max. water level on top of the ridges (cm)	31
Mean paddy yield (kg ha^{-1}), 7 observations	1010
Min. and max. paddy yield measured (kg ha^{-1})	450–2180

Table 5a pH (1:2.5) and EC (1:2.5) of the ridges (0–20 cm) and the standing water (not diluted) in the fields of category 5

	pH	EC (mS cm^{-1})
Soil, dry season	4.5	3.0–6.0
Soil, rainy season	4.5–5.5	1.0–4.0
Standing water	4.0–5.0	2.0–6.0

Table 5b Some field and yield characteristics of the fields of category 5

Mean height of the ridges (cm)	34
Mean max. water level on top of the ridges (cm)	31
Mean paddy yield (kg ha^{-1}), 7 observations	1730
Min. and max. paddy yield measured (kg ha^{-1})	620–2730

ridges are high and water is plentiful. However, drainage possibilities are limited due to the low drainage capacity of the creek.

The water level in the fields increases faster than in the fields of category 5 and, although the ridges are leached, there are no possibilities for draining acidity and salinity. The salinity and acidity originate from the fields in the depression as well as from the surrounding high-lying fields. Farmers transplant when the water level in the fields is decreasing. At the same time, pH decreases rapidly and EC increases, resulting in poor crop performance.

The future of the system

Farmers make optimal use of the natural resources of the area. The rice farming system has flexibility that has enabled it to continue for 5 generations. However, rainfall has now decreased and labour availability is less, due to migration in the dry season, so

Table 6a pH (1:2.5) and EC (1:2.5) of the ridges (0–20 cm) and the standing water (not diluted) in the fields of category 6

	pH	EC (mS cm^{-1})
Soil, dry season	3.5–4.0	< 8.0
Soil, rainy season	4.0–4.5	1.0–3.5
Standing water	3.5–4.0	1.0–5.0

Table 6b Some field and yield characteristics of the fields of category 6

Mean height of the ridges (cm)	24
Mean max. water level on top of the ridges (cm)	35
Mean paddy yield (kg ha^{-1}), 7 observations	350
Min. and max. paddy yield measured (kg ha^{-1})	270–1020

the resiliance of the system is less. Traditional ceremonies are held less frequently, and only in years when there has been a reasonable rice yield, as in 1986.

To maintain the pillar on which the Balanta society is built – the rice cultivation system – external inputs will be needed. Experiments with interventions of the project showed that the construction of small drainage structures, which do allow saline water intake, can help farmers with their water management. The construction should not induce lowering of the groundwater table, and water management units should be adjusted to the present organizational structures. Sedimentation should be avoided and, therefore, drainage devices should be built as far upstream as possible.

Fertilizer trials showed that the application of 30 kg N and 30 kg P_2O_5 in fields with mean yields of 1000 kg paddy ha^{-1} could increase the yield by about 500 kg paddy ha^{-1} (Ukkerman and van Gent 1989). The use of fertilizers can be decided by the individual farmer, provided that fertilizers are available when they are needed.

References

Department of Rural Engineering and Irrigation 1988. Rural engineering project, Bissàssema, Guinea-Bissau. Final report Phase II. Agricultural University Wageningen (Dutch and Portugese)
Volume I: Main report, 74 p.
Volume II: Bolanha rice farming, 70 p.
Volume III: Rural engineering, 85 p.
Volume IV: Soil fertility, 79 p.
Volume V: Soils, 50 p. and 4 maps
Volume VII: Bibliography

Elshout, S. van den 1987. Various aspects of acid sulphate soils: salinity, acidity and fertility. Department of Soil Science and Geology, Agricultural University Wageningen

Moormann, F.R. and N. van Breemen 1978. Rice: soil, water, land. IRRI. Los Baños

Pons, L.J., P.A.M. van Gent and N.M. Pons-Ghitulescu. Soil formation in an acid sulphate soil sequence near Tite, Quínara district, Guinea-Bissau. Paper presented at the 3rd International Congress on Acid Sulphate Soils, Dakar

Ukkerman, H.R. and P.A.M. van Gent 1989. Fertilizer trials in the bolanha rice cropping system used by the Balanta people of Guinea-Bissau. Acid sulphate soils newsletter No. 2, ISSS, Wageningen

Zaag, P. van der 1986. Rice production in the Basse-Casamance, Senegal: from surplus to subsistence. Department of Rural Engineering and Irrigation, Agricultural University Wageningen (Dutch)

Farmers' experiences in using acid sulphate soils: Some examples from tidal swampland of southern Kalimantan, Indonesia

Muhrizal Sarwani[1], Mansur Lande[1], and Wim Andriesse[2]

[1] Banjarbaru Research Institute for Food Crops (BARIF), P.O. Box 31, Banjarbaru 70712, Kal-Sel, Indonesia
[2] DLO-The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen, The Netherlands

Abstract

Millions of hectares of tidal swamplands in Indonesia have been opened-up by two ethnic population groups, the Banjarese in southern Kalimantan and the Buginese in Sumatra. They are very skillful at reclaiming coastal swamps with acid sulphate soils for the cultivation of rice as well as other crops such as coconut, citrus and rambutan. Farmers' management in utilizing coastal swamp soils is greatly influenced by socio-economic and micro-ecological conditions. The latter vary according to natural land, water and vegetation. The Banjarese farmers apply escape mechanisms in their cropping system, starting from their water management system, the land preparation and subsequent transplantation sequence as well as in the choice of the varieties grown and, eventually, the switch to crops other than rice. Their indigenous knowledge is very valuable for, and applicable in land evaluation, land use planning and land development projects.

Introduction

Tidal swamplands are among the major natural resources of Indonesia. These vast lands occur mostly along the coasts of Sumatra, Kalimantan and Irian Jaya. In their natural state, they are rich in plant and animal life. Also, they offer tremendous potential for food production as well as space for the rapidly expanding population of Indonesia. Prospects for swampland development are great, indeed, but so are the problems. Soil constraints severely limit agricultural development.

Soils in the tidal swamps are mainly of marine/estuarine alluvial origin and peats (Driessen and Sudjadi 1984). Soils developed in alluvium include both actual and potential acid sulphate soils while most of the peats in Indonesia are underlain by pyritic sediments. These potentially acid conditions severely restrict agricultural productivity and development options. There are some 1.5 to 2 million ha of these acid sulphate soils in Indonesia (NEDECO/Euroconsult/BIEC 1984).

Reclamation of tidal swampland in southern Kalimantan has been carried out over some hundred years already by the Banjarese population who live mainly along the coast and, further inland, on the river floodplains of the area. Only in the 1920s, large scale reclamation started, especially near Banjarmasin (Figure 1). Some 40 years later, by 1965, almost 65 000 ha of tidal swampland had been reclaimed by the Banjarese in South Kalimantan, mainly along the banks of the Barito river (Schophuys 1969; Idak 1982).

It is estimated that, in total, the Banjarese in Kalimantan have opened-up approximately 1 million ha of swampland (BARIF 1985) but because they switch to crops other than rice or have abandoned the older lands, the remaining Banjarese riceland is presently only about 165 000 ha in southern Kalimantan (Collier et al. 1984). In comparison, lands reclaimed in the framework of the Indonesian government's transmigration projects covered in total approximately 33 000 ha in the period 1969 to 1974, 242 000 ha between 1974 and 1979, and 396 000 ha between 1979 and 1984. Out of the latter total, some 96 500 ha are in South and Central Kalimantan provinces. These lands are earmarked for transmigrants from Java and Bali.

Farmers' techniques of, and approaches to, local and traditional cultivation are usually micro-topographically oriented (Watson and Willis 1985). This traditional approach incorporates the interaction of crop varieties, soil and water management, and socio-economic factors. There are many examples of successful management of tidal swampland in general, and of acid sulphate soils in particular, using local and traditional techniques. The following discussion puts into perspective the strategies and practices of Banjarese farmers in utilizing tidal swamplands for crop cultivation and in coping with the specific soil constraints of sulphate acidity and related toxicities. Most of the information was gathered by interviewing the farmers during extensive soil surveys in the Pulau Petak area of southern Kalimantan.

Tidal swampland of Indonesia with special reference to Pulau Petak in Southern Kalimantan

Climate

Southern Kalimantan has a humid tropical climate. Annual rainfall is between 2100 and 3200 mm with seven to nine wet months (rainfall > 100 mm). During the wet season (October/November through May/June), monthly rainfall averages 250 mm, while from July through September it is about 100 mm/month. Daily temperatures ranges between 25 and 35 °C with a slight seasonal variation, and relative humidity varies between 75 and 90 per cent.

Hydrology

Kselik (1990) has subdivided the study area into four tidal land classes (Figure 1). This classification is based on the tidal flooding regime as well as on the drainage characteristics. Type A comprises the areas between mean low tide and mean high neap tides, which are under the influence of daily flooding and drainage. Type B covers the areas between mean high neap tides and mean spring tides. These areas are flooded during spring tides only but they are subjected to daily drainage. Type C is land above spring tides but, still, under the unfluence of the tide. There is no tidal flooding in these areas but they are permanently drained. Type D land is beyond the influence of tide; there is no tidal flooding and limited drainage. The watertable in this areas drops only during the dry season.

Pulau Petak has an extensive and very intricate system of drainage canals that has been dug by the Banjarese farmers on their own initiative, as well as by government agencies that became involved in the 1970's and 80's.

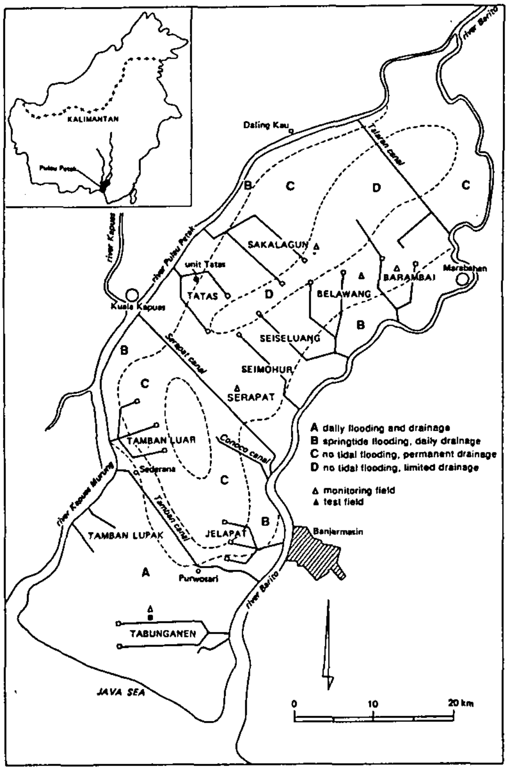


Figure 1 Location of Pulau Petak and tidal land classes (Kselik 1990)

Physiography and topography

Pulau Petak comprises five major physiographic units: alluvio-marine plains which occupy the largest area, river levees, coastal ridges, old river beds and peat domes (Janssen et al. 1990). The river levees are found along the Barito and Kapuas Murung/ Pulau Petak rivers and along old river beds. The peat domes, which at one time covered large areas, are hardly found nowadays. Reportedly, they were between 2 and 3 m thick (Van Wijk 1951). Where peat is still present, in the centre of Pulau Petak (see Figure 2), it is less than 1.5 m thick.

Over the whole area, slopes are generally less than 1 per cent but river levees and coastal ridges, both belonging to active systems as well as from former rivers or coastlines, form subdued local relief with height differences of up to 1 m.

Soils

There are two major soil types in the area (Hendro Prasetyo et al. 1990):
The soils of the alluvio-marine plains and the old river beds have a brown layer, 20-60 cm, overlying a gray layer which is generally pyritic (up to 8 per cent FeS_2). These soils are rich in organic matter (5-14 per cent), poorly drained, half to nearly ripe and most of them are mottled. The pH is between 3 and 4. A peaty thin layer (10-20 cm) overlies most of these soils. In terms of Soil Taxonomy (Soil Survey Staff 1987), they

are classified as Sulfaquents (the potential acid sulphate soils) and Sulfaquepts (the actual acid sulphate soils) (Sutrisno et al. 1990).

The soils of the levees and coastal ridges have similar texture but they are better drained, strongly mottled, nearly ripe to ripe. Their organic matter content is between 4 and 6.5 per cent and pyrite content is low (FeS_2 < 1.5 per cent). Soil reaction is slightly acid to neutral (pH 5-6). Gray pyritic subsoil occurs at greater depth (> 125 cm). In Soil Taxonomy, these soils are classified as Tropaquepts mainly.

Scattered over the island and in the remaining peat domes, peat soils occur (Figure 2).

The art of tidal swamp cultivation; some examples from Banjarese farmers

With abundant fresh water available, especially during the wet season, tidal swamps seem an ideal setting for wetland rice cultivation. This has been recognized by the Banjarese farmers in Kalimantan and the Buginese armers in Sumatra. For centuries,

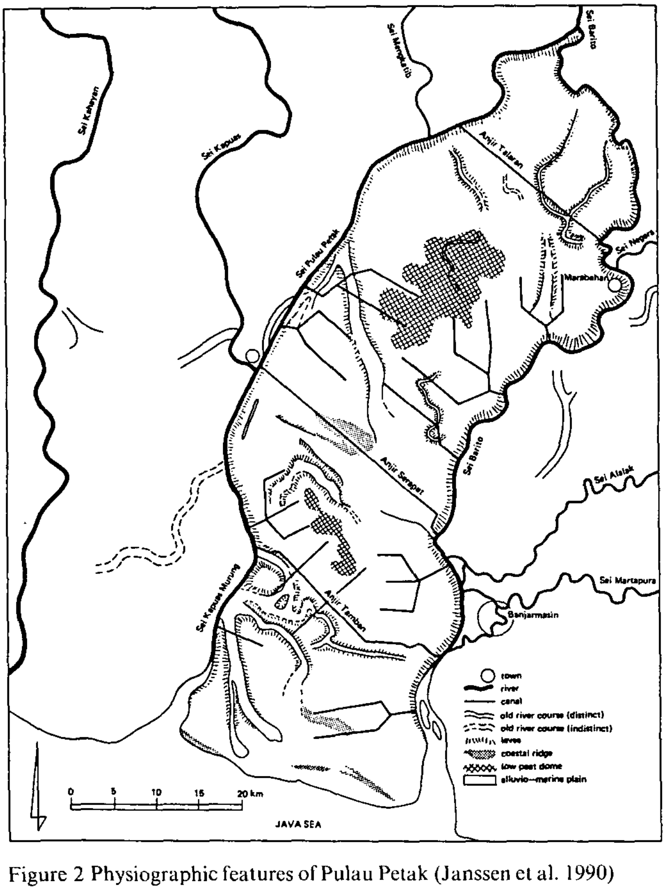


Figure 2 Physiographic features of Pulau Petak (Janssen et al. 1990)

the Banjarese have been opening-up and cultivating tidal swamplands in Kalimantan. It is believed that the Buginese, who in fact originate from Sulawesi, have learned from the Banjarese during their contacts in South and East Kalimantan. Both the Banjarese and the Buginese are very skilful at reclaiming the tidal swamps for the production of rice as well as other crops such as coconut, orange, rambutan, mango and clove (Schophuys 1969, Noorsyamsi and Hidayat 1974, Damanik 1990).

In Kalimantan, some 1 million ha of tidal swampland and in Sumatra some 0.9-1 million ha have been reclaimed by these two peoples (BARIF 1985). In Kalimantan, however, not more than 500 000 ha of these lands are presently being cultivated and only about one-third of this area is used for rice (Collier et al. 1984). In addition, some 96 500 ha of swamplands has been reclaimed in the framework of government-sponsored transmigration projects, involving the settlement of Javanese and Balinese farmers.

Choosing the land

Opening new land starts with a scrutiny of the vegetation on the banks of rivers and creeks. Dense foliage is taken by the farmers as an indicator of generally favourable soil conditions. Obviously, the slightly higher-lying, better-drained, non-potentially acid soils of the river levees and coastal ridges are preferred. Not only are the physical conditions better for settlement and for cultivation but, also, the adjacent natural water courses provide easy access. For the latter reason, of course, much spontaneous settlement and cultivation has taken place along the main canals, i.e. the Tamban, Serapat and Talaran canals, that were constructed by the government since the 1920s (Figure 1).

Nipa palm (*Nipa fruticans*) is an indicator of brackish or saline water whereas sago palm (*Metroxylon spp.*) indicates fresh water conditions. The Buginese generally avoid saline or brackish areas, the Banjarese, however, accept both areas as long as the nipa growth is not too dense, as that would reflect unripe soil conditions. The Banjarese avoid peats more than 1 m, but they do like to reclaim the land surrounding such peat domes as the good-quality water flowing from these domes is preferred for irrigation.

Land reclamation and rice cultivation

After clearing trees and shrubs from the selected site by slashing and burning, small drainage ditches are dug, called 'handils', some 0.5-1 m depth and 2-3 m wide. Their size depends on the magnitude of the tidal movement: close to the sea the handils are smaller than inland. Usually, they are dug perpendicular to the river or canal.

The Banjarese work in groups of seven to ten to dig the handils. The name handil originates from the Dutch word 'aandeel', meaning a share or part of the work (Idak 1982). The person chosen as the group leader (kepala handil) has the right to the land at the head of the handil. Usually his name is used for that of the handil. For each family, a plot of 15 × 30 depa (1 depa = 1.7 m) is marked out (Idak 1982). In larger areas, the parcels could be up to 30 × 30 depa (Collier et al. 1984). The user rights of the selected sites are awarded by the village head (kepala kampung). A family that wants more land is allowed to extend the handil further inland. People settling later may do the same (handils thus may extend up to 2-3 km inland) or they compensate those who opened up the land.

Secondary drainage ditches are built perpendicular to the handils. Near the sea, in tidal land class A, intervals between these ditches are generally 10 depa. Their depth is approximately 0.5 m and their width 0.3 m. In contrast, secondary ditches are not made in areas belonging to land class C. Instead, tabat (small weirs made of clay or ironwood) are built here, at the head of the handil, to conserve water during the cultivation cycle. The tabats are usually constructed in February when rainfall begins to decrease.

Land preparation for rice cultivation is very simple. It consists of slashing and cutting the weeds or peeling the land with a tajak, a scythe-like tool with a short handle. The cut vegetation is left in the field for 10-15 days and is then gathered into heaps which are turned over every week or so. Upon complete decomposition, this compost is spread over the land prior to planting. The land is neither plowed nor harrowed (Noorsyamsi and Hidayat 1974). The compost not only serves as a source of nutrients, but it also helps to keep the underlying soil, including any sulphidic material in a relatively reduced state (Arifin 1989).

Tidal rice is usually sown at the beginning of the wet season, in October or November, on rather dry seedbeds and the seeds are covered with ash. The seeding rate is approximately 5 kg seed for a 150 m^2 seedbed that, after two transplantings, will serve 1 ha. After 30-40 days, the seedlings are transplanted to the lowest parts of the rice field. This is repeated after 40 days into larger areas which still cover only about one-third of the total area to be planted. Final transplanting depends on the water level in the main field. On type A land, the planting should be ready by February, whereas type B or C lands are planted from March through April. Traditional, tall, photoperiodic varieties are used that take some 9 to 10 months till maturity. The crop is harvested in August-September by cutting the panicles with a knife. The yields range widely from 1 to 4 tons/ha. The higher yields are obtained on non-acidified soils (Muhrizal Sarwani, unpublished farmers' interview data). Rats are a main pest adversely affecting rice yields.

Adaptation of Banjarese cropping systems to soil changes

After some 3-5 years of cultivation, the rice yields start to decrease. The yield decline is caused by a number of factors, including acidification which is promoted by drainage and by the gradual disappearance of the peat layer. The Banjarese then gradually switch to other crops. In general, the conversion from rice-based cropping systems into coconut-based cropping systems is gradual and starts with the arrangement, in rows, of individual heaps of dug-out soil material 75 × 75 × 75 cm, called tembokan (Figure 3). On top, a small heap 30 × 30 × 30 cm of topsoil material is placed (the

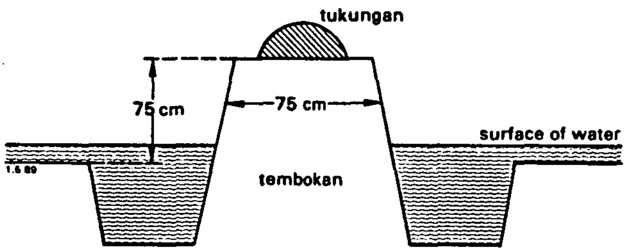


Figure 3 Cross-section of a tembokan (Arifin 1989)

tukungan) in which coconut or other seedlings are planted. Each year, new topsoil is added to the tembokan which, eventually, forms a long raised-bed, or sorjan. Acid formed in the sorjans is flushed away by tidal floods or by percolating rainwater. Throughout the years of building the sorjans, rice is cultivated in the in-between basins. Eventually, if these basins become too deep for cultivation, they may be used for fish.

Farmers are keenly aware of the higher economic returns of tree crops as compared to rice cultivation (KEPAS 1985). Earning extra income is very important with respect to a possible pilgrimage to Mecca which, within the Banjarese society, is a well established aspiration. Especially on type A lands having strong tidal influence, even if the rice yields are not decreasing, the farmers initiate tukungan across their paddy fields in order to grow coconut, orange, mango, clove and coffee. The same holds true for the higher lying areas (type B lands).

Acidified areas beyond the influence of the tides (land type C) are used for the cultivation of such acid-tolerant crops as pineapple, rambutan and ketapi (*Sandoricum koetjape*) on raised beds. Observations near the Talaran canal in the northern part of Pulau Petak showed that these crops perform very well even at soil pH between 3 and 4. Very often, the pH of the water standing on these soils is as low as 2.5.

Not all the rice land is converted, however, and commonly about three quarters of the land in Pulau Petak is left idle. Especially if subsidence and stagnating water play a role in yield decreases, the land may be abandoned altogether.

Discussion and conclusions

The Banjarese farmers have long recognized that water management, together with the use of acid- or salt-tolerant crops or crop varieties, is the key to successful management of tidal swampland in general and acid sulphate soils in particular. The handil drainage system allows limited oxidation of pyrite while toxic elements produced can be leached by the tides or rainwater. The size of the handils is adapted to either the occurrence of pyrite at shallow depths, where the handils are shallow but wide; or to the amplitude of the tidal fluctuation, if the rise and fall is great the handils are narrow an deep.

Also, the drainage intensity is adapted to the physical conditions. In the low-lying areas with daily tidal flooding, type A lands where pyrite generally occurs within 50 cm from the surface, drainage ditches are approximately 10 depa (17 m) apart. Here, flushing of acids formed in the topsoil during the dry season is enhanced by the use of brackish tidal water. On type C lands which, in Pulau Petak, contain both potential and actual acid sulphate soils, the farmers use rainwater to leach acids and toxic elements by opening the tabats two months prior to transplanting. If rainfall is insufficient, it is supplemented with the water from the remaining peat domes which is of good quality (Klepper et al. 1990). Konsten et al. (1990) found that, during the wet season, the pH of the surface water in type C lands increases gradually while the salinity of the water decreases.

Raw salt is sometimes applied to the rice fields at the beginning of the rainy season. Applications of 100-200 kg/ha are given when farmers feel that rice yields are declining. The practice is then repeated every 2 to 3 years. Raw salt replaces Al from the adsorption complex (Van Mensvoort et al. 1991) and it also alleviates iron toxicity problems in the same way as leaching with brackish water (Muhrizal Sarwani, unpublished data).

The method of land preparation is also noteworthy. By applying the ajak only, the farmers practise minimum tillage. Neither plowing nor harrowing is done. In other words, the pyrite in the subsoil is not disturbed and any peat is kept as such. At the same time, green manuring is being practised as the decomposed organic matter eventually is spread over the fields. Ottow et al. (1991) have pointed to the additional beneficial effect of organic matter in alleviating iron toxicity. The system of triple transplanting seems a typical local adaptation to acid sulphate conditions and related toxicities (Sevenhuysen et al. 1989). The use of old seedling rice plants to alleviate primary iron toxicity has been recommended in a number of studies (Noorsyamsi and Hidayat 1974; Van Breemen and Moorman 1978; Prade et al. 1988).

The surface peat layers play a key role in the cultivation of the acid sulphate soils in southern Kalimantan. Not only are they a source of nutrients but, also, they regulate loss of water due to evaporation in the dry season and they maintain reduced conditions in the soil underneath, preventing the oxidation of pyrite.

We conclude that the Banjarese farmers apply escape mechanisms in their cropping systems; starting from their water management system, the land preparation and subsequent transplantation sequence as well as in the choice of the varieties grown and, eventually, the switch to crops other than rice. Their practices are adjusted to the microtopography, hydrology and soil. Local custom calls for group participation in reclamation works, while economic and changing ecological conditions determine the decisions of individual farmers to change to crops other than rice. Tidal swamp cultivation by the Banjarese has proven to be a sustainable and equitable system (KEPAS 1985) though at low level of productivity. Research as well as development projects on acid sulphate soils, and tidal swampland in general, can benefit from integration of the knowledge and experience of local farmers (Watson and Willis 1985; Noorsyamsi and Sarwani 1989). This interaction could also facilitate acceptance of new technology by the local farmers.

References

Arifin 1989. Land use and land evaluation in Pulau Petak. In: Genesis, classification, land evaluation and use of acid sulphate soils: Report of a general consultancy mission. Survey Component. LAWOO/AARD Mission Report 18. Research Program on Acid Sulphate Soils in the Humid Tropics. LAWOO, Wageningen. pp. 23-28

BARIF 1985. A masterplan of Banjarbaru Research Institute for Food Crops: 1985 to 2000. BARIF, Banjarbaru

Breemen, N. van and F.R. Moorman 1978. Iron toxic soils. In: Soils and Rice. International Rice Research Institute, Los Baños. pp. 781-800

Collier, W., B. Rachman, Supardi, B. Ali, Rahmadi and A.M. Jurindar 1984. Cropping systems and marginal land development in the coastal wetlands of Indonesia. Workshop on research priorities in tidal swamp rice. Banjarmasin, June 1981. IRRI, Los Baños

Damanik, M. 1990. Farming systems and productivity in Pulau Petak. In: AARD/LAWOO Papers Workshop in Acid Sulphate Soils in the Humid Tropics. Bogor, November 1990. AARD, Bogor. pp. 204-209

Driessen, P.M. and M. Sudjadi 1984. Soils and specific soil problems of tidal swamps. In: IRRI 1984. Workshop on research priorities in tidal swamp rice. Banjarmasin, June 1981. IRRI, Los Baños. pp. 143-160

Hendro Prasetyo, J.A.M. Janssen and Alkasuma 1990. Landscape and soil genesis in Pulau Petak. In: AARD/LAWOO Papers Workshop on Acid Sulphate Soils in the Humid Tropics. Bogor, November 1990. AARD, Bogor. pp. 18-29

Idak, H. 1982. Development and history of rice cultivation in South Kalimantan, Indonesia. Mimeograph, Banjarmasin

Janssen, J.A.M., Hendry Prasetyo, Alkasuma and W. Andriesse 1990. Landscape genesis and physiography of Pulau Petak as basis for soil mapping. LAWWO/AARD Scientific Report No. 18. Research Programme on Acid Sulphate Soils in the Humid Tropics. LAWOO, Wageningen

KEPAS 1985. Tidal swamp agro-ecosystem of Southern Kalimantan. Workshop report on the sustainable intensification of tidal swamplands in Indonesia. Banjarmasin, South Kalimantan. July 1983. Kelompok Penelitian Agro-ekosistem, Agency for Agricultural Research and Development, Jakarta

Klepper, O. Gt.M. Hatta, Sunardi and H.D. Rijksen 1990. Organic matter input and decomposition before and after development of acid sulphate conditions on Pulau Petak, Kalimantan. In: AARD/LAWOO Papers Workshop on acid sulphate soils in the humid tropics. Bogor, November 1990. AARD, Bogor

Konsten, C.J.M., Supardi Suping, I.B. Aribawa and I. Putu Gedjer Widjaja-Adhi 1990. Chemical processes in acid sulphate soils in Pulau Petak, South and Central Kalimantan. In: AARD/LAWOO Papers Workshop on acid sulphate soils in the humid tropics. Bogor, November 1990. AARD, Bogor. pp. 109-135

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

Mensvoort, M.E.F. van, Duong Van Ni and J. van der Schans 1991. Improvement of acid sulphate soils by leaching with salt or brackish water. In: Deturck, P. and F.N. Ponnamperuma (editors) 1991: Rice production on acid soils of the tropics. Inst. Fundamental Studies, Kandy

NEDECO/Euroconsult/BIEC 1984. Nationwide study of coastal and near-coastal swampland in Sumatra, Kalimantan and Irian Jaya. Tidal Swampland Development Project (P4S), Directorate General of Water Resources Development, Min. of Public Works, Jakarta

Noorsyamsi, H. and O.O. Hidayat 1974. The tidal swamp rice culture in South Kalimantan. Contrib. Cent. Res. Inst. Agric. Indonesia. 10: 1-8

Noorsyamsi, H. and M. Sarwani 1989. Management of tidal swampland for food crop Southern Kalimantan experiences. IARD Journal (11): 18-24

Ottow, J.C.G., K. Prade, W. Bertenbreiter and V.A. Jacq 1991. Strategies to alleviate iron toxicity of wetland rice on acid sulphate soils. In: Deturck, P. and F.N. Ponnamperuma (editors): Rice production on acid soils of the tropics. Inst. Fundamental Studies, Kandy

Prade, K., J.C.G. Ottow and V. Jacq 1988. Excessive iron uptake (iron toxicity) by wetland rice (*Oryza sativa* L.) on acid sulphate soils in the Casamance, Senegal. In: Dost, H. (editor): Selected papers of the Dakar symposium on acid sulphate soils. ILRI Publ. no. 44, ILRI, Wageningen. pp. 150-162

Schophuys, H.J. 1969. Prespectives of lifting water for irrigation and drainage in Indonesia in general, in Sumatra and Kalimantan in particular. Mimeograph. Bogor

Sevenhuysen, R.J., S. Saragih and R.A.L. Kselik 1989. Water management in rice fields on acid sulphate soils in Indonesia. LAWOO/AARD Scientific Report no. 9. Research Programme on acid sulphate soils in the humid tropics. LAWOO, Wageningen

Soil Survey Staff 1987. Keys to Soil Taxonomy (third printing). SMSS Technical Monograph No. 6. Cornell Univ., Ithaca, N.Y.

Sutrisno, J.A.M. Janssen and Alkasuma 1990. Classification of acid sulphate soils: a proposal for improvements of the Soil Taxonomy System. In: AARD/LAWOO Papers Workshop on acid sulphate soils in the humid tropics. Bogor, November 1990. AARD, Bogor. pp. 71-80

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

Wijk, C.L. van 1951. Soil survey of tidal swamps of South Borneo in connection with the agricultural possibilies. Contr. Gen. Res. Sta. No. 123

Cultivation of sugarcane on acid sulphate soils in the Mekong delta

Truong thi Nga, Duong van Ni and Vo-Tong Xuan

Soil Science Department, University of Cantho, Cantho, Vietnam

Abstract

Sugarcane has long been a profitable crop on acid sulphate soils in the Mekong Delta. However, little attention was paid to cultural practices. Following interviews with farmers about on their normal cultural practices, soil and plant samples were taken for chemical analysis, and soil-plant relationships were analyzed.

Sugarcane can grow in pH 3.5-5 with aluminium concentrations of up to 17 cmol(+) kg^{-1} soil. Cane yields on such soils were 60-80 t ha^{-1}. Only one variety, Co 775, was planted by the farmers and it seems to possess high tolerance to aluminium toxicity. On slightly acid soil, urea (50-250 kg N ha^{-1}) and superphosphate (0-25 kg P ha^{-1}) were applied. On acid soils (Sulfic Tropaquepts), no fertilizer was applied. Aluminium concentration affected the growth of sugarcane but, with fertilizer application, cane yield was increased and aluminium concentration in the leaves was low. The presence of aluminium caused deficiency of K, Ca, Mg in the leaves of sugarcane.

Introduction

Sugarcane is an important crop in the Mekong Delta (Derevier 1991), satisfying local demand for sugar, while the by-products such as bagasse for fuel or paper making and molasses for industrial processing can bring additional income to cane growers. However, till now, little attention has been paid to improving farmers' cultivation on acid sulphate soils. In this study, farmers were interviewed on all aspects of cane cultivation, and plant and soil analyses were performed to determine the nutritional status of sugarcane on acid sulphate soils, with a view to finding optimum fertilizer applications and cultivation techniques.

Materials and methods

The study was carried out in the villages of Vi thuy, Hoa luu, Hiep hung, and Hoa an, in Hau giang province. Twenty farmers in each village were interviewed. In each of these locations, sampling sites were selected (22 in Vi thuy, 11 in Hoa luu, 22 in Hiep hung and 18 in Hoa an). At each site, one composite soil sample was taken over 1000 m^2, depth 0-20 cm. The soil samples were analyzed for pH, EC (both in 1:2.5 extract), extractable acidity and aluminium in 1N KCl extract, total N, exchangeable K, Ca, Mg in 1N ammonium acetate extract. At each corresponding location, plant growth conditions were described and plant samples were taken for analysis. The plant samples were analyzed for N, P, K, Ca, Mg, and Al after wet digestion.

Results

Cultivation techniques

Sugarcane variety Co 775 was the most widely used. It has a violet rind and is said to be resistant to attacks by insects, and tolerant of acidity and drought. The maximum yield registered was about 100 tons raw cane ha^{-1} compared with common yields of 60-120 t ha^{-1} in other soils of the Mekong Delta.

Cane is cultivated on raised beds, rarely on the natural surface. This is necessary because the land is flooded in the rainy season. The height of the beds depends on the flood level. In general, beds are 20-40 cm above the flood level. In the dry season, watertables are generally at 80-100 cm below the surface, which might result in water stress to the plants. Some farmers irrigate sugarcane by sprinkling water over the top of the raised beds by a pump or by hand. In most cases, however, irrigation is not applied, or only when cane is planted in the dry season.

Cane is mainly planted from December to February. March to April is not suitable for cane growth because the farmers must then irrigate several times during early growth. Harvesting is from September to January. Many farmers harvest whenever the price of cane is high. In the study, 2 or 3 ratoon crops are also taken, but cane is sometimes grown in rotation with rice (e.g. in Phung hiep district, Haugiang). In Thot not district (Hau giang), farmers plant sugarcane as annual crop because the flood level is high. Sugarcane is planted directly in the field without raised beds in January and is harvested in September. Then rice is planted in September and harvested in December.

Usually, special plots are cultivated for raising cuttings. Cuttings are placed close together and watered regularly. When roots develop, the cuttings are transplanted in rows. The advantages of this system are not clear – a strong root system, possibly, but time is lost this way.

Commonly, cuttings are planted end to end, one row on each raised bed which is 4-6 m wide and 50-250 m long. Some farmers plant two rows or placing the cuttings parallel. The distance between rows is 1 m. Plant density is high at about 80 000 plants ha^{-1}. This seems a waste of cuttings. In addition, double rows or dense planting leads to competition for light, limiting growth.

At two, four and six months after planting, hilling up is done to stimulate the development of the root system. Simultaneously, fertilizers are applied to the rows. Most commonly, farmers apply urea or diammoniumphosphate. The quantity depends on the financial capacity of each family, varying from 50 to 250 kg N ha^{-1}. Only a few farmers apply phosphorus fertilizer. Potassium is not applied at all and farmers claim that potassium would inhibit plant growth.

Dead leaves are removed regularly, 2 or 3 times during crop growth. This is to control pests and insects. Many farmers, however, do not do this regularly, considering it to be too laborious.

Sugarcane flowers in September. Many farmers let this occur naturally. Others use chemicals such as 2,4-D to harvest their canes after 8-9 months, just before flowering, because they have observed that flowering lowers the sugar content but they were not aware that premature harvesting also gives plants with low sugar content.

Economic return
At Thot Not, on non-acid soil, total outlay for rice was VND (Vietnamese Dong) 2.5 million per ha to obtain 5 t rice ha^{-1}, giving a VND 2.5 million profit. In comparison, outlay for sugarcane was VND 6.5 million ha^{-1}, and a yield of 120 t ha^{-1}, giving a 6.75 million profit.

This calculation was based on sugarcane planting as an annual crop. If it is ratooned, the difference will be higher, because cane growers spend on land preparation only once in three years. In an acid soil such as Hoa an, there is still a relative advantage in growing sugarcane, but with higher investments (see Table 1).

Yield and yield components
On fertile soils and with sufficient water, sugarcane can tiller up to 8 plants per hill. On acid sulphate soils with little or no fertilizers applied, tillering is reduced greatly, not more than 3-5 plants per hill. This is a reason why farmers increased planting density. Maximum height of sugarcane can be 3.5-4 m at harvesting time. At Hoa an, 9-month-old cane about to be harvested was only 145 to 250 cm high. Plants also showed a low number of internodes, 18-23 per plant and internodes were between 5 to 12 cm long. These yield components reflect well the nutritional and water supply status of sugarcane (Blackburn 1984). The diameter of the plants at harvest was 2.5-3 cm. The average weight was about 1.1 kg per cane.

Soil and plant analysis
Cane yields are low on acid sulphate soils. Chemical analyses of plant and corresponding soil samples can shed some light on their relationships.

Results for the Vi thuy village showed low pH values (3.7-4.6). Extractable aluminium varied strongly from less than 1 to over 8 cmol(+) kg^{-1} soil. The soils were relatively rich in nitrogen (about 0.2 per cent) and poor in P (0.06 per cent). Exchangeable potassium was at a good level, 0.3 cmol(+)kg^{-1} soil. Plant analysis showed a particularly low content of calcium (see Table 3) of only 0.05 per cent average. Nitrogen was also low (average 1.2 compared with around 2 per cent normal). P and K were normal. Farmers only apply a small quantity of phosphorus which is, apparently, enough, but Ca is not applied. The aluminium content in leaves averaged 200 mg kg^{-1}.

Table 1 Comparison of incomes per hectare (in VN Dong) between rice and sugarcane grown in Hoa an station (1991)

Expenditures	Rice	Sugarcane
Land preparation	450 000	400 000
Planting material	200 000	800 000
Weeding, hilling up	150 000	1 000 000
Fertilizers	750 000	750 000
Insecticides	100 000	
Harvesting	200 000	500 000
Total	1 850 000	2 700 000
Income	4 000 kg rice 1 000 VNd kg^{-1}	60 tonnes cane 110 000 VNd t^{-1}
Profit	2 150 000	3 150 000

7000 VNd = U.S. $1

At Hoa an station, aluminium in soil was high 6.7-12.3 cmol(+)kg^{-1} soil. These values, although they are not a direct measure of the growth of sugarcane because they are the total content, indicate an influence on cane development. High aluminium can fix phosphorus (Clarkson 1967) and compete with calcium and magnesium outside and inside the cell wall (Siegel and Haugg 1982, Grimme 1980). Aluminium can destroy cells of roots, thereby limiting the uptake of water and nutrients. Leaf analysis showed that:

- The percentage of N varied from 0.07-1.3 per cent;
- The percentage of phosphorus varied from 0.2-0.37 per cent;
- Soil K was 0.1-1.5 cmol(+)kg^{-1}.

The results indicate that the sugarcane lacked nitrogen, potassium and had a low phosphorus content. No fertilizer was applied at Hoa an station. Phosphorus has a striking effect on root and shoot development of cane. In acid sulphate soils, with high aluminium, P is fixed by aluminium inside and outside of the root system (Clarkson 1967). The immobilisation of phosphorus might be prevented by addition of more phosphorus in the form of apatite or superphosphate (Mengel and Kirby 1989).

Aluminium toxicity is an important problem in sugarcane growing regions with acid soils. In our case, the range of aluminium was 6-12 cmol(+)kg^{-1} which could inhibit root growth, although we did not find any correlation between soil and leaf analysis.

Al-soil and N-leaf $r = 0.094$
Al-soil and P-leaf $r = 0.071$
Al-soil and Ca-leaf $r = 0.122$
Al-soil and Mg-leaf $r = 0.202$

Many authors (inter alia Cooke 1982) have discussed soil and leaf analysis and concluded that it is difficult to establish correlations of these parameters. But in the greenhouse, where we can control the test conditions, the correlation may be good. To tell us when to fertilize and with what element to achieve optimum yields, leaf analysis is more reliable than soil analysis.

Table 2 Comparison of some soil analysis

	Vithuy	Hoa luu	Hiep hung	Hoa an
per cent N	0.18	0.23	0.23	0.14
Total P (per cent)	0.05	0.07	0.068	0.062
Available P (mg kg^{-1})	47	56	45	–
K (cmol(+) kg^{-1})	0.3	0.3	0.3	0.1
pH (H_2O)	4.2	4.5	4.7	3.4
pH (KCl)	3.85	3.51	3.5	–
ECE ($mscm^{-1}$)	0.25	0.29	0.18	0.59
Al (cmol(+) kg^{-1})	3.9	5.7	2.2	10.3
Total acid (cmol(+) kg^{-1})	6.1	7.4	3.3	11.5
Ca (cmol(+) kg^{-1})			5.5	
Mg (cmol(+) kg^{-1})			4.8	

Table 3 Comparison of leaf analysis

	Vithuy	Hoa luu	Hiep hung	Hoa an	N level[1]	C level[2]
per cent N	1.19	1.22	1.16	1.09	2.2-2.6	< 1.8
per cent P	0.28	0.33	0.31	0.28	0.2-0.3	< 0.2
per cent K	1.76	1.19	1.13	1.12	1.0-1.6	< 0.9
per cent Ca	0.05	0.1	nd	0.13	0.2-0.45	< 0.2
per cent Mg	0.2	0.32	nd	0.17	0.15-0.32	< 0.12
Al mg kg^{-1}	200	200	130	400		
Length of 4th leaf	163.9	175	165.1	108.7		
Width of 4th leaf	5.0	5.1	5.8	3.3		

[1] Normal and [2] critical levels from Guscho and Wali 1979
nd = not determined

Comparison of 4 locations
Results presented in Table 2 show that total N was lowest on Hoa an; phosphorus varied little; K was low in all locations but especially in Hoa an.

When comparing the leaf analysis at 4 locations (Table 3) we found that the mineral composition varied little. The aluminium concentration in leaves in Vi thuy, Hoa luu and Hiep hung was lower than in Hoa an. Length and width of 4th leaves were lower in Hoa an than in other places.

Conclusions

Sugarcane tolerates the acid conditions of the Mekong Delta. However, planting techniques are often not optimal, nor is irrigation and fertilizer application.

Acceptable yields and sugar contens of cane on acid sulphate soil are feasible when attention is paid to water and nutrient requirements. With continuous cropping, especially where farmers take 2-3 ratoons without fertilizer application, soils are quickly depleted. Aluminium is limiting mineral uptake and yield of cane on acid soil.

Acknowledgements

This study was supported by the VH10 and the EEC-STD2 projects of Wageningen and Cantho universities.

References

Blackburn, F. 1984. Sugarcane. Longman House, New York

Clarkson, D.T. 1966. Interaction between aluminium and phosporus on root surfaces and cell wall material. Plant and Soil 27, 347-356

Cooke, G.W. 1982. Fertilizing for maximum yield. Granada, London

Derevier, A. 1991. Mission d'evulation des possibilites de culture de la canne à sucre au Vietnam. Institut de Recherches Agronomiques Tropicals et des cultures vivrières, Montpellier

Gascho, G.P. and A.M.O. Wali 1979. The sugarcane journal 8.

Grimme, H. 1982. The effect of Al on Mg uptake and yield of oats. Plant Nutrition 1, 198-203
Mengel and Kirby 1980. Principles of plant nutrition. International Potash Institute, Berne
Siegel N. and A. Haug 1983. Calmodulin-dependent formation of membrane potential in barley root plasma membrane vesicles: a biochemical model of aluminium. Physiology of Plant 59, 285-291

Recent advances in integrated land uses on acid sulphate soils

Vo-tong Xuan

Director, Farming Systems R&D Centre, University of Cantho, Cantho, Vietnam

Abstract

A first-hand account is given of land uses on acid sulphate soils in Vietnam that have not been clearly documented elsewhere. On potential acid sulphate soils, accounts of rice-fish, rice-shrimp, and rice-molting crab systems are presented. On acid sulphate soils, depending on the water regime, the land can be put under rice, upland crops, and fruit tree production. Recent advances in shallow drainage for rice cultivation are described. New findings on the low-input cultivation of Eucalyptus on annually-flooded, severely-acid soils are reported. The crucial component of management, in all cases, is appropriate water management. Soil nutritional aspects must also be well taken care of in order to ensure good yields.

Introduction

During the past few years, advances in the reclamation of acid sulphate soils have opened new horizons to agricultural development in many countries. The dramatic increase in rice production in the Mekong Delta since 1989 has demonstrated that, as long as fresh water is made available for irrigation, farmers can grow any crop with little technical difficulty. Even the most severe acid sulphate soils in the Plain of Reeds and the Longxuyen-Hatien Quadrangle can yield 8-10 t rice ha^{-1} $year^{-1}$. Of course, the question remains whether it is economically beneficial.

The use of acid sulphate soils has been reviewed by several authors during the last decade. The most recent review, by Dent (1992), covers a large number of successful reclamation methods and includes collaborative research from Thailand, Indonesia and Vietnam that has not been reported in scientific journals. Earlier, Vo-Tong (1984), Vo-Tong et al. (1986), Dent (1986), Roelse et al. (1990), Bos (1990), and Deturck and Ponnamperuma (1991) have reported on indigenous technologies as well as research results on more profitable land uses on these problem soils. This review gives an account of the latest developments in integrated land use systems which have been applied in Vietnam but have not been reported before. The management systems are grouped according to the soil and hydrological conditions under which they operate.

Systems for potential acid sulphate soils

Many of the problems that arise from development of potential acid sulphate soils can now be solved by the use of brackish or saline water to remove soil acidity or suppress acidification. Work in Vietnam on the use of salt and brackish water on rice fields (Vo-Tong et al. 1986, Van Mensvoort et al. 1991), confirmed by Seiler (1989), has shown that a controlled, high watertable and inactivation of existing acidity, or the accelerated oxidation of pyrite by shallow drainage and subsequent leaching of acidity by salt- or brackish water, can overcome the farmers' problems.

Saline sulphidic peat and muck

Areas with peaty topsoil and daily saline tidal influence are found in defoliated and newly-cleared *Rhizophora* and *Avicennia* forests. In the Mekong Delta, polders of about 10 ha per unit have been constructed. Each polder has a network of drainage ditches. A culvert with a flap gate regulates the water level inside the polder at the depth where the sulphidic subsoil occurs.

The first crop after land clearing was pumpkin (*Cucurbita* spp.). Starting with the first rains, farmers raised pumpkins in small plots, then transplanted them into the peaty soil. Rain supplied fresh water which flushed the acid and salts from the topsoil as well as supplying the crop. During the first two years, without any fertilization, the farmers obtained an average yield of 20 t pumpkin ha^{-1}. In the third year, they constructed raised beds to plant a rotation of soybean-corn-soybean throughout the entire rainy season from May to December. Other farmers constructed ridges to plant sweet potato, intercropped with short-duration rice. The yield of 80-day soybeans was about 2 t ha^{-1}, while the rice in the furrows between ridges gave about 1 t ha^{-1}. As the peaty materials are washed away, derris replaces most of the upland crops.

Unripe saline clays and saline sulphidic clays

Areas with strong, daily tidal movement and abundant, fresh sediment are found in swamps of various species of *Acanthaceae*, *Acrosticaceae*, *Ceriop scandolleura*, and *Nipa fruticans*. Marine sediment accretion may be up to 5 cm $year^{-1}$. The reduced subsoil at depths of 20 to 40 cm contains about 0.3 to more than 1 per cent pyrite S. Several land use systems have been successful on these soils.

The rice-shrimp system

Under this integrated system, farmers can rely on a crop of rice during the rainy season, then raise shrimps during the dry season. Improvements since earlier reports (Vo-Tong 1984 and Vo-Tong et al. 1986) have been achieved during the last two years.

Polders of various sizes, but not more than 10 ha, are built. Within each polder, a network of ditches serves as drainage system during the rainy period but, in the dry season, it serves as a refuge pond for raising shrimp fry. A flapgate lets brackish or saline water into the polder in order to keep the soil wet and prevent oxidation of pyrite. The tidewater also carries into the fields shrimp fry bred naturally in the creeks. Full moon and new moon are periods for letting in shrimp fry. Grown shrimps are caught monthly until the start of the rainy season.

In the rainy season, the salts on the soil surface are flushed into the ditches and out of the polder through the flapgate. During high tides, the flapgate remains shut to keep out salt water. Seedlings of medium-term rice varieties, such as IR42, can be used but, nowadays, with the advent of short-duration rice varieties, farmers need not raise seedlings elsewhere; they can broadcast the seeds directly onto the fields. The rice varieties are selected so that they mature before the onset of the saline water intrusion.

After harvesting rice, while the soil is still wet, polder owners let in the saline water immediately to trap the fish *Pseudapocryptes lanceolatus* and may obtain about 150-200 kg ha^{-1} within three weeks. Then they start the shrimp culture cycle again. Shrimp yields of 300-500 kg ha^{-1} $year^{-1}$ and paddy rice of 4-5 t ha^{-1} $year^{-1}$ may be achieved. Fresh sediment deposited annually is scraped off the field onto the surrounding dike. When the raised dike becomes high enough, coconuts can be planted on it.

The rice-molting crab system

During the last two years, several farmers have quit shrimps to raise crabs instead. The market for crabs, especially molting crab, is increasingly good. Nguyen Thanh Nghiep (personal communication) describes this practice by a group of coastal farmers in Canduoc district, Longan province. The practice is similar to the rice-shrimp system, except that the dike is smaller and the trenches are smaller and shallower. After harvesting rice, farmers place the grown-up crabs in trenches excavated in the rice field. The crabs have previously been treated to initiate quick molting. Brackish water is allowed to circulate freely while the crabs are fed daily with rice bran or dried cassava chips. After three weeks, the crabs molt completely, and are ready for sale. Molting crabs fetch four times the price of ordinary crabs.

When the monsoonal rains start, the saline water in the field is drained off, ready for the following crop of traditional, transplanted rice.

Fishponds

In Asia, tidal soils are widely used for aquaculture, but the regenerating acidity of acid sulphate soils causes slow growth and poor product quality. In the Philippines, Brinkman and Singh (1982) and Singh (1987) found that rapid pyrite oxidation of the pond bottom, followed by adequate flushing of the toxic substances from the pond using saline water, and, finally, liming could create favourable conditions for fish and shrimp growth.

Systems for actual acid sulphate soils

On empoldered coastal ridges and thick marine deposits with severely acid horizons deeper than 80 cm, farmers should take great care of their dikes to prevent salt water intrusion. This is in contrast with the rice-shrimp system. The farmers start land preparation by early ploughing, immediately after harvesting the main wet season traditional rice crop. The turned-over soil clods are thus left fallow until monsoon rains are about to start. Previously, after a few rains which softened the soil, farmers broadcast rice seeds of medium-term varieties. Nowadays, short-duration HY rices are broadcast on the dry soil for the first cropping season, before the normal crop of transplanted, medium-term varieties. The 'dry seeding method' has become an important technology for the rainfed lowland rice cultivation. By double cropping, yields of 6 to 9 t ha^{-1} $year^{-1}$ can be obtained with rain as the sole source of water.

Raw acid sulphate mucks in empoldered coastal backswamps

In these areas, tidal movement is slight and the surface often becomes dry during the dry season. Jarosite occurs at 10 to 50 cm depth.

The most profitable practice is shallow drainage to grow one crop of a medium-term rice (Vo-Tong et al. 1982). This system consists of shallow ditches (30-60 cm deep, 60-100 cm wide and 9 m apart) excavated by hand. The excavated slices of soil are spread evenly on the 9 m strips, forming slightly-raised beds. The ditches are connected to a deeper drainage canal running to a flapgate in the main dike. With the first heavy rain, normally in April, rainwater flushes the acid soil on the ridges and removes toxic substances which are collected in the shallow ditches and in the drainage canals. The outlet gates remain closed until the drainage water is level with the surface of the raised beds. Then, with the next rains, the accumulated water is allowed to run through the canals and out to the river at low tide. The cycle is repeated 2 or 3 times before the entire region is naturally flooded and drainage is no longer possible.

Seedlings, 45 to 60 days old (about 80 to 100 cm tall) are transplanted on to the raised beds which are by then submerged under 10 to 40 cm of water. Traditional, medium-term rice varieties such as Tai Nguyen, Lun Can, Trang Mot Buoi and Trang Tep are commonly used. Yields of 2.5 to 3.8 t ha^{-1} were obtained compared to 0.2 to 0.5 t ha^{-1} on undrained soils.

During the last two years, we have seen a major change in the practice of shallow drainage. Instead of dredging the old trenches after the third year, new trenches are excavated starting from the middle of the raised beds. The excavated earth is used to cover the old trenches. Short-duration HY rice is dry-seeded on the new raised beds. To conserve precious fresh water from the last rainy season and to avoid capillary rise of toxic substances during the dry season, the soil surface may be covered with straw mulch, about 5 cm thick (Gora Beye 1973).

These practices add another dimension to rainfed rice cultivation. Varietal screening and water management for rice on acid sulphate soils have received attention in India (Singh and Mongia 1987). The principle of keeping the acid or sulphidic subsoil flooded for as long as possible has proved successful elsewhere though, admittedly, usually where the acid layer is much deeper below the surface, for example Bloomfield and Powlson (1977) and Chew et al. (1984) in Malaysia, and Sudjadi (1984), Bos (1990) and Roelse et al. (1990) in Indonesia for a variety of crops.

Raw acid sulphate clays with a thin, peaty topsoil: Medium to deeply flooded, high groundwater during the dry season

On low sites along the rivers Vaico East and Vaico West, during the low flow period in the dry season, water management by gravity with brackish water is possible. Farmers have constructed polders of various sizes, each having a culvert fitted with a flapgate to regulate water inside the polder. Within the polders, raised beds of 5 to 8 m wide separated by ditches of various depths (30 to 60 cm) and widths (50 to 100 cm), depending on the depth to jarosite, have been constructed. The raised beds are planted with cassava, kenaf, jute or yams.

Cassava *(Manihot esculenta)*

Usually, the entire polder is flooded from September to November. When water recedes, the farmers till the soil on the raised beds and plant cassava which grows during the dry season and is harvested in May. To supress acidification of the topsoil, river water is let the polder up to the top of the jarositic layer. After three years of upland crops, rice can be grown on the same beds.

Kenaf *(Hibiscus cannabis)* and jute *Corchorus spp)*

The jute or kenaf germinates and grows with the residual moisture in the soil to a height of about 50 cm when the soil becomes totally dry. It survives the drought through the dry season and resumes growth again when the rains come. The crop is harvested in August, yielding about 1.5 t fibre ha^{-1}. After three years, the land can be planted to rice, with moderate yield at first (2-2.5 t ha^{-1}) increasing (to 3-4 t ha^{-1}) over a couple of years.

Yam *(Dioscorea esculanta)*

To plant yams, farmers construct high ridges before the first rains and leave them unplanted throughout the rainy season. The ridges are gradually submerged in the flood. This is a good method of leaching toxic substances. As the flood subsides, the ridges are tilled and yam cuttings are planted. Harvesting is in April, before the next rainy season starts, and the whole cycle starts again. Several farmers, in the fifth year, instead of continuing with yam, planted high-yielding rice on levelled fields. Rice yield was about 4 t ha^{-1}.

Raw acid sulphate clays with medium to deep groundwater during the dry season

In areas that are flooded to a depth of less than 60 cm during the rainy season, farmers grow pineapple or sugarcane quite successfully. First, they construct polders of different sizes, depending on their land tenure. Then raised beds are built 4 to 5 m wide and about 60 cm higher than the original land surface. The width of the resulting excavated ditches between the raised beds varies according to the amount of soil needed to build the beds. Care should be taken not to excavate pyritic material and not to expose jarosite layers on top of the beds. Ideally, the excavated topsoil should be set aside first, then the excavated jarositic subsoil deposited on the bed and, finally, the excavated topsoil is spread evenly over the top of the bed. The beds are left to be leached by rainwater through one whole wet season before planting pineapple or sugarcane. The beds can be irrigated with impounded ditchwater even if it is acidic.

Yields of pineapple are usually from 6 to 8 t ha^{-1}, and sugarcane from 30 to 60 t ha^{-1}. Truong Thi Nga et al. (1993) found that, although both sugarcane and pineapple can tolerate acid sulphate soil pH from 3 to 5, it is essential that these crops be supplied with adequate water, K and Ca.

Raw acid sulphate clays and unripe sulphidic clays on deeply flooded floodplain, high watertable in the dry season

Depressed areas where it is always wet are dominated by the grass *Ischaemum* sp., which can elongate during high flood. Farmers have long been using these areas as pastures for cows and water buffalo, and in this marshy environment, fresh water fish grow abundantly. If it dries out, the soil becomes extremely acidic, there will be no more fish, nor *Ischaemum* grass, and no water buffalo or cow can graze.

Raw acid sulphate clay and ripe acid sulphate clay with peaty topsoil, low groundwater table in the dry season

These strongly acid soils are typical of the Plain of Reeds and the Plain of Hatien. Soil variability is so great that even within 50 m more than two different types of acid sulphate soils are found. Studies from the Philippines showed that these soils can be used for biomass energy plantations (Koffa 1991). In Vietnam, based on careful surveys through years of experience, farmers planted *Melaleuca leucodendron* or *Eucalyptus* spp.

Melaleuca

Melaleuca planting is simple. If the supernatant water is cloudy, seedlings 1 m tall are transplanted. The best way is to drive a deep hole into the soil and insert carefully the root of a seedling without packing the soil afterwards. In those places where supernatant, acidic water is clear, the soil is usually ploughed while still dry, then farmers wait until August or September when field water level is about knee-high. They go out in sampan boats to broadcast *Melaleuca* seeds, which have been mixed with burned rice husk. The seeds sink to the bottom and start to germinate and grow while submerged. As water level increases gradually to 1-1.5 m, the young plants increase in height in water. After the flood water recedes, the plants keep on growing in dry soil. The water regime has little influence on plant growth.

An average *Melaleuca* forest can yield about 100 to 120 m^3 ha^{-1} after five years. Once planted, regrowth is by dropped seeds. However, measures should be taken to avoid forest fires during the dry season: shallow canals 4 to 5 m wide and about 1.5 m deep are dug, and the whole area must be empoldered so that floodwater can be retained inside after the flood subsides. Fish from the flood are thus trapped inside too. Flowers of *Melaleuca* have long been recognized as good feed for honeybees, so honey production can be integrated with *Melaleuca* production. The lowest areas can be used for integrated lotus-fish production.

Eucalyptus

Several *Eucalyptus* spp. have been tested with different planting methods during the last four years (Tran Duy Phat 1991). It has been found that, instead of raising costly high beds to avoid flooding, inexpensive land preparation using a mouldboard plough to make ridges and furrows is adequate. *Eucalyptus* is transplanted into the ridges. It can survive inundation for two months without harm. This is another low-input development of the severe acid sulphate soils.

Reed mace

Reed mace is a good raw material for handicraft production such as weaving sacks, shopping bags, hats, sleeping mats, etc. In very severe acid sulphate soils where *Eleocharis* spp. dominate, it can be eradicated by using reed mace as a biological method of weed control. Seedlings of reed mace, with 2-3 tillers, are transplanted at a distance of 1 m apart in the *Eleocharis* field. At each transplant site, a small area should be cleared of *Eleocharis* by uprooting. The reed mace will tiller and expand into the surrounding area and will shade the *Eleocharis*. Within one year, the field produces reed mace.

Deeply flooded acid sulphate clays with jarosite deep in the profile

Floating rice

In areas annually flooded to more than 1 m in the wet season, followed by low water table during the dry season, floating rice is grown in rotation with water melon, sesame, or mung bean. If, however, fresh water can be made available cheaply, an early-maturing high-yielding rice crop can be broadcasted when the flood is about to recede. In the Mekong Delta this is often called 'acid-avoidance rice cultivation'.

Water melon

Another profitable practice by some advanced farmers was observed in the My lam village in the Mekong Delta. Land preparation is similar to that for yams. Ridges are established before the onset of the monsoon rains and the annual flood; left to soak during the entire flood season; then, as the water recedes and the tops of the ridges are just exposed, water melon seedlings are transplanted. For the next 80 days, water melon can grow well with residual water in the furrows.

Conclusion

Although there are still problems to be solved, it appears that existing technologies for the development of the various acid sulphate soils can bring higher income for farmers. The essential component of these systems is appropriate water management, and this can be decided only by precise land evaluation and planning.

Polders should be of appropriate sizes. If fresh water is available at all time, even high-yielding production can be achieved. When production depends solely on rainfall and natural flooding, there are ways to cope. For integrated agroforestry-aquaculture development on these soils, early land preparation should be done immediately after the end of the rainy season to avoid upward flux of toxic substances during the dry period. Suitable crops or animals can be introduced at an appropriate time.

Of course, development depends on the market and the ability of the farmers or local government to invest.

References

Bloomfield, C. and D.S. Powlson 1977. The improvement of acid sulphate soils for crops other than paddy. Malaysian Agricultural Journal 51 (1), 62-76

Bos, M.G. 1990. Research on acid sulphate soils in the humid tropics. In: Papers Workshop on Acid Sulphate Soils in the Humid Tropics 20-22 November 1990. Agency for Agricultural Research and Development, Bogor

Brinkman, R. and V.P. Singh 1982. Rapid reclamation of brackish water fishponds in acid sulphate soils. In: H. Dost and N. van Breemen (editors): Proceedings of the Bangkok symposium on acid sulphate soils. International Institute for Land Reclamation and Improvement Publication No. 31, 318-330, Wageningen

Chew, P.S., K.K. Kee, and L.H. Ooi 1984. Management of coconuts and cocoa on acid sulphate soils. Planter 60 (704), 483-500

Dent, D.L. 1986. Acid sulphate soils: a baseline for research and development. International Institute for Land Reclamation and Improvement Publication No. 39, Wageningen

Dent, D.L. 1992. Reclamation of acid sulphate soils. In: R. Lal and B.A. Stewart (editors): Soil restoration. Advances in Soil Science 17,79-121. Springer-Verlag, New York

Deturck, P. and F.N. Ponnamperuma (editors) 1991. Rice production on acid soils of the tropics. Institute of Fundamental Studies, Kandy, Sri Lanka

Gora Beye 1973. A simple method of de-salting the 'tanne' soils of Casamance: straw-mulching. Agronomie Tropicale 28(5), 537-549

Koffa, S.N. 1991. Potential use of problem soils energy plantations in the Philippines. Biosource Technology 36(2), 101-111
Roelse, K., J. Luijendijk, Waluyono and W.A. Segeren 1990. Reclamation and management of acid sulphate soils in tidal lowlands, Indonesia. Proceedings 14th International Congress on Irrigation and Drainage, Rio de Janeiro. No. 1-B, 533-558
Seiler, E. 1989. Acid sulphate soils, their formation and agricultural use. Tropenlandwirt 90 (October), 137-155
Singh, N.T. and A.D. Mongia 1987. Problems and prospects of different components of ecosystem in the Adaman and Nicobar Islands. Indian Society of Coastal-Agricultural Research 5(1), 77-84
Singh, V.P. 1987. Reclamation of fishponds in acid sulphate soils. Water quality Bulletin 12(4), 159-162, 168
Sudjadi, M. 1984. Problem soils in Indonesia and their management. FFTC book series. No. 27, 58-73
Tran Duy Phat 1991. Performance of Eucalyptus spp. under flooded conditions of the Longxuyen-Hatien quadrangle (in Vietnamese). Report read at the 1991 Vietnam Farming Systems Network Conference, Hue 26-28 August 1991
Truong Thi Nga, Duong Van Ni and Vo-Tong Xuan 1993. Cultivation of sugarcane on acid sulphate soils. In: D.L. Dent and M.C.F. van Mensvoort (editors). Selected papers of the Ho Chi Minh City symposium on acid sulphate soils. International Institute for Land Reclamation and Improvement Publication No. 53, 123-128, Wageningen
Van Mensvoort, M.E.F., D.V. Ni and J. van der Schans 1991. Improvement of acid sulphate soils by leaching with salt or brackish water. In: P. Deturck and F.N. Ponnamperuma (editors). Rice production on acid sulphate soils of the Tropics. Institute of Fundamental Studies, Kandy, Sri Lanka
Vo-Tong Xuan 1984. Present land use on potential and actual acid sulphate soils in the Mekong Delta. In: S. Panichapong, L. Moncharoen and P. Vijarnsorn. Proceedings of the Fourth International Forum on Soil Taxonomy and Agrotechnology Transfer, 195-203, Bangkok
Vo-Tong Xuan, Nguyen Kim Quang, and Le Quang Tri 1982. Rice cultivation on acid sulphate soils in the Vietnamese Mekong Delta. In: H. Dost and N. van Breemen (editors): Proceedings of the Bangkok symposium on acid sulphate soils. International Institute for Land Reclamation and Improvement Publication No. 31, 251-259, Wageningen
Vo-Tong Xuan, Nguyen Van Sanh, Duong Van Ni, Ngo Thi Ut and Huyn Minh Hoang 1986. Rice-shrimp cultivation on potential acid sulphate soils of the Mekong Delta. Paper read at the Third International Symposium on Acid Sulphate Soils, Dakar

Rice production on acid sulphate soils of Sri Lanka

P. Deturck[1], K.D.N. Weerasinghe[2], D.A.B.N. Gunarathna[2], J.P. Lexa[2] and K. Vlassak[1]

[1] KU Leuven, Kardinaal Mercierlaan 92, B-3001 Heverlee.
[2] University of Ruhuna, Faculty of Agriculture, Mapalana,Kamburupitiya, Sri Lanka.

Abstract

Implementation of a flood protection scheme on acid sulphate soils in the Nilwala Ganga in South Sri Lanka has lead to severely-reduced rice yields.

Agronomical and fertilizer experiments suggest that transplanting of three-week-old healthy rice seedlings was superior to direct seeding, which is the usual practice in South-West Sri Lanka. NPK fertilization increased the grain yield significantly. The response of rice, however, decreased with increasing fertilizer rate. At low fertilization, an acceptable yield was obtained by increasing the plant density, which is an interesting alternative for resource-poor farmers. Finely-ground locally available apatite proved to be a useful P source for rice. Addition of *Gliricidia maculata* in combination with phosphate and a small dose of inorganic fertilizer was effective to secure high rice yields. Rice varieties developed in Sri Lanka for adverse soil conditions were also evaluated. BW 267-3, BW 297-2, BW 272-8 and BW 272-3 were among the highest-yielding varieties.

Introduction

The West and South-West coastal belt of Sri Lanka encloses an area of 30 000 ha of low-lying lands (Balasuriya 1987) some of which have only been marginally productive for agriculture due to frequent flooding and salt water intrusion. In the seventies, the government of Sri Lanka decided to drain these marshes and reclaim them for rice cultivation.

The Nilwala Flood Protection Scheme near Matara, is one of these drainage projects. The objectives of this scheme were:
- To protect the town of Matara, and other villages from floods;
- To extend the total area cultivable with rice;
- To ensure double cropping of rice on lands with elevations > 0.6 m above mean sea level (MSL);
- To increase the rice yield through introduction of improved cropping practices.

The implementation of the Scheme involved the reconditioning of existing drainage canals and the construction of new drainage canals, bunds, control regulators, access roads and pump houses to drain excess water from the lowest rice lands. No facilities for irrigation were provided.

With the completion of the engineering work, the occurrence of major floods was eliminated and the drainage condition of the soils in the project area improved. Contrary to the plans, on about 1000 ha with an elevation between 0.3 and 0.6 m above MSL rice yields sharply decreased. Cultivation of rice was not longer possible on another 300 to 500 ha. Balasuriya (1987) and Dent (1987) drew attention to the problem of acid sulphate soils in the area, the latter recommending a detailed soil survey as a basis for managing the problem.

Soil survey

An area of about 2000 ha on the right bank of the Nilwala river was selected for a semi-detailed soil survey (0.3 observations ha^{-1}). A detailed survey (3 observations ha^{-1}, 1:5000) was done in sector 24 of the scheme (50 ha) in which a range of soil and water conditions are represented. Recent air photographs (1:25000), engineering survey sheets and an earlier soil map (1:25000) of the Nilwala Ganga basin (Jayawardane et al. 1980) were used as base maps. The soils were classified at the great group level according to Soil Taxonomy (1990). Subgroups were identified in the field in concurrence with a proposal for the classification of acid sulphate soils by Pons et al. (1986).

The important physico-chemical parameters of the surface layer (0-30 cm) and the pyrite content of the sub-surface layer (> 50cm) were determined on 60 samples. The pH (1:1 water suspension) of the air-dried surface horizon was generally < 3.5. The available Al concentration ranged between 12 and 250 mmol Al kg^{-1} with an average of 100 mmol Al kg^{-1}. Due to the high organic matter and active iron content, submergence of these soils leads to a strong accumulation of ferrous iron in the soil solution. Pyrite was found in the subsurface of sulfic great groups and subgroups in concentrations ranging from 2 to 8 per cent.

It is clear that the low productivity of the rice lands in the Scheme is mainly due to excessive drainage and oxidation of a pyrite-rich subsoil. The ensuing strong acidity of the soil directly affects the rice plant as a result of aluminum and iron toxicities and indirectly decreases the availability of P and other nutrients. Besides the depth of the sulfuric horizon or sulfidic materials, other land qualities affecting the productivity of rice include the availability of water, the occurrence of salinity and the frequency and duration of flooding.

Soils with a sulfuric horizon or sulfidic materials within 50 cm of the soil surface are not considered suitable for rice production. In order to compile a set of recommendations for the management of acid sulphate soils with a sulfuric horizon or sulfidic materials between depths of 50 to 150 cm from the soil surface, a series of agronomical, fertilizer and varietal screening experiments was carried out. In the experiments presented in this paper, the level of the watertable was not controlled, except to prevent acute oxidation of the sulfidic subsoil.

Cultural practices for rice on acid sulphate soils

Crop establishment

In South-West Sri Lanka, pregerminated rice seeds are broadcast onto puddled soils without much standing water. Because of the watertable fluctuations in the Nilwala

Ganga floodplain, transplanting of vigorous seedlings may have several advantages:
- Accumulation of a floodwater layer of more than 5 cm after direct seeding will lead to low germination, need for resowing and delay in the cropping schedule;
- Transplanting reduces the drainage requirement in the beginning of the growth season, which limits the risk of acidification, and aluminum and iron toxicity;
- Vigorous seedlings have a higher tolerance to adverse conditions prevailing in the beginning of the cropping cycle.

We compared the effect of transplanting and direct seeding on the growth and yield of rice. Pregerminated seeds were spread evenly on the saturated soil surface at a rate of 120 kg ha^{-1}. Twenty days later, healthy 3-week old seedlings, raised in a nursery, were transplanted on an adjacent plot at a density of 130 to 140 plants m^{-2} (3 seedlings per hill at 15 × 15 cm). Both treatments were fertilized according to the recommendations of the Department of Agriculture for mineral soils of the Low Country Wet Zone (Nagarajah 1986). The variety used was BG 379-2, a popular, high-yielding 4-month variety. Pesticides were applied when required.

The effect of crop establishment on the yield of rice grown on a Sulfic Histic Hydraquent is presented in Table 1. The higher yield of the transplanted crop was expressed in a higher plant length, number of fertile tillers, panicles m^{-2}, spikelets per panicle, and a reduction in the percentage of empty seeds. The effect of transplanting was more pronounced in zones with high drought and flood risk. In areas with better water control, the difference in net production may not be sufficient to recommend transplanting because of the labour needed for transplanting.

Plant density

In January 1990, the fertilizer prices in Sri Lanka were doubled. Resource-poor farmers are now unwilling to apply the recommended fertilizer rates, especially in areas with a high risk of crop failure. A field experiment was conducted on a Typic Sulfihemist to find out if increased plant density could compensate for a reduced level of fertilization. Seedlings of BW 272-3, a high yielding 3½-month variety, were transplanted with a spacing of 20 × 20 cm at three densities: 50, 100 and 150 plants m^{-2}, corresponding to 2, 4 and 6 seedlings per hill, respectively. No fertilizers were applied.

Plant density had a significant effect on the growth and yield of rice (Table 2). Higher plant density reduced the number of tillers per plant, but was adequately remunerated by an increased number of panicles m^{-2}. The plant height, number of seeds per panicle,

Table 1 Effect of crop establishment on the yield of rice grown on a Histic Sulfic Hydraquent, Kiralakele, 1987-1988 wet season

Crop establishment	Yield	Plant height	Fertile tillers	Panicle density	Spikelets per panicle	Empty seeds	Net prod.*
	t ha^{-1}	cm	nr per plant	nr m^{-2}	nr	%	t ha^{-1}
Transplanting	5.2	94	1.7	266	115	13.5	2.4
Direct seeding	3.8	81	0.7	240	96	16.2	1.9

* Net production = yield – costs

Table 2 Grain yield, productive tillers, and panicle density of rice grown on a Typic Sulfihemist under different plant density levels, Kiralakele, 1988 dry season

Plant density (no m^{-2})	Grain yield (t ha^{-1})	Productive tillers per plant	Panicle density per m^2
50	2.4 b	2.7 a	154 c
100	2.9 a b	1.9 b	183 b
150	3.4 a	1.7 b	227 a

In a column, means followed by a common letter are not significantly different at the 5% level by Duncan's Multiple Range Test

percentage empty seeds and 1000-seed weight were not affected by plant density.

On lands marginally suitable for rice production, we recommend increasing the plant density to obtain a reasonable grain yield, even in the absence of NPK fertilizer. Nguu and De Datta (1979) also reported that, without fertilizer or with low levels (60 kg N ha^{-1}), the grain yield increased either linearly or curvilinearly with increased plant density.

Fertilization of acid sulphate soils

The beneficial effects of NPK fertilization on the yield of rice grown on acid sulphate soils are well documented (Attanandana and Vacharotayan 1986). Balasuriya (1987) reported that rice generally responded favourably to NPK fertilizer on the oligotrophic and mesotrophic soils of the South-West coastal belt of Sri Lanka but specific fertilizer recommendations for acid sulphate soils are not available in Sri Lanka.

Data from our field experiments with a low (50 kg N ha^{-1}, 10 kg P ha^{-1} and 20 kg K ha^{-1}) and intermediate (90 kg N ha^{-1}, 20 kg P ha^{-1} and 50 kg K ha^{-1}) rates confirm that fertilization has a significant positive effect on yield. Application of the intermediate NPK level, however, did not increase the yield in comparison with the low NPK level. The yield response to the low and intermediate NPK doses were 19 and 10 kg grain per kg NPK, respectively.

Even on fields with high fluctuations in the watertable, a low NPK fertilizer application is essential. Seedling establishment, submergence tolerance, and tillering improved after a small basal NPK dressing. On soils with better water management, a higher quantity of NPK fertilizer will be beneficial.

Rock phosphate

Rock phosphate has been successfully introduced in paddy production on acid sulphate soils of the Mekong Delta (Le Van Can 1982). According to Chien et al. (1990) the agronomic effectiveness of rock phosphate is high on acid sulphate soils due to the low pH, high organic matter content and high P-fixing capacity of these soils.

Sri Lanka has a deposit of rock phosphate at Eppawala with an estimated reserve of 40 million ton. This deposit has been little exploited because the P solubility was thought to be too low for direct application to annual crops. Dahanayake and Subasinghe (1991) suggested that the agronomic effectiveness of the rock phosphate could be increased by mechanical separation of the primary apatite crystals from the second-

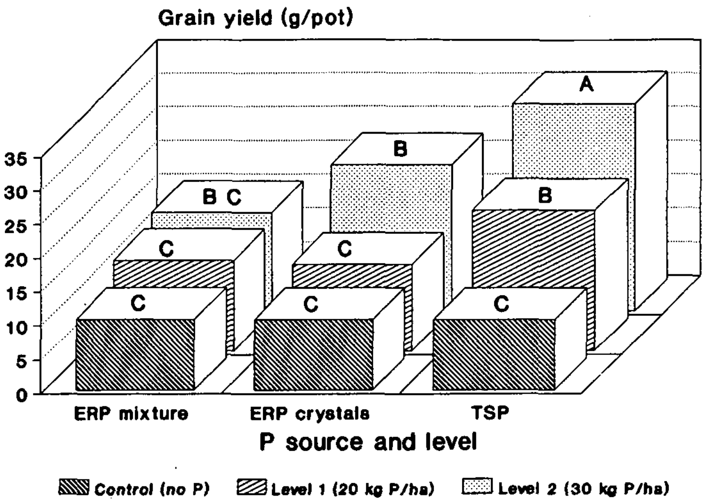


Figure 1 Response of rice grown on a potential acid sulphate soil to different levels of rock and triple super phosphate.
ERP crystals = Eppawala rock phosphate pure apatite crystals
ERP mixture = apatite crystals and matrix

ary matrix. The apatite crystals have a phosphate content of 30 to 40 per cent and low R_2O_3 and Cl values. The matrix consists of secondary phosphate minerals and siliceous and ferruginous components and has a phosphate content ranging from 10 to 30 per cent.

Rice (variety AT 76-1) was grown in a greenhouse on a potential acid sulphate soil to evaluate its response to phosphate. Three P fertilizer products were compared (finely ground < 80 mesh) pure Eppawala apatite crystals, a mixture of secondary matrix and apatite crystals (70/30 ratio), and triple superphosphate (20 and 30 kg P ha^{-1}). The different P sources and levels were incorporated into the soil one day before the rice seedlings were planted. Recommended rates of N and K were applied to all treatments.

Plants which received the highest dose of triple superphosphate matured 9 days earlier and yielded significantly better than other plants (Figure 1). This demonstrates that the current P recommendation (20 kg P ha^{-1}) is not adequate for acid sulphate soils. It is encouraging to note that a comparable rice yield was achieved by application of apatite crystals at 30 kg P ha^{-1}.

Replacement of triple superphosphate by Eppawala apatite crystals could increase the farmer's net return and save some valuable foreign currency, but direct application of untreated Eppawala phosphate on a low rate of apatite crystals or a low dose of ERP-crystals was not effective in increasing rice yield.

Green manures

Touré (1982), working on acid sulphate soils in Senegal, reported that application of green manures led to strong reduction and a build-up of toxins, and adversely affected rice yield. However, favourable experience with rice grown in nutrient-defi-

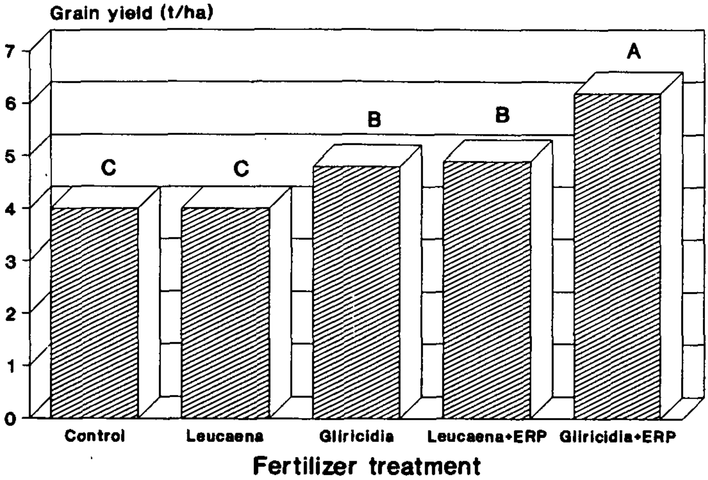


Figure 2 Effect of application of green manures and rock phosphate on the grain yield of rice grown on a potential acid sulphate soil, Watagedera 1991 dry season. Control = $\frac{1}{2}$ recommended NPK; *Gliricidia*/*Leucaena* = 3 t ha^{-1} fresh biomass; ERP = Eppawala rock phosphate (20 kg P ha^{-1})

cient Ultisols (Deturck and Vlassak 1991) prompted us to use green manures with low C/N ratios. A field experiment was laid out on a Sulfic Hydraquent at Wategedera in the 1991 dry season. Fresh biomass of *Gliricidia maculata* and *Leucaena leucocephala* was incorporated at a rate of 3 t ha^{-1}, two weeks before transplanting. All plots received half of the recommended fertilizer dosage (Nagarajah 1986). Because green manures are low in P, 20 kg P ha^{-1} was added in two of the treatments as well.

Application of *Gliricidia* had a pronounced positive effect on the availability of N, Ca, Mg and especially, K but did not significantly lower the redox potential. The water soluble Fe concentration in green manure-amended treatments increased, but not significantly in comparison with the control. No symptoms of Fe toxicity or other physiological disorders were observed.

A very good rice yield was obtained in the treatment with *Gliricidia* and rock phosphate (Figure 2). Incorporation of *Leucaena* was not as effective as *Gliricidia*. A combination of green manuring (3 t ha^{-1}), rock phosphate application (20 kg P ha^{-1}), and NPK fertilization looks like a suitable practice for securing high rice yields on potential acid sulphate soils.

Improvement of rice on acid sulphate soils

The performance of rice varieties and breeding lines developed in Sri Lanka for adverse soil conditions was evaluated on the acid sulphate soils of the Nilwala Ganga floodplain for several seasons by Pathirana and Chandrasiri (1991). They reported that BW 267-3, BW 297-2, BW 272-8 and BW 272-3 were among the highest-yielding varieties: they had a higher number of panicles per m^2, more spikelets per panicle and less empty seeds. With adequate management, these varieties have a yielding capacity of 6 t ha^{-1} on potential acid sulphate soils with a soil and water pH above 5.0.

To seek a better understanding of the physiological mechanisms of stress tolerance, we compared the physio-chemical and microbiological properties in the rhizosphere of a tolerant and a susceptible variety. In a pot experiment, BG 94-1, a variety susceptible to adverse soil conditions and BW 267-3, a tolerant variety, were grown on an acid sulphate soil and their rhizosphere was sampled at regular intervals. The recommended rate of NPK fertilizer was added.

In the susceptible variety, the plants were stunted and showed clear symptoms of iron toxicity. The total microbial population and the iron- reducing bacteria were found to be more abundant in the rhizosphere of the susceptible variety for the entire growth season (Table 3). However, the population of iron-reducing bacteria fluctuated and the difference between the two varieties was significant only at periods of high plant metabolism.

Increased microbial activity in the susceptible variety lead to a slightly higher concentration of water soluble Fe in the rhizosphere and resulted in a higher Fe uptake. Analysis of the nutrient content of the shoot showed that the tolerant variety was better provided with essential nutrients. Benckiser et al. (1984) proposed that a multi-nutritional soil stress is the cause of iron toxicity of wetland rice. In susceptible varieties, a deficiency of essential nutrients would affect the cell permeability and synthesis of high molecular weight organic compounds. More plant-derived organic material, thus, would be released in the rhizosphere with a consequent explosive growth of the microbial biomass. Our data support this hypothesis.

In developing new rice varieties for acid sulphate soils, incorporation of tolerance to aluminum and iron toxicity at the seedling stage merits consideration. In this respect, it is essential to breed rice lines with an efficient nutrient uptake mechanism and high oxidizing activity of the roots.

Conclusion

Our field survey and lab analyses confirm the occurrence of actual and potential acid sulphate soils in Sri Lanka. This has major implications for the reclamation of 30 000

Table 3 Shoot iron content and total microbial population, iron-reducing bacteria, and iron-concentration in the rhizosphere of two rice varieties grown on an acid sulphate soil

	Rhizosphere parameters*			
Variety	Total microbial population **	Iron reducing bacteria **	Soluble iron (mg l^{-1})	Shoot iron content %
BG 94-1***	22×10^5	3.3×10^3 a	570 a	0.07 b
BW 267-3****	9×10^5	2.3×10^3 a	520 a	0.05 a

* Means of four samples (4, 7, 9 and 11 weeks after submergence) and three replicates
** counts per gram of soil
*** Susceptible to soil stresses
**** Tolerant to soil stresses

In a column, means followed by a common letter are not significantly different at the 5% level by Duncan's Multiple Range Test to 40 000 ha of low-lying lands along the South West coastal belt. Before the government decides to implement other land reclamation and flood protection schemes, it is of paramount importance to do a thorough feasibility study, including a soil survey that pays specific attention to the question of acid sulphate soils.

Two strategies can be recommended for the management of acid sulphate soils for rice production. On lands with moderate suitability, rice production can be intensified by a combination of practices:

- Broadcasting pregerminated seeds (100-120 kg ha^{-1});
- Applying an intermediate NPK fertilizer dose (N50, P10, K20 kg ha^{-1});
- Using high-yielding varieties with moderate resistance to soil stresses.

Crop management of lands with marginal suitability for rice production due to high risk of floods, drought or soil stresses should include these operations:

- Transplanting vigorous seedlings;
- Increasing plant density (up to 150 plants m^{-2});
- Applying low amounts of NPK;
- Replacing TSP with rock phosphate (minimum dose 30 kg P ha^{-1});
- Incorporating green manures of low C/N ratio (3t ha^{-1});
- Utilizing tolerant varieties with good yield potential.

The actual yield that can be obtained with improved crop management, however, will very much depend on the level of water management. Oxidation of the pyrite-rich subsurface should be prevented at all costs and a certain amount of vertical drainage to flush out toxic reduction products is needed.

Acknowledgements

Experiments reported in this paper were conducted as part of the Sri Lanka – Belgium Ruhuna Agricultural Development Project and the Sri Lanka French Agricultural Research Development Project. The financial support of the Belgian and French Co-operation is gratefully acknowledged.

References

Attanandana, T. and S. Vacharotayan 1986. Acid sulphate soils: their characteristics, genesis, amelioration and utilization. South-East Asian Studies, 24(2), 154-180

Balasuriya, I. 1987. Reclamation and development of rice cultivation on coastal low-lying lands of Southern and Western Sri Lanka. Tropical Agriculture Research Series, 20, 213-224

Benckiser, G., J.C.G. Ottow, I. Watanabe and S. Santiago 1984. The mechanism of excessive iron-uptake (iron toxicity) of wetland rice. Journal of Plant Nutrition, 7(1-5), 177-185

Chien, S.H., P.W.G. Sale and L.L. Hammond 1990. Comparison of the effectiveness of phophorus fertilizer products. In: Phosphorus requirements for sustainable agriculture in Asia and Oceania, 143-156. IRRI, Manila

Dahanayake, K. and S.M.N.D. Subasinghe 1991. Mineralogical, chemical and solubility variations in the Eppawala phosphate deposit of Sri Lanka – a case for selective mining for fertilizers. Fertilizer Research, 28, 233-238

Dent, D.L. 1987. Environmental impact report on the Nilwala Ganga Flood Protection Scheme. Land Use Policy and Planning Division, Ministry of Lands and Land Development, Colombo

Deturck, P. and K. Vlassak 1991. Potassium management on wet Ultisols grown to rice. In: Rice production on acid soils of the tropics, 191-196. P. Deturck and F.N. Ponnamperuma (editors). Institute of Fundamental Studies, Kandy

Jayawardane, N.E., L.D. Jinadasa, J.A.D.K. Perera and K.A. de Alwis 1980. Soils of the Nilwala Ganga basin. Land Use Division Publication No. 80.3, 8p. and map 1:25 000. Irrigation Department, Colombo

Le Van Can 1982. Rock phosphate in rice production on acid sulphate soils in Vietnam. In: Proceedings of the Bangkok symposium on acid sulphate soils, 187-194. H. Dost and N. van Breemen (editors). International Institute for Land Reclamation and Improvement Publication No. 31, Wageningen

Nagarajah, S. 1986. Fertilizer recommendations for rice in Sri Lanka: a historical review. Journal of the Soil Science Society of Sri Lanka, IV, 3-29

Nguu, N.V. and S.K. De Datta 1979. Increasing efficiency of fertilizer nitrogen in wetland rice by manipulation of plant density and plant geometry. Field Crops Research, 2, 19-34

Pathirana, R. and P.A.N. Chandrasiri 1991. Evaluation of rice genotypes grown on acid soils of the Nilwala river basin, Southern Sri Lanka. In: Rice production on acid soils of the tropics, 265-270. P. Deturck and F.N. Ponnamperuma (editors). Institute of Fundamental Studies, Kandy.

Pons, L.J., M.E.F. van Mensvoort and Le Quang Tri 1986. A proposal for the classification of mineral Vietnamese acid sulphate soils according to Soil Taxonomy. Paper presented at the 3rd International Symposium on Acid Sulphate Soils, January 1986, Dakar

Soil Survey Staff 1990. Keys to Soil Taxonomy, Fourth Edition. SMSS Technical Monograph no. 6. Virginia Polytechnic Institute and State University, Blacksburg

Tennakoon, D. 1982. South-West coast drainage and land reclamation project: an assessment of results. Research Study no. 54. Agrarian Research and Training Institute, Colombo

Touré, M. 1982. Improvement of acid sulphate soils: effects of lime, wood ash, green manure and preflooding. In: Proceedings of the Bangkok symposium on acid sulphate soils, 223-234. H. Dost and N. van Breemen (editors). International Institute for Land Reclamation and Improvement Publication No. 31, Wageningen

Fertilization of nitrogen, phosphorus, potassium and lime for rice on acid sulphate soils in the Mekong Delta, Vietnam

Do Thi Thanh Ren, Vo Thi Guong, Nguyen My Hoa, Vo Quang Minh and Tran Thanh Lap

Soil Science Department, Can Tho University, Vietnam

Abstract

The effects of NPK fertilizers and lime on rice yield are investigated in various types of acid sulpate soils after leaching of water-soluble acid.

In Typic Sulfaquepts, N fertilizer had no effect on rice yield. Phosphorus application did increase yield, thermophosphate and superphosphate being more effective than apatite. Various application methods of phosphorus gave no difference on rice yield and P content of grain and straw. Supplying P at different growth stages made no difference to yields. Potassium had no effect on the first three crops and a negative effect on the fourth crop.

Liming under good water management and with NPK fertilizers greatly increased rice yield in four consecutive crops. Even at low doses (1.0 t ha^{-1}), lime showed a positive effect, especially from the second crop, and there was a clear residual effect from heavier lime applications.

In Sulfic Tropaquepts, where the sulfuric horizon is between 50 and 80 cm, rice yields increased significantly at 50 to 100 kg N ha^{-1} and 30 to 60 kg P_2O_5 ha^{-1}. Potassium had no significant effect on yield.

In Sulfic Tropaquepts, where the sulfuric horizon is deeper than 80 cm, the highest rice yield was obtained at 120 kg N ha^{-1} and 30 kg P_2O_5 ha^{-1}. There was no response to potassium fertilizer.

Introduction

For rice growing in acid sulphate soils the important adverse factors are toxicities, of iron and aluminum, and nutrient deficiencies, which lead to low yields and, often, crop failure. Sulfaquepts (Soil Survey Staff 1990) have a sulfuric horizon within 50 cm, an extremely low pH (below 3.5) and high concentrations of Al^{3+}, Fe^{2+} and SO_4^{2-}. Where the sulfuric horizon occurs deeper than 50 cm, the soil is less toxic and crop production is better than on Sulfaquepts.

Earlier studies (Nhung and Ponnamperuma 1966, Dent 1986) indicated that the soil must be improved first by leaching of water-soluble acid and, next, by liming and fertilization. Application of lime after preliminary leaching raises soil pH and leads to a decreased concentration of iron and aluminum in the soil solution. There is a clear response of rice to nitrogen and phosphate in combination with lime. The research presented here investigated the effect of N, P, K fertilizer and lime on the rice yield of the different kinds of acid sulphate soils in the Mekong Delta.

Table 1 Some chemical characteristics of soils used

Soil Type Soil Survey Staff 1990	pH H_2O 1:5	N %	C %	Total P % P_2O_5	Exch. K $mmolkg^{-1}$	Exch.Al $mmolkg^{-1}$
Typic Sulfaquepts	3.5	0.49	7.03	0.09	1.6	138
Sulfic Tropaquepts	3.9	0.40	5.84	0.13	–	–
Sulfic Tropaquepts	4.2	0.29	2.90	0.08	–	67
Sulfic Tropaquepts	4.0	–	–	–	3.8	–
Sulfic Tropaquepts	3.9	–	2.21	–	–	60
Sulfic Tropaquepts	4.7	0.40	–	0.13	–	–
Sulfic Tropaquepts	4.9	0.16	2.59	0.05	3.0	–
Sulfic Tropaquepts	4.0	0.24	5.59	0.03	–	–

Fertilizer use on Sulfaquepts

N P K fertilizers

Experiments were carried out at Hoa An station. The first row of Table 1 gives some chemical properties of the topsoil. The soil was ploughed and harrowed then leached twice with good quality water. Fertilizer was applied according to a split plot design with three replicates, using plots of 18 m^2. Urea was given at three levels; 0, 50 and 100 kg N ha^{-1}. Superphosphate was applied at 0, 45 and 90 kg P_2O_5 ha^{-1}, and potassium sulphate at 0 and 60 kg K_2O ha^{-1}. The experiment was repeated four times (two wet seasons and two dry seasons) on the same plot.

In the first crop (wet season) all plants died within 15 days after transplanting. During the following dry season, about one third of the crop survived but there were no reliable yield data. Growth improved during the third and fourth crops, giving yields between 0.8 and 2.9 t ha^{-1} (Table 2). Even without any ferilizer, more than 1 t ha^{-1} was obtained. This is probably due to the leaching which is done before transplanting and the repeated leaching of the soil surface with irrigation water.

Without K, N tended to increase rice yield, but the effect was rather small and the increase of yield was not significant. After applying 60 kg ha^{-1} of K_2O, N had

Table 2 Effect of N, P, K fertilizers on rice yield (t ha^{-1}) on a Typic Sulfaquept

Treatment		K_0		K_{60}	
		3rd crop	4th crop	3rd crop	4th crop
P_0	N_0	1.17	1.20 gh	1.56	1.11 gh
	N_{50}	1.15	1.46 fgh	1.14	0.76 h
	N_{100}	1.43	1.50 efg	1.33	0.82 h
P_{45}	N_0	1.56	2.73 ab	2.05	2.00 cdef
	N_{50}	1.50	2.87 a	2.25	1.74 def
	N_{100}	2.23	2.30 abcd	1.97	1.59 efg
P_{90}	N_0	1.45	2.21 bcd	1.83	2.40 bcde
	N_{50}	1.77	2.70 ab	1.92	2.06 cdef
	N_{100}	1.82	2.42 abc	1.84	1.84 cdef

Numbers followed by the same letter are not significantly different at 5 per cent level

Table 3 Effect of sources and rates of P fertilizer on rice yield on a typic Sulfaquept (t ha^{-1})

Treatment		1st crop wet season		2nd crop dry season		3rd crop wet season		4th crop dry season	
N.P.K.		L_0	L_1	L_0	L_1	L_0	L_1	L_0	L_1
50.00	.30	–	0.51	–	1.61	0.21 c	0.19 c	0.7 f	1.1 e
50.60 A	.30	–	0.13	–	2.00	0.37 c	1.16 b	1.3 e	1.6 d
50.120 A	.30	–	0.66	–	2.50	0.23 c	1.66 ab	1.4 de	2.0 cd
50.180 A	.30	–	0.63	–	3.29	0.56 bc	1.58 ab	1.8 cd	2.9 a
50.30 S	.30	–	0.78	–	2.15	0.28 c	1.47 ab	1.9 c	2.1 c
50.60 S	.30	–	0.74	–	3.20	0.33 c	1.93 a	2.6 ab	2.2 c
50.90 S	.30	–	0.87	–	3.76	1.14 a	1.90 a	2.8 a	2.8 ab
50.30 T	.30	–	0.78	–	2.82	0.34 c	1.11 b	2.2 bc	2.4 bc
50.60 T	.30	–	0.83	–	3.65	0.53 bc	2.00 a	2.4 ab	2.8 ab
50.90 T	.30	–	0.98	–	4.04	0.96 ab	1.99 a	2.7 a	3.2 a

Means followed by a same letter are not significantly different at the 5% level.
L_0 : Without lime
L_1 : 2 tons lime ha^{-1}
A : Apatite
S : Superphosphate
T : Thermophosphate

no effect and tended to decrease yields in the dry season (the fourth crop). K – N antagonism could explain the depressed grain yield.

45 kg P_2O_5 ha^{-1} gave a significantly higher yield, but increasing P to 90 kg ha^{-1} did not further increase the yield. Both panicles per m^2 and the number of grains per panicles increased upon P application and decreased upon K application.

Effect of sources and rates of P fertilizers

The experiment was carried out for four consecutive crops (two wet seasons and two dry seasons) at the same location as the N P K experiment. Apatite was applied at three levels: 60, 120 and 180 kg ha^{-1} of P_2O_5, thermophosphate and superphosphate were applied at 30, 60 and 90 kg ha^{-1} of P_2O_5, and lime as $CaCO_3$ at 0 and 2 t ha^{-1}. The experiment was based on a split plot design with three replications. As a basic fertilizer dressing, 50 kg ha^{-1} N as urea and 30 kg ha^{-1} K_2O as KCl were applied.

In the unlimed plots of the first two crops, all rice plants died. Later on, phosphate invariably helped the plant to recover quickly after transplanting and increased the number of tillers and the plant height. Fertilization with superphosphate and thermophosphate resulted in higher yields than with apatite (Table 3). In general, when the soil was improved by liming, plants showed a good response to 30 kg P_2O_5 ha^{-1} to 60 kg P_2O_5 ha^{-1}. Applying more than 60 kg P_2O_5 ha^{-1} did not increase the yield very much. Double amounts of apatite were needed compared to the other P sources. The P content in rice was significantly higher in P-treated plots than in controls: 0.58 versus 0.43 percent P_2O_5 in leaves at tillering, 0.45 versus 0.35 percent P_2O_5 in leaves at panicle initiation, and 0.43 versus 0.17 percent P_2O_5 in the seeds. Phosporus application helped rice plants absorb more potassium at the tillering stage (3.4 percent compared with 2.8 per cent).

The average efficiency of P uptake was 4 percent for apatite and 16 percent for

Table 4 Effect of application time on rice yield on severely acid sulphate soil

Treatments	Yield (t ha^{-1})
Control – without P	0.7 b
90 kg P_2O_5 ha^{-1} Superphosphate (S) 1 day before transplanting (DBT)	2.7 a
60 kg P_2O_5 ha^{-1} (S) 1 DBT and 30 kg at 15 days after transplanting (DAT)	2.5 a
45 kg P_2O_5 ha^{-1} (S) 1 DBT and 45 kg at 15 DAT	1.8 a
45 kg P_2O_5 ha^{-1} (S) 1 DBT and 45 kg at 30 DAT	2.1 a
45 kg P_2O_5 ha^{-1} (S) 1 DBT, 22.5 kg at 30 DAT and 22.5 kg at 45 DAT	2.0 a
90 kg P_2O_5 ha^{-1} Di-ammonium phosphate (DAP) 1 DBT	2.3 a
60 kg P_2O_5 ha^{-1} (DAP) 1 DBT and 30 kg at 15 DAT	1.9 a
45 kg P_2O_5 ha^{-1} (DAP) 1 DBT and 45 kg at 15 DAT	1.8 a
45 kg P_2O_5 ha^{-1} (DAP) 1 DBT and 45 kg at 30 DAT	1.9 a
45 kg P_2O_5 ha^{-1} (DAP) 1 DBT, 22.5 kg at 30 DAT and 22.5 kg at 45 DAT	2.3 a
CV (%)	20.53

Means followed by a same letter are not significantly different at the 5 per cent level

superphosphate and thermophosphate. The effect of liming was dramatic in the first and second crop, but decreased with the third and fourth crops. During the fourth crop, the unlimed plot gave a good yield which may be attributed to the repeated leaching and flooding.

Time of P application

The effect of application time on the rice yield was tested on the same soil type at Hoa An station. The treatments are described in Table 4, which also shows that rice yields were not significantly different between the various treatments.

Application methods of P fertilizer

Thirteen different methods of application of phosphate fertilizer were tested. The methods are described in Table 5, which also shows that the various application methods gave no difference in rice yield.

Table 5 Effect of application methods on rice yield on severely acid sulphate soils

Application methods	Yield (tha^{-1})
Control – Without P	0.78 b
Superphosphate broadcast	2.79 a
Superphosphate applied in row	2.67 a
Superphosphate dip the roots in fertilizer and broadcast	2.41 ab
Superphosphate dip the roots in fertilizer and apply in row	2.19 ab
Superphosphate soak the roots in 5‰ solution and broadcast	2.30 ab
Superphosphate soak the roots in 5‰ solution and apply in row	2.55 ab
Di-Ammonium phosphate broadcast	2.33 ab
Di-Ammonium phosphate applied in row	2.01 ab
Di-Ammonium phosphate dip the roots in fertilizer and broadcast	2.40 ab
Di-Ammonium phosphate dip the roots in fertilizer and apply in row	2.67 a
Di-Ammonium phosphate soak the roots in 1‰ solution and broadcast	2.43 ab
Di-Ammonium phosphate soak the roots in 1‰ solution and apply in row	1.95 b
CV (%)	19.82

Means followed by a same letter are not significantly different at the 5 per cent level

Table 6 Average yields obtained in the various lime treatments. The numbers after the R indicate during which crop the lime was applied

Lime dose ($t\ ha^{-1}$)	Yield ($t\ ha^{-1}$)								
	R_1 (1)	R_{12} (2)	R_1 (2)	R_{123} (3)	R_{13} (3)	R_1 (3)	R_{1234} (4)	R_{13} (4)	R_1 (4)
0	0.07d	0.74c	0.64c	0.25	0.37	0.13	1.31d	1.45d	1.17b
0.5	0.13d	1.71b	1.20bc	0.83	0.36	0.28	1.68d	1.38d	1.53b
1.0	0.25d	1.74b	1.59b	1.04	0.47	0.42	2.31c	1.61d	1.57b
3.0	0.82c	2.73a	1.45b	2.99	2.10	1.01	3.88b	2.54c	1.31b
6.0	1.61b	3.01a	2.48a	4.03	2.67	1.65	4.15b	3.31b	1.64b
10.0	2.39a	3.15a	2.55a	4.42	3.57	2.22	4.75a	4.35a	1.99a

The 3rd crop had insufficient data for statistical calculations
Figure between parenthesis indicates first, second, third and fourth crop

The effect of lime on rice yield

The effects of applying lime at different times and at different rates were studied. It was found that applying lime at different times before transplanting had no significant effect on yield. In Table 6, the average yields obtained at different rates of single and repeated lime application are shown. In the first crop, with liming at low dose of 0.5 – 1.0 t ha^{-1}, yield did not increase significantly compared to the no-lime treatment. But liming at 3, 6, 10 t ha^{-1} gave a significant increase in yield. In the second, third and fourth crop, repeated application even at 1 t ha^{-1} gave an increase in yield though the residual effect of these low doses was small. Yields also increased in the repeated application of 3, 6, 10 t ha^{-1}.

The residual effect of lime was strong in the rates of 6, 10 t ha^{-1}. The effect of liming at 6 t ha^{-1} in the first crop persisted into the 3rd crop; liming at 10 t ha^{-1} persisted into the 4th crop. Note that yields tend to be highest in the dry season crops (second and fourth) compared to the wet season crops.

Repeated application seems to be more effective than a single application of the same amount of lime, but the differences are very small.

The effect of liming on chemical changes

Table 7 shows some soil analytical data at the beginning of the first and second crop after liming. Regardless of the lime level (and even in the unlimed plot) the initial pH of the surface soil of the second crop is about one unit higher than at the first crop, and extractable aluminum has decreased strongly. This difference may be attributed to the prolonged flooding and soil reduction in the wet season, followed by a repeated leaching of the surface soil with irrigation water. Possibly, the high extractable Al values during the first crop may have included some soluble aluminum. Lime levels up to 3 t ha^{-1} have little effect on pH, extractable Al and exchangeable Ca. In the plants, however, liming increases the Ca content and decreases the Fe content, even at the lowest rate of application. The phosphorus content is not affected, but N contents are higher at high lime doses. Results in Table 8 indicate that the yield increase at low dosage is mainly due to improved calcium nutrition and depressed uptake of iron.

Table 7 Some chemical data for the 0-10 cm surface soil, just before planting the crops, as a function of the total amount of lime applied

Soil test		Total lime applied ($t\ ha^{-1}$) over 2 crops							
		0	0.5	1	3	6	10	12	20
1st crop	pH	3.5	3.5	3.6	3.7	3.6	3.7	–	–
	P[1]	2.5	2.9	3.0	2.0	2.7	1.7	–	–
	Al[2]	172	185	180	184	143	138	–	–
2nd crop	pH	4.4	4.6	4.7	4.9	4.6	4.6	5.0	5.9
	P[1]	1.9	1.7	1.7	1.5	1.8	1.2	1.3	2.2
	Al[2]	90	82	85	85	59	24	37	18
	Ca[3]	8	8	9	1	29	27	22	30

[1] – Available P ($mg\ P\ kg^{-1}$)
[2] – Extractable Al ($mmol(+)kg^{-1}$) in 1 M KCl
[3] – Exchangeable Ca ($mmol(+)kg^{-1}$) in 1 M Ammonium acetate

Economic effects

Although the effect of liming on yield is strong, a benefit:cost analysis (including the cost of the blank fertilizer treatment) showed that most lime treatments were uneconomic. In the fourth crop, the B:C ratio increased from 0.6 at 0.5 t lime ha^{-1} to 1.21 at repeated application of 3 t ha^{-1}, and to 1.5 at single application of 10 t ha^{-1}. It should be remembered, however, that the favourable water management conditions have undoubtledly played an important role in the relatively high yields obtained and that the results reported here cannot be extrapolated directly to farmers' fields where water management might not be optimal.

Fertilizer use on Sulfic Tropaquepts

Twelve experiments were carried out on Sulfic Tropaquepts at different places in the Mekong Delta. Soil analysis data are given in row 2 to 8 of Table 1. Nitrogen was applied as urea at 4 levels (0, 60, 90 and 120 kg N ha^{-1}) or at 3 levels (0, 50, 100 kg N ha^{-1}). Superphosphate and thermophosphate were applied at 0, 30, 60 kg P_2O_5

Table 8 Chemical analysis of the rice plants at tillering stage (N, P, Fe) and at harvest (Ca) as a function of lime applied. N, P and Fe in leaves, Ca in straw

Plant test		Total lime applied ($t\ ha^{-1}$) over 2 crops							
		0	0.5	1	3	6	10	12	20
1st crop	N (%)	2.1	2.2	1.2	2.1	2.1	–	–	–
	P_2O_5 (%)	0.43	0.38	0.41	0.44	0.37	–	–	–
2nd crop	N (%)	3.6	3.1	3.6	3.3	4.0	4.2	4.0	3.9
	P_2O_5 (%)	0.55	0.49	0.57	0.46	0.63	0.61	0.55	0.58
	Ca (%)	0.18	0.27	0.29	0.20	0.26	0.34	0.41	0.42
	Fe($mg\ kg^{-1}$)	870	480	440	580	260	350	180	250

Table 9 Effect of different doses of nitrogen on rice yield (t ha^{-1}) on sulfic Tropaquepts

kg N ha^{-1}	Exp. 1	Exp. 2	Exp. 3
0	1.4 c	2.1 d	2.3 d
50	2.6 b		
60		3.7 c	5.3 c
90			6.2 b
100	3.3 a		
120		6.1 a	6.9 a
180		5.1 b	

Numbers followed by the same letter are not significantly different at 5% level

ha^{-1} (experiments 1, 2 and 3, respectively). In some experiments, phosphate was applied in combination of half superphosphate and half thermophosphate. Potassium chloride was applied at 0, 30, 45 and 60 kg K_2O ha^{-1}.

Results (Table 9) showed that application of N gave significantly higher yields than the control treatment. The highest yield was obtained at the highest level of N application. Phosphate fertilization gave significantly higher yields than the control but increasing P applications over 30 kg ha^{-1} did not always further increase yield, and there was no difference between the effects of superphosphate and thermophosphate.

In all experiments, rice yields showed no response to potassium fertilizer. This could be due to sufficient K supply, especially under submerged conditions. The mineral fraction of soils in Trans Bassac area is about 50% illite (Brinkman et al. 1993), which is rich in potassium.

Conclusion

Nitrogen application on severely acid sulphate soils gave no effect on rice yield. There was a clear effect on slightly acid sulphate soils at 50 to 100 kg N ha^{-1}.

Phosphate application increased rice yield more efficiently than other nutrients. The most efficient P fertilization was obtained at 60 kg P_2O_5 ha^{-1} for apatite and 30 kg P_2O_5 ha^{-1} for superphosphate and thermophosphate. Raising P application to 60 kg P_2O_5 ha^{-1} had a significant yield increase in only half of the experiments on slightly acid sulphate soils. Using various methods of P application made no difference on rice yield, as was the case when supplying P at different growth stages. Application of superphosphate, thermophosphate or a combination of half superphosphate and half thermophosphate gave no differences between them effect.

In all experiments, K applications gave the same yield, except on severely acid sulphate soils where K had a negative effect on the fourth consecutive crop.

Lime had a significant positive effect on yields, on Ca uptake in the plants and it depressed the uptake of Fe, even at low doses of 1.0 t ha^{-1}. The application of lime, however, is economically unattractive because of high prices in the Mekong Delta.

References

Brinkman, R., Nguyen Bao Ve, Tran Kim Tinh, Do Phuoc Hau and M.E.F. van Mensvoort 1993. Acid sulphate materials in the Western Mekong Delta Vietnam. Submitted to Catena

Dent, D. 1986. Acid sulphate soils – a baseline for research and development. International Institute for Land Reclamation and Improvement Publication No. 39, 82-83, Wageningen

Nhung, Mai Thi My and F.N. Ponnamperuma 1966. Effect of calcium carbonate, manganese dioxide, ferric hydroxide and prolonged flooding on chemical and electrochemical changes and growth of rice in a flooded acid sulphate soil. Soil Sci. 102, 29-41

Soil Survey Staff 1990. Keys to Soil Taxonomy. Fourth editon, SMSS Tech. Mag. 19, Cornell University, Ithaca

Soil permeability, interflow and actual acidity in acid sulphate soils, South Kalimantan, Indonesia

A.F.J. Hamming and A.L.J. van den Eelaart

Euroconsult, Arnhem, The Netherlands

Abstract

Pumping tests in shallow wells and a drainage test revealed very high KD-values of up to 3500 m^2/day in Pulau Petak, Kalimantan, Indonesia. Such high values make significant groundwater flow likely, even with the minor hydraulic heads found in the Indonesian tidal lands.

The top and subsoil with many cracks and rootholes are the main contributors to the high transmissivity. The very deep layers are unripe and mainly fine to medium textured soils, formed below low water level. The thickness and ripeness of the oxidized part of the soil profile (the so-called brown layer), the presence of large pores (diameter > 5 mm), the orientation and shape of the pores, and the actual depth of the groundwater, strongly correlate with the permeability. Actual acidity in a soil may be the result of the balance between the influx of toxic groundwater from the higher parts (interflow) and the net outflow of surface and groundwater into adjoining drainage canals. Water in tidal schemes is usually in direct, open connection with the tidal rivers. Accumulation of acids in canals and reduced tidal effects are likely in areas at more than 5-7 km from the river. The reduced tidal flushing capacity with good quality river water contributes to the accumulation of toxic groundwater and gradually increases the actual acidity in the soil-profile of relatively low lying sites.

It appears that actual acidity caused by interflow is difficult to distinguish from actual acidity caused by in situ oxidation of pyrite. It is thought that the acidity caused by interflow can be removed quickly by intercepting, leaching and flushing by an intensive shallow drainage, and a supply system with good quality canal water.

Introduction

During the first phase (1988-91) of the AARD/LAWOO research on acid sulphate soils in the Pulau Petak region, South Kalimantan, Indonesia, it became evident that the acidification of the soils and groundwater is not so much caused by in situ pyrite oxidation, but mainly by inflow of acid water. This was in line with previous experiences in tidal lands throughout Indonesia.

Permeability

Pumping tests in Pulau Petak in shallow pits were carried out to determine the permeability (Hamming et al. 1990). Earlier, a drainage test was performed in the same area (Van den Eelaart and Boissevain 1986). All tests revealed extremely high permeabilities. Hydraulic transmissivities of up to 3500 m^2/day were measured with groundwater levels close to the soil surface.

Tests done with lower groundwater levels showed much smaller transmissivities although still dramatic: 200 – 500 m^2/day. Observations of recovery tests in soil pits revealed that the peaty top layer, if present, and the brown oxidized layer (which overlays the grey, reduced, pyritic layer) contribute most to the groundwater flow. These brown layers are usually ripened and contain many cracks. The cracks can easily develop in the kaolinite clays of Pulau Petak: under saturation, swelling is limited due to the clay's low absorption capacity whereas shrinkage occurs during dry spells.

Many big rootholes (formed by the roots of mangrove trees like *Rhizophoria, Bruguieria* and *Nipa* with an anisotropic distribution) were observed and they also contribute significantly to the high permeability. Much lower in permeability are the areas with many small woody remnants from *Sonneratia* which show mainly a vertical orientation. For the brown layer a hydraulic conductivity of 800 m/day was determined at the Unit Tatas experimental site.

A numerical hydraulic model of the Unit Tatas irrigation/drainage system confirmed that water levels are highly influenced by groundwater flow.

Poor drainage restricts the ripening of the grey layer; few cracks were generally observed. Even with abundant wood remnants present, permeability was relatively low. The highest permeabilities were found in soils having numerous cracks in the brown layer, combined with an anisotropic orientation of the rootholes in the grey layer.

Actual acidity

Most tidal swamp clays contain pyrite at various depths. The danger of acidification depends on the hydrological characteristics of the site. For this reason Van den Eelaart (1991) and Kselik et al. (1993) made proposals for a division of the tidal lands in Water Management Zones, based on the hazard of acidification, to indicate the agricultural potentials. The most productive soils are the tidal swamp clays which can be irrigated at high tide. They have the smallest risks of rapid deterioration under cultivation, independent of the presence and depth of pyrite in the profile. Tidal irrigation potential is mainly limited by the capacity of the canal system. Densely spaced and sufficiently large canals are needed to convey large amounts of water in a short time. Only the lower locations within 3 km from the river have potential for tidal irrigation.

The highest risk of acidification is found in places at more than 5-7 km from the river. The tidal influence is limited here and low velocities and small tidal ranges prevail. In these slack water conditions acid, stagnant water accumulates easily. Topography and hydrology determine the spatial variation of actual acidity. Acidity produced in the dry season is mobilized after rainfall and accumulates by interflow in the lower areas where acid, stagnant slack water conditions in the canals contribute heavily to the problem. This type of actual acidity cannot be distinguished from actual acidity caused by in situ oxidation of pyrite.

Figure 1 shows the variations in time and space of acidity between two secondary canals with slack water problems in Belawang, South Kalimantan. Figure 2 suggest

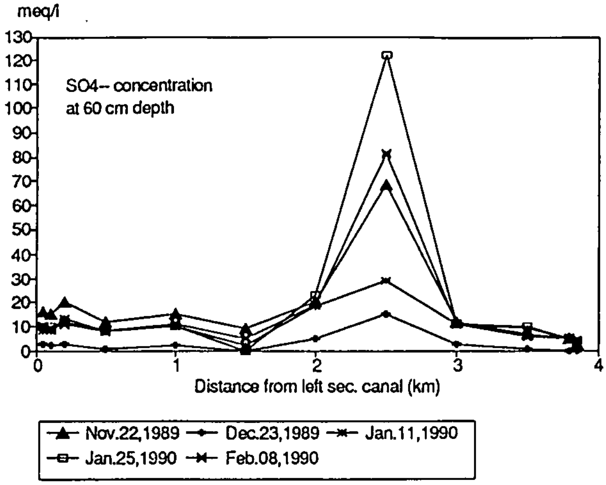


Figure 1 Actual acidity measured along transect Belawang at various dates

that a high groundwater level in the dry season at km 2.5 (low area with most severe acidity problems) is related to interflow from higher areas. Table 1 indicates a significant difference in Total Actual Acidity (TAA) between places near and further from

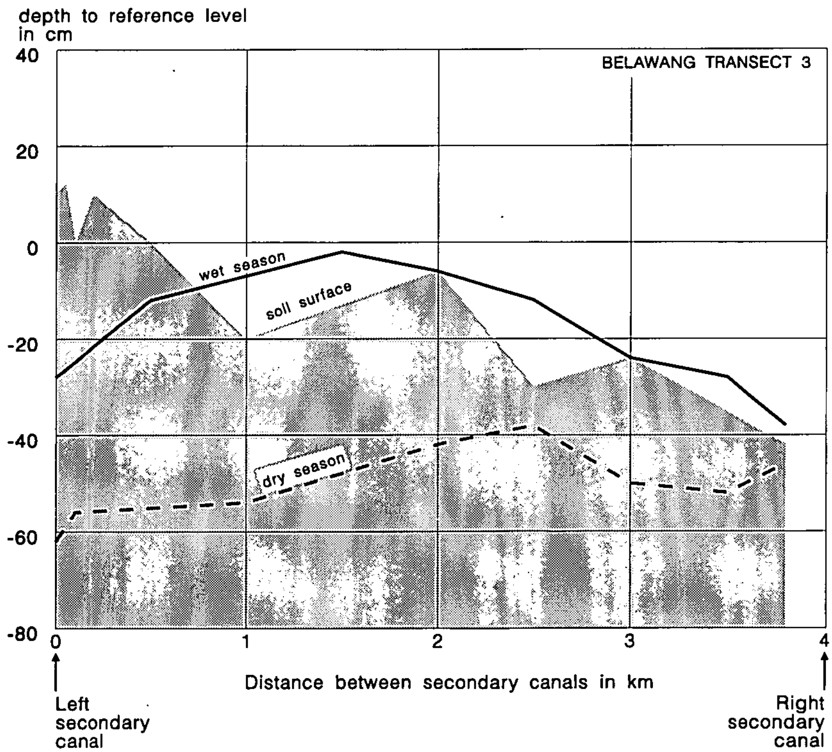


Figure 2 Topographic and water levels along transect Belawang

Table 1 Chemical soil parameters of transects Belawang, dry season (1989) with slack water conditions in adjoining canal sections

	0-20 cm depth		20-40 cm depth
	near canal*	from canal**	
Org.matter %	16	16	12
pH (water)	4.2	3.6	3.9
TAA (me/kg)	280	380	360
TPA (me/kg)	420	420	430
EC dS m^{-1}	0.11	0.22	.22

* From km 0 to 1.5 (6 data) TAA = Total Actual Acidity
** From km 1.5 to 3.8 (6 data) TPA = Total Potential Acidity

canals, but no such difference was found in Total Potential Acidity (TPA).

The actual acidity problem related to the lateral inflow of acids from nearby sources was also noted by Janssen et al. (1992), who discuss the problem that Soil Taxonomy does not provide solutions to characterize actual acidity caused by interflow of acid in the spatial and dynamic system of a tidal development scheme. In fact, in situ acidification as a cause of severe actual acidity might be unimportant for most of the tidal lands of Indonesia. This requires that land evaluation should pay more attention to the hydrological land qualities and less to in situ soil characteristics.

Removal of acidity

It is thought that the acidity caused by interflow can be removed quickly by intercepting, leaching and flushing in an intensive shallow drainage and supply system with good quality canal water.

At the Unit Tatas experimental fields, an interceptor drain, which was constructed to avoid the acid inflow from the adjoining gelam forest, lowered the SO_4^{2-} concentrations in the fields at the start of the wet season. Agronomic experiments showed that with an interceptor drain, yields increased 0.6 ton per hectare (Sevenhuysen 1991). Similar effects of fast improvements by leaching and interception were found by van den Eelaart and Boissevain (1986).

Replacing groundwater with good quality canal water is essential for improvement. Consequently, the possibilities for improvement in the water management zone with slack water conditions are bleak, unless sources of good quality water can be found elsewhere.

Locations with acid, stagnant slack water conditions in the adjoining canals which are impossible to improve, are only suitable for tree crops and timber plantations. The tree crops should be planted on 1 m high raised mounds to safeguard proper drainage. In South Kalimantan *Rambutan* fruit trees thrive well in these conditions and provide a good cash income.

References

Eelaart, A.L.J. van den, and W. Boissevain 1986. Evaluation and improvement of water management for potential acid sulphate soils in tidal lands of South Kalimantan. Lowland symposium, supporting papers, Jakarta, Indonesia

Eelaart, A.L.J. van den 1991. Potentials, phased development and water management in tidal lands. Termination Report of AARD/SWAMPS II Project. Vol. II. Indeco/Euroconsult, Jakarta, Indonesia

Hamming, A.F.J., Tagus Vadari, and Khairal Anwar 1989. Observations soil permeabilities in Pulau Petak, South Kalimantan. Scientific Report No. 17, Vol. I & II LAWOO/CRS/BALITTAN, Banjarmasin, Indonesia

Janssen, J.A.M., W. Andriesse, Hendro Prasetyo and A.K. Bregt 1992. Guidelines for soil surveys in acid sulphate soils in the humid tropics. AARD/LAWOO, Bogor, Indonesia

Kselik, R.A.L. 1990. Water management on acid sulphate soils at Pulau Petak, Kalimantan. Papers workshop on acid sulphate soils in the humid tropics. AARD/LAWOO, Bogor, Indonesia

Kselik, R.A.L., K.W. Smilde, H.P. Ritzema, Kasdi Subagyono, S. Saragih, Mauliana Damanit, and H. Suwardjo. 1993. Integrated soil and water management, soil fertility and cropping systems research on acid sulphate soils in South Kalimantan, Indonesia. In: D.L. Dent and M.E.F. van Mensvoort (editors): selected papers of the Ho Chi Minh City Symposium on acid sulphate soils. ILRI Publication 53, ILRI, Wageningen, The Netherlands

Sevenhuysen, R.J. 1990. The water management puzzle, a summary of the research. Papers workshop on acid sulphate soils in the humid tropics. AARD/LAWOO, Bogor, Indonesia

Water management on rice fields at Hoa An, Mekong Delta, Vietnam

K. Hanhart[1], Duong van Ni[2]

[1] Department of Soil Science and Geology, Agricultural University in Wageningen, P.O. Box 37, 6700 AA Wageningen, The Netherlands
[2] Department of Soil Science, University of Can Tho, Can Tho, Vietnam

Abstract

In the past, attempts to reclaim severe acid sulphate soils in the Mekong Delta for cultivation of rice or a rainfed, short-duration, summer-autumn crop have resulted in repeated failures. Recently, farmers have been able to grow an irrigated winter-spring crop followed, directly, by a rainfed summer-autumn crop. Field experiments at Hoa An station aim to develop a set of agronomic and water management practices that will be useful to farmers. Initial results highlight the importance of controlling the water status of highly organic raw acid sulphate soils by levelling, as opposed to leaching. Pollution of surrounding surface water has also been monitored.

Introduction

Since 1980, the University of Can Tho, Vietnam, and the Wageningen Agricultural University, The Netherlands, have cooperated to develop reclamation strategies of acid sulphate soils in the Mekong Delta. In 1989, experiments were started on the effect of water management practices on rice performance on a severe acid sulphate soil in Hoa An station, Hau Giang Province, 30 km from Can Tho.

Hoa An is situated in the broad depression of the Camau peninsula, and is connected to the Mekong river and the Gulf of Thailand by the Cung canal which was dug in the thirties to facilitate transport, drainage of surplus water during the rainy season, and irrigation. Since salinity has not moved up to the point where fresh water is taken from the Mekong river, the canal carries fresh water all year round. However, due to siltation and encroachment of houses into the canal, the capacity of the canal for irrigation and drainage has decreased considerably.

The experimental field is connected to the main Cung canal by a secondary canal dug in 1981. This has a width of 5 m and a depth of 1.5 m but is almost completely blocked by water hyacinth. For the irrigated winter-spring crop, water is pumped from the secondary canal into a tertiary irrigation ditch. The field is drained by ditches into the same secondary canal but at some distances from the intake. The drainage and irrigation possibilities of the Hoa An station are limited due to the low elevation, the bad condition of the canals and its location at a meeting point of tides from the East China Sea and the Gulf of Thailand. This situation is typical for many acid sulphate lands in the Mekong Delta.

Land use

Traditionally, farmers have transplanted a long-stem rice variety during the flood.

Yields are low, less than 1 t ha^{-1}, probably due to toxicities associated with deep reduction. Other farmers attempted to broadcast a summer-autumn crop. Yields were very low or plants died due to severe Fe and Al-toxicity at the start of the rainy season, followed by toxicities associated with deep reduction in later growing stages. In the water management experiments described hereafter, an irrigated winter-spring crop is directly followed by an early summer-autumn crop. In 1990, the mean yield of the winter-spring crop was 2 t ha^{-1}. In 1991, a new field was reclaimed and the winter-spring crop yielded 3.8 t ha^{-1}. The summer-autumn crop looked very promising but was drowned in last year's deep flood. This year, 1992, farmers around the station are changing to the winter-spring, summer-autumn cropping system.

Soils

At Hoa An, the soils are raw acid sulphate soils with a sulfuric horizon less than 40 cm from the surface. Under *Eleocharis dulcis* reed, a ripe topsoil, rich in organic matter, about 20 cm thick, is developed. Below this is a firm, ripe or nearly ripe layer of slow permeability. This slowly-permeable layer is not caused by ploughing, since the land has never been cultivated before. Cultivation for rice produces a soft, puddled topsoil but the remaining firm layer below is crucial to water management.

The sulfuric horizon can be recognized easily by the striking yellow mottles of jarosite and orange/brown iron hydroxydes. At a depth of about 1.2 m, the grey, permanently reduced, sulfidic layer is found.

The clay content of the Hoa An soil varies between 55 to 65 per cent. The bulk density of the cultivated topsoil and sulfuric horizon is 0.9-1.0 g cm^{-3} while that of the firm layer is somewhat higher: 1.1-1.2 g cm^{-3}. In Table 1, saturated hydraulic conductivities for the various soil layers are presented. Note the great difference between the saturated conductivities within the profile. The conductivity of the topsoil is low, but increases strongly in the course of the dry season when cracks develop. The conductivity of the firm layer is very low so water can be kept on the field easily and the topsoil is separated well from the severely-acid horizon below. The high conductivity of the sulfuric horizon is caused by a system of interconnected pores and cracks. At the end of the dry season, cracks are found well into the sulfuric horizon. Also, 1-2 mm diameter round root channels of the *Eleocaris dulcis* reed vegetation are found, even in the sulfidic layer. The cracks and pores are usually lined with jarosite and ped faces are stabilized by iron oxides.

Table 1 Saturated hydraulic conductivity of the different soil horizons at Hoa An (Tran Minh Thuan, personal communication)

	K_{sat} m day-1	
	horizontal	vertical
Topsoil	0.015	0.038
Firm layer	0.002	0.001
Sulfuric horizon	1.064	0.256
Sulfidic horizon	21.542	3.237

Acidification of the topsoil and the role of deep cracks

The amount of KCl-extractable acidity in the sulfuric horizon is roughly 200 mmol (+) kg^{-1} dry soil. The overlying topsoil, which originally did not contain any acidity, contains around 120 to 150 mmol (+) kg^{-1} KCl-extractable acidity. The acidification of the topsoil by the underlying sulphuric horizon is probably caused by three processes (Figure 1).

A) Diffusion of acidity through the firm layer. Due to the very low permeability of this layer, diffusion is very slow but in the course of years it may be an important contribution to acidity in the topsoil;
B) In the course of the dry season, cracks develop which, at the end of the dry season, extend into the sulphuric horizon. Due to the strong evaporative conditions at the end of the dry season, acid water moves to the cracks, bringing acidity which precipitates as soluble Al- and Fe-salts along the crack wall. When the rainy season starts, the acid salts are dissolved by water ponding in the cracks and the acidity is mixed with the surface water by diffusion, mixing of the water by raindrops and closing of the cracks, pushing the acid water out of the soil;
C) Acidification of the surface water by acidity leaching from canal spoil. Especially the first years after the digging of a canal, strong pollution of surrounding topsoil takes place.

Cracking of the firm layer at the end of the dry season and, thereby, yearly re-acidification of the topsoil, can be prevented by the cultivation of an irrigated winter-spring crop. The winter-spring crop should be followed directly by an early summer-autumn crop. In the absence of a close network of tertiary canals, dry season water levels

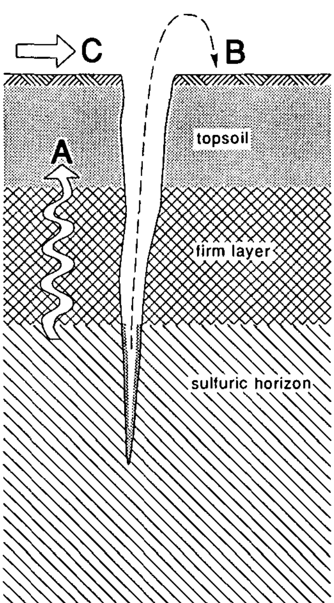


Figure 1 Acidification of the topsoil by deep cracks (A), diffusion (B) and canal spoil (C)

fall deep due to evapotranspiration. In the presence of tertiary canals, at small drain distance, groundwater levels are controlled by the canal water levels, influenced by the Mekong river (Thuan 1989). Cultivation of a winter-spring + summer-autumn cropping system and digging of tertiary canals are, therefore, the first and, probably, most important steps in improving severe acid sulphate soils.

Composition of the soil solution in the topsoil during the year

The concentration of acidity in the soil solution of the sulphuric horizon is constant throughout the year. The pH is around 3.5, the concentration of soluble aluminum 100 to 400 mg l^{-1} and the concentration of Fe^{2+} is 300 to 600 mg l^{-1} (Bakker et al. 1990). However, the amount of acidity and toxic components in the topsoil changes very strongly during the year. The climate in the Mekong Delta is characterized by a dry season from January to May, followed by a rainy season from June to December. The composition of the soil solution is strongly influenced by the seasonal changes, inducing oxidation and reduction processes. The soil solution of the topsoil in Hoa An was measured from time to time over several years of experimentation. Based on these observations, a possible explanation of the seasonal variation of the composition of the soil solution is given below. Further year-round monitoring is needed to confirm this.

From the redox point of view, a year can be divided into three periods (Figure 2):
I Continuous oxidation during the dry season, starting at the recession of the flood;
II Alternating oxidized and reduced conditions during the first part of the rainy season;
III Continuously-reduced conditions during the flood or submerged period.

In general, acidity is liberated by oxidation processes in the topsoil. Acidity is, however, consumed as a result of reduction processes in the topsoil. In this respect, the oxidation and reduction of iron plays a major role:

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

$$Fe(OH)_3 + 1/4\,CH_2O + 2H^+ \rightarrow Fe^{2+} + 1/4\,CO_2 + 11/4\,H_2O \qquad (2)$$

Period I, continuous oxidation during the dry season
After the recession of the flood during the dry season, and in the absence of an irrigated winter-spring crop, the watertable falls below the soil surface, resulting in strong oxidation of the topsoil, and the pH decreases to values below 4. At decreasing pH levels, aluminumhydroxides are increasingly hydrolysed to, respectively, $Al(OH)_2^+$, $Al(OH)^{2+}$ and Al^{3+} (Raupach 1963). At the end of the dry season, the pH of the soil solution is below 4 and the concentration of soluble aluminum reaches its peak. The high concentration of soluble aluminum is, furthermore, attributed to the low water content at the end of the dry season.

Period II, alternating oxidized and reduced conditions during the first part of the rainy season
The first rains dilute the soil solution. In the presence of a low drain level, soluble

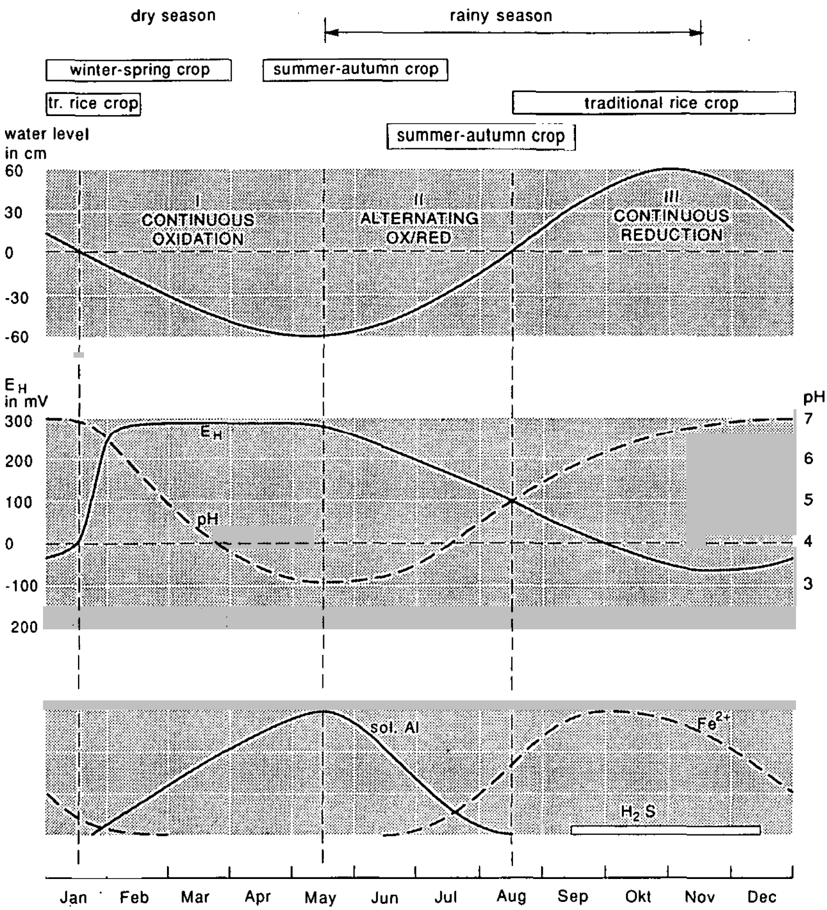


Figure 2 Schematic presentation of the seasonal redox and leaching processes influencing the composition of the soil solution in the topsoil of an uncultivated raw acid sulphate soil at Hoa An

aluminum is leached into the drainage system through interconnected cracks to the drains. Upon gradual closing of the cracks, acidity is removed by surface runoff. When the topsoil becomes submerged after a heavy rainfall, temporary soil reduction takes place. Two to three weeks after submergence, the concentration of ferrous iron reaches a peak (Ponnamperuma 1972). Usually, an early season drought occurs in July/August and, during this time, the topsoil may be re-oxidized. Several oxidation/reduction cycles may occur, each of them followed by a peak in ferrous iron. During this period, the concentration of soluble aluminum will gradually decrease due to leaching, surface flushing and a gradual rise in pH upon soil reduction.

Period III, continuous reduction during the flood

Usually in September, the amount of rainfall can no longer be drained off and a prolonged period of waterlogging persists until January. In Hoa An, the flood reaches a maximum depth of 50 cm. Now, in turn, nitrates, manganese, IV, iron III, ferric-iron, sulphate and carbon-dioxide are reduced by decomposing organic matter in the order of their respective redox-potentials (Ponnamperuma 1972). Since all reduction reactions consume acidity, the pH rises and the last soluble aluminum precipitates as aluminum-hydroxides. The concentration of iron II ferrous iron decreases due to diffusion into the flood water and the precipitation as FeS. Locally, sulphate reduction takes place in the presence of decomposing root remnants, and hydrogen sulphide is formed which can be toxic to rice roots at low concentrations (Tanaka and Yoshida 1970). At the end of the flood, the pH of the soil solution is near neutral, soluble aluminum is very low, iron II ferrous iron around 100 ppm, and there is no H_2S.

Figure 2 indicates that the highest concentrations of soluble aluminum and iron II ferrous iron are found at the start of the rainy season. This may explain the failure of farmers' attempts to grow early summer-autumn crops. Furthermore, the incorporation of the root remnants of the reed vegetation triggers strong reduction upon submergence resulting in other toxicities, which would affect traditional rice varieties transplanted in August.

The optimal time to start the cultivation of a crop is, therefore, at the end of the flood. Continuous submergence of the topsoil by irrigation preserves the optimal conditions throughout the cultivation of the winter-spring crop. Furthermore, the yearly re-acidification of the topsoil by deep cracks is prevented. At the end of the winter-spring crop, the soil is dried for two weeks to facilitate ripening. A summer-autumn crop can be grown directly after harvesting the winter-spring crop. The dry period should be kept as short as possible to prevent acidification of the topsoil and cracking of the underlying firm layer.

Field experiments

The objective of the field experiments at Hoa An during the dry seasons of 1990–1992 is to develop agronomic and water management strategies for farmers on severe acid sulphate soils. Based on the considerations mentioned above, after reclamation a winter-spring rice crop was broadcast before the recession of the flood. This crop was directly followed by a summer-autumn crop but monitoring was concentrated on the winter-spring crop.

Before the recession of the flood in 1990, a 1.4 ha field was reclaimed. The reed was cut manually and carried to the side of the field. The field was ploughed and puddled by four-wheel tractor but not levelled. Rice was broadcast and continuously irrigated until ripening. The mean yield was 2 t ha^{-1}. The rice plants growing along the sides of the field, however, yielded 4 t ha^{-1}. Explanations were sought in three directions:

- Deep reduction
  The centre of the field was lower than the sides. The soil was continuously submerged, attempts to drain the centre of the field failed due the low elevation. Plants may have suffered from a nutritional disorder associated with deep reduction;
- Leaching
  The topsoil along the drains was better leached than in the centre;
- Oxygen flow
  Along the sides of the fields, the water flow through the topsoil to the drain is higher compared to the center and brings oxygen into the soil, preventing deep reduction of the topsoil.

1991 dry season experiment

The 1991 experiment attempted to test the explanations mentioned above. To validate the deep reduction hypothesis, two irrigation treatments were applied:

- W_i: Alternating wet and dry conditions in the topsoil. Regular drying of the field was achieved using a long irrigation interval;
- W_c: Continuous submergence of the topsoil (farmers' practice).

The 'leaching effect' and 'oxygen flow effect' were investigated in two ways. Firstly two inter-drain spacings were compared:

- D_{15}: 15 m;
- D_{30}: 30 m.

The effect of the drain on the leaching rate, the composition of the soil solution and the redox-potential within the field were studied in transects:

- S_1: Along the side of the field;
- S_2: At one-fourth of the field length;
- S_3: At the centre of the field.

The water management and drain spacing treatments were randomized in one block consisting of four plots (Figure 3). The transect study is executed in block 2, in 4 plots. In order to prevent disturbance of the soil during the measurements, bridges were built along the transects. The size of a plot was 30 * 30 m. In order to cope with the high spatial variability observed in acid sulphate soils, 12 measuring points were installed per plot. Land preparation and cultivation were identical to the 1990 trial. Before broadcasting the rice, the topsoil was flushed four times to remove acid surface water developed after the land preparation.

In the main experiment, the following were monitored:

- Daily water levels in canals and fields;
- Composition of the soil solution and the surface water. The soil solution was taken

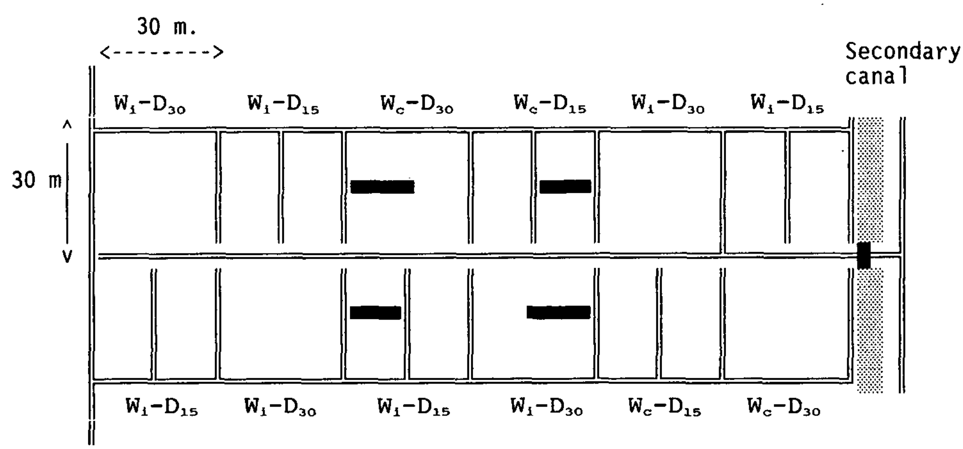


Figure 3 Layout of the field

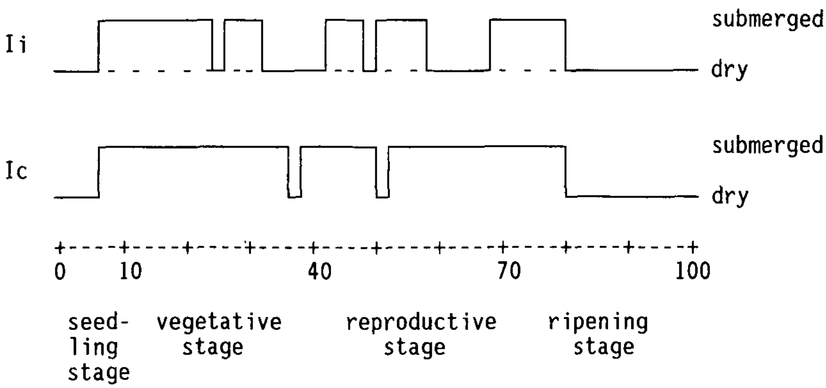


Figure 4 Submerged and dry state of the topsoil in the two water management treatments

from a depth of 15 cm by suction from ceramic cups buried in topsoil. The soil solution was taken:
2 days before sowing (DBS): before the seedling stage;
8 days after sowing (DAS): at the end of the seedling stage;
42 DAS: at the end of the vegetative stage;
64 DAS: during the reproductive stage;
85 DAS: during the ripening stage.
The soil solution was analyzed for pH, EC, soluble aluminum, total titratable acidity after complete oxidation of the sample, and content of dissolved iron II estimated using indicator paper.

In the transect study, the following were monitored:
- Leaching rates through the topsoil, determined by the measurement of pressure heads in the topsoil and sulfuric horizon using piezometers. Leaching rates were calculated by a water flow model based on the finite element method;
- Redox potential in the topsoil at 5, 10 and 15 cm;
- Composition of the soil solution as in the main experiment.

Results of the 1991 winter-spring crop

Water levels
The irrigation schedule in the two water management treatments is shown in Figure 4. In the alternating submerged/dry treatment 6 distinct dry periods can be observed. In the continuously submerged treatment, the soil was left dry during the seedling stage, to prevent floating of rice seeds, and during the ripening stage. In the first period of cultivation, it was possible to keep water on the field for 8 days. During the reproductive stage, this period was reduced to 4 days due to a higher evaporative demand and occurrence of shallow cracks in the topsoil in the W_i treatment.

Composition of the soil solution
The composition of the soil solution in the water management treatments is presented in Figure 5. The pH in the W_c treatment remained at around 5 during the submergence of the soil, but pH decreased sharply after drying of the soil. In the W_i treatment,

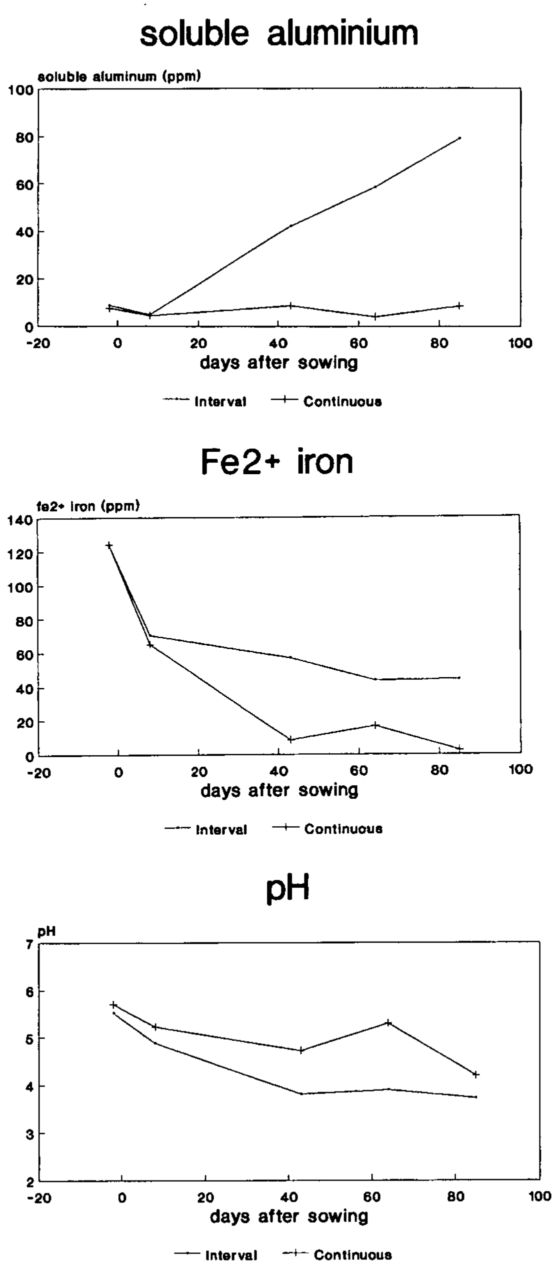


Figure 5 Composition of the soil solution

the pH decreased directly to values around 4 during the vegetative and reproductive stages. During the ripening stage, the pH further decreased to 3.7.

The concentration of soluble aluminum fluctuated between 5 to 10 ppm in the W_i treatment, it increased steadily to reach 80 ppm during the ripening stage.

Table 2 Plant performance in the water management- and drainage-treatments

Treatment	Day 48:		At harvest time:			
	Plant height (cm)	Tiller number per 0.25 m^2	Yield (ton ha^{-1})	Tiller number per 0.25 m^2	Weight per panicle (grams)	Empty grains (%)
Ii	34.4*	200*	3.8	183	0.532	9.4*
Ic	39.5*	234*	3.6	196	0.453	14.3*
n	48	48	12	36	36	36

Note: The values indicated by * are significantly different at an 0.05% interval

In the W_c treatment, the estimated level of Fe^{2+} remains at a low level of 10 to 20 ppm. The low concentration may be explained by precipitation as ferrous sulphide. In the W_i treatment, the estimated concentration is higher compared to the W_c treatment: 40 to 60 ppm, perhaps due to repeated peaks after periods of oxidation. No significant differences were found in the D_{15} and D_{30} drain spacing treatments and S_1, S_2, S_3 locations in the transect study.

Plant performance

In the W_i treatment, plant development was normal during the seedling stage but, during the vegetative stage, both roots and shoots were stunted. At the start of the reproductive stage, plant height and number of tillers were low (Table 2). However, the plants recovered and showed normal development until harvest.

In the W_c treatment, early development was luxuriant but, in the reproductive stage, plants/roots lost their brown colour, turned white, then black and, finnaly, died.

There was no significant difference between the yields of the W_i and W_c treatments. The percentage of empty grains in the W_c treatment was, however, significantly higher compared to the W_i treatment.

Results of the transect study

No significant differences in redox potential, composition of the soil solution and leaching rate were found at varying distances from the side of the field. The calculated leaching rates were rather erratic.

Economics

In Table 3, the initial investments needed to reclaim the land, together with the variable costs of cultivation and yield are presented. The break-even point of cultivation is at 2.15 t ha^{-1}. With the production of 3.9 t ha^{-1}, the profit is sufficient to pay back the initial investments for canal digging and land preparation. It is expected that yields in the future crops will improve due to gradual leaching of toxic substances and better levelling.

Pollution

The quality of the irrigation water was good throughout the cultivation of the crop. The quality of the drainage water was, however, very bad (Table 4).

Table 3 Economic parameters of the 1991 winter-spring in thousands VND ha^{-1} and kg rice ha^{-1}

Unit	Initial investments				Variable costs	Yield	Yield -Var. costs	Yield -var. costs -init. inv.
	digging of canals	cutting + moving reed	pulling roots after puddl.	leveling				
VND/ha	846	176	176	382	1 938	3 500	1 562	18
kg rice/ha	940	196	196	424	2 153	3 889	1 735	20

The pH of the drainage water varied between pH 3.4 and 2.6. The amount of drainage water from the field is equal to a water layer of 154 mm per crop. The amount of acidity leached into the canals is roughly 5 000 mol soluble aluminum per ha per crop, an a total acidity of 23 000 mol acidity per ha per crop.

Discussion

Deep reduction

The results from the 1991 trial indicate clear effects of the water management on the agronomic parameters, composition of the soil solution and the redoxpotential. The rice plants in the soil under continuous submergence showed symptoms of iron toxicity during the reproductive stage and, in a later stage, a large part of the root system died. Although the plant symptoms indicate iron toxicity, iron cannot be held directly responsible for the nutritional disorder observed. The estimated level of dissolved iron in the W_c treatment never exceeded 10 ppm. Soluble aluminum during the reproductive stage did not exceed 5 ppm. The soluble aluminum level in the W_i treatment showed much higher values. At the start of the reproductive stage a redox potential of +6 mV was measured in the root zone of the W_c plots. The redox potential in the regularly oxidized plots was significantly higher: +290 mV. Unfortunately the redoxmeasurement during flowering failed. In soil solution samples, taken during the reproduc-

Table 4 Quality of surface water and amount of toxic elements leached into the surrounding canals

	Days after sowing:				
	-2	8	41	64	85
Irrigation canal:					
pH	–	6.3	6.8	6.3	6.8
soluble aluminum (ppm)	1.3	–	7.2	1.8	1.35
total acidity (mol/l)	0.29	–	0.56	0.23	0.15
Drainage canal:					
pH	–	3.4	2.9	2.9	2.6
soluble aluminum (ppm)	19.5	–	56.7	148	129
total acidity (mol/l)	0.29	–	10.7	26.2	23.3

tive stage in the W_c plots, a strong H_2S smell was detected. Large amounts of black decaying remnants of *Eleocaris dulcis* roots were found. The roots were incorporated into the soil during the land preparation.

Based on these observations, the following mechanism is believed to be involved (Moorman and Van Breemen 1978, Van Breemen 1980), (see Figure 6). In order to survive in a predominantly reduced environment, the rice plant pumps oxygen downward through the root, creating an oxidized zone around it. In this oxidized zone around the root, iron III is precipitated as a brown crust of Fe^{2+} hydroxides, preventing the uptake of excess Fe^{2+} ions, usually present in reduced soils. Locally, in the presence of decomposing root remnants, very strong reduction takes place. In these reduced conditions, reduction of sulphates to sulphides can take place, which can be recognized by a black colour and strong H_2S smell. In the presence of a decomposing root remnant, the iron III hydroxides in the oxidized layer are reduced to Fe^{2+}, as can be seen by the disappearing of the brown crust around the root. Now Fe^{2+} ions can freely enter the root and the rice plant, resulting in brown colouring of the plant. In a later stage, rice roots are covered by black FeS and die. The dead rice roots are added to the amount of fresh decomposing organic matter. The nutritional disorder asso-

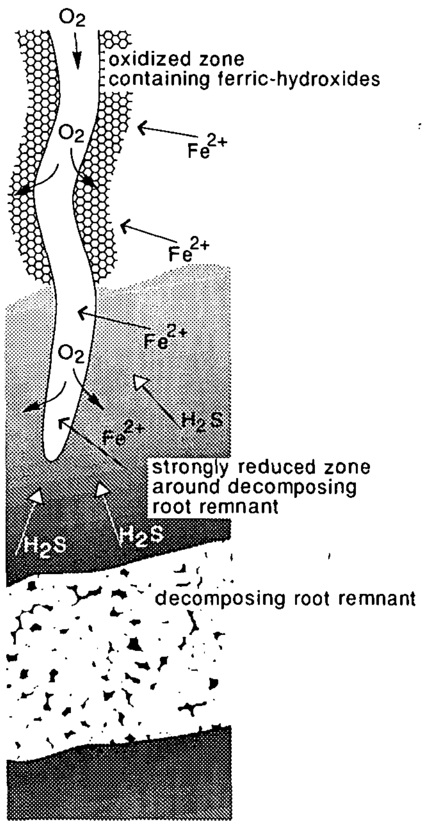


Figure 6 Presumed mechanism of H_2S-induced iron toxicity

ciated with deep reduction may therefore be described as H_2S-induced iron toxicity.

To prevent the deep reduction, in the W_i treatment, the topsoil was oxidized regularly by applying a long irrigation interval. This resulted in a nutritional disorder during the vegetative stage. Plants and roots were stunted. The estimated level of iron III during the vegetative stage was around 50 to 70 ppm. At this level no toxicity is to be expected, even at low nutrient levels. No clear leaf symptoms were observed. The concentration of soluble aluminum in the W_i treatment was significantly higher compared to the W_c treatment. During the vegetative stage the concentration increased from 5 to 40 ppm. In the W_c treatment soluble aluminum increased from 5 to 8 ppm. Concentrations of soluble aluminum considered toxic for rice roots mentioned in the literature vary widely (Van Mensvoort et al. 1985; Tanaka and Yoshida 1970; Tanaka and Navasero 1966; IRRI 1978). Since nutritional disorders other than aluminum toxicity are not expected, it may be concluded that the plants were suffering from a mild form of aluminum toxicity.

In the course of the reproductive stage, the plants in the W_i treatment recovered despite an increasing concentration of soluble aluminum. The key to recovery can probably be found in the physical soil condition. In the course of the reproductive stage, due to repeated drying of the soil in the W_i treatment, shallow cracks were formed. Root development was concentrated in the suitable environment along the cracks. In the soil matrix only some thick, stunted roots, typical for aluminum toxicity, were found.

The leaching effect

The lack of evidence supporting the 'leaching theory' may be explained by the physical characteristics of the soil. Before cracking, hardly any flow occurs due to the low permeability of topsoil and hardpan. After repeated drying of the topsoil, cracks occur between 20 to 30 cm large soil prisms, and the cracks penetrate down to the transition between the topsoil and hardpan. Water is able to move relatively fast through the large cracks without influencing the soil solution inside the soil matrix.

The oxygen-flow effect

No significant differences between redoxpotentials were found along the transects, and between the 15 and 30 m. drain distance. The redoxstatus seems to be fully controlled by the wetting or drying of the heavy clay soil, rather than by oxygen transported by water flow.

It must, however, be noted that the yields of fields having a drain spacing of 15 to 30 m, as in the 1991 winter-spring crop were 3.8 ton/ha, whereas the yield in the field having a drain spacing of 70 m (1990 winter-spring) yielded only 2 ton/ha. The large difference in yield between the fields may be explained by the bad leveling of the 70 m. field, while the 30 and 15 m fields were excellently levelled.

Conclusions and recommendations

1) The cultivation of an irrigated winter-spring crop on a severe acid sulphate soil in Hoa An station is economically and technically feasible.

2) There is strong evidence for the effect of strong reduction on plant performance. Plants growing under continuously submerged conditions were suffering from a nutritional disorder which can be described as H_2S-induced iron toxicity. The nutritional disorder occurred in the course of the reproductive and ripening stages and resulted in a significantly higher percentage of empty grains. Regular oxidation of the topsoil as a remedy to the nutritional disorder associated with deep reduction brings about another nutritional disorder: aluminum toxicity. Regular oxidation of the topsoil does not result in a significantly higher yield. An ideal water management strategy may be found by limiting the dry periods to one or two periods just before the flowering. This way, aluminum toxicity during the vegetative stage is prevented, as well as deep reduction during the flowering. It may be helpful to dry the soil intensively to induce cracking of the topsoil.
3) The redoxstatus of the soil seems to be more important than the leaching rate in determining plant performance, occurrence of nutritional disorders and composition of the soil solution. The redoxstatus of the soil can be controlled by managing the drainage. No evidence was found to support the role of the flow of oxygen-rich water through the topsoil into the drains in controlling the redox status of the soil.
4) Good leveling is essential to control the drainage. If equipment or labour are scarce, shallow drains can be used to drain surface water from the lowest parts of the field.
5) Pollution of surrounding canals by acid drainage water from a newly reclaimed field is a fact. Irrigation and drainage canals should be separated at tertiary level. At primary and secondary level, sufficient flow is needed to prevent undesirable high concentrations of acidity in the canal water.

References

Bakker, N. 1990. Water management on acid sulphate soils, experiment E-73. Technical report no. 4, VH-10 project. Internal VH-10 publication, Wageningen Agricultural University, the Netherlands

Bos, J. 1984. Spatial variability of potential and actual acid sulphate soils in the Mekong delta, Vietnam. Thesis written in partial fulfillment of the MSc. degree. Dept. of Soil Science and Geology, Agricultural University Wageningen, the Netherlands

Breemen, N. van 1980. Acidity of wetland soils, including Histosols, as a constraint to food production. In: Soil related constraints to food production in the tropics. IRRI, Los Baños, Laguna

Hanhart, K. and Duong van Ni 1992. The effect of water management treatments on the cultivation of an irrigated dry season rice crop on a severe acid sulphate soil in Hoa An station, Vietnam. VH-10 project, technical report no. 9. Agricultural University, Wageningen

IRRI 1978. Annual report for 1977, 97-103 Los Baños, Laguna

Moormann, F.R. and N. van Breemen 1978. Rice: soil, water, land. International Rice Research Institute, Los Baños

Ponnamperuma, F.N. 1972. The chemistry of submerged soils. Advances in Agronomy, 24, 29-96

Raupach, M. 1963. Solubility of simple Al-compounds expected in soil. Australian Journal of Soil Research, 1, 28-62

Tanaka, A. and S.A. Navasero 1966. Growth of the rice plant on acid sulphate soils. Soil Science and Plant Nutrition 12, 107-114

Tanaka, A. and S. Yoshida 1970. Nutritional disorders of the rice plant in Asia. IRRI technical bulletin 10, 51 p. IRRI, Los Baños, Laguna

Thuan, Tran Minh 1989. A study of the lowering of the ground water level. A case study in the Plain of Reeds, Vietnam. Unpublished thesis presented in partial fulfillment of the requirements for the degree of MSc. Agricultural University Wageningen

Van Mensvoort, M.E., R.S. Lantin, R. Brinkman and N. van Breemen 1985. Toxicities of wetland soils, 123-138. In: Wetland soils: characterization, classification and utilization. Proceedings workshop on characterization, classification and utilization of wetland soils. IRRI, Los Baños, Laguna

Integrated research on water management, soil fertility and cropping systems on acid sulphate soils in South Kalimantan, Indonesia

R.A.L. Kselik[1], K.W. Smilde[2], H.P. Ritzema[1], Kasdi Subagyono[3], S. Saragih[4], Mauliana Damanik[4] and H. Suwardjo[3]

[1] ILRI, P.O. Box 45, 6700 AA Wageningen, the Netherlands
[2] Institute for Soil Fertility Research IB-DLO, P.O. Box 30003, 9750 RA Haren, the Netherlands
[3] Centre for Soil and Agroclimate Research, Jl. Ir. H. Juanda 98, Bogor, Indonesia
[4] Banjarbaru Research Institute for Food Crops, Banjarbaru, Indonesia

Abstract

In Pulau Petak, S. Kalimantan, four hydrological regimes and two kinds of soils (potential acid sulphate soils and actual acid sulphate soils) were distinguished. Soil and hydrological conditions and farmers' practices were monitored at 3 sites and field experiments conducted at two more sites.

At one experimental site (Tabunganen) control of water level was not possible because of wet season flooding and the high hydraulic conductivity of the soil, but double cropping of rice was possible. At the other site (Unit Tatas), the use of irrigation water from different sources gave no significant differences in rice yield. However, strong positive yield responses for rice were obtained from interception of acid drainage water from adjacent forest land, puddling and lime.

It is not necessary to lime to neutrality – yields doubled and a linear response was obtained up to 1 125 CaO kg ha^{-1}. Liming once every 2 or 3 crops is quite effective. Yield responses to P and K were less spectacular. Upland crops (maize, soybean, cassava and groundnut) were grown successfully with a shallow drainage system. Again, lime increased yields. Based on the results of the experiments and monitoring, strategies for agricultural development for each combination of soil and hydrological type are put forward.

Introduction

Of the estimated 12 million ha of potential and actual acid sulphate soils in the world, about 1.5 million ha are found on the islands of Kalimantan and Sumatra, Indonesia (Langenhoff 1986).

Since 1987, the Indonesian Agency for Agricultural Research and Development (AARD) and the Dutch Land and Water Research group (LAWOO) have undertaken multidisciplinary collaboration on 'Research on Acid Sulphate Soils in the Humid Tropics' to develop strategies for an ecologically-sound development of the tidal land with (potential) acid sulphate soils in the humid tropics. The aim is to improve agricultural production by:

– Improving the yield of crops currently cultivated, mainly rice;
– Crop intensification and diversification: to enable the introduction of a second crop

in the dry season including dryland crops (soybean, maize, peanut) as a second crop or a double crop.

This paper reports the integrated soil and water management, soil fertility and cropping systems experiments of this project, which are aimed at developing applicable systems to overcome and reduce acidity problems at farm level.

General description of the research area

Pulau Petak island is situated in the lower delta of the Barito river (Figure 1). The total area is approximately 220 000 ha.

Early settlers improved natural creeks and dug small canals (handils), penetrating two to ten km land inwards from the creeks. Systematic reclamation started around 1920. Since 1970, the Indonesian government has constructed nine, large, forked drainage systems to open the area for transmigration. Up to now, some 150 000 ha have been reclaimed; half is still cultivated, while the remaining area has been abandoned.

Climate, topography and soils

The climate is tropical without a dry season, with a maximum annual rainfall of more than 3000 mm and a minimum annual rainfall of less than 1 900 mm. Daily Penman evaporation ranges between 3.7 and 4.9 mm with an annual average of 1 493 mm (Reppprot 1987).

The land is flat with a general upward slope of about 1 cm/km to the north east. The following physiographic units can be distinguished: alluvio-marine plains, river levees, coastal ridges, old riverbeds and low peat domes (AARD & LAWOO Volume 2, 1992).

Broadly, two types of soils have been recognized, both acid sulphate soils. The first occurs in relatively low-lying, naturally waterlogged parts of the landscape. It is characterized by a brown layer (20-60 cm thick), overlying a grey layer. These soils are rich in organic matter (5-14 percent) and half to nearly ripe. The pyrite content is low in the brown layer and high in the grey layer.

The second type occurs on the relatively high parts of the landscape. It is strongly mottled and, in general, ripe. The organic matter content varies between 4 and 6.5 percent and the pyrite content is low till the subsoil is reached at > 125 cm.

Hydrology

The hydrological areas are based on the tidal land classification commonly used for tidal swamp areas in Indonesia (Kselik 1990), adjusted to incorporate the effects of drainage. Four tidal land classes are recognized (Figure 1):

Type A: Between mean low tide and mean high neaps. Daily irrigation by tidal flooding during high tide and daily drainage during low tide;

Type B: Between mean high neaps tide and mean high springs. Irrigation by tidal flooding during spring tide and, always, drainage during low tide;

Type C: Above high spring tides. No tidal flooding, permanent drainage. Tidal movement only affects groundwater;

Type D: Beyond the influence of daily tides, limited drainage.

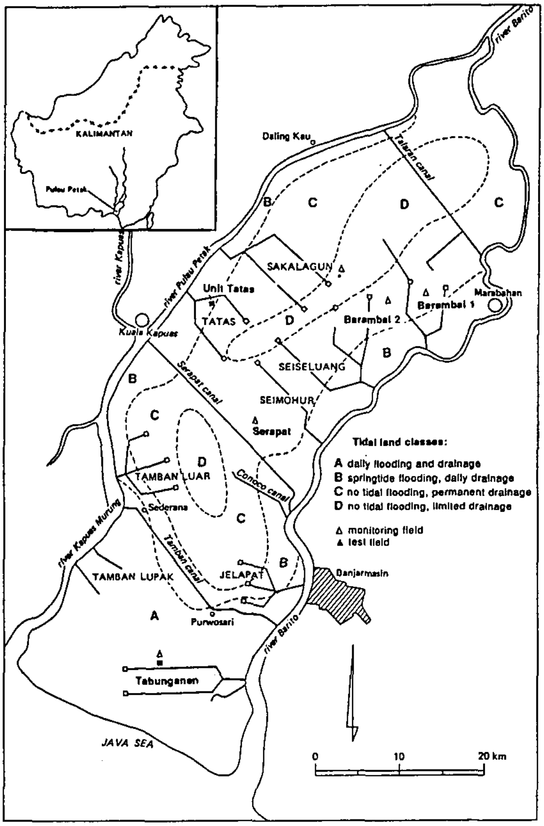


Figure 1 Pulau Petak. Tidal land classes and location of monitored and test fields

Description of the research sites and monitored fields

Two research sites in two geographically different areas were selected.

The main differences between the two selected sites are twofold: the soils in Tabunganen are potential acid sulphate soils and the area is under daily tidal influence; the soils in Unit Tatas are actual acid sulphate soils and the area can be irrigated only during spring tides.

The test site in Tabunganen is located in a tertiary unit of 30 ha, approximately 700 m from the northern secondary canal of the Tabunganen forked system. The area consists mainly of sawahs on which local rice varieties are grown. The crop grows for nine months and is transplanted three times. Coconuts are planted on the bunds that separate the rice fields. Some farmers plant oranges and cassava on raised beds. The tertiary canals are in open connection with the secondary canal. The size of the experimental field is approximately 0.5 ha.

Water balances have been calculated for Tabunganen and Unit Tatas, covering one year and consisting of rainfall (R), evapotranspiration (E), surface inflow, which is either irrigation water or surface flow from adjacent backswamps (Q_{ins}), groundwater

Table 1 Description of the research sites

Name of research site	Tabunganen	Unit Tatas
Location	South Kalimantan	Central Kalimantan
Year of reclamation	1980	1975
Elevation (m above sea level)	0.80	2.00
Physiography	backswamp	backswamp
Land use	rice field/coconut	rice/cassava/soybean/peanut/maize
Tidal Land Class	Type A	Type B
Irrigation	daily tidal	spring tide
Drainage possibilities	poor	good
Hydraulic transmissivity (m^2/day)	80	1500
Tidal water	brackish	fresh
Type of acid sulphate soil	potential	actual
Soil classification	typic sulfaquent	sulfic hydraquent
Depth of peat layer	10 cm	5 cm
Depth of brown topsoil	45 cm	90 cm
Starting depth of pyrite	45 cm	95 cm
Ripeness mineral soil	nearly ripe	nearly ripe
Cracks in soil	no	yes: 45-130 cm
Mottles of iron oxides	no	yes: 0-130 cm

inflow (Q_{ing}) and outflowing water which can be surface runoff and groundwater outflow (Q_{out}) (Table 2). Storage is negligible over a one year period. Because no significant differences in rainfall were found between sites, the long-term averages from the Banjarbaru Meteorological Service were used.

In Tabunganen, the water balance is dominated by the daily inflow and outflow of surface water and groundwater. Because of the high transmissivity of the topsoil and high watertables, the flow components of groundwater and surface water cannot be separated.

The low elevation of the site increases the risk of flooding during the wet season but, on the other hand, makes it possible to maintain a high watertable during the dry season (Figure 2).

The main constraints in the area are excessive flooding at the start of the wet season, especially on the somewhat lower-lying fields, salinity in the dry season, and a slight acidification of the topsoil at the end of the dry season.

The test site Unit Tatas is located on the northern branch of the Unit Tatas forked system at the experimental station of the Banjarbaru Research Institute for Foodcrops. The test fields are situated between two tertiary canals at approximately 400 m from the secondary canal of the forked system. The size of the test fields is 2.7 ha and the size of the tertiary unit is 5 ha.

Table 2 Water balances (mm) in the experimental field

Research site	R	E	Q_{ins}	Q_{ing}	Q_{out}
Tabunganen	2412	1529		38810	39992
Unit Tatas sawah	2412	1529	12860	2177	15930
Unit Tatas drained	2412	1529	–	6203	7046

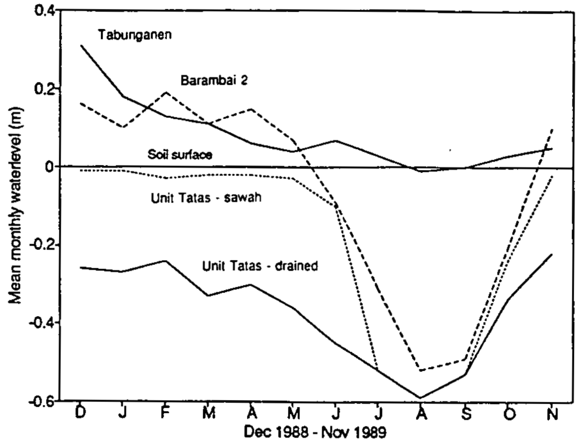


Figure 2 Monthly average water levels in Tabunganen, Unit Tatas and Barambai 2

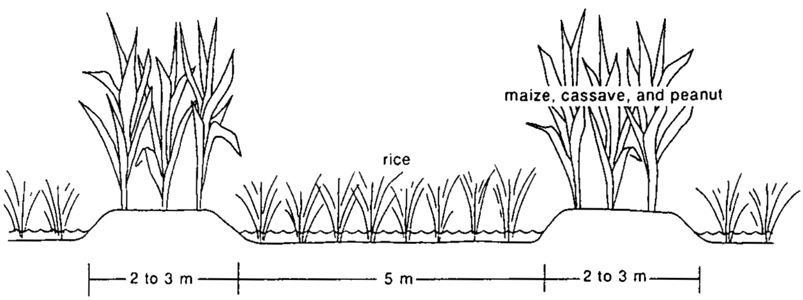


Figure 3 The sorjan system

The main crop in the area is rice of a local variety but, palawija crops like soybean, cassava, peanut and maize are grown on sorjans (raised beds). In between the raised beds, rice is planted (Figure 3).

The land is higher than at Tabunganen and irrigation is only possible during spring tides. Drainage is always possible. Farmers conserve water by means of stoplogs in the tertiary canal so that drainage can be restricted in rice fields, or stimulated to enable dryland crops to be grown.

One major problem is the inflow of acid water from the adjacent secondary forest (Figure 4). The construction of an interceptor drain reduced the inflow considerably.

The main constraints in Unit Tatas are acidity, low fertility, and drought at the end of the wet season.

Monitored fields

Serapat

Serapat was reclaimed around 1920 and, thus, represents one of the oldest reclaimed areas of Pulau Petak. Because of its relatively high elevation, the area has good drainage but no tidal irrigation is possible. The tide only influences the fluctuation of

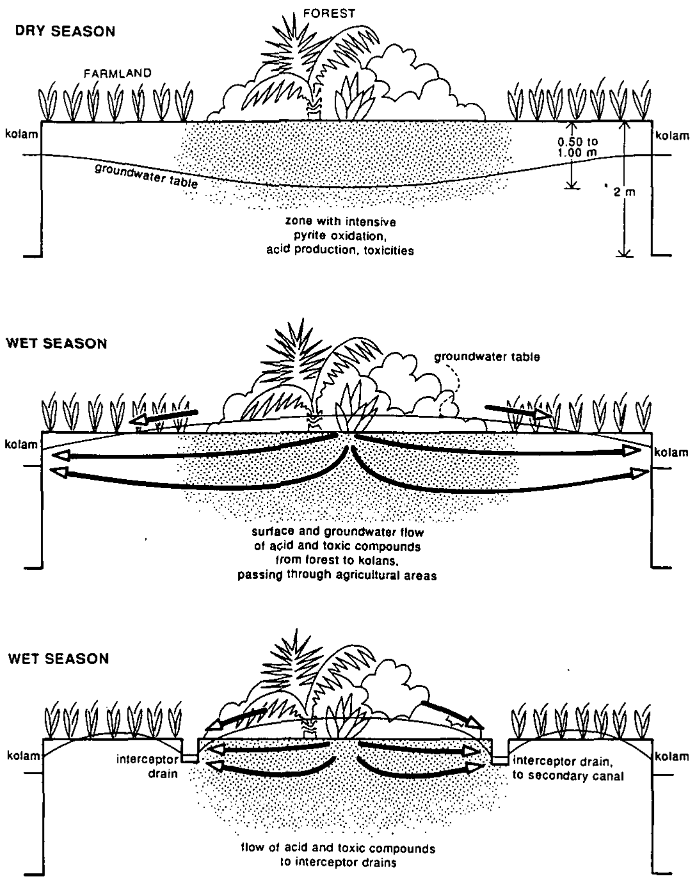


Figure 4 Inflow of acid water from secondary forest to agricultural areas and the influence of an interceptor drain

the watertable. The soil is a Sulfic Tropaquent. The only crop cultivated in the area is rice of the local variety. Yields vary between 2.3 and 2.8 t ha^{-1}. The main constraints are the low pH of the topsoil and the acidity of the surface water and groundwater.

Barambai 1

Barambai 1 also has good drainage and no possibility of tidal irrigation. The soil is a Sulfic Fluvaquent. To be able to grow rice, farmers block the drainage system. Fruit trees (rambutans) are grown on raised beds. Rice yields vary between 1.9 and 2.8 t ha^{-1}. In this area, too, the main constraints are the low pH of the topsoil and acidity of the surface water and groundwater.

Barambai 2

Barambai 2 lies outside the zone of tidal influence. It has poor drainage conditions and no possibility of irrigation. During the wet season, rainfall and the inflow from nearby swampy areas cause ponding (Figure 2). The soil is a potential acid sulphate soil with a peat layer on top. Because of the presence of the peat layer, soil conditions are better than in Barambai 1; consequently, rice yields are slightly higher (around 2.9 t ha^{-1}). During the dry season, however, the watertable drops and some acidification takes place, resulting in acid water at the start of the rainy season. Burning of the peat layer may aggravate the problem.

An integrated research approach

The research was aimed at integrating aspects of soil and water management, soil fertility and crop rotation, and was organized to fit the cropping systems of the local farmers. Water management involved irrigation, water conservation and drainage but, in Tabunganen, no measures could be taken at tertiary level (i.e. structures in tertiary canals) since this would influence other people's fields. Water management experiments were, therefore, conducted at field level only. In Unit Tatas, the complete tertiary unit could be used, so experiments were carried out at tertiary and at field level. In Tabunganen, fertilizers were applied as a basal dressing of N, P and K. In Unit Tatas the effects of N, P and K fertilizers and lime were studied. The cropping systems experiments in Unit Tatas introduced high-yielding rice varieties, palawija crops, and double cropping of rice and palawija crops.

Experiments at Tabunganen

The objectives of the trials in Tabunganen were to create conditions enabling double cropping of rice and to study the effect of water management on yields. To these ends, flood hazard in the wet season and salt water intrusion in the dry season were to be reduced. Four different water managements were implemented:
- Continuous drainage;
- Intermittant drainage (2 weeks of drainage, 1 week daily tidal irrigation);
- Daily tidal irrigation;
- Rainfall conservation.

The test field was divided into plots by field bunds and, in each plot, one of the four water management strategies was applied. Water levels in each plot and rainfall were monitored half hourly by means of automatic registration equipment. Drainage was performed by means of 40 cm deep, open drains with wooden flapgates in plots 1 and 2 and hand operated inlet/outlet structures in the plots 3 and 4.

Double cropping consisted of one high-yielding variety (IR42) followed by a local rice variety (Pandak). The local variety grows nine months from seedbed till harvest. During this time, it is transplanted three times. The final transplant to the test fields took place in April, after harvest of the high-yielding variety. Basic fertilizer dressing of 90 kg N, 90 kg P_2O_5 and 50 kg K_2O ha^{-1} was applied for the high-yielding variety.

Figure 5 shows monthly water levels in the plots 2, 3 and 4 and yields of IR42 in these plots. Water levels during the first months of the monitoring period were high. During December 1988 and January 1989, not only the test fields but the whole area was inundated by the Barito River. Field 4 experienced the deepest flooding, which was fatal for field 4, too deep and fatal for the young rice plants, resulting

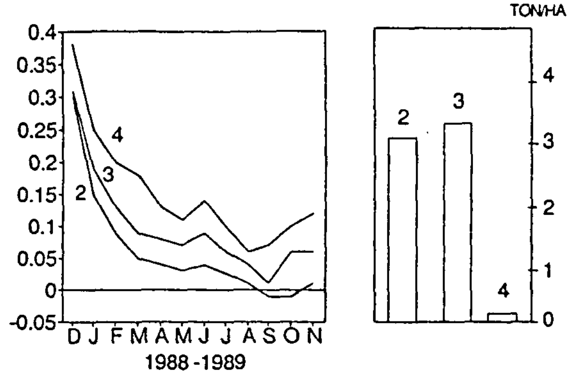


Figure 5 Average monthly water levels and yields in three plots in Tabunganen

in a loss of the harvest. Table 3 shows the results of both the first crop (IR42) and the second crop (Pandak).

Controlling the water levels at field level was not possible for various reasons. The dams bordering the tertiary canals are too low to keep the water levels below the periods of heavy rainfall and high water level in the river. The tertiary canals must drain the water that enters the tertiary block at high tide and the rain that falls during this period. During the relatively drier periods, water levels in the different experimental plots could still not be controlled satisfactorily due to leakage of the field bunds and the permeability of the soil. Pumping tests at the location showed that the hydraulic transmissivity of the first two metres is about 80 m^2 day^{-1}.

The experiments showed that double cropping is possible but, for optimal results, water levels must be controlled. Combined with double cropping, this would increase the productivity of area substantially.

Yields of local and HYV were comparable but, to reach the same yield as the HYV, the local variety had to grow twice as long.

Table 3 Yields (t/ha) of the first and second rice crop in Tabunganen 1988/1989

Field	Crop 1 High Yielding Variety (IR42)	Crop 2 Local Variety (Pandak)
1	3.1	3.2
2	2.8	3.0
3	3.1	3.8
4	0.1	3.1

Experiments at Unit Tatas

The main constraints for plant growth in Unit Tatas are iron and aluminum toxicity and nutrient deficiencies. Also, a poor water quality and water retention was observed in the sawahs. The objective of the trials was to improve the agricultural production by combined water management and fertilizer applications. During two years, 1988/1989 and 1989/1990, double cropping of rice and palawija crops was practised.

Water management trials were conducted at field and tertiary level. In the original situation, the tertiary drains were in open connection with the secondary canal. Only during spring tides were the water levels high enough to inundate the fields. At the rear end, the tertiary block is closed off from the gelam forest (*Melaleuca cajuputi*) by a dam. The test fields are bordering the gelam forest. During the wet season, from December till June, water is ponded in the forest and can be used for irrigation.

In the new situation (Figure 6), the following water management system was designed at tertiary level. Two flapgates were built in the tertiary canals to create a one-way flow system separating irrigation and drainage water. The flapgate in the irrigation canal opens at high tide and the flapgate in the drain opens at low tide. Thus, the irrigation and drainage to and from the field can be controlled, and a head-loss is created between the irrigation and drainage canals resulting in a groundwater flow which removes toxic elements from the soil. At field level, in the sawahs (Figure 6: fields 2, 3 and 4) field bunds were made to separate the fields, and small inlet and outlet structures were installed. Each field could be irrigated or drained individually and options like water conservation or flushing of the fields became available. Fields 2, 3 and 4 were divided into two blocks. Each block was irrigated from a different source (canal, forest or rain).

In field 1 (Figure 6) a shallow drainage system was dug, to conduct experiments with palawija crops. It had an outlet to the drainage canal but was never irrigated.

Water management included flushing and shallow drainage, and puddling to

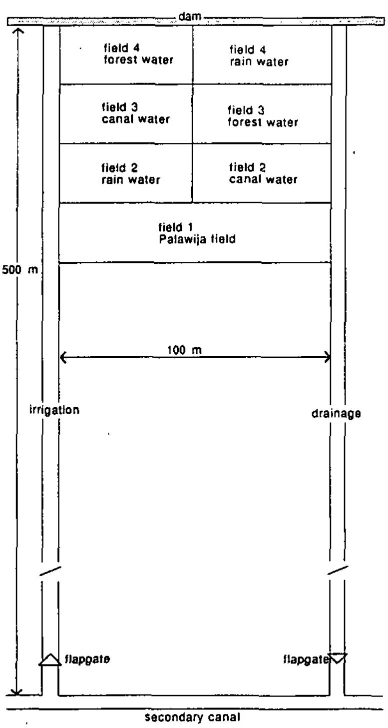


Figure 6 Layout of the experimental fields in Unit Tatas

increase water retention in the sawahs to prevent drought stress. A split-plot design was used with water management as the main treatment, puddling in sub-blocks as a second treatment and fertilizer in sub-plots as the third treatment.

During 1988-1989 the following water management options were carried out:
- Shallow drainage of the palawija field;
- Irrigation of the sawahs with canal water;
- Irrigation of the sawahs with water from the forest;
- Rainwater conservation only;
- Puddling of the sawahs.

For monitoring, a network of piezometers was installed. From these piezometers and from the surface water, water samples were taken weekly. In the different blocks, water level recorders were installed to measure the water levels in the irrigated fields and in the palawija field.

In the fertilizer experiments, lime, nitrogen, potassium and phosphorus were applied. It is impractical to aim at complete neutralization because of the massive quantities of lime required. Moderate lime application of up to 1000 kg ha^{-1} should suffice to control toxic Al^{3+}. Other expected effects of lime were to depress Fe^{2+} and H_2S peaks after flooding; increase of soil pH if applicable, improve base saturation, increase P-availability to crops; improve fertilizer efficiency and improve crop root growth. Residual effects of such small dressings are expected to be low so there will be a need for regular treatment.

Prade et al. (1988) report extreme sensitivity of rice seedlings to soil Fe^{2+}, which reaches high levels just after flooding. They recommend postponing transplanting until 1-3 weeks after flooding. According to Yamauchi (1989), Fe^{2+} toxicity and K deficiency, both causing brown mottling or 'bronzing', are interrelated. Application of K alleviates the syndrome by increasing plant K and reducing plant Fe^{2+}.

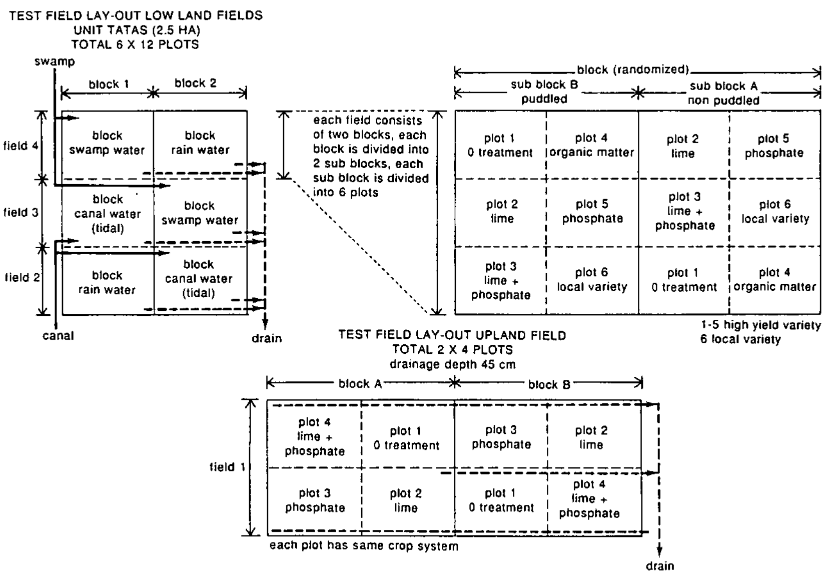


Figure 7 Design Unit Tatas experiment

Table 4 Effects of water management and fertilizer on high-yielding rice in Unit Tatas averaged over the wet and dry season of 1988/1989. Yields in t ha^{-1}

Treatment	Water source		
	Rain	Canal	Forest
Control	0.97	1.26	1.12
Fertilizer	1.59	1.62	1.45
Lime	2.08	2.26	2.31
Lime + Fertilizer	2.46	2.25	2.51

At low pH, P is retained as insoluble $AlPO_4$ or $FePO_4$, causing P deficiency which can be alleviated by application of P and lime.

N supply is expected to be low because of slow organic matter turnover in acid conditions while N fixation by leguminous crops is suppressed.

Fertilizer experiments in the 1988/1989 wet and 1989 dry season

Figure 7 shows the randomized sub plots for wetland rice supporting high-yielding varieties with fertilizer treatments and traditional varieties without fertilizers. Treatments applied were combinations of P (0 and 90 kg P_2O_5 ha^{-1}) and lime (0 and 1500 kg CaO ha^{-1}) with an extra 750 kg CaO ha^{-1} and organic matter in the form of rice straw in the dry season.

The layout for the upland (palawija) field included two randomized blocks (replicates) with fertilizers. Crops were high-yielding rice (wet season), peanut and soybean (dry season). P and lime applications were similar to the those for wetland fields. All plots received a standard N and K dressing.

The three sources of irrigation water differed in water quality. pH values of forest, canal and rain water were 2.5-3, 3.8-4.5, and about 6.5, respectively.

Table 4 shows yields of sawah rice during the first year in the non-puddled fields. Different sources of water produced no significant differences.

Data from the piezometer network showed that there was a groundwater flow from the gelam forest in the direction of the secondary canal and that the quality of this water was very poor. This flow influenced the experiments in the three sawahs 2, 3 and 4. As the wet season begins, in December, this water starts flowing through the soil from the forest to the secondary canal. Pumping tests showed that the hydraulic transmissivity of the soil varied between 1000 and 2000 m^2 day^{-1}. The flow of the groundwater could be monitored by means of piezometers which were placed in the fields 2, 3 and 4. As an indicator, the SO_4^{2-} content of groundwater was used. Figure 8 shows concentrations at different dates in fields 2, 3 and 4. The highest concentrations of SO_4^{2-} first appear in the field closest to the gelam forest (field 4) and a few months, later, also in field 2. The quality of the irrigation water apparently had only minor influence on the quality of the groundwater (see water quality data in Figure 8). As the pyritic layer in Unit Tatas starts at 90 cm below soil surface and the watertable during the observation period never dropped deeper than 15 cm below soil surface, there was no oxidation of pyrite in situ.

To improve this situation during the next year, an interceptor drain of 1 metre deep and 1 metre wide was dug between field 4 and field 3.

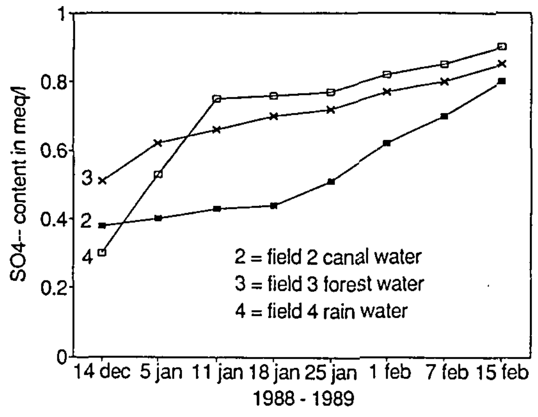


Figure 8 SO_4^{2-} concentration of groundwater over time in fields 2, 3 and 4 in Unit Tatas

Table 5 Lowland and upland crop yields in t/ha

	Lowland		Upland	
Treatment	1st harvest HYV, wet season	2nd harvest HYV, dry season	rice	peanut
Control	1.17	1.08	0.79	0.32
Phosphate	1.55 ns	1.43 *	1.08 ns	0.50 ns
Lime	2.33 *	2.04 **	1.60 *	1.80 **
Lime + Phosphate	2.31 *	2.37 **	2.00 *	1.93 **
Organic matter	–	1.21 ns	–	0.38 ns

ns = not significant
* = significant at 5%, ** = significant at 1%

Results of the fertility experiments (Table 5) showed a highly significant response to lime, both in HYV rice and peanut. Application of 1.5 CaO t ha^{-1} doubled rice yields, both in the wet and dry season (lowland), and also under upland conditions. Yield increase in peanut was even more spectacular. Only the dry season lowland rice responded to P. Organic matter, i.e. rice straw left in the field, had no significant effect on yield. Surprisingly, the traditional variety without lime and fertilizer attained a similar yield to the HYV, but over twice the growth period (Table 6).

Lime had a negative effect on leaf Fe^{2+}. The traditional rice variety had lower leaf Fe^{2+} contents than HYV rice (Figure 9). It remains to be elucidated if this is associated with a difference in tolerance of Fe^{2+} between the traditional and HY varieties. High peaks in leaf Fe^{2+} just after transplanting were not observed (cf. Prade et al. 1988).

Table 6 Local varieties Unit Tatas (one crop only), yield in t ha^{-1} at various water treatments

	Rain	Canal	Swamp
Non-puddled	1.61	2.35	2.25
Puddled	2.25	2.84	2.42

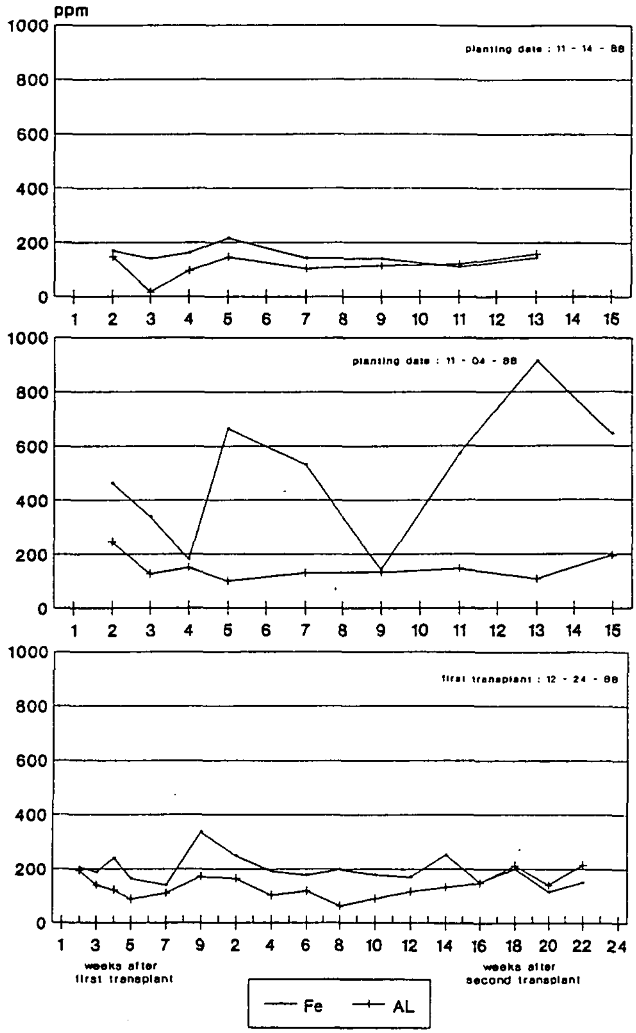


Figure 9 Effect of liming and variety on Fe and Al contents of rice leaves; Top: High Yielding Variety (limed); centre: High Yielding Variety (control); bottom: Traditional Variety

1989/1990 Experiments in Unit Tatas

During the second year, water management was as follows:

- Shallow drainage of the palawija field;
- Irrigation with canal water;
- The use of an interceptor drain;
- Puddling of the sawahs by hand tractor.

From the experiments in the first year, it appeared that puddling by foot was not very effective. Therefore, during the second year, a small, hand tractor was used. As

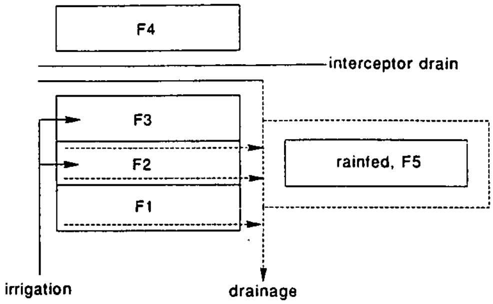


Figure 10 1989/1990 experimental design Unit Tatas

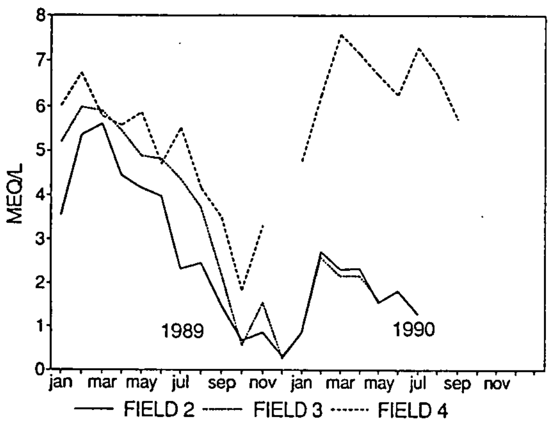


Figure 11 Concentration of SO_4^{2-} in groundwater before and after construction of the interceptor drain in Unit Tatas

the water from the gelam forest was of such poor quality, it was no longer used as irrigation water. Instead fields 2 and 3 were irrigated with canal water only. Field 4, which was now on the forest side of the interceptor drain, was used only for comparison of groundwater quality. A separate field 5 was established to carry out experiments under rainfed conditions (Figure 10).

Fertilizer treatments in fields 2 and 3 included all combinations of two K rates (0 and 50 K_2O kg ha^{-1}) and four lime rates (in CaO kg ha^{-1}: 0, 2250 residual, 1125 fresh, 2250 residual + 1125 fresh). The rainfed field (field 5) received fresh lime at rates of 0, 375, 750 and 1125 kg ha^{-1}. Separate experiments were conducted for zinc application and for split applications of K. All plots received a standard dressing of N and P_2O_5.

Upland rice, cassava, soybean, peanuts and maize were tested in field 1. Randomized subplots were tested for lime application as in field 2 and 3.

1989/1990 Results and discussion

The effect of the interceptor drain can be seen in Figure 11, which shows the concentra-

Table 7 Effects of water management and fertilizers on rice yields in Unit Tatas, wet season 1989/1990 in t ha^{-1}. Standard fertilizer dressing: 135 kg N ha^{-1}, 90 kg P ha^{-1}

Treatment	Water Management			
	Field 2		Field 3	
	NP	P	NP	P
Control	1.81	2.38	1.61	2.15
Fertilizer (potassium)	1.90	2.47	1.78	2.40
Fresh lime	2.92	3.42	2.84	3.51
Fresh lime + Fertilizer	3.17	3.38	3.08	3.58
Residual lime	3.17	3.95	2.86	3.42
Residual lime + Fertilizer	3.56	4.26	3.38	3.83
Residual lime + Fresh lime	3.07	3.90	3.15	3.71
Residual + Fresh + Fertilizer	3.49	4.26	3.13	3.75

NP = non-puddled, P = puddled

tions of SO_4 in the groundwater before and after the construction of the drain.

Comparison of Table 4 and Table 7 shows that the yields in the second year were considerably higher than in the first year. The effect of the interceptor drain is obvious. Puddling had a remarkable effect on yields, with an average increase of 20 percent. Crop yield responded positively to applied potassium (Table 7), but split applications of potassium showed no additional effect, nor did the application of zinc (data not shown). Both fresh and residual lime had a significant positive effect on crop yields, and there was a significant interaction between fresh and residual lime: in the presence of residual lime, there was no response to fresh lime.

There was a significant, almost linear response to fresh lime in the rainfed field (Table 8).

Yields of upland rice, cassava, maize and peanuts increase significantly with application of K fertilizers (Table 9). Those upland crops and, also, soybeans have significantly higher yields as a result of fresh lime application (1125 CaO ha^{-1}) whereas residual lime, in combination with fresh lime, had no significant effect. The results show that palawija crops can be grown in the wet season. It is then possible to drain for 14 and 21 hours a day during spring and neap tides, respectively.

Table 8 Rice yields (t ha^{-1}) Unit Tatas rainfed field in the 1989/90 season with for different levels of fresh lime. Standard dressing: 135 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1}

Liming (CaO kg/ha)	Potassium	
	0	1
0	1.60	1.54
375	2.18	2.10
750	2.62	2.43
1125	2.85	2.97

Table 9 Yields (t ha^{-1}) of upland rice, cassava, soybean, maize and peanut on the palawija field, Unit Tatas, in the wet and dry seasons of 1988/1989 and 1989/1990

Treatment	1988/1989				1989/1990					
	wet season		dry season		wet season			dry season		
	UR	C	S	P	M	S	P	M	S	P
Control	0.8	2.6	0.1	0.3	0.02	0.4	0.4	0.2	0.5	1.6
Fert.	2.2	3.2	0.1	0.4	0.6	1.4	1.2	1.2	0.2	1.3
Lime	1.6	3.8	1.6	1.8	–	–	–	3.5	2.0	2.6
Lime + Fert.	2.0	4.7	2.1	1.9	0.7	1.6	1.4	5.1	1.9	2.8
Fresh + Residual Lime + Fert.	–	–	–	–	0.4	1.8	1.6	4.4	2.2	3.9

UR = Upland Rice, C = Cassava, S = Soybean, P = Peanut, M = Maize

Water management strategies and soil fertility options as basis for development strategies in Pulau Petak

From the experiments in Tabunganen and Unit Tatas, several water management and soil fertility options to improve crop production have been derived (AARD/LAWOO, Volume 4 1992):

- Tidal irrigation to reduce water shortages and to improve leaching;
- Puddling to improve water conservation;
- Drainage to reduce flood hazard, to intercept the inflow of low-quality water from neighbouring areas, to improve leaching, or to grow dryland crops;
- Liming in small quantities (1 to 1.5 t ha^{-1}) to reduce the adverse effects of acidification by controlling toxicity. Liming also produced a long-term effect on both rice and dryland crops;
- Application of standard fertilizers (phosphate, potassium and nitrogen), although their effects are less than lime.

An economic evaluation showed that not all options have the same potential benefits, and that the soil and hydrological conditions determine which option is most suitable for a specific area (Sevenhuysen 1990). The procedure for land evaluation developed for Pulau Petak also used type of soil and hydrological conditions as most important land qualities (AARD/LAWOO, Volume 2, 1992). Development strategies for the five most, widespread combinations of soil and hydrological conditions in Pulau Petak are given below:

Hydrological type A with potential acid sulphate soils

Keep the soils from becoming acid and, at the same time, improve drainage conditions (i) to eliminate the flood hazard during the wet season and (ii) to increase leaching in the dry season by using the daily tide. This will enable double rice cropping: a HYV followed by a local variety. Water conservation by puddling is not an option because of the low bearing capacity of the soil. Liming is not needed because acidification is not a major problem.

Hydrological type B with acid sulphate soils

(i) Leaching of acid from the topsoil by improved drainage, and (ii) introduction of double cropping rice dryland crops or a combination of the two. This requires a one-way flow system for spring-tide irrigation, in combination with a shallow drainage system for leaching and watertable control. If applicable, the drainage will also intercept the inflow of acid water from nearby swamp areas. Water conservation can be improved by puddling. Liming will reduce the negative effects of acidity.

Hydrological type C with potential acid sulphate soils

These soils remain potential acid sulphate soils because their poor drainage restricts oxidation. Under these conditions, the only on-farm water-management option is puddling. Other options, like improved drainage, have to be implemented at a higher level (secondary or primary level). Improved drainage will facilitate the discharge of the acid water at the beginning of the rainy season. If drainage conditions are improved, however, care should be taken to keep water levels near the soil surface in the dry season; otherwise severe acidification will occur.

Hydrological type C or D with acid sulphate soils

In these areas, irrigation water is not available to leach the soils. The only source of leaching water is rainfall, which can be used for this purpose if the field drainage system is improved. Puddling can increase water conservation in rice fields. Because of the good drainage, crop diversification by the introduction of dryland crops seems to be a promising option. Soil fertility options include liming and improved standard dressings.

Hydrological type D with potential acid sulphate soils

Most of these areas are still covered by peat. Great care should be taken to conserve this layer. Drainage is required to reduce the waterlogged conditions in the wet season, but the drainage base should be kept near the soil surface to reduce oxidation of the peat layer.

References

AARD & LAWOO 1992. Research on acid sulphate soils in the humid tropics. Final report phase I, volume 2: Guidelines for soil surveys in acid sulphate soils in the humid tropics: The main problems considered. ILRI, Wageningen

AARD & LAWOO 1992. Research on acid sulphate soils in the humid tropics. Final report phase I, volume 4: Water management and soil fertility research on acid sulphate soils in Kalimantan, Indonesia. ILRI, Wageningen

Kselik R.A.L. 1990. Water management on acid sulphate soils at Pulau Petak, south Kalimantan. In: Papers workshop on acid sulphate soils in the humid tropics, 249-275

Langenhoff R. 1986. Distribution, mapping, classification and use of acid sulphate soils in the tropics: a literature study. Interne mededeling 74, stencil 6978. The Netherlands. Soil Survey Institute, Wageningen

Prade K., J.C.G. Ottow and V. Jacq 1988. Excessive uptake (iron toxicity) by wetland rice (Oryza sativa L.) on an acid sulphate soil in the Casamance, Senegal. In: Dost, H. (editor): Selected Papers of the Dakar Symposium on acid sulphate soils, 150-162. Publ. 44, International Institute for Land Reclamation and Improvement, Wageningen

Reppprot 1987. Regional physical planning program for transmigration, Review of phase I results, East and South Kalimantan, Volume Two, annexes 3-6
Sevenhuysen, R.J. 1990. The water management puzzle: A summary of the research. In: Papers workshop on acid sulphate soils in the humid tropics, 338-346
Yamauchi M. 1989. Rice bronzing in Nigeria caused by nutrient imbalances and its control by potassium sulphate application. Plant Soil 117: 275-286

Rehabilitation of rice fields in the acid sulphate soils of Lower Casamance, Senegal

J.P. Montoroi[1], J. Albergel[2], A. Dobos[3], M. Fall[3], S.Sall[3], A. Bernard[2], D. Brunet[2], G. Dubée[2] and P. Zante[1]

[1] ORSTOM, 70-74 Route d'Aulnay, 93140 Bondy France
[2] ORSTOM, BP 1386, Dakar-Hann Senegal
[3] ISRA, BP 1320, Ziguinchor-Djibelor Senegal

Abstract

The Casamance region in the south of Senegal is historically a region of rice production for home supply. Since the recent drought, the production stagnated while an increased population demands more and more rice imports.

Since the seventies, the government has taken measures to increase the degree of self-sufficiency in rice. Among these, the development of 'mangrove rice' production with the construction of dams is one of the most important. During the very dry years in the beginning of the eighties, the main objectives were to protect the ricefields from salinization and to rehabilitate the areas of acid sulphate soils. The anti-salt dams did not increase rice production.

A 150 ha polder in the small valley of Djiguinoum, directly in connection to the Casamance river, was chosen to try a new water management system. Sluices allow drainage of salts and acids at the beginning of the rainy season and, also, maintain water for rice culture.

Three fields on a degraded area (about 1 ha) were equipped with an outer dike and a drainage network connected to the main river. Traditional techniques, used by the farmers, were applied for the rice cultivation. During two consecutive years a significant increase in yield was obtained. In the first year, salt movement in the soil was controlled by the dam. In the second year ploughing, tolerant varieties and fertilization were also tested.

A social inquiry was held, investigating whether the rice culture actually had any chance to become again a main interest for the population.

Introduction

The effects of the recent droughts are now well known in lower Casamance, especially in the mangrove environment (Marius 1979, Marius et al. 1986; Boivin et al. 1986, Loyer et al. 1988, Pages and Debenay 1987, Pages et al. 1987, Le Brusq et al. 1987, Dacosta 1989, Montoroi 1990, Mougenot et al. 1990). The principal consequences are:

- Decrease and destruction of the mangrove vegetation;
- Increasing salinity in coastal waters;
- Chemical degradation of lowland soils;
- Decreasing rice production, increasing activities in the uplands;
- Increased erosion in the uplands;
- Migration to the cities.

The Casamance region is historically occupied by a population of farmers and fishermen, the Diolas. Rice is the staple crop. Rice cultivation has a dominant role in Diola society, although drought and migration have diminished it. The stagnation of rice production means shortage at the end of long dry seasons but more-rewarding crops, like peanuts, can pay for imported rice.

Management of the 'mangrove soils' is an old custom in this region and water management is well-adapted to conditions of normal rainfall (Pelissier 1966). However, with the dramatic decrease in rainfall (Figure 1), soils have become very saline and severely acid.

The government wanted to develop rice production, especially in the mangrove area, because national self-sufficiency dropped from 40 per cent in 1970 to 20 per cent in 1984. To this end, the construction of dams across the main branches of the Casamance river has been studied. The aim was to protect the mangrove forest and to adapt the water management to the soils; for example, to avoid acifidication during the dry season.

During the very dry years at the beginning of the eighties, the high levels of salinity in the rivers made it necessary to revise the water management.

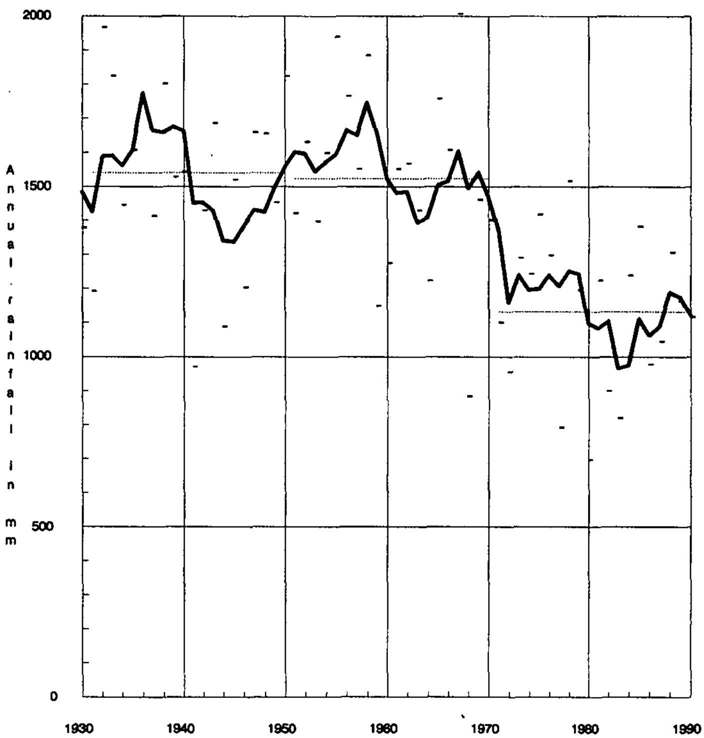


Figure 1 Annual rainfall in Ziguinchor during the period 1930-1990
- Full line: five year averages
- Dotted lines: average annual value for twenty year periods: 1931-1950: 1541 mm; 1951-1970: 1524 mm; 1971-1990: 1133 mm

It was necessary to protect the rice fields from salinization. The construction of small, anti-salt dams with a water control structure, hand-made by the people, was externally supported (USAID/SOMIVAC/ISRA 1985). Some of these dams have been effective, especially in the sandy valleys, but not in other cases. The rice production was lower than planned.

Some technical solutions for the reclamation of acid sulphate soils were tested in Casamance before the drought (Beye 1973a,b, 1974, 1977, Beye et al. 1978). Here the results of a field experiment in the Djiguinoum valley are presented. The sluice of the anti-salt dam has been improved to facilitate the water management and different culture techniques have been tried in rice fields.

Environmental situation

The Djiguinoum valley is located on the right bank of the Casamance river, 15 km northeast of Ziguinchor. The catchment has a surface of 26 km^2 (Figure 2). The anti-salt dam is situated near Djilakoun. 150 ha is flooded in the rainy season. The field experiment is situated near the Ziguinchor track, about 1 km north of the dam, on an acid sulphate soil.

The surface horizon is well-structured; the clay content was between 70 and 75 per cent with a silt fraction of 20 per cent. pH value was 3.5 for the surface horizon and 2.5 at depth; exchangeable aluminium was 40 mmol kg^{-1}; total sulphur 3-5 per cent by mass in the subsoil. The groundwater level was at 1.2-1.4 m at the end of the dry season with a pH of 4, an EC of 16 dS m^{-1} and high soluble aluminium (0.6 mmol l^{-1}). Salts are observed on the surface and form a weak crust mixed with clay in some places.

The red soils of the surrounding uplands support forest and peanut culture.

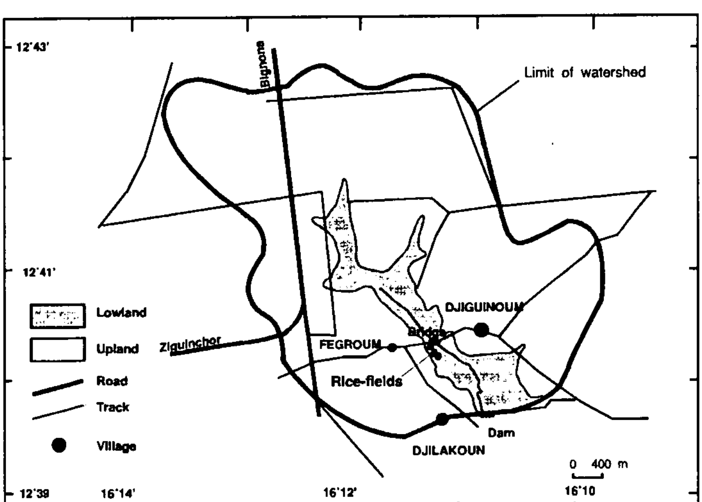


Figure 2 Field experiment site in the catchment of Djiguinoum

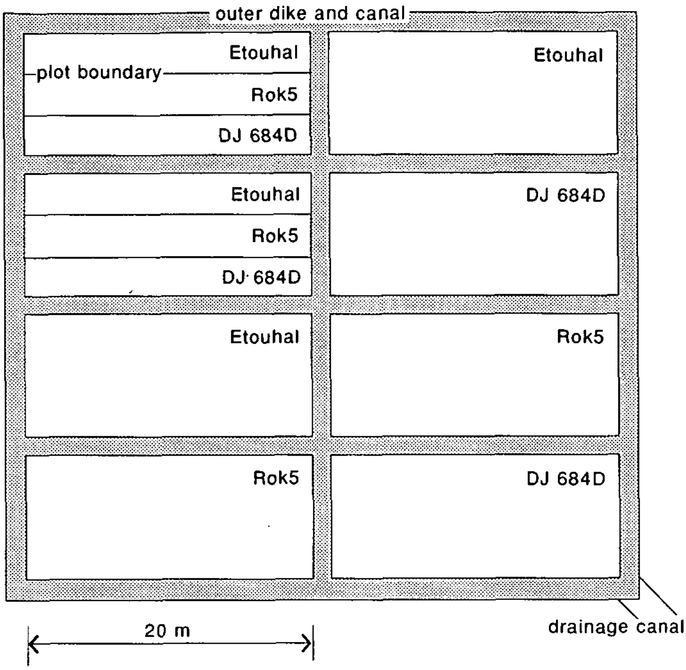


Figure 3 Traditional rice field with salt-tolerant varieties used in 1990. The two rice-plots divided in three strips are not ploughed before plantation time. No fertilization.

Methods

Water management

The original sluice was made of wooden boards and regulating the water level was hard when the upstream side was full of water. A new system, installed in 1988, consists of manually-operated vertical slide gates (Albergel et al. 1990). Four rules are applied at the anti-salt dam to improve the water management:

- Wash out the first runoff, which contains a high level of salts, at the beginning of the rainy season;
- Maintain an appropriate water level for rice during the wet season;
- Avoid flooding of the track crossing the valley;
- Open the sluices when the upstream level is at least 4 cm higher than the downstream level.

Field experiment

A traditional field (Figure 3) and an hexagonal field (Figure 4) were constructed with a local tool, the 'kayendo' (Marzouk-Schmitz 1988). The traditional rice field has eight plots each 20 m by 10 m separated by drainage canals. A surrounding canal allows drainage to the river. In 1990, two plots were divided into three strips and left untilled. The others were tilled. Three salt-tolerant varieties were tested.

Each of two hexagonal rice fields was divided in three lozenge-shaped plots which

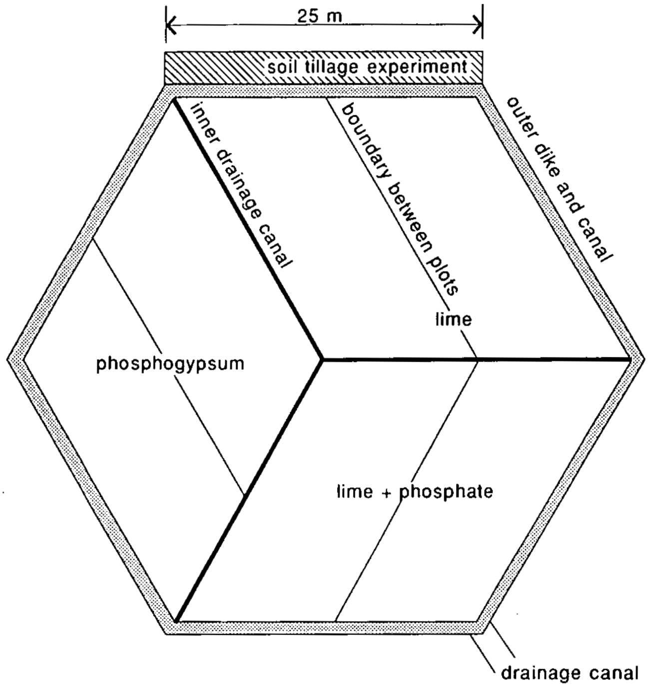


Figure 4 Hexagonal rice field with different fertilizer treatments

received different fertilizer treatments (lime, lime plus phosphate, and phosphate plus gypsum) for only one rice variety (Rok 5). The cultivated surface of this rice field was 1875 m^2. For the second hexagonal field, fertilizers were mixed with rice straw. The rice was transplanted into flooded fields in August and harvested in December. The chemical composition of the drainage water in tilled plots was monitored. The soil solution was extracted every week with in-situ water samplers installed at different depths. A rainfall simulator was used on a bare and a tilled soil to observe runoff and salt movements.

Results

Water management

The variations of upstream and downstream water levels are shown in Figure 5.

Effect of water management on soil salinity

Water management by the anti-salt dam diminishes the salt level in the topsoil (Figure 6). The electrical conductivity at 25 cm depth decreased from 30 to 10 dS m^{-1} in 1990. Salinity increased rapidly at the end of the rainy period. The salt profile is always increasing with depth, even during the flooded period.

At depth, the groundwater salinity remains high all year, showing a sharp increase of the salt profile in the wet season. The lowest salt level in the surface water is about

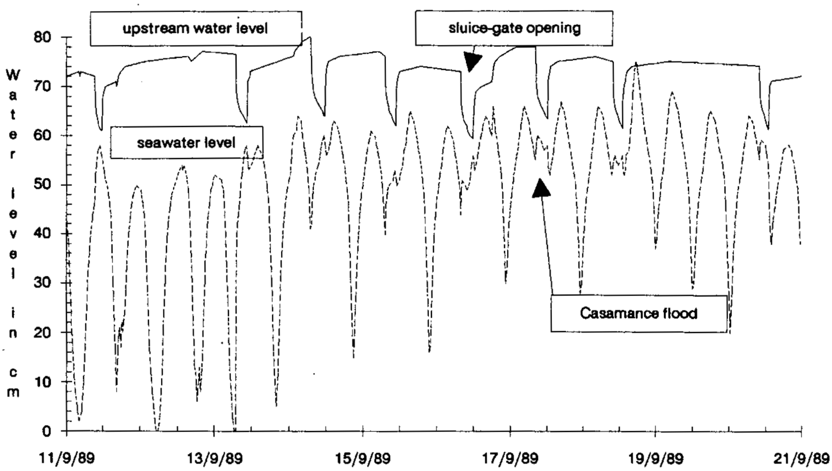


Figure 5 Upstream and downstream water levels at the anti-salt dam of Djilakoun in September 1989

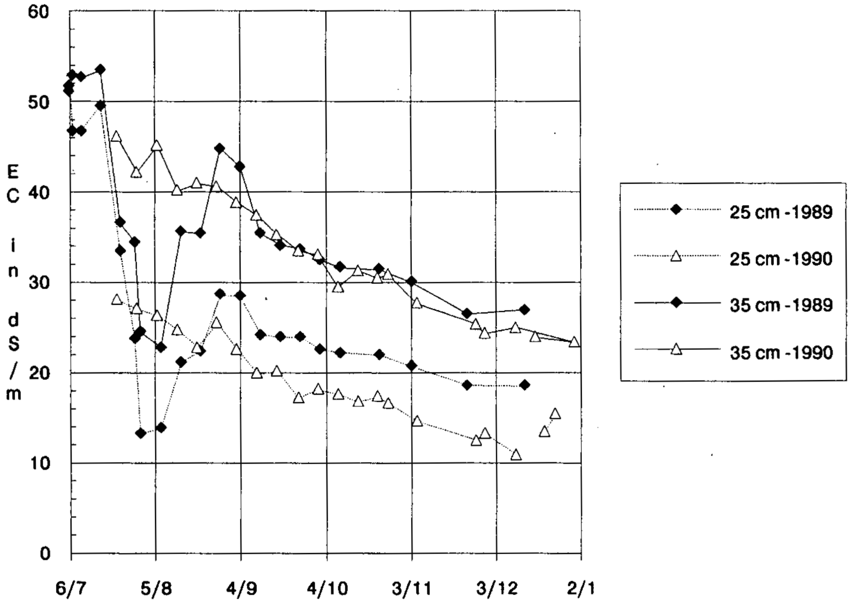


Figure 6 Effect of water management on the electrical conductivity (EC, in dS m^{-1}) of a cultivated acid sulphate soil in the Djiguinoum valley over two rainy seasons

3 dS m^{-1} (Table 1). Rice roots grow only in the upper few centimetres, being unable to tolerate the salinity below.

Redistribution of salts

Tillage helps to decrease the salt content in the surface soil (Figure 7). On bare soil, the rainfall runs off, a salt crust is formed after each shower and infiltration is not effective.

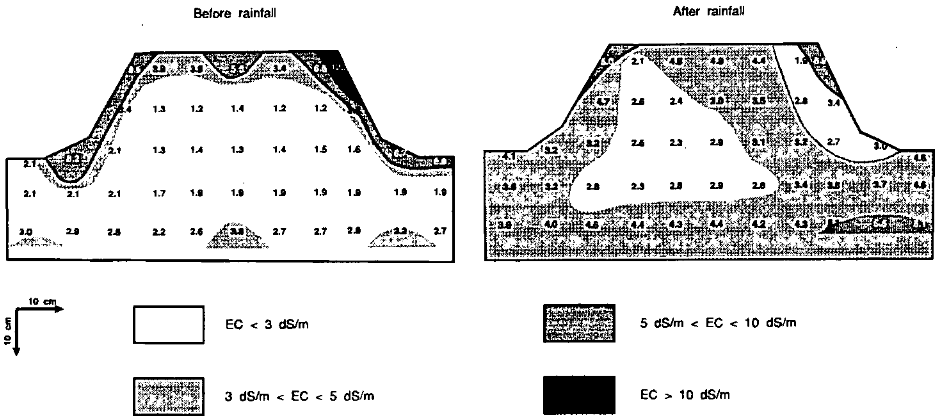


Figure 7 Redistribution of salts in a cross-section of a tilled plot after three simulated rainshowers (60 mm during one hour for each shower)

Rice production

The yields obtained in 1989 and 1990 were higher than the average yield of the Casamance region (about 1 t ha^{-1}). The results for the traditional rice field were better in 1989 than in 1990 (Table 2). The rainy season pattern was different and the water management had to be adapted. The salinity decrease was less effective. The lower yields obtained in the hexagonal rice field (Table 3) may be explained by a different planting density (125 000 plants per ha against 200 000 for the traditional rice field).

Table 1 Chemical composition of the surface water on 16 September 1989 (Brunet and Zante 1990)

pH	EC (dS/m)	Soluble ions, mmol per litre								
		Na	K	Ca	Mg	Cl	SO4	Al	Fe	Si
3.6	3.1	2.1	0.7	0.85	2.25	21	3.65	0.2	0.001	0.07

Table 2 Average paddy rice yield (in t/ha) for different, salt-tolerant varieties of rice and tillage in the traditional rice field (Brunet and Zante 1990, Brunet et al. 1991)

	Rice variety	1989	1990
Tillage	ROCK 5	2.8	2.8
	DJ 684 D	2.6	1.0
	ETHOUHAL	2.8	1.9
No tillage	ROCK 5	–	2.2
	DJ 684 D	–	0.8
	ETHOUHAL	–	2.1

Table 3 average paddy rice yield (in t ha^{-1}) for different type of fertilizers in the hexagonal ricefield (Dobos et al. 1991)

Treatment plot	Yield
A lime	1.0
B lime + phosphate	1.2
C phosphate + gypsum	0.7
Reference	0.5

Conclusion

The levels of rice production obtained in the experimental plots must be regarded with some caution. Several problems must be solved before regional extension can be advocated. Two successful years is a good basis but, in Casamance, each valley has a particular configuration and the techniques must be adapted to each case. Knowledge of the environmental conditions is required: for example, a hydrological study is needed as a basis for dam design and construction.

A major problem of water management is that all users depend on the water level control at the dam. The risk of conflicts between users is high because they cannot regulate individually, and users must be trained in the operation and maintainance of the dam. New management schemes will be needed to reclaim all the fields in a valley, for example with intermediate sluices.

The field experiment in the Djiguinoum valley has stimulated the local population to struggle against the effects of the drought on their fields. They want to come back to the valley with the desire to copy the management model used by the project (Sall 1991). An organizational structure will be essential to develop the whole valley. Socio-economic conditions have changed in the Casamance and future projects should consider this reality.

References

Albergel J., D. Brunet, G. Dubee, J.P. Montoroi and P. Zante 1990. Gestion d'un barrage anti-sel en Basse Casamance (Sénégal). In: A. Kergreis et J. Claude (editors): Utilisation rationelle de l'eau des petits bassins versants en zone aride, Ed. Aupelf-Uref, John Libbey Eurotext, Paris, 275-285

Beye G. 1973. Une méthode simple de dessalement des sols de tanne de Casamance: le paillage. Agro. Trop., 28, 5, 537-549

Beye G. 1973. Etude comparative de différents engrais phosphatés pour la fumure phosphatée du riz en sols de rizière très acides de basse Casamance. Agro. Trop., 28, 10, 937-945

Beye G. 1974. Etude comparative de l'action de la potasse et de la paille enfouie sur le développement et le rendement du riz sur sol argileux de basse Casamance. Agro. Trop., 28, 8, 803-811

Beye G. 1977. Influence de la longueur de la submersion avant repiquage et de l'enfouissement de paille sur les propriétés physico-chimiques de deux sols de rizière et sur le développement et les rendements du riz. Agro. Trop., 32, 1, 31-40

Beye G., M. Toure and G. Arial 1978. Action de la paille enfouie sur les caractéristiques physico-chimiques des sols submergés de rizière de basse Casamance et sur le développement du riz. Agro. Trop., 33, 4, 381-389

Boivin P., J.Y. Loyer, B. Mougenot and P. Zante 1986. Sécheresse et évolution des sédements fluvio-marins au Sénégal; cas de la basse Casamance. Symp. Int. INQUA-ASEQUA Changements globaux en Afrique durant la Quaternaire, Trav. et Doc. ORSTOM n° 197, 43-48

Brunet D. 1988. Etude pédologique de la vallée de Djiguinoum (Basse Casamance). Multigr., ORSTOM/ Dakar

Brunet D. and P. Zante 1990. Essai rizicole de la vallée de Djiguinoum, Basse Casamance. Rapport agro-pédologique. Multigr., ORSTOM/Dakar

Brunet D., P. Zante and J.L. Duprey 1990. Essai rizicole en culture traditionelle. Vallée de Djiguinoum (Basse Casamance). Rapport agro-pédologique 1990. Multigr., ORSTOM/Dakar

Dacosta H. 1989. Précipitations et écoulements sur le bassin de la Casamance. Thèse 3ème cycle, UCAD, Dakar

Dobos A., M. Fall and J.P. Montoroi 1991. Amélioration de la fertilité des rizières de basse Casamance (Sénégal) en relation avec la gestion des eaux de ruissellement d'un bassin versant: premiers résultats et perspectives. Séminaire Gestion agroclimatique des précipitations. Une voie de réduction du gap technologique de l'agriculture tropical agricaine, 9-13 Décembre 1991, Bamako (Mali)

Le Brusq J.Y., J.Y. Loyer, B. Mougenot and M. Carn 1987. Nouvelles paragénèses à sulfates d'aluminium de fer et de magnésium, et de leur distribution dans les sols sulfatés acides du Sénégal. Science du Sol, 25(3), 173-184

Loyer J.Y., P. Boivin, J.Y. Le Brusq and P. Zante 1988. Les sols du domaine fluvio-marin de Casamance (Sénégal): évolution récente et réévaluation des contraintes majeures pour leur mise en valeur. In: H. Dost (editor): Selected papers of the Dakar symposium on acid sulphate soils. 16-23. Publ. 44, International Institute for Land Reclamation and Improvement, Wageningen

Marius C. 1979. Effets de la sécheresse sur l'évolution phytogéographique et pédologique de la mangrove en basse Casamance. Bulletin de l'IFAN, t.41, sér. A, n°4, 669-691

Marius C. 1985. Mangroves du Sénégal et de la Gambie. Ecologie, pédologie, géochimie, mise en valeur et aménagement. Trav. et Doc. 193. ORSTOM

Marius C., J. Lucas and Y. Kalck 1986. Evolution du golfe de Casamance au Quaternaire récent et changements de la végétation et des sols de mangroves liés à la sécheresse actuelle. Symp. Int. INQUA-ASEQUA Changements globaux en Afrique durant la Quaternaire, Trav. et Doc. 197, 293-295; ORSTOM

Marzouk-Schmitz, Y. 1988. Instruments aratoires, systèmes de cultures et différenciation intra-éthnique. Cah. ORSTOM, sér. Sci. Hum., vol XX, 3-4, 399-425

Montoroi J.P. 1990. Les sols et l'agriculture dans le domaine estuarien de basse Casamance. Séminaire Conservation et utilisation durable des ressources naturelles du bassin hydrographique de la Casamance, 22-26 Octobre 1990, Ziguinchor (Sénégal)

Mougenot B., P. Zante, and J.P. Montoroi 1990. Détection et évolution saisonnière des sols salés et acidifiés du domaine fluvio-marin de basse Casamance au Sénégal, par imagerie satellitaire. In: P. Lafrance et J.M. Dubois (editors): Apports de la télédétection à la lutte contre la sécheresse, Editions Aupelf-Uref, John Libbey Eurotext, Paris

Pages J. and J.P. Debenay 1987. Evolution Saisonnière de la salinité de la Casamance. Description et essai de modélisation. Rev. Hydrobiol. trop., 0, 3-4, 203-217

Pages J., J.P. Debenay and J.Y. Le Brusq 1987. L'environnement estuarien de la Casamance. Rev. Hydrobiol. trop., 20, 3-4, 191-202

Pelissier P. 1966. Les paysans du Sénégal-Les civilisations agraires du Cayor à la Casamance. Imp. Fabrègue, St Yrieix

Sall S. and O. Diop 1991. Projet pilote 'Casamance'. Bas-fond de Djiguinoum Rapport de synthèse: socio-économie. Multigr., ORSTOM/ISRA/R3S USAID/SOMIVAC/ISRA 1985. Actes de la 11ème Table Ronde sur les barrages anti-sel, 12-15 juin 1985, Ziguinchor

Metal availability and uptake by rice in acid sulphate soils

P.A. Moore, Jr. and W.H. Patrick, Jr.

Abstract

Metal availability and uptake by rice was evaluated in 132 flooded acid sulphate soils from the Central Plains region of Thailand and in a growth chamber experiment utilizing 50 of the same soils. Soil and plant metal analyses were conducted at the panicle differentiation stage of growth in both studies and in the soil prior to transplanting in the growth chamber study. The R.D. 23 rice variety was used in the growth chamber study, while 88 different varieties were sampled in the field study. Metal activities in soil solutions were determined from free metal concentrations using GEOCHEM. Exchangeable metals were determined from sodium acetate extracts buffered to the soil pH.

The results found in this study indicated that Fe^{2+} activities are seldom in equilibrium with pure Fe solid phases in these soils. This was believed to be due to (1) transient redox conditions, and/or (2) the presence of ill-defined ferric oxides. Equilibria calculations also indicated that these soils were undersaturated with respect to most Ca, Mg, and Mn solid phases, and their activities were believed to be controlled by cation exchange. The Al^{3+} activities were very pH dependent and appeared to be controlled by jurbanite at low pH and amorphous $Al(OH)_3$ at high pH. Plant analyses indicated that Fe uptake was correlated to Fe^{2+} activity. However, a better relationship was found between uptake and E′-Fe (the divalent charge fraction in soil solution due to Fe^{2+}). Calcium, Mg and Mn uptake were also found to be more closely related to E′-Ca, E′-Mg, and E′-Mn than with the activities of these ions. Multiple correlation between soil parameters and growth indices indicated that the two most important variables affecting rice growth on these soils were A_{Fe} (the ratio of Fe^{2+} activity to the sum of the activities of divalent cations) and pH. While A_{Fe} was considered to be a measure of Fe stress (Fe toxicity combined with basic cation deficiencies), pH measurements reflected the availability of many nutrients and toxins, such as P and Al.

Introduction

In a review of the literature on soil chemistry in relation to the growth of rice in acid sulphate soils, Satawathanant (1986) listed the following problems associated with decreased crop yields: (1) adverse effects of H^+, (2) Al toxicity, (3) Fe toxicity, (4) sulfide toxicity, (5) electrolyte stress, (6) adverse effects of CO_2 and organic and inorganic acids, (7) P deficiency, (8) low base status, and (9) impaired microbial activities. The objectives of this study were to determine what controls the availability of metals in acid sulphate soils and to elucidate the relationships between soil physicochemical parameters, such as metal availability, and rice growth in these soils.

Materials and methods

Field sampling for this study was conducted between May and September in 1984 in the Central Plains region of Thailand. One hundred thirty-four paddy fields characterized as Sulfic Tropaquepts, Typic Sulfaquepts, Typic Sulfaquents and Typic Tropaquepts on farmers' fields and at research stations were sampled at the panicle differentiation (P.D.) stage of growth. Selection of the sample sites was based on a newly-revised map of the acid sulphate soils of Thailand (Osborne 1984 – personal communication). The P.D. stage of growth has been recommended as the best time for collection of rice tissue samples for analysis (Mikkelsen 1970). Approximately 88 different rice varieties were sampled in this study.

Redox potential and pH measurements were made on the soil.Samples were centrifuged for 20 minutes at 5000 rpm to abstract soil solutions which were then filtered under N_2 gas through 0.45 um millipore filters.Aliquots were taken for pH, electrical conductivity, titratable alkalinity, titratable acidity, anions, sulfides, total water- soluble metals and soluble organic bound metals. Anions were analyzed by ion chromatography. Soluble organic-bound metals were obtained by shaking 10 ml of the soil solution with 1 g of cation exchange resin for two hours. In order to determine exchangeable metals, a 25 g subsample of the centrifuged soil was extracted with 100 ml of deaerated 1 M sodium acetate. The pH of the sodium acetate was adjusted to that of each soil by addition of nitric acid. The centrifuge tubes were then capped and purged with N_2. After the samples were shaken for two hours, they were centrifuged, filtered, and acidified as described above. Metal analyses were conducted by ICAP. The computer program GEOCHEM (Sposito and Mattigod 1979) was used to speciate metals and calculate ionic strength. The divalent charge fraction in the exchanger phase (E-Mi) and the divalent charge fraction in soil solution were calculated as described by Sposito et al. (1983).

A growth chamber study was conducted utilizing 50 of the soils from the field study and R.D. 23 rice variety from Thailand. Soil analyses were conducted prior to transplanting (21 d after flooding) and at panicle differentiation. Plant tissue analyses were conducted at P.D. A complete description of this experiment, as well as the field study, is given in Moore and Patrick (1989a).

Results and discussion

Metal Solubility

The soil electron activity (pE) and pH measurements taken in the growth chamber and field studies prior to metal sampling are shown in Figure 1. This figure represents a stability diagram of the Fe minerals considered important in acid sulphate soils (Van Breemen 1976). These data indicate that many of the pe-pH measurements taken in this study fell in the Fe^{2+} field, indicating possible disequilibrium with respect to Fe minerals. However, disequilibrium with respect to Fe minerals cannot truly be ascertained from this figure since it is accurate only for the conditions specified. A few of the measurements fell in the jarosite and pyrite fields, with the remainder in the siderite and amorphous $Fe(OH)_3$ fields.

Measurements taken in the growth chamber experiment indicated that soil pH

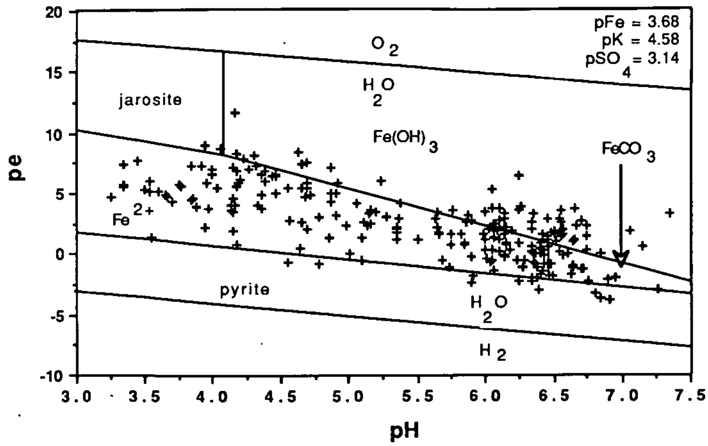


Figure 1 Stability relations of Fe minerals in acid sulphate soils with pe-pH measurements taken prior to metal sampling in the growth chamber and field studies

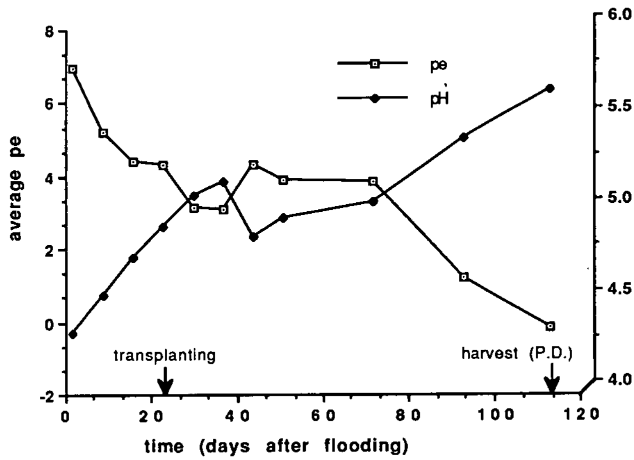


Figure 2 Average pe and pH measurements of the 50 soils studied in the growth chamber study as a function of time after flooding

increased and Eh decreased with time in the 50 soils studied (Figure 2). Transient redox conditions such as this are probably normal in most flooded acid sulphate soils since large amounts of acidity must be neutralized before pH values can approach neutrality. These constant fluctuations in the redox environment may result in disequilibrium with respect to Fe minerals.

In Figure 3 log Fe^{2+} activity + 2 pH is plotted as a function of pe + pH in a similar manner as that by Schwab and Lindsay (1983). These data indicate that equilibrium between Fe^{2+} and pure Fe oxides or hydroxides was the exception rather than

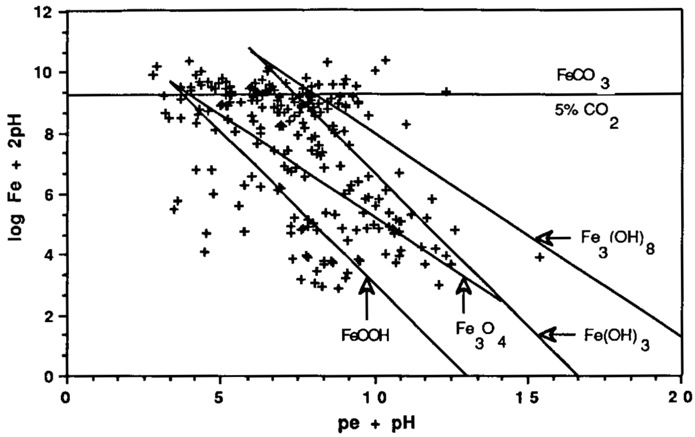


Figure 3 The relationship between measured Fe^{2+} activities and redox conditions in the growth chamber and field studies, with theoretical solubilities for Fe minerals

the rule in the soils studied. This may be due to the presence of ill-defined ferric oxides as described by Van Breemen (1969) and Langmuir and Whittemore (1971). Another explanation of these findings would revolve around the dynamic nature of the redox conditions in these soils as mentioned above. With constantly changing redox conditions, equilibria between Fe^{2+} and Fe minerals may be hampered.

The divalent charge fraction in the soil solution attributable to Fe^{2+} (E′-Fe) is plotted as a function of the divalent charge fraction on the CEC accounted for by Fe (E-Fe) in Figure 4. This figure represents an exchange isotherm in which Fe^{2+} is being exchanged for other divalent metals (in this case, the metals are Ca^{2+}, Mg^{2+} and Mn^{2+}).

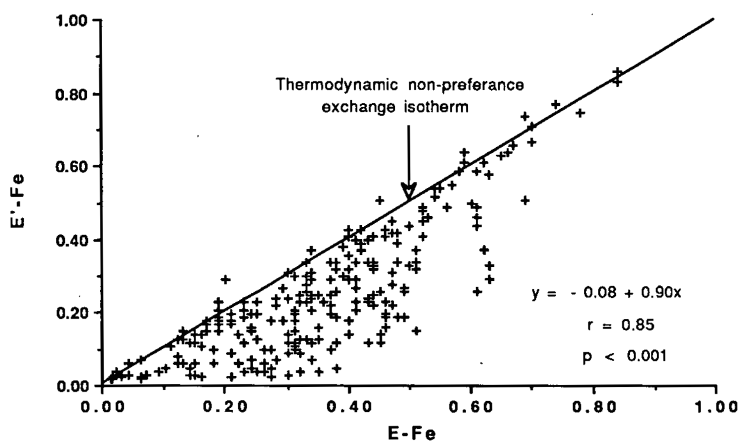


Figure 4 The relationship between the divalent charge fraction due to Fe^{2+} (E′-Fe) in solution versus that on the CEC (E-Fe) in the growth chamber and field studies

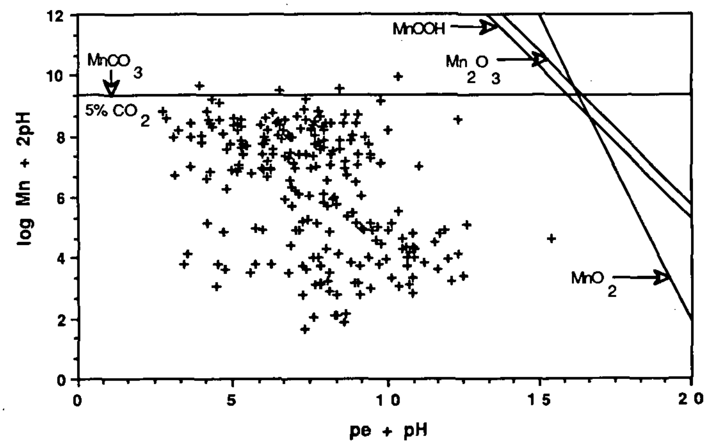


Figure 5 The relationship between Mn^{2+} activities and redox measurements in the growth chamber and field studies with theoretical solubilities of Mn minerals

The thermodynamic non-preference isotherm is represented by the solid line that makes a 45 degree angle with both coordinate axes (Sposito 1981). Since it was not possible to distinguish Fe^{2+} from $FeHCO_3$ on the exchange complex, all exchangeable Fe was assumed to be Fe^{2+}, resulting in an overestimation of E-Fe for samples with high concentrations of $FeHCO_3^+$. The production of Fe^{2+} and the accompanying increase in exchangeable Fe will cause E′-Fe and E-Fe to increase. Thus Fe^{2+} governs the cationic composition of the soil solution. Although the concentrations of Ca^{2+} and other ions in solution may increase as the result of Fe exchange, their availability to plants may actually decrease due to decreases in the mole fraction.

When log Mn^{2+} + 2pH was plotted as a function of pe + pH in a manner similar to that of Schwab and Lindsay (1983), most of the points appeared below the lines, indicating undersaturation with respect to these phases (Figure 5). Oxides and hydroxides of Mn are probably not controlling Mn solubility since Mn^{2+} activities were much lower than would be predicted with solubility of MnOOH, Mn_2O_3 and MnO_2. It should be noted that under oxidized conditions the pH's of these soils are very acid (around 4.0), which would hinder the formation of Mn oxides and hydroxides.

Under acid conditions the soils were undersaturated with respect to rhodocrosite, implying that this solid phase should not be responsible for the measured solubilities of Mn^{2+} observed under these conditions (Moore and Patrick 1989a). However, the two soils with the highest pH values appeared to be near equilibrium with rhodocrosite. These data confirm that, under basic conditions, rhodocrosite may form in flooded soils as predicted by Schwab and Lindsay (1983). The maximum IAPs' and equilibrium constants for several other Mn minerals (Moore and Patrick 1989a) indicate that phosphate and silicate minerals probably did not play an active role in governing Mn solubility in these soils.

Another possible mechanism governing the level of Mn^{2+} in solution is cation exchange. In order to determine if exchange reactions were important in governing the solubility of Mn^{2+}, E′-Mn was plotted as a function of E-Mn as shown in Figure

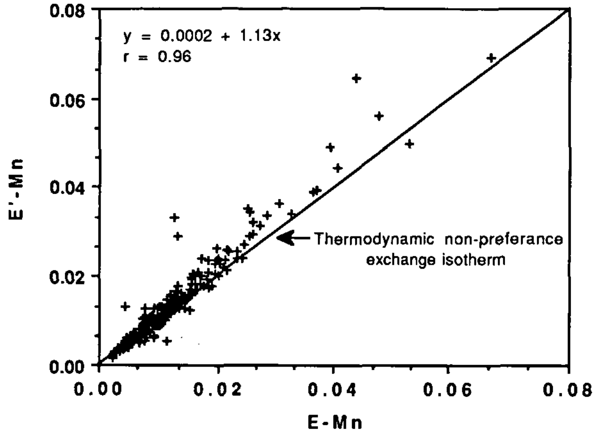


Figure 6 The relationship between E-Mn and E′-Mn in the growth chamber and field studies

6. These data provide strong evidence that Mn^{2+} activities in flooded acid sulphate soils are in equilibrium with Mn on the exchange sites. Van Breemen (1976) stated that Mn was mainly in the dissolved and exchangeable form in flooded acid sulphate soils. If this is the case and water soluble and exchangeable Mn are in equilibrium as shown in Figure 6, then exchange reactions are likely to control Mn solubility. Gotoh and Patrick (1972) also suggested that exchange reactions play an important role in regulating water, soluble Mn in flooded soils.

The soil solutions from the field and growth chamber studies were undersaturated with respect to Ca and Mg minerals (Moore and Patrick 1989c). However, there was a highly significant relationship found between Ca^{2+} and Mg^{2+} activities and exchangeable Ca^{2+} and Mg^{2+}. Therefore, reactions were suspected as the mechanism governing the solubility of these ions. In order to test this hypothesis, E′-Ca (the divalent cationic charge fraction in the soil solution accounted for by Ca^{2+}) was plotted as a function of E-Ca (the divalent cationic charge fraction on the CEC accounted for by Ca^{2+}) as shown in Figure 7. These data provide strong evidence that Ca^{2+} activities in flooded acid sulphate soils are in equilibrium with Ca on the exchange complex. These results, along with the lack of evidence for solubility control by mineral equilibria, indicates that Ca^{2+} activities are probably governed by exchange reactions in these soils. The divalent charge fraction in the soil solution attributable to Mg^{2+} (E′-Mg) is plotted as a function of that on the CEC due to Mg (E-Mg) in Figure 8. These data indicate that Mg^{2+} activities were somewhat higher than would be predicted on the basis of non-preferential cation exchange.

The negative log of Al^{3+} activity (pAl^{3+}) is plotted as a function of pH in Figure 9. As would be expected, pAl^{3+} was positively correlated to pH, with a maximum of 3.5 at low pH and a minimum of 12.4 at high pH. Corresponding values for water soluble Al varied from 0.002 to 130 mg Al l^{-1}, with an average of 2.91 mg Al l^{-1}. Under acidic conditions, (pH 5.2) concentrations of aluminum sulphate complexes calculated by GEOCHEM were generally higher than Al^{3+} (data not shown). Porewater SO_4^{2-} concentrations varied from 0.5 to 6800 mg S l^{-1}, with an average of 385 mg S l^{-1}.

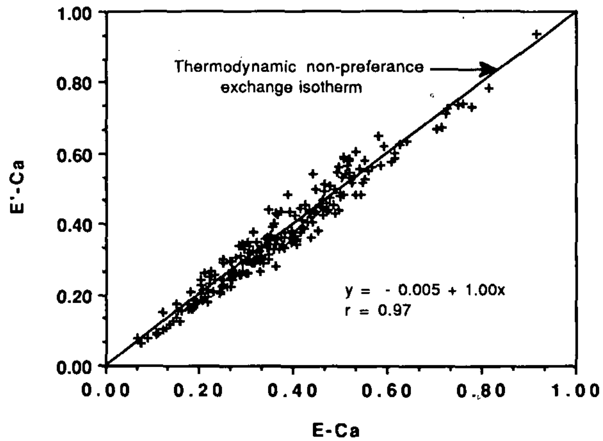


Figure 7 The relationship between E′-Ca and E-Ca in the growth chamber and field studies

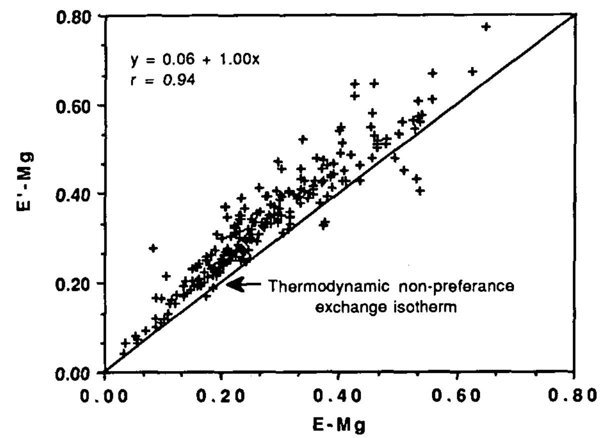


Figure 8 The relationship between E′-Mg and E-Mg in the growth chamber and field studies

In Figure 10, $pAl(OH)_3$ is plotted as a function of $2pH + pSO_4^{2-}$. From this figure, it would appear that jurbanite or some type of basic aluminum sulphate is controlling Al solubility at low to medium pH values (3.5 to 6.0), while at the higher pH range, and at lower sulphate activities, amorphous $Al(OH)_3$ seems to provide the limits of Al solubility in these soils.

Van Breemen (1973) provided evidence indicating that a basic aluminum sulphate with a stoichiometry of $AlOHSO_4$ (pK = 17.2) determined the upper limit of dissolved Al in acid sulphate soils and acid mine spoils. Nordstrom (1982) supported these findings and proposed that the solid phase controlling Al solubility in natural waters was dependent on both pH and SO_4^{2-} activity. He indicated that jurbanite provided the upper limits for Al^{3+} solubility in acid soils, depending upon SO_4^{2-} activity. At higher

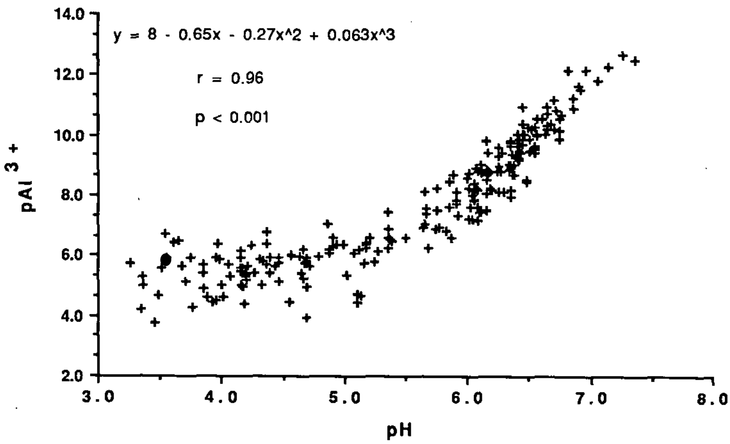


Figure 9 The relationship between Al^{3+} activity and pH in the growth chamber and field studies

pH values alunite or gibbsite would be the controlling phase outlined in his scheme. He also calculated that the solubility product of jurbanite (pK = 17.8) was close to that of Van Breemen's basic aluminum sulphate and concluded that they were probably one and the same. The data shown in Fig. 10 appear to conform to the results found by Van Breemen (1973) and the paradigm set forth by Nordstrom (1982), with jurbanite and amorphous $Al(OH)_3$ being the dominant phases at the pH's and SO_4^{2-} activities observed in this study.

One possible geochemical route for Al in acid sulphate soils which undergo alternate periods of wetting and drying would involve both cation exchange and precipitation/dissolution reactions, which are linked to the pH-redox status of the soil. On this hypothetical pathway, aluminum hydroxides such as gibbsite or amorphous $Al(OH)_3$

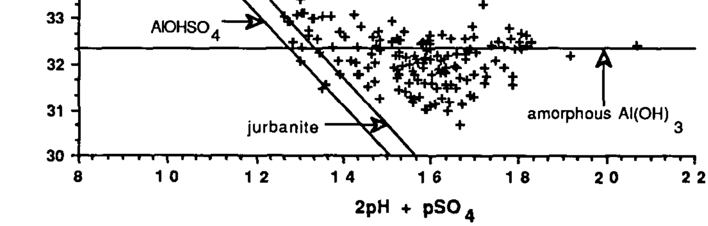


Figure 10 The relationship between $pAl(OH)_3$ and $2pH + pSO_4^{2-}$ in the growth chamber and field studies with theoretical solubility isotherms for $AlOHSO_4$, jurbanite, gibbsite and amorphous $Al(OH)_3$

would begin to dissolve as acid is produced following Fe^{2+} oxidation at the beginning of the dry season. As Al^{3+} activities increase, Al^{3+} would replace other cations such as Ca, Mg and Mn on the CEC as described by Van Breemen (1973). This process would continue until the activities of Al^{3+} and SO_4^{2-} reached the point of jurbanite saturation, at which time precipitation of this mineral phase would begin. However, before this process could be fully initiated, large quantities of Al^{3+} in solution would be removed by exchange processes, buffering the amount in solution. The amount of Al held on the CEC would not only be dependent on the Al^{3+} activity, but on the magnitude and nature of the CEC. When the rains return at the beginning of the monsoon season, the redox of the soil would decrease due to flooding. This would result in the reduction of Fe oxides and hydroxides which would, in turn, cause increases in pH. With increases in pH, jurbanite would become metastable with respect to Al hydroxides such as amorphous $Al(OH)_3$, which would then begin to precipitate (assuming no kinetic limitations). However, as Al^{3+} disappeared from solution it would be replaced by Al^{3+} from the CEC until a new equilibrium was reached. This release of Al^{3+} from the CEC would consume hydroxide, buffer the pH and, thus, the Al^{3+} activity until most of the Al on the CEC had been inactivated. At the end of the monsoon season the cycle would be repeated.

Metal Uptake by Rice

Leaf Fe contents of the plants sampled in the growth chamber and field study are plotted as a function of pFe^{2+} at panicle differentiation in Figure 11. This figure indicates that the relationship between leaf Fe and the Fe^{2+} activity was rather poor. Leaf Fe varied from 25 to 1205 mg kg^{-1}, with an average of 113 mg kg^{-1}. Iron toxicities may have occurred since the reported critical Fe content in rice leaves is 300 mg kg^{-1} (Tanaka and Yoshida 1970). Bronzing, a symptom of Fe toxicity in rice, was observed in the field and in the growth chamber study in samples with high Fe contents. The mean leaf Fe value was comparable to that found by Westfall et al. (1973) in the Y-leaves of healthy rice (98 mg kg^{-1}).

Leaf Fe contents are plotted as a function of E′-Fe in Figure 12. These data indicate

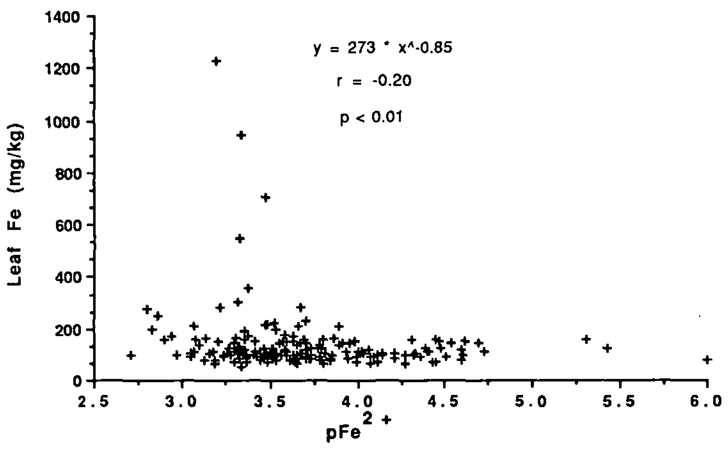


Figure 11 The relationship between leaf Fe and Fe^{2+} activity in the growth chamber and field studies

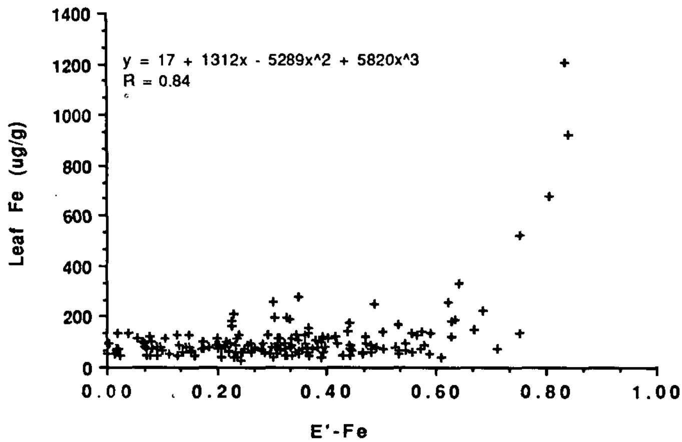


Figure 12 The relationship between leaf Fe and E′-Fe in the growth chamber and field studies

that leaf Fe contents were more closely related to E′-Fe than Fe^{2+} activity alone. The reason for this is probably that E′-Fe takes into account the competition of other ions, whereas Fe^{2+} activity does not. Similarly, E′-Mn, E′-Ca and E′-Mg were found to better predictors of Mn, Ca and Mg uptake, respectively, than their activities.

These data may also explain why Fe toxicity in rice is often associated with deficiencies in Ca and Mg. Ottow et al. (1983), Benckiser et al. (1984b) and Howeler (1973) indicated that Ca and Mg play an important role in Fe toxicity in rice. They stated that a multiple nutritional stress was the main cause of Fe toxicity in rice. Benckiser et al. (1984b) suggested that fertilization with N, P, K, Ca and Mg improved the Fe excluding mechanism of the plant, since root tissues had lower Fe and higher K, Ca and Mg than unfertilized plants. Howeler (1973) reported that the symptoms of Fe toxicity were inversely related to leaf content of P, K, Ca and Mg. Ottow et al. (1983) ascribed Fe toxicity to insufficient supplies of K, P, Ca and Mg, rather than to high levels of active Fe.

If E′-Fe is large, then Fe uptake may occur at the expense of other cations such as Ca and Mg. This hypothesis assumes that divalent cation uptake by rice is somewhat non-specific. Evidence for this was provided by Moore and Patrick (1988) who showed that the uptake of divalent cations (Ca, Cu and Mg) was significantly higher in Zn-deficient rice, whereas the uptake of monovalent cations was lower. They suggested that Zn-deficient rice concentrates divalent cations at the expense of monovalent cations due to the increased production of a divalent cation carrier. If the same process were occurring in Ca and/or Mg-deficient rice growing in a soil where Fe was the dominant cation in solution, then Fe uptake would be accelerated and concentrations in the plant would reach toxic proportions. This would also explain why K deficiencies often also occur (ie – divalent uptake at the expense of monovalent).

If 300 mg kg^{-1} is indeed the critical leaf Fe content for Fe toxicity in rice, then it would appear from the data shown in Figure 12 that Fe toxicity in rice can be expected to occur when E′-Fe exceeds 0.75, and is somewhat independent of the Fe^{2+} activity. This may be due to the oxidation of Fe^{2+} by the roots of healthy plants, since the leaf Fe contents remained roughly constant until E′-Fe exceeded 0.60.

Manganese uptake by the plants in the growth chamber experiment at panicle differentiation was significantly correlated ($R = 0.61$) with Mn^{2+} activity (Moore and Patrick 1989a). These results are consistent with those found by Schwab and Lindsay (1983) who also showed Mn uptake to be related to Mn^{2+} activity. Other workers have shown that Mn uptake by rice was correlated with Mn in solution (Tanaka and Navasero 1966a; Yoon et al. 1975). The correlation between Mn uptake and E′-Mn was slightly better than that found for Mn^{2+} activity alone (Figure 13). Therefore, E′-Mn may be a better indicator of Mn availability to rice than Mn^{2+} activity. Iron uptake was also shown to be more closely related to E′-Fe than Fe^{2+} activity. The ratio of Ca^{2+} activity to the sum of the activities of all cations in the soil solution has been shown to be a better indicator of Ca deficiency in cotton and sudangrass than Ca^{2+} activity (Adams 1966, Bennett and Adams 1970). The results of this study and those found by Adams and his co-workers demonstrate that under many circumstances activity ratios may be more suitable parameters to investigate than activities alone when studying nutrient uptake. This is probably due to the fact that activity ratios reflect ion competition for nutrient uptake sites of the plant. If competitive inhibition for uptake sites is occurring, then it is logical to include competing ions in availability indices.

The highest Mn uptake in the growth chamber experiment occurred at an intermediate level of E′-Mn (Figure 13). Although this rather anomalous point would appear to contradict the hypothesis that metal uptake is influenced by ion interaction, it in fact illuminates a more specific interaction; that of Fe and Mn. Manganese uptake is plotted as a function of the negative log of the Mn^{2+}/Fe^{2+} activity ratio in Figure 14. This figure shows that the highest Mn uptake occurred when the Mn^{2+}/Fe^{2+} activity ratio was very high, suggesting that Fe is antagonistic to Mn uptake in rice. These data also indicate that Mn uptake by rice is more closely related to the Mn:Fe ratio than any of the other parameters studied. Tanaka and Naversero (1966b) indicated that high Fe levels in nutrient solutions resulted in decreased Mn uptake by rice. Prasit-

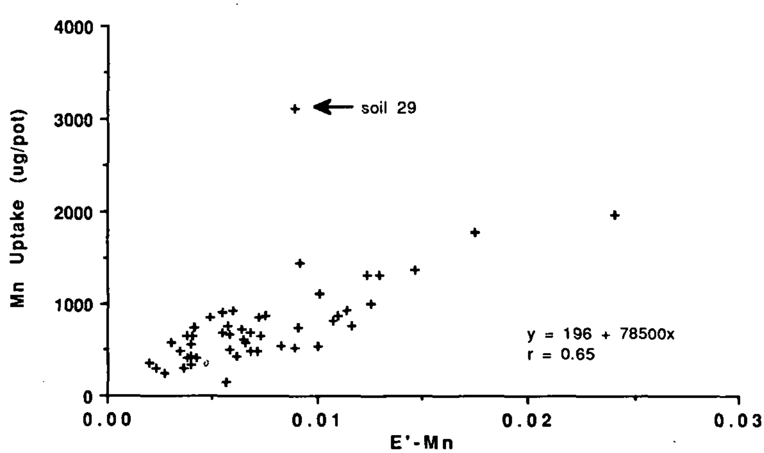


Figure 13 The relationship between Mn uptake and E′-Mn in the growth chamber and field studies

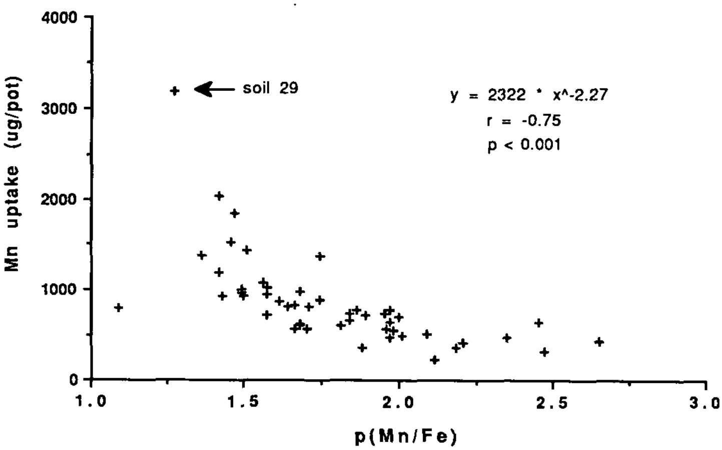


Figure 14 The relationship between Mn uptake and the ratio of Mn/Fe activities in the growth chamber study

tikhet (1987) also indicated that Mn uptake by rice was highly correlated with the Mn/Fe activity ratio. The interaction shown between these ions may be due to similar physico-chemical characteristics, such as the ability to undergo oxidation-reduction reactions.

Leaf Mn contents from the plants sampled in the field study increased with increases in the Mn^{2+}/Fe^{2+} activity ratio, as was found in the growth chamber study (Moore and Patrick 1989a). Leaf Mn varied from 34 to 1551 mg kg^{-1}. Since the critical Mn level in rice for toxicity to occur has been suggested to be 6000 mg kg^{-1} (Tanaka and Yoshida 1970), Mn toxicity was not suspected. The average leaf Mn content found in this study was somewhat lower than that found by Yoon et al. (1975) in the Y-leaves of rice grown in Arkansas (810 mg kg^{-1}).

Calcium uptake is plotted as a function of pCa^{2+} in Figure 15. The highly significant correlation shown by these data indicates that Ca uptake increased with increases in Ca^{2+} activity, as would be expected. Calcium uptake is plotted as a function of E′-Ca in Figure 16. The higher correlation coefficient indicates that E′-Ca was more closely related to Ca uptake than Ca^{2+} activity, as was the case for Fe and Mn. This was believed to be due to competitive inhibition for uptake sites by ions of similar charge, as mentioned earlier. Leaf Ca contents observed in the field study followed the same trends as that found in the growth chamber study (Moore and Patrick 1989c). The correlation between leaf Ca and E′-Ca ($r = .60$) was also much better than that between leaf Ca and Ca^{2+} activity ($r = .44$), providing further evidence that activity ratios are better availability indices for metal uptake by rice than activity alone. Leaf Ca contents observed in the field study varied from 0.087 to 0.79%, with an average of 0.26%. Calcium deficiencies may have occurred since the reported critical Ca level in rice is 0.15% (Tanaka and Yoshida 1970). The mean leaf Ca value was comparable to that found by Westfall et al. (1973) in the Y-leaves of healthy rice (0.24%).

Magnesium uptake is plotted as a function of pMg^{2+} in Figure 17. These data indicate that Mg uptake was significantly correlated with Mg^{2+} activity, as would be expected. Magnesium uptake is plotted as a function of E′-Mg in Figure 18. These

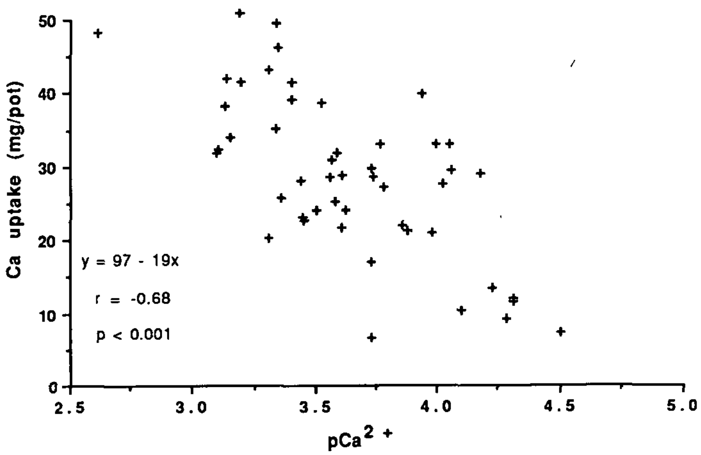


Figure 15 The relationship between Ca uptake and Ca^{2+} activity in the growth chamber study

data indicate that Mg uptake was more closely related to E′-Mg than Mg^{2+} activity. Leaf Mg was significantly correlated with E′-Mg, indicating Mg uptake trends under field conditions were similar to that observed in the growth chamber experiment (Moore and Patrick 1989c). Leaf Mg varied from 0.080 to 0.34%, with a mean of 0.19%. Magnesium deficiencies may have occurred since the critical Mg level in rice reported by Tanaka and Yoshida (1970) was 0.10%. The mean leaf Mg observed in the field was comparable to that found by Westfall et al. (1973) in healthy rice Y-leaves (0.18%).

Aluminum uptake was not significantly correlated with Al^{3+} activity (Figure 19) or any other parameter measured in this study. Mortality associated with Al toxicity occurred on soil 81 in the field study and on soil 12 in the growth chamber study.

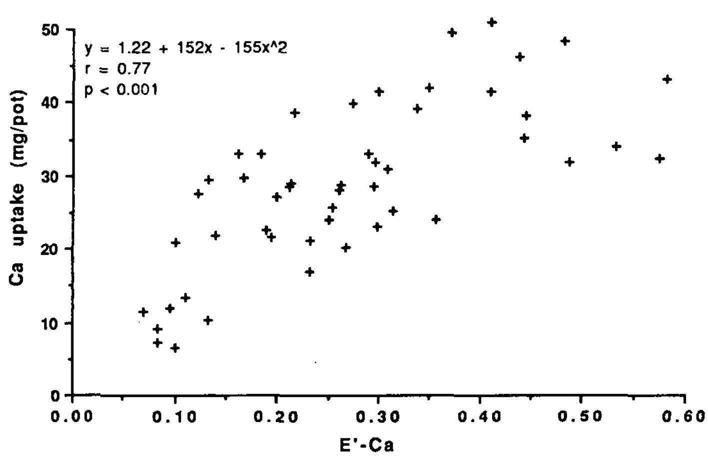


Figure 16 The relationship between Ca uptake and E′-Ca in the growth chamber study

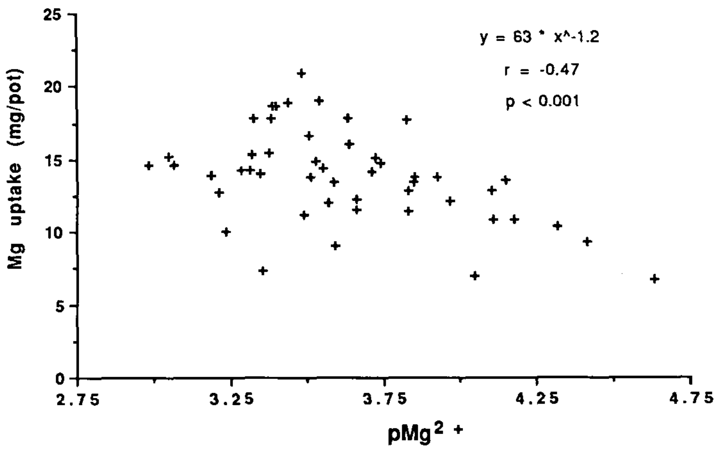


Figure 17 The relationship between Mg uptake and Mg^{2+} activity in the growth chamber study

The leaves of the plants at site 81 had an orange tinge to them and angled downward as if they had been broken at the node. Yoshida (1981) indicated that symptoms of Al toxicity in rice were interveinal orange-yellow discolorations of the tips, followed by brown mottling. Death of the plants grown on soil 12 in the growth chamber study occurred shortly after transplanting. The symptoms observed on soil 12 were chlorosis of the whole plant and a general lack of turgor. Three days after transplanting the tissue turned brown. Although the tissue Al concentration was over 700 mg kg^{-1} in the leaves of the plants growing on soil 45 in the field study, they appeared to be surviving. However, the stand was very sparse and the plants were stunted and somewhat yellow. Thawornwong and Van Diest (1974) and Tanaka and Naversero (1966c) concluded that leaf Al contents are not useful indicators of Al toxicity. Leaf P was negatively correlated with Al^{3+} activities ($r = -.42$, $n = 175$), indicating an interaction

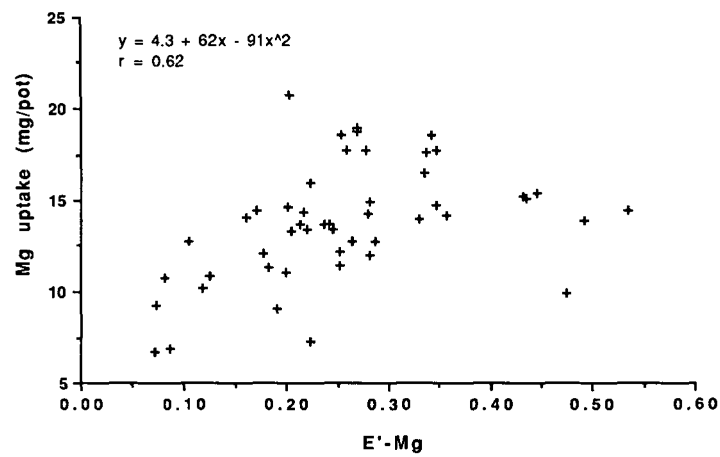


Figure 18 The relationship between Mg uptake and E′-Mg in the growth chamber study

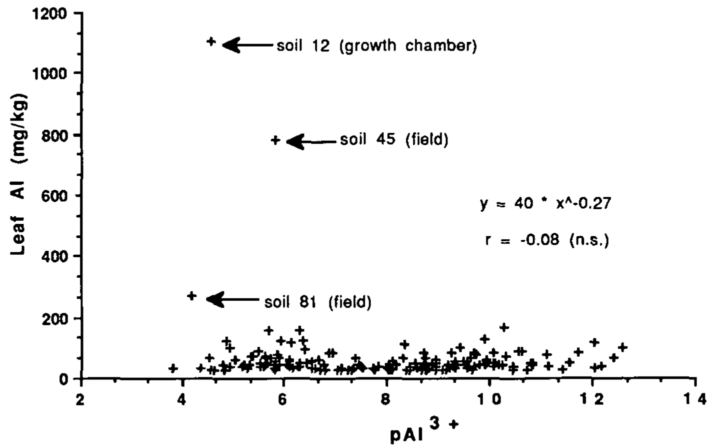


Figure 19 The relationship between leaf Al and Al^{3+} activity in the growth chamber study

may have occurred (Figure 20). Most of these soils were at equilibrium with or supersaturated with respect to variscite ($AlPO_4$), indicating that precipitation of this phase could be occurring (Moore and Patrick 1991). Interference in P uptake and/or assimilation has been suggested as the mechanism of Al toxicity in rice (Tanaka and Navasero 1966c).

Rice Growth

In a series of papers concerning metal availability to rice in acid sulphate soils, we have shown that Ca, Fe, Mn and Mg uptake are more closely correlated to the divalent charge fraction of these metals (E′-metal) than to their activities in solution (Moore and Patrick, 1989a, b and c). However, a re-examination of the data has revealed that uptake of most of these metals is more closely correlated with a new term, which

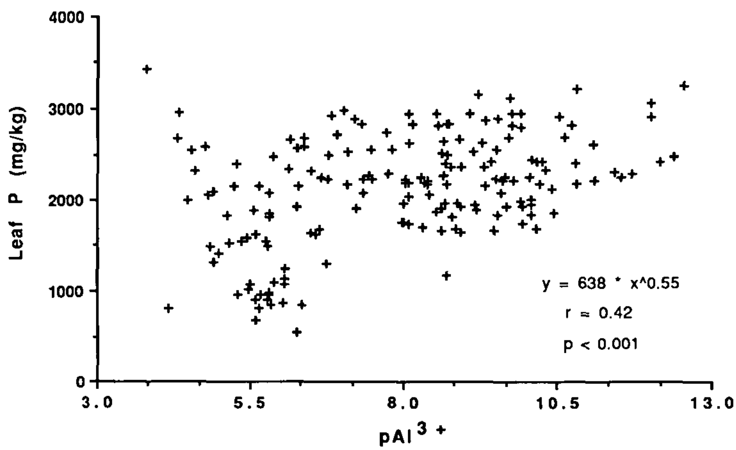


Figure 20 The relationship between leaf P and Al^{3+} activity in the growth chamber study

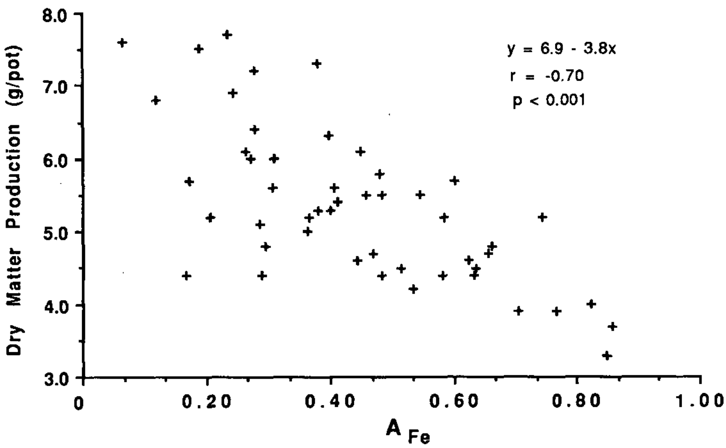


Figure 21 The relationship between dry matter production and A_{Fe} in the growth chamber study

we will refer to as the divalent activity ratio, calculated as follows

$$A_{Mi} = a_{Mi}/(a_{Ca} + a_{Fe} + a_{Mn} + a_{Mg}) \quad (1)$$

where a is the activity of metal Mi in the soil solution (Moore et al. 1990). The divalent activity ratio is probably a better indicator of nutrient availability than the divalent charge fraction for the same reasons that ion activities are better than concentrations (ie – complexing is taken into consideration).

Many researchers studying mineral imbalances in rice have found that when there is a deficiency of one nutrient, then uptake of other nutrients with the same charge is increased, while uptake of nutrients with different charges decreases. Moore and Patrick (1988) showed that uptake of divalent cations increased, whereas uptake of monovalent cations decreased in Zn-deficient rice. We attributed this phenomenon to an increase in the production of divalent cation carriers by plant roots in response to the Zn deficiency. Similarly, Moore and Patrick (1989b) indicated that Fe toxicity was more likely to occur in Ca-deficient plants if the dominant divalent cation in the soil solution was Fe. Increased divalent carrier production in response to low Ca apparently caused increased Fe uptake until plant Fe concentrations reached toxic proportions. If competitive inhibition for uptake sites on plant roots is based on charge alone, then it is logical to include the effects of the competing ions in availability indices, as well as include the degree of complexing.

Dry matter production in the growth chamber experiment is plotted as a function of A_{Fe} in Figure 21. These data indicate the deleterious effects of disproportionately high Fe^{2+} activities on the growth of rice in acid sulphate soils. Although Fe^{2+} activities were also negatively correlated with dry matter production (Moore et al. 1990), the effect of A_{Fe} was much stronger, indicating the ratio of Fe^{2+} activity to that of the other divalent metals was more important than Fe^{2+} alone. Dry matter production was positively correlated with A_{Ca}, indicating that these soils may be deficient in Ca (Figure 22). Several researchers have indicated that Ca may play an important role in Fe toxicity in rice (Benckiser et al. 1984; Howeler 1973; Ottow et al. 1983). These

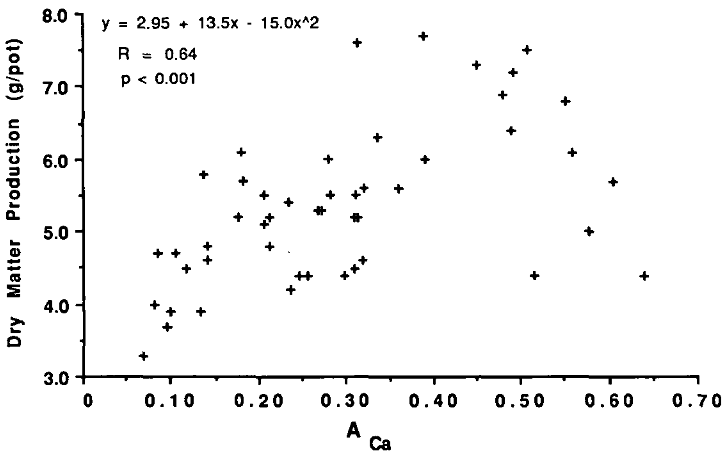


Figure 22 The relationship between dry matter production and A_{Ca} in the growth chamber study

researchers have usually indicated that Fe toxicity is a result of a multiple nutritional stress and not simply the result of excess Fe. These findings are easily interpreted when activity ratios are employed. When A_{Fe} is high, then A_{Ca} is low and Fe uptake will occur at the expense of Ca uptake. This may not only result in Fe toxicity, but in Ca deficiency as well.

Dry matter production was negatively correlated with Al^{3+} activities, which may be indicative of the adverse effects of Al on rice growth (Figure 23). As mentioned earlier, this was probably due to interference with P uptake and/or assimilation. Dry matter production was positively correlated with soil pH (Figure 24). Care must be taken, however, when using pH as an indicator of soil productivity in soil testing for acid sulphate soils since it is highly dependent upon the oxidation status of the soil being evaluated. For example, the pH of all 50 soils studied in the growth chamber

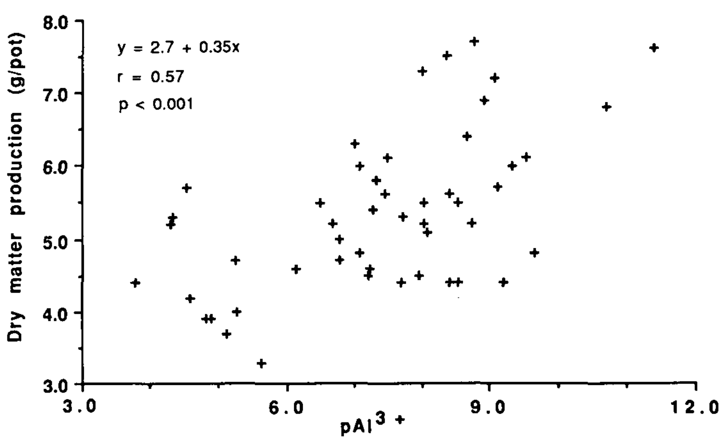


Figure 23 The relationship between dry matter production and Al^{3+} activity in the growth chamber study

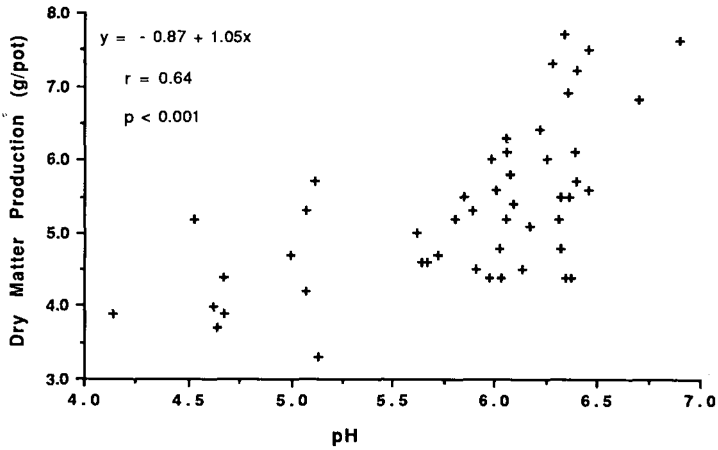


Figure 24 The relationship between dry matter production and pH in the growth chamber study

study was within 0.5 units of pH 4.0 prior to flooding and was not significantly correlated with dry matter production or the pH at P.D. (data not shown). Meaningful pH measurements can only be attained after the soil has been flooded and reduction has occurred. The authors suggest that pH measurements for soil testing purposes should be made by directly inserting a glass electrode into a soil that has been flooded with as excess amount of distilled water for a period of 28 days.

In order to delineate the roles played by the various physico-chemical agents that appear to be limiting rice growth on acid sulphate soils, growth indices were modelled using multiple regression (MAXR). Whereas simple correlation measures only the relationship between individual variable, more intricate associations may be determined from statistical analyses that evaluated relationships between many variables. The results of this analysis indicated that the best three-variable regression equation for dry matter production in the growth chamber study included pH, ionic strength, and A_{Fe}. No other variables met the 0.15 significance level for entry into the model. This would indicate that salinity, acidity, and Fe stress were the dominant factors influencing rice growth on these soils. It should be noted that Fe stress not only involves high Fe^{2+} activities, but also a low base status. Similarly, since pH has an intimate association with the Al and P status of the soil, it probably reflects the effects of these variables on growth.

Results from the field study indicated that pH and A_{Fe} composed the best two-variable equation for yield. No other variables met the 0.15 significance level for entry into the model. These findings support those observed in the growth chamber study. These results indicate why lime is so effective on acid sulphate soils; not only is the increase in pH beneficial to the plants, increases in Ca cause A_{Ca} to increase, with a simultaneous decrease in A_{Fe}.

References

Adams, F. 1966. Calcium deficiency as a causal agent of ammonium phosphate injury in cotton seedlings. Soil Sci. Soc. Amer. Proc. 30:485-488

Benckiser, G., J.C.G. Ottow, I. Watanabe and S. Santiago 1984. The mechanism of excessive iron-uptake (iron toxicity) of wetland rice. J. Plant Nutr. 7:177-185

Bennett, A.C. and F. Adams 1970. Calcium deficiency and ammonia toxicity as separate causal factors of $(NH_4)_2HPO_4$-injury to seedlings. Soil Sci. Soc. Amer. Proc. 34:255-259

Boyle, F.W., Jr. and W.L. Lindsay 1986. Manganese phosphate equilibrium relationships in soils. Soil Sci. Soc. Am. J. 50:588-593

Breemen, N. van 1969. The effect of ill-defined ferric oxides on the redox characteristics of flooded soils. Neth. J. Agric. Sci. 17:256-260

Breemen, N. van 1973. Dissolved aluminum in acid sulphate soils and in acid mine waters. Soil Sci. Soc. Amer. Proc. 37, 694-697

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

Breemen, N. van 1976. Genesis and solution chemistry of acid sulphate soils in Thailand. Agric. Res. Rep. (Versl. Landbouwkd. Onderz.) 848, PUDOC, Wageningen

Gotoh, S. and W.H. Patrick, Jr. 1972. Transformation of manganese in a waterlogged soil as affected by redox potential and pH. Soil Sci. Soc. Am. Proc. 36:738-742

Gotoh, S. and W.H. Patrick, Jr. 1974. Transformations of iron in a waterlogged soil as influenced by redox potential and pH. Soil Sci. Soc. Amer. Proc. 38:66-71

Howeler, R.H. 1973. Iron-induced oranging disease of rice in relation to physico-chemical changes in a flooded oxisol. Soil Sci. Soc. Amer. Proc. 37:898-901

Langmuir, D., and D.O. Whittemore 1971. Variations in the stability of precipitated ferric oxyhydroxides. In J.D. Hem (ed.) Nonequilibrium systems in natural water chemistry. Advan. Chem 106:209-234

Mikkelsen, D.S. 1970. Recent advances in rice plant tissue analysis. Rice. J. 73:2-5

Moore, P.A., Jr. and Patrick, W.H., Jr. 1988. The effects of zinc deficiency on alcohol dehydrogenase activity and nutrient uptake by rice. Agron. J. 80:882-885

Moore, P.A., Jr. and Patrick, W.H., Jr. 1989a. Manganese availability and uptake by rice in acid sulphate soils. Soil Sci. Soc. Am. J. 53:104-109

Moore, P.A., Jr. and Patrick, W.H., Jr. 1989b. Iron availability and uptake by rice in acid sulphate soils. Soil Sci. Soc. Am. J. 53:471-476

Moore, P.A., Jr. and Patrick, W.H., Jr. 1989c. Calcium and magnesium availability and uptake by rice in acid sulphate soils. Soil Sci. Soc. Am. J. 53:816-822

Moore, P.A., Jr. and Patrick, W.H., Jr. 1991. Aluminum, boron, and molybdenum availability and uptake by rice in acid sulphate soils. Plant and Soil 36:171-181

Moore, P.A., Jr., Attanandana, T., and Patrick, W.H., Jr. 1990. Factors affecting rice growth on acid sulphate soils. Soil Sci. Soc. Am. J. 54:1651-1656

Nordstrom, D.K. 1982. The effect of sulphate on aluminum concentrations in natural waters: some stability relations in the system Al_2O_3-SO_3-H_2O at 298 K. Geochim. Cosmochim. Acta 46:681-692

Ottow, J.C.G., G. Benckiser, I. Watanabe and S. Santiago 1983. Multiple nutritional stress as the prerequisite for iron toxicity of wetland rice (Oryza sativa L.) Trop. Agric. (Trinidad) 60:102-106

Pons, L.J. and N. van Breemen 1982. Factors influencing the formation of potential acidity in tidal swamps. Proc. Bangkok Symp. Acid Sulphate Soils. ILRI Publ. 31. Wageningen

Prasittikhet, J. 1987. Metal availability and rice growth under controlled redox potential and pH in acid sulphate soils of Thailand. Ph.D. Diss. Louisiana State University, Baton Rouge (Diss. Abstract 11431)

Satawathananont, S. 1986. Redox, pH and ion chemistry of acid sulphate soils of Thailand. Ph.D. diss., Louisiana State University, Baton Rouge (Diss. Abstr. 87-10589)

Schwab, A.P. and W.L. Lindsay 1983. Effect of redox on the solubility and availability of iron. Soil Sci. Soc. Am. J. 47:201-205

Schwab, A.P. and W.L. Lindsay 1983. The effect of redox on the solubility and availability of manganese in a calcareous soil. Soil Sci. Soc. Amer. J. 47:217-220

Sposito, B., C. Jouany, K.M. Holzclaw and C.S. LeVesque 1983. Calcium-magnesium exchange on Wyoming bentonite in the presence of adsorbed sodium. Soil Sci. Soc. Am. J. 47:1081-1085

Sposito, G. and S.V. Mattigod 1979. GEOCHEM: a computer program for the calculation of chemical equilibria in soil solutions and other natural water systems. The Kerney Foundation of Soil Science. Univ. of California

Swarup, A. 1981. Effect of iron and manganese application on the availability of micronutrients to rice in sodic soil. Plant Soil 60:481-485

Tanaka, A. and S.A. Navasero 1966a. Manganese content of the rice plant under water culture conditions. Soil Sci. Plant Nutr. 12:67-72

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

Tanaka, A. and S.A. Naversero 1966c. Aluminum toxicity of the rice plant under water culture conditions. Soil Sci. and Plant Nutr. 12:9-14

Tanaka, A. and S. Yoshida 1970. Nutritional disorders of the rice plant in Asia. IRRI Tech. Bull. 10

Thawornwong, N. and A. van Diest 1974. Influences of high acidity and aluminum on the growth of lowland rice. Plant and Soil 41:141-159

Westfall, D.G., W.T. Flinchum and J.W. Stansel 1973. Distribution of nutrients in the rice plant and effect of two nitrogen levels. Agron. J. 65:236-238

Yoon, S.K., J.T. Gilmour and B.R. Wells 1975. Micronutrient levels in the rice plant Y leaf as a function of soil solution concentration. Soil Sci. Soc. Am. Proc. 39:685-688

Yoshida, S. 1981. Fundamentals of Rice Crop Science. International Rice Research Institute, Los Banos

Effects of liming and P-fertilization on cereals grown on an acid sulphate soil in Sweden

Ingrid Öborn

Dept. of Soil Sciences, Swedish University of Agricultural Sciences. Box 7014, A-750 07 Uppsala, Sweden

Abstract

A field experiment was carried out to study the effects of liming (calcite, dolomite) and P-fertilization (superphosphate, apatite) of the yield of oats, barley and spring wheat and the availability of Ca, Mg, K, P, Al and Cd in an acid sulphate soil in Sweden. The soil, a Fluvaquentic Humaquept (Gleyic Cambisol), was drained and diked.

Liming (6 ton ha^{-1} CaO, calcite) raised the pH of the topsoil from 4.8 to 5.6, and increased yields by 7 per cent for oats, 18 per cent for wheat and 32 per cent for barley. Dolomite had less of an effect, probably owing to an unfavourable K:Mg balance in the already Mg-rich soil. The yield response to 40 and 80 kg P (superphosphate) was 26 and 34 per cent, respectively, and was similar for the different crops. The apatite treatment had no effect during the experimental period. The contents of Ca, Mg, K, P, Al and Cd in grain and straw from wheat were determined and discussed. Application of lime (calcite) in combination with yearly P-fertilization seems to be the best long-term management practice.

Introduction

In Sweden, acid sulphate soils traditionally called gyttja soils (Wiklander, Hallgren 1949; Wiklander et al.. 1950a) or alum soils (Hannerz 1933; Kivinen 1944), cover approximately 140 000 ha (Ekström 1953; Öborn 1989). They have developed mainly in sulphidic sediments deposited during the Litorina period of the Baltic Sea (7200-4000 BP) (Figure 1). The relatively fast uplift, e.g. 0.5 cm/year in the studied area, brings the sediments to the surface where they oxidize. In addition, at the end of the 19th century, many shallow lakes in central and eastern Sweden were artificially drained; acid sulphate soils developed which were, often, covered by fen-peat. To keep the watertable at 0.7-1.0 m depth in areas still suitable for agriculture, the drainage systems have been continuously improved and, at some locations, dikes have been built.

Traditionally, oats (*Avena sativa*), rye (*Secale cereale*), timothy (*Phleum pratense*) and other ley grasses, and potatoes (*Solanum tuberosum*) are cultivated on the acid sulphate soils. These crops are relatively tolerant of acid conditions as compared with the more sensitive wheat (*Triticum aestivum*), barley (*Hordeum spp.*), clover (*Trifolium sp.*), and peas (*Pisum sp.*), which are other common crops in Scandinavia.

Low amounts of plant-available P seem to be a main limiting factor in most Swedish acid sulphate soils, except in newly oxidized soils or soil horizons where the pH is extremely low. Only a few experimental attempts to improve the fertility of acid sulphate soils have been reported in Scandinavia. In pot and field experiments, Torstens-

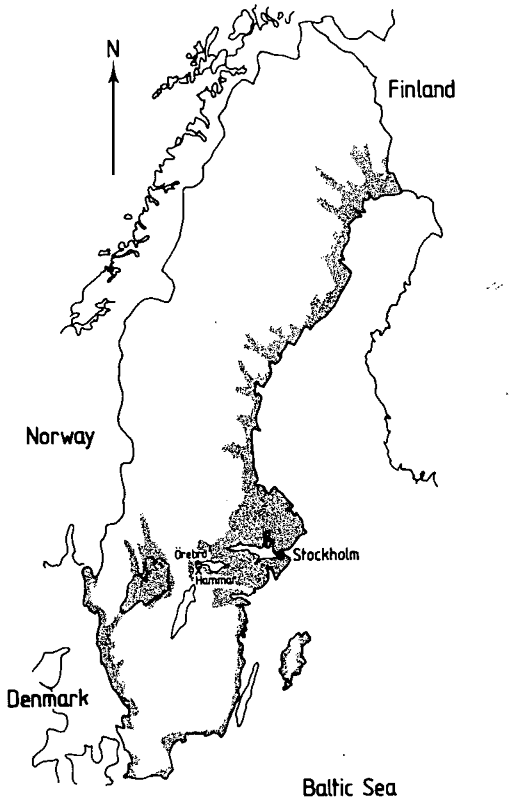


Figure 1 Map showing the experimental site and climatic station. The extent of the Litorina sea, about 6500 BP, is shaded (after Ekström 1953)

son and Eriksson (1938a,b) drilled granulated superphosphate (30 kg/ha P) to different depths in an attempt to increase the effectiveness of applied P fertilizer. The treatments resulted in increased root development and grain yield in oats and barley.

The present field experiment studies the effects of liming and P fertilization on the grain yield of spring wheat (*Triticum aestivum*), barley and oats (*Avena sativa*). Two spring wheat varieties differing in their sensitivity to Al and two types of barley, four-rowed barley (*Hordeum vulgare*) and two-rowed barley (*Hordeum distichum*) were included in the trial. In the liming treatment, dolomite and calcite were compared; in the P-treatment, superphosphate and apatite were used. In addition, the contents of Ca, Mg, K, P, Al and Cd in grain and straw of wheat were determined.

Site description

The Hammar Farm is located 25 km SE of Örebro (Figure 1) at 59°10′N 15°10′E and an altitude of 22 mm. The experimental field was situated in a flat depression forming the Kvismaren Valley, consisting of sediments with a high clay content (50-60 per cent), 1-1.5 per cent organic C and about 1 per cent S. The surface layer had a higher organic matter content (8-10 per cent C), but lacked a peat layer. Mica was the dominating clay mineral.

The area was drained and cultivated at the end of the 19th century but became a wet pasture after some decades. It was diked and recultivated in 1983. At present, the groundwater table is at about 70 cm depth during the growing season, and the field is used for cereal and potato production. The mean monthly air temperature, precipitation and potential evapotranspiration are shown in Figure 2. The mean amounts of precipitation (Örebro, Väder och vatten 1984-89) for June, July and August 1984-89 (the growing season) were 71 (22-126), 78 (333-148) and 88 (40-130) mm, respectively.

The Hammer clay soil has an umbric epipedon and a cambric horizon. It may be classified as a Fluvaquentic Humaquept (Soil Survey Staff 1975) or Gleyic Cambisol (FAO 1988). Physical and chemical properties of the Hammer soil have been presented by Öborn (1989). Before the start of the trial, six profiles (0-100 cm) were sampled to cover the variations in the experimental field (Table 1).

Experimental design

A split plot design with three replicates was used, with lime treatments in the main plots (1000 m^2) and P fertilization in the subplots (250 m^2) (Figure 3). The liming rates were 0, 3 and 6 t ha^{-1} CaO. Two types of lime from local quarries were used, sedimentary lime and crystalline dolomite (only for the 6 ton CaO treatment). The finely ground lime was spread before sowing the first year (1984) and mixed to 10 cm depth. 0, 40 and 80 kg ha^{-1} P was added yearly during four years, whereupon residual effects were studied for two years. Granulated superphosphate and apatite (only for the 80 kg P) treatment were used. P was mixed into the surface layer, 0-10 cm, by rotary cultivation.

The cereals grown were spring wheat (*Triticum aestivum* L.), barley (*Hordeum* L.) and oats (*Avena sativa* L.; var. Puthi). In addition, two spring wheat varieties differing in their sensitivity of A1 were used: Drabant, which was sensitive, and Kadett, which was relatively tolerant (Lind et al.. 1987; Pettersson and Strid 1989). Two types of barley, i.e. four-rowed barley (var. Agneta) and two-rowed barley (var. Pernilla) were

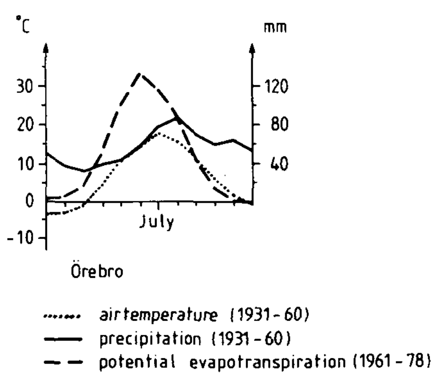


Figure 2 Climatic data from Örebro (59°15′N, 15°13′E). The mean monthly values of air temperature (AT), precipitation (P) and estimated potential evapotranspiration (PE). Mean annual values: AT 5.9°, P 656 mm and PE 552 mm (Taesler 1972; Eriksson 1981)

Table 1 Chemical properties of the field before the start of the experiment (sampled May 2 1984) means of n samples, max. and min. values in parentheses

Horizon	Depth (cm)	pH (1:2.5)		C[1] (%)	S[1] (%)	P-AL $mg\,kg^{-1}$
		H_2O n=6	$CaCl_2$, 0.01 M n=6	n=3	n=3	n=6
Ap	0–25	5.0 (4.5–5.3)	4.6 (4.2–4.9)	8.9 (8.1–10.5)	0.19 (0.13–0.24)	16 (8–26)
Bwg1	25–40	4.4 (3.8–4.8)	4.0 (3.6–4.3)	–	–	5 (2–9)
Bwg2	40–55	4.4 (3.7–4.9)	4.0 (3.4–4.4)	1.3 (1.3–1.4)	0.20 (0.04–0.34)	–
Bwg2	55–70	4.5 (3.6–5.2)	4.0 (3.4–4.6)	–	–	–
Cg	70–85	4.5 (3.6–5.3)	4.1 (3.5–4.8)	–	–	–
Cg	85–100	4.7 (4.0-5.3)	4.3 n=5 (3.8-4.8)	1.1 (1.0-1.2)	0.58 (0.02-1.57)	–

Table 1 (cont.)

Horizon	Depth (cm)	CEC[2] pH 7 $mM\,kg^{-1}$ n=4	BS[2] (%) n=4	Exchangeable cations[1], $mM\,kg^{-1}$				Titr.[1] acid $mM\,kg^{-1}$ n=4
				Ca^{2+} n=6	Mg^{2+} n=6	K^+ n=6	Al^{3+} n=6	
Ap	0–25	385 (325–475)	35 (18–48)	111 (47–185)	16 (9–24)	4.6 (3.6–5.8)	95 (8–289)	245 (201–266)

[1] C, S total elemental analyzer; Ex. Ca, Mg, 0.5 M NH_4OA_C at pH 7;
Titratable acid: soil + 0.04 M NaOH (to pH 7)
[2] $CEC_{pH\,7} = Ca^{2+} + Mg^{2+} + K + \text{Titr. acid}$
$BS = (Ca^{2+} + Mg^{2+} + K^+) * 100/CEC_{pH\,7}$

included in the trial. Every subplot was split into five miniplots (50 m^2), each of which was sown with a different one of the five experimental crops (Figure 3). During year 4, only three crops, i.e. wheat (var. Kadett), barley (var. Pernilla) and oats, were sown. During years 5 and 6 wheat (var. Drabant) was the only crop. Every year, K (40 kg KCl ha^{-1} and N ($CaNO_3$) were applied before sowing. The $CaNO_3$ was applied at rates of 60 and 90 kg ha^{-1} to barley/oats and wheat, respectively.

During six years, soil samples (0-20 cm) were taken in the subplots at harvest. In addition during the first year, samples were also collected immediately before and one month after liming/P-fertilization. In year 6, grain and straw were cut from every plot for chemical analysis.

Figure 3 shows only block 1. The treatments and crops were randomized in blocks 2 and 3.

Laboratory methods

Soil samples were air-dried (35 °C) and sieved (2 mm). pH was measured in deionized

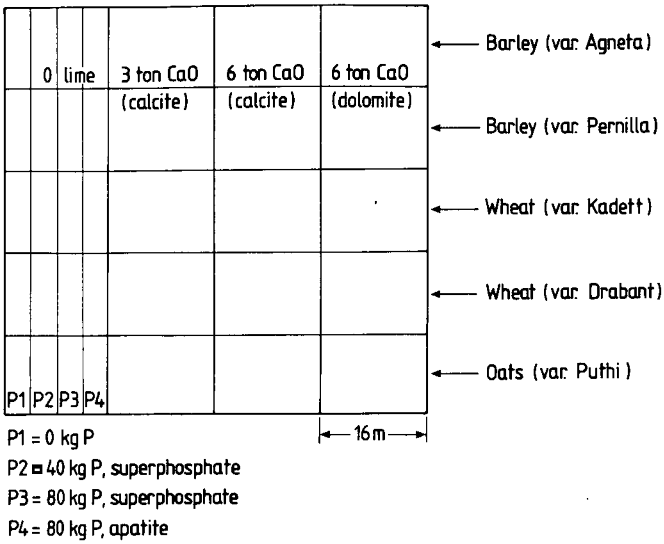


Figure 3 The field experiment at Hammar Farm had a split plot design with lime in the main plots, P in the subplots, and three replicates (blocks).

water at a soil solution ratio of 1:2.5. Contents of easily-soluble P, Ca, Mg and K were determined in ammonium lactate (AL)-extract (0.1 M NH_4-lactate and 0.4 HOAc, pH 3.75; Egnér et al. 1960). P was measured by flow injection analysis (FIA), and the cations by atomic absorption. Exchangeable aluminium was measured in 1 M KCl-extract (Barnishel and Bertsch 1982) by FIA (Zöltzer 1982).

The grain and straw were extracted (the ignition excluded) and analyzed for Cd and Al according to Andersson (1976). In addition, Ca, Mg, K and P were determined by atomic absorption spectrophotometry and ICP, respectively.

Results and discussion

Effects of liming and P fertilization on soil chemistry

The response of soil pH to liming is shown in Figure 4. The liming effect seemed to have stabilized after three (calcite) or four (dolomite) years. The mean pH and base saturation (brackets) of the field was initially 4.8 (29 per cent), and after six years it was 5.0 (28 per cent) with no lime, 5.3 (33 per cent) with 3 t ha^{-1} CaO (calcite), 5.6 (42 per cent) with 6 t ha^{-1} CaO (calcite) and 5.5 (39 per cent) with 6 t ha^{-1} CaO (dolomite). Exchangeable aluminium showed the same pattern, being 79 mg Al kg^{-1} at the start and had decreased to 62, 21, 6 and 9 mg Al kg^{-1} in the different lime treatments by year 6.

The AL-extractable K was around 110-120 mg kg^{-1} during the experimental period. The dolomite application increased the Mg-AL from 120 to 390 mg kg^{-1}, which changed the K:Mg ratio from 1 to 0.3. The optimal range for the ratio is 1-3 (Johansson and Hahlin 1977), hence K might have become a limiting element. After four yearly applications of superphosphate, in total 160 and 320 kg ha^{-1} P, the P-AL had increased

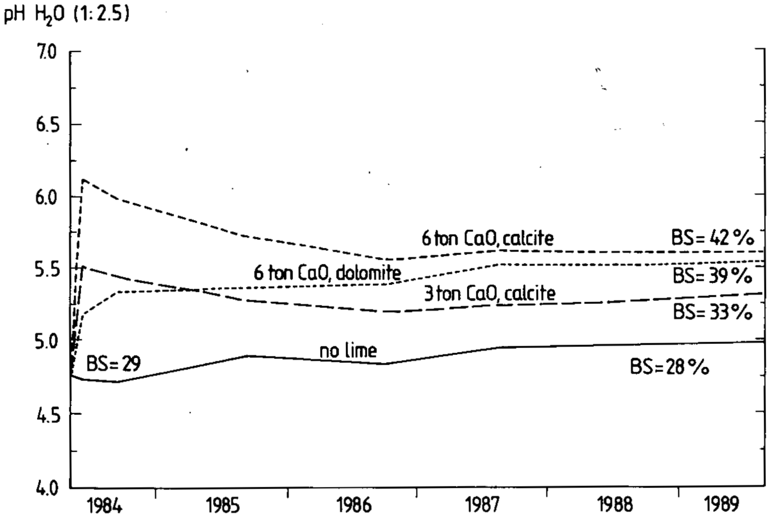


Figure 4 Influence of liming on soil pH (H_2O; 1:2.5) and base saturation. The lime was added in May 1984.

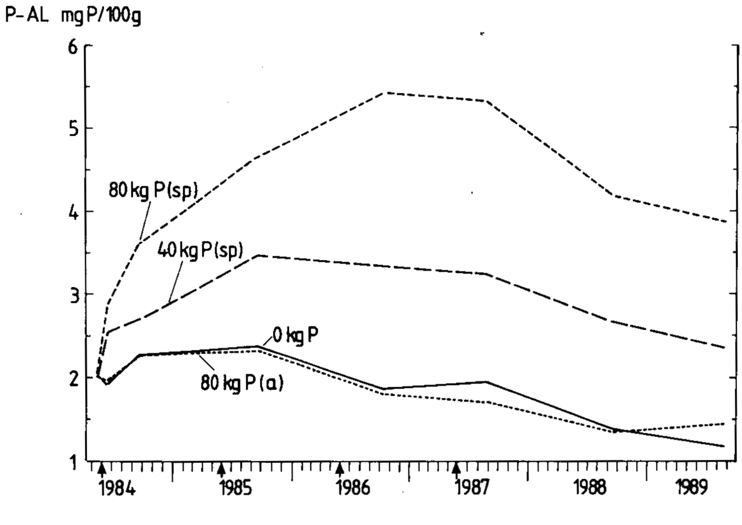


Figure 5 Effects of P fertilization on easily-soluble P (P-AL; Egnér et al. 1960). P was applied yearly from 1984 to 87 as superphosphate (sp) and apatite (a). The residual effects were evaluated in 1988-89.

from 20 to 32 and 53 mg P kg^{-1}, respectively (Figure 5), but after another two years it was 23 and 39 mg P kg^{-1}. Since the decrease in P-AL corresponded to the P uptake in grain, no P-fixation seemed to have taken place. In the no P and apatite (320 kg P) treatments P-AL decreased to 13 mg P kg^{-1} over the six year period, which showed that apatite – P is rather insoluble and not AL-extractable. The highest liming rate increased P-AL significantly in years 3 and 4.

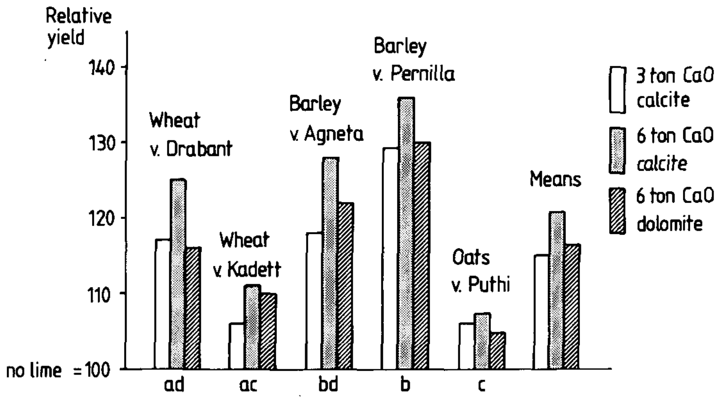


Figure 6 Response of grain yield (means of 3-5 years) to liming. Crops with the same letter are not significantly different at the 0.05 per cent level. The absolute yields for no lime plots as an average of the experimental years in kg ha^{-1}; Drabant 3460 (2690-4040, n = 5); Kadett 3720 (1970-4920, n = 4); Agneta 2790 (2000-3270, n = 3); Pernilla 3160 (2610-3640, n = 4); and Puthi 3520 (1270-5450, n = 4)

Effects of liming and P fertilization on grain yield

Liming

The average increases in the grain yield of the cereals studied in response to liming were 15 and 21 per cent, respectively, after the 3 and 6 t CaO (calcite) applications, and 16 per cent in the dolomite (6 t CaO) treatment. The lower response to dolomite may have been due to the unfavourable K:Mg ratio in the soil, as mentioned earlier. Because Mg-rich minerals as chlorites and amphiboles occur in the parent material, dolomite is unsuitable as lime in this area. The effect of liming on the grain yield of the various crops is presented in Figure 6. Barley showed the highest response to liming, the relative yield (no lime = 100) after 6 t CaO (calcite) being 136 per cent (122-143, 4 years) for the two-rowed var. Pernilla and 128 per cent (111-148 n = 3) for the four-rowed var. Agneta. The response of the two spring wheat varieties differed with relative yields of 125 per cent (114-141, n = 5, var. Drabant) and 111 per cent (104-121, n= 4, var. Kadett), respectively, after addition of calcite (6 t CaO). Oats showed the lowest response to liming, with a relative yield of 107 per cent (97-114, n = 4).

P fertilization

The average increase in yield was 26 and 34 per cent, respectively, in response to 40 and 80 kg P ha^{-1} of superphosphate. In most years, the yield of the two varieties was significantly higher after addition of 80 kg P. However, this was not the case for barley and oats. Apatite did not have any measurable effects during the experimental period. There were notable differences between the years in absolute yield levels as well as response to P (Figure 7). Late sowing in the springs 1985 and 1986, followed by dry early summers may be the account for the lower P utilization in 1985 and 1986. In 1987, the oats were harvested too late and had poor quality. The effects of

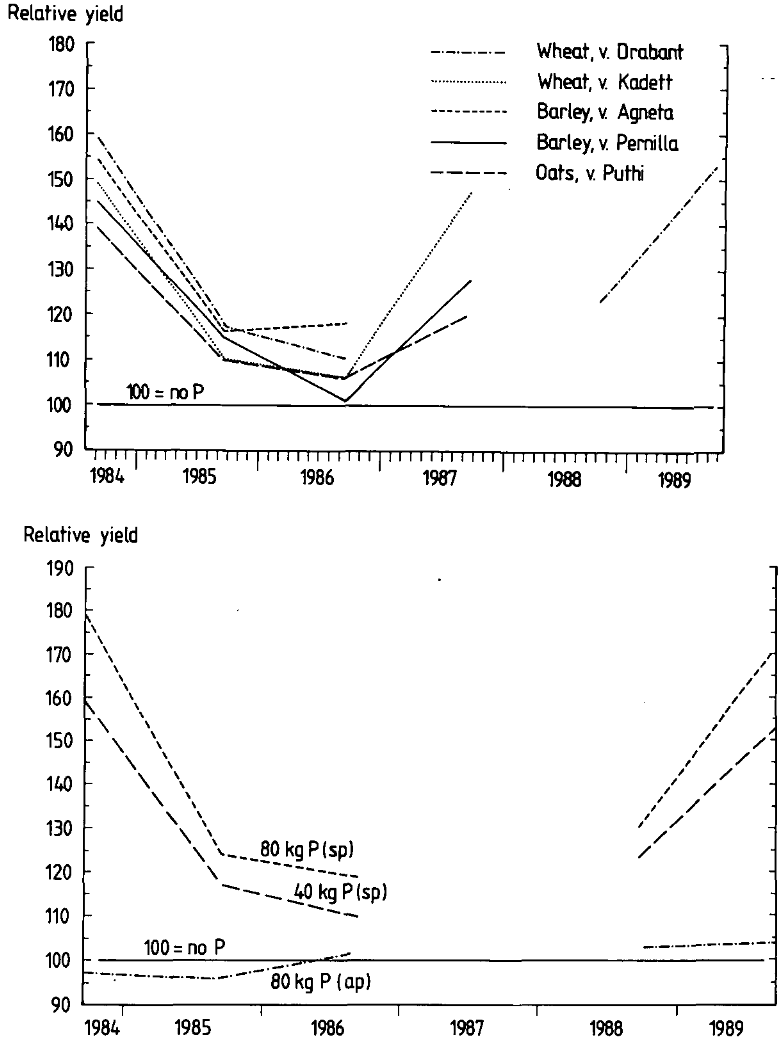


Figure 7 Effects of P fertilization on grain yield. 40 (7a) and 80 kg P ha^{-1} was applied yearly from 1984 to 1987 as superphosphate and apatite (7b, wheat var. Drabant), after which the residual effects were studied during 1988-89. The absolute yields for the no-P plots as an average of the experimental years were Drabant 3330 (2700-4080, n = 5); Kadett 3440 (1630-4830, n = 4); Agneta 2780 (2290-3220, n = 3); Pernilla 3450 (2980-3810, n = 4); Puthi 3270 (1190-4670, n = 4)

P fertilization on the grain yield were rather uniform among the crops, the differences between the crops were not significant ($P > 0.05$).

Comparison with average yields in the region

The average yields in Örebro county for the experimental period 1984-1989 were 4550 (5650-3580) kg ha^{-1} of spring wheat, 3820 (3380-4760) of barley and 3860 (3330-5060) kg ha^{-1} of oats (Jordbruksstatistisk årsbok 1985-90). In 1984, the highest average yields ever were harvested for spring wheat as well as barley and oats. The lowest yields during the period were measured in 1987 for spring wheat and barley, and 1986 for oats. The regional average yields can be compared with the 3 t CaO + 40 Kg P treatment where the yields were 4300 (2380-5670) of spring wheat, and 4040 (2740-5970) and 3870 (1480-5980) kg ha^{-1} of barley and oats, respectively.

Influences of liming and P fertilization on the uptake of Ca, Mg, K, P, A1, and Cd in grain and straw

Mg levels in grain and straw were higher and the Ca and K contents lower in the dolomite treatment as compared with the calcite treatment (Table 2). The highest lime applications decreased the Cd level in straw but did not affect A1 levels significantly. P-fertilization, apatite excluded, increased the content of P in grain at both application rates. K and Mg contents were elevated as well. Cd levels in grain were enhanced where superphosphate had been applied. The same result was obtained in long-term field experiments in Sweden (Andersson and Simán 19191), where the increase was ascribed to Cd supplied in fertilizer.

Table 2 Average contents (μg/g) of Ca, Mg, K, P, A1 and Cd in wheat, var. Drabant, year 6, as related to liming rate (t ha^{-1}) and P fertilization level (kg ha^{-1} * 4 years)

	Ca	Mg	K	P	A1	Cd
Liming, grain						
0 lime	310^{a}	854^{c}	3456^{ab}	2501^{a}	2.91^{a}	0.062^{a}
3 calcite	294^{a}	887^{bc}	3510^{a}	2567^{a}	2.75^{a}	0.061^{a}
6 calcite	285^{a}	929^{ab}	3535^{a}	2746^{a}	2.58^{a}	0.057^{a}
6 dolomite	253^{b}	996^{a}	3392^{b}	2712^{a}	2.68^{a}	0.056^{a}
LSD	31	69	112	333	0.52	0.020
Liming, straw						
0 lime	1685^{ab}	358^{b}	5521^{a}	293^{a}	28.8^{a}	0.161^{a}
3 calcite	1690^{ab}	376^{b}	5621^{a}	258^{a}	27.7^{a}	0.147^{ab}
6 calcite	1794^{a}	465^{ab}	5938^{a}	312^{a}	27.4^{a}	0.127^{ab}
6 dolomite	1568^{b}	621^{a}	5271^{a}	268^{a}	28.2^{a}	0.118^{b}
LSD	158	163	1874	212	6.1	0.042
P fertilization, grain						
0 P	291^{a}	903^{bc}	3435^{ab}	2539^{c}	2.71^{a}	0.056^{b}
40 P superphosphate	284^{a}	923^{ab}	3498^{ab}	2693^{b}	2.75^{a}	0.060^{ab}
80 P superphosphate	279^{a}	951^{a}	3544^{a}	2835^{a}	2.67^{a}	0.064^{a}
80 P apatite	289^{a}	888^{c}	3417^{b}	2460^{c}	2.80^{a}	0.057^{b}
LSD	13	31	113	129	0.32	0.006
P fertilization, straw						
0 P	1630^{b}	431^{b}	5412^{a}	264^{a}	29.0^{a}	0.125^{a}
40 P superphosphate	1722^{ab}	465^{ab}	5783^{a}	290^{a}	26.0^{a}	0.145^{a}
80 P superphosphate	1749^{a}	484^{a}	5796^{a}	308^{a}	28.0^{a}	0.145^{a}
80 P apatite	1636^{b}	440^{ab}	5358^{a}	269^{a}	29.1^{a}	0.139^{a}
LSD	107	49	462	45	5.8	0.021

Means with the same letters are not significantly different (0.05 level).
LSD = least significant difference at 0.05 level

Summary and conclusions

Clear differences in sensitivity of the cereals to acidic conditions were observed (barley > spring wheat > oats). The grain yields of spring wheat and oats responded best to P fertilization, while barley yield was enhanced most by liming. In general, yields of all crops were increased by applications of both lime and phosphate. Dolomite seems to offer no advantage on this type of acid soil, which is already relatively rich in Mg.

The high lime application decreased the exchangeable Al considerably and increased the P-availability during years 3 and 4, but it is uncertain whether these effects could be enhanced further by increasing the liming dose (Ståhlberg 1982). The 80 kg P level was applied in order to compare the effects of superphosphate and granulated apatite. The dosage of apatite was recommended by the supplier. However, in this experiment, neither the grain yield nor easily soluble P (P-Al) was enhanced by apatite. Hence, it appears to be unsuitable as a P-fertilizer for cereals on this type of soils.

When P-Al is 20 mg hg^{-1}, the recommended dose of P is 30-40 kg ha^{-1} (Hahlin and Ericsson 1981). However, in view of of the high cost of P fertilizer and the fact that only ca. 15 kg P ha^{-1} is removed annually as grain harvest, there are good reasons for evaluating the effects of application rates below 40 kg ha^{-1}. Application of lime (calcite) in combination with yearly application of phosphate seems to be the best long-term management practice.

References

Andersson, A. 1976. On the determination of some heavy metals in organic material. Swedish J. Agric. Res. 6, 145-150

Andersson, A. and G. Simán 1991. Levels of Cd and some other trace elements in soils and crops as influenced by lime and fertilizer level. Acta Agric. Scand. 41, 3-11

Barnishel, R. and P.M. Bertsch 1982. Aluminium. In: Page, A.L., R.H. Miller, D.R. Skeeney. Methods of soil analysis, part 2, 2nd ed., Am. Soc. Agron., Madison Wsc. 275-300

Egnèr, H., H. Riehm and W.R. Domingo 1960. Untersuchungen über die chemische Bodenanalyse als Grudlage für Beurteilung des Nährstoffzustandes des Böden. II. Chemische Extraktions-methoden zur Phosphor- und Kaliumbestimmung. Annalen d. landw. Hochschule Schwedens, 26, 199-215

Ekström, G. 1953. Åkermarkens matjordstyper. In: Atlas över Sverige, 63-64, 1-6. Svenska Sällskapet för Antropologi och Geografi. Generalstabens Litografiska Anstalts Förlag, Stockholm (with English summary)

Eriksson, B. 1991. Den 'potentiella' evapotranspiration i Sverige. Swedish Meteorological and Hydrological Institute, Reports Meteorology and Climatology RMK 28 (with English summary)

FAO 1988. Soil map of the world. Revised legend. World Soil Resources Report 60. FAO, Rome

Hahlin, M. and J. Ericsson. 1981. Fosfor och fosforgödsling. Aktuellt från lantbruksuniversitetet 294, Sveriges lantbruksuniversitet, Konsulentavdelningen, S-750 07 Uppsala

Hannerz, E. 1933. Om så kallade alunjordat. In: Ulander A. (editor), Berättelse öover verksamheten vid kemisk-växtbiologiska anstalten och frökontrollanstalten i Luleå, pp. 114-138

Johansson, O.A.H. and J.M. Mahlin 1977. Potassium/magnesium balance in soil for maximum yield. Proceedings of the international seminar on soil environment and fertility management in intensive agriculture, Tokyo.

Jordbruksstatistisk årsbok (Yearbook of Agricultural Statistics with English summary) 1985-1990.

Kivinen, E. 1944. Sulfat- eller alunjordar, deras egenskaper och synpunkter på deras odling. Sven. Vall. Mosskulturfören. Tidskr. 2, 153-164

Lind, C., T. Lundborg and C. Halldén 1987. Aluminium och ura jordat miljöproblem i tiden. Sveriges Utsädesförenings Tidskrift 97, 163-171 (with English summary)

Öborn, I. 1989. Properties and classification of some acid sulfate soils in Sweden. Geoderma 45, 197-219

Öborn, I. 1991. Some effects of chemical weathering in three cultivated acid sulfate soils in Sweden. In: Wright R.J., V.C. Baligar and R.P. Murrman (editors): Plant-soil interactions at low pH. Developments in Plant and Soil Sciences 45, 55-63. Kluwer Academic Publishers

Pettersson, S. and H. Strid 1989. Aluminium toxicity in two cultivars of wheat (*Triticum aestivum L.*) with different sensitivity to Al as affected by level of nutrient supply. Swedish J. Agric. Res. 19, 183-191

Soil Survey Staff 1975. Soil Taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys. USDA Handbook No. 436, U.S. Government Printing Office, Washington D.C.

Ståhlberg, S. 1982. Estimation of the requirement of liming by determination of exchangeable soil aluminium. Act. Agric. Scand. 32, 357-367

Taesler, R. 1972. Klimatdata för Sverige. Sveriges meteorologiska och hydrologiska institut & Statents Institut för Byggnadsforskning, Stockholm

Torstensson, G. and S. Eriksson. 1938. Studien über die Festlegung der Phosphorsäure in Gyttjaböden. Annalen d. landw. Hochschule Schwedens 5, 377-403

Torstensson, G. and S. Eriksson 1983. Studien über die Festlegung der Phosphorsäure in Gyttjaböden II. Annalen d. landw. Hochschule Schwedens 6, 89-107

Väder och vatten 1984-1989. Sveriges Meteorologiska och Hydrologiska Institut

Wiklander, L. and G. Hallgren 1949. Studies on gyttja soils, I. Distribution of different forms of iron, manganese, and calcium carbonate in a profile from Kungsängen. Ann. R. Agric. Coll. Sweden, 16, 811-827

Wiklander, L., G. Hallgren, N. Brink and E. Jonsson 1950. Studies on gyttja soils, II. Some characteristics of two profiles from northern Sweden. Ann. R. Agric. Coll. Sweden, 17, 24-36

Wiklander, L. G. Hallgren and E. Jonsson 1950. Studies on gyttja soils III. Rate of sulphur oxidation. Sweden. Ann. R. Agric. Coll. Sweden, 17, 425-440

Zöltzer, D. 1982. Entwiclung automatischer Durchflußsysteme zur Bestimmung von Eisen und Aluminium im Wasser und in Bodenlösung. Institut für Anorganische Chemie, Georg August-Universität, Göttingen

Microbiological characteristics of acid sulphate soils: a case study in Ho Chi Minh City environs

Nguyen thi Thanh Phung[1] and Phan Lieu[2]

[1] IAS, 121 Nguyen Binh Khiem, Ho Chi Minh City, Vietnam
[2] OPRI, 104 Huynh van Banh, Ho Chi Minh City, Vietnam

Abstract

The structure and activity of the microflora of acid sulphate soils and non-acid soils under different land uses are compared. The total microorganism content of acid sulphate soils is always low but varies significantly according to vegetation and the extent of amelioration. Even with high contents of organic matter, microorganisms are inhibited in acid sulphate soils, so nutrients are not made available quickly to crops. Under *Eucalyptus*, *Actinomycetes* assume a dominant status in the microflora. In acid sulphate soils, denitrifying bacteria are abundant, while *Thiobacilli* are abundant in sulphidic soils and raw acid sulphate soils but decrease in ameliorated soils.

Materials and methods

Sample locations were as follows:
- Acid sulphate soils near Ho Chi Minh City:
  - l_1 Nhi xuan farm, Binh chanh district;
  - l_2 Xuan thai son village, Ho Chi Minh district;
  - l_3 Le minh xuan farm, Binh chanh district;
- Non-acid soils, in Hau giang province:
  - l_4 and l_5, Can tho district.

Sample s1 (l_1) was taken from a waterlogged potential acid sulphate soil under *Eleocharis* marsh, with a profile form of Ah Go Gr, pH 4.5 to 5.0 but with air dry pH 3.4. Samples s2 to s10 were from acid sulphate soils with prominent jarosite within 40-50 cm of the surface. Samples s11 to s13 were not acid sulphate soils. The first two had no clear horizon differentiation other than an A horizon, the last had an Ap Bg Cg morphology.

At each location, the soil was sampled at 0-20 cm and 20-40 cm. For the acid sulphate soils, the soil material in both layers belongs to the A horizon, without pyrite, but is subject to toxins coming up from the underlying Bj or Gj horizons, especially in the dry season.

Samples were collected during the dry season (November to April) between 1980 and 1989. Samples were stored in a refrigerator and analyzed within 72 hours of collection. Microorganisms were revealed on solid or dilute media (Krassilnikov 1966); *Thiobacillus* by the 9k liquid medium (Sylverman 1958). Microorganism content takes the 3-repetition average values and is expressed as the number of cells per 1 g dried soil.

Results

Total microorganism content

The microfloral structure of the soils is presented in Table 1. The total microorganism content (TMC) of acid sulphate soils is, in every case, very low – between 220 and 900×10^3 cells per gram and more than an order of magnitude less than in the non-acid sulphate soils. The high values of soluble toxins such as Al^{3+}, Fe^{2+}, Mn^{2+} are probably responsible for inhibiting microorganisms in the acid sulphate soils.

As a rule, microorganisms are concentrated in the surface layer but the fallow acid sulphate soil (s2) shows a higher number of bacteria in the subsurface layer. Possibly, this is related to heating of the surface under sparse vegetation during the dry season in a tropical climate.

TMC varies significantly under different vegetation. In similar soils it is higher in cultivated soils than in fallow land, and highest under legumes like *Stylosanthes*. In cultivated soils, Al^{3+} is much less than in uncultivated soils and this may account for the richer microflora. TMC is low in the acid sulphate soil under first year pineapples (s6), compared with other cultivated acid sulphate soils, possibly because of toxic raw subsoil material brought to the surface during construction of raised beds.

Usually, soil organic matter content relates closely to TMC (Nguyen thi Thanh Phung 1977, 1982; Phan Lieu and Nguyen thi Thanh Phung 1984), but not in acid sulphate soils. In these soils, although the content of organic matter and total N is very high, soil acidity and toxic elements inhibit microorganism development. For the same reason, soil organic matter is not being mobilized into assimilable plant nutrients.

The pH has a strong effect on microorganism development. In the potential acid sulphate soil with in situ pH 4.9, TMC is higher than that in actual acid sulphate soils with pH below 3.5 (893×10^3 and 369×10^3 cells/g, respectively). In ameliorated acid sulphate soils (s3, s8, s10) with pH 3.7-4.8 TMC is higher than in unameliorated soils (s2, s5) with pH 2.2-3.4.

Microfloral structure

Bacteria generally dominate in the microflora and occupy 50-90 per cent of TMC (Table 1). But there is a special case in acid sulphate soils under *Eucalyptus*:

- s4: actinomycetes dominate all other microorganisms and occupy 82-88% of TMC;
- s5: actinomycetes, although not exceeding bacteria, occupy 38-47 per cent of TMC.

This is extraordinary. Possibly eucalyptus secretes antibiotic substances into the rhizosphere that inhibit bacteria and, perhaps, fungi but which do not affect actinomycetes to the same degree. Under other crops in acid sulphate soils, fungi are more common than actinomycetes, which is not the case in other kinds of soil where actinomycetes outnumber fungi (Nguyen thi Thanh 1977, 1982).

Physiological groups

In acid sulphate soils, the number of denitrificators varies within large limits of 10^5-10^{10} cells/g, in the surface layers up to 10^9-10^{10} cells/g, greatly exceeding the content in the non-acid soils (10^5-10^6 cells/g). It could be said that waterlogging had promoted denitrification.

Table 1 Microfloral structure $\frac{0\text{–}20\ \text{cm}}{20\text{–}40\ \text{cm}}$

Sample/location	Vegetation	Structural groups $10^3 \times$ cells/g: Bacteria	Actinom.	Fungi	TMC*	Physiological groups Cells/g: Denitrif.	Clostridium	Ammonif.	Nitrite	Nitrate	Thiobact.
$s1/l_1$	Eleocharis	$\frac{663}{148}$	$\frac{200}{13}$	$\frac{30}{0}$	$\frac{893}{161}$	$\frac{10^9}{10^5}$	$\frac{10^4}{10^2}$	$\frac{10^8}{10^5}$	$\frac{10^2}{10^1}$	$\frac{10^3}{10^2}$	$\frac{10^{10}}{10^9}$
$s2/l_2$	Myrtles and weeds	$\frac{211}{268}$	$\frac{135}{18}$	$\frac{23}{12}$	$\frac{369}{398}$	$\frac{10^{10}}{10^5}$	$\frac{10^3}{10^2}$	$\frac{10^8}{10^4}$	$\frac{10^2}{0}$	$\frac{10^2}{0}$	$\frac{10^{10}}{10^8}$
$s3/l_3$	Eleocharis	$\underline{478}$	$\underline{126}$	$\underline{161}$	$\underline{765}$	$\underline{10^6}$	$\underline{10^5}$	$\underline{10^5}$	$\underline{10^4}$	$\underline{10^4}$	$\underline{10^7}$
$s4/l_4$	3 year old Eucalyptus	$\frac{83}{10}$	$\frac{416}{75}$	$\frac{6}{0}$	$\frac{505}{85}$	$\frac{10^9}{10^{10}}$	$\frac{10^3}{10^3}$	$\frac{10^7}{10^6}$	$\frac{10^2}{0}$	$\frac{10^2}{10^1}$	$\frac{10^{10}}{10^7}$
$s5/l_2$	3 year old Eucalyptus	$\frac{236}{200}$	$\frac{161}{180}$	$\frac{23}{0}$	$\frac{420}{380}$	$\frac{10^9}{10^{10}}$	$\frac{10^3}{10^3}$	$\frac{10^7}{10^8}$	$\frac{10^2}{0}$	$\frac{10^1}{10^2}$	$\frac{10^9}{10^{10}}$
$s6/l_1$	1 year old Pineapples	$\frac{191}{35}$	$\frac{10}{0}$	$\frac{18}{13}$	$\frac{219}{48}$	$\frac{10^5}{10^5}$	$\frac{10^3}{10^2}$	$\frac{10^6}{10^5}$	$\frac{10^1}{0}$	$\frac{10^2}{0}$	$\frac{10^9}{10^9}$
$s7/l_1$	2 year old Pineapples	$\frac{310}{155}$	$\frac{1.5}{0}$	$\frac{68}{34}$	$\frac{380}{189}$	$\frac{10^5}{10^4}$	$\frac{10^4}{10^3}$	$\frac{10^7}{10^6}$	$\frac{10^2}{0}$	$\frac{10^2}{10^1}$	$\frac{10^8}{10^9}$
$s8/l_3$	3 year old Pineapples	$\underline{474}$	$\underline{120}$	$\underline{188}$	$\underline{782}$	$\underline{10^6}$	$\underline{10^5}$	$\underline{10^6}$	$\underline{10^5}$	$\underline{10^4}$	$\underline{10^6}$
$s9/l_1$	1 year old Stylosanthes	$\frac{491}{66}$	$\frac{0}{33}$	$\frac{71}{70}$	$\frac{562}{169}$	$\frac{10^6}{10^7}$	$\frac{10^5}{10^4}$	$\frac{10^8}{10^4}$	$\frac{10^3}{10^2}$	$\frac{10^3}{10^2}$	$\frac{10^7}{10^6}$
$s10/l_3$	3 year old Stylosanthes	$\underline{656}$	$\underline{181}$	$\underline{233}$	$\underline{1070}$	$\underline{10^5}$	$\underline{10^6}$	$\underline{10^6}$	$\underline{10^6}$	$\underline{10^5}$	$\underline{10^4}$
$s11/l_4$	Uncultivated	$\underline{8425}$	$\underline{422}$	$\underline{405}$	$\underline{9272}$	$\underline{10^6}$	$\underline{10^7}$	$\underline{10^7}$	$\underline{10^5}$	$\underline{10^5}$	0
$s12/l_4$	Legumes and rice	$\underline{11837}$	$\underline{801}$	$\underline{424}$	$\underline{13062}$	$\underline{10^5}$	$\underline{10^7}$	$\underline{10^7}$	$\underline{10^5}$	$\underline{10^7}$	0
$s13/l_5$	Rice	$\underline{654}$	$\underline{234}$	$\underline{186}$	$\underline{1074}$	$\underline{10^5}$	$\underline{10^5}$	$\underline{10^5}$	$\underline{10^4}$	$\underline{10^4}$	0

* TMC – Total Microorganism Content

Ammonificator content varies from 10^4 to 10^8 cells per gram in acid sulphate soils and from 10^6 to 10^7 cells per gram in other soils. Nitrite and nitrate bacteria are few in acid sulphate soils 10^1 to 10^6 cells per gram, on average 10^2 cels per gram.

Clostridium content is low in acid sulphate soils, commonly varying between 10^2-10^4 cells per gram. A relatively high value of about 10^6 cells per gram appears under *Stylosanthes*. In non-acid soils, *Clostridium* amounts to 10^7 cells per gram.

The sulfor oxidizing microorganism *Thiobacillus* was also detected. In non-acid soils, *Thiobacillus* is absent. In ameliorated acid sulphate soils (cultivated with pineapple or *stylosanthes*) the content of these microorganisms decreases with time from 10^{10} to 10^4-10^7 cells per gram. Thus, *Thiobacillus* content could be considered as a criterion for the improvement level of these soils.

Conclusions

1. Acid sulphate soils are very poor in microorganisms but the TMC is strongly influenced by cultivation regime and vegetation.
2. Low pH strongly inhibits microorganism development.
3. Bacteria are the most numerous microorganism in acid sulphate soils, except under Eucalyptus where actinomycetes represent 38-80 per cent of TMC.
4. In acid sulphate soils, there is an abundance of denitrifyers, as opposed to nitrifying and nitrogen-fixing bacteria.
5. Thiobacilli are present in acid sulphate soils and, especially, potential acid sulphate soils but decrease in ameliorated soils.

References

Dent, D.L. 1986. Acid sulphate soils: a baseline for research and development. Pub. 39, International Institute for Land Reclamation and Improvement, Wageningen

Krasilnikov, N.A. 1966. Methods of study of soil microorganisms and their metabolism. MGU Publishers, Moscow (in Russian)

Nguyen thi Thanh Phung 1977. About biological activity of some soil types of Vietnam. J. Agric. Sci. and Techn., Hanoi, 3, p. 174-180 (in Vietnamese)

Nguyen thi Thanh Phung 1982. The structure of microflora in agricultural ecosystems of Vietnam. J. Agric. Sci. and Techn., Hanoi, 7, p. 294-300 (in Vietnamese)

Phan Lieu and Nguyen thi Thanh Phung 1984. The biological activity of coastal sandy soils in Vietnam. J. Agric. Sci. and Techn., Hanoi, 2, p. 55-62 (in Vietnamese)

Silverman, M.P. 1967. Mechanism of bacterial pyrite oxidation. J. Bateriol., 4, p. 1046-1051

Leaching of acid from the topsoil of raised beds on acid sulphate soils in the Mekong delta of Vietnam

Geert Sterk

Department of Water Resources, Wageningen Agricultural University, The Netherlands

Abstract

Flooding forces farmers in the Mekong delta to make raised beds for dryland crops. On acid sulphate soils, both potential and actual acid material may be placed on the bed during construction (traditional method). The acidity is toxic to plants. Research was done on three raised beds to determine the process of leaching of acid from the topsoil by rainfall. Rainfall simulations on large soil columns showed that bypass flow is an important process in the distribution of rainfall in the topsoil at the start of the rainy season. The quantity of acid which is leached out with the bypass flow is highest when the bed is newly constructed, and is decreases rapidly with age. After seven years, hardly any acid is leached out. Contrary to the leaching efficiency, the acid content in the topsoil is not decreasing. It is concluded that the remaining acid is strongly bound to the clay minerals in the form of exchangeable aluminium and not soluble in the soil moisture in the pores, because crop growth is possible after a few years.

Introduction

In the Mekong delta of Vietnam are an estimated 1.6 million hectares of acid sulphate soils. Large parts of this area are flooded yearly during the rainy season. Therefore, raised beds are commonly used for growing dryland crops. By constructing a raised bed on an acid sulphate soil, both acid and potential acid material is placed on top of the bed (traditional method), or in the middle of the bed (new method), see Figure 1. Here only the first type of beds is considered. Before crops can be grown on traditionally constructed raised beds, the acidity, traditionally-constructed, has to be leached out from the topsoil.

In the heavy-textured topsoil, shrinkage cracks will be formed during the dry season. At the start of the rainy season these cracks will induce bypass flow, which is defined as vertical flow of free water through macropores in an unsaturated soil matrix (Bouma 1986). Bypass flow is an important process in the distribution of rainfall in the topsoil and, probably, the main mechanism of leaching. Research was done to quantify the process of leaching of acid from the topsoil of traditionally constructed raised beds. Changes in the leaching efficiency and the acid content of the topsoil were also evaluated.

Methods

For the experiments, three raised beds were chosen at the Hoa An field station of

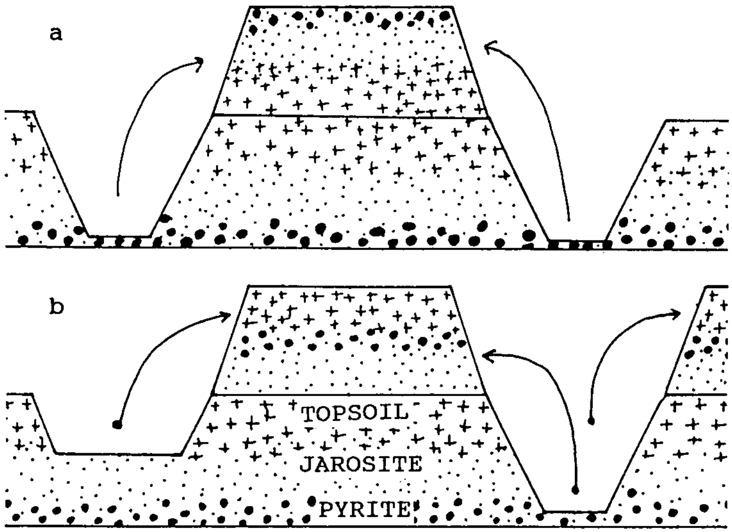


Figure 1 Construction methods for raised beds in the Mekong Delta; a) traditional method, and b) new method

the University of Can Tho (central Mekong delta). The ages of the raised beds were 3 months (A), 1 year (B), and 7 years (C). The youngest bed was constructed on a Sulfic Tropaquept, while the older beds were situated in an area with mainly Sulfaquepts (Soil Survey Staff 1975). Cracks were divided into three groups: large cracks (> 1.0 cm width), medium cracks (0.2 to 1.0 cm width) and small or no cracks (< 0.2 cm). This division is based on the cracks that could be distinguished at the soil surface. For each group, the surface area on the raised bed was estimated.

Just before the start of the 1991 rainy season, three groups of three large soil columns (20 cm diameter and 25 cm depth) were sampled from the topsoil of the raised beds.

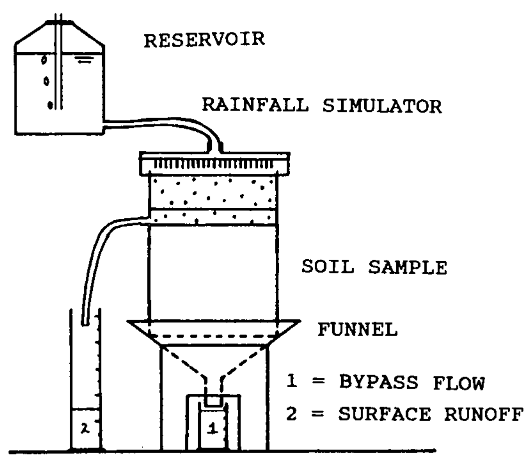


Figure 2 Apparatus

Each sample represented a different crack pattern. By means of a small rainfall simulator, a short-duration, high-intensity shower (36.3 mm in 30 min) was added to the soil in the columns. The measurement of bypass flow (Bp) was according to Bouma et al. (1981), see Figure 2. Bypass flow and surface runoff (Sr) were measured directly. Aggregate infiltration (I) was obtained by measuring the moisture in the soil samples before and after rainfall addition. After two days, the experiments were repeated. The changes in leaching efficiency with time were determined by measuring the total acidity (Ta) in the bypass flow from the soil columns. The development of acid content with age in the topsoil was determined by measuring extractable acidity (Ea) which is the amount of acid ions extracted from the soil with a 1 M KCl solution, at two depths, 0-3 and 12-15 cm. Total and extractable acidity were determined by titration.

Results and discussion

Table 1 shows the division of the surface area into crack patterns and the corresponding samples for the three raised beds. On the youngest bed (A) no division was possible because cracks varying in width from small (< 0.2 cm) to large (> 1.0 cm) covered the whole surface. These cracks were not shrinkage cracks, but voids between the clods that were excavated during construction of the bed. Therefore, the three samples were taken at random from this bed.

The results of the rainfall experiments are given in Table 2. During the first rainfall

Table 1 Division of the surface area of the raised beds according to crack patterns

Raised bed	Large cracks (> 1.0 cm)		Medium cracks (0.2 – 1.0 cm)		Small or no cracks (< 0.2 cm)	
	Area	Sample	Area	Sample	Area	Sample
A *)	–	–	–	–	–	–
B	20%	B1	25%	B2	55%	B3
C	0%	–	15%	C1	85%	C2,C3

*) no division possible; A1, A2, and A3 were randomly taken

Table 2 Results of the rainfall experiments

Sample	First shower			Second shower		
	I (mm)	Bp (mm)	Sr (mm)	I (mm)	Bp (mm)	Sr (mm)
A1	19.7	16.6	0	7.3	29.0	0
A2	19.0	17.3	0	6.5	29.8	0
A3	20.0	16.3	0	8.9	27.4	0
B1	3.2	33.1	0	3.0	33.3	0
B2	5.7	30.6	0	5.5	30.8	0
B3	7.5	28.3 *	0.5	4.1	15.2	17.0
C1	2.8	33.5	0	3.8	32.5	0
C2	3.8	4.7	27.7	4.7	8.1	23.5
C3	13.0	20.0	3.3	7.7	23.6	5.0

* value is too high because of unreal bypass flow

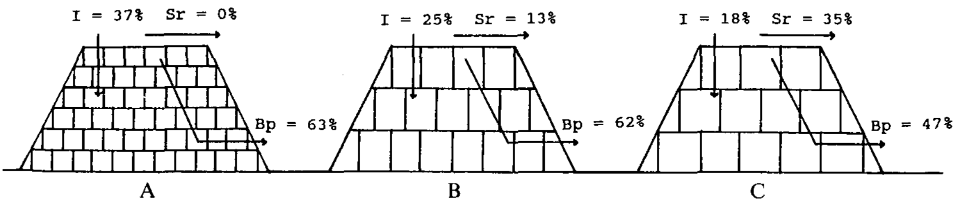


Figure 3 Distribution of rainfall in the topsoil of three raised beds.

experiment (sample B3) water was seen to flow between the soil and the tube. This resulted in too much bypass flow. Before continuing the experiments, some pure kaolinite clay was put into the opening between the soil and the tubes of all the samples, in order to prevent water flowing along the tube.

From these results and the division of the surface area in crack patterns (Table 1) the distribution of rainfall from two showers in the topsoil of the three raised beds was calculated. Figure 3 shows the results. The structure of the soil is schematized by blocks.

Bypass flow and aggregate infiltration are of decreasing importance with increasing age of the bed. Consequently, more precipitation is lost to surface runoff on older beds. This alteration is caused by a loss of structure in the topsoil. A few years after construction the soil becomes more compacted and the number of cracks declines.

The total acidity in the bypass flow from the soil samples is shown in Table 3. The amount of acid leached out with bypass flow declines quickly with the age of the bed. From the oldest bed, hardly any acid is leached out.

The total acidity in the bypass flow from the A samples consisted for 55 per cent of aluminium (Al^{3+}), whereas this value increased to 77 per cent for the B samples. For the C samples it may even be higher, but this could not be concluded because of inaccuracies in the measurements.

When the pH in the soil drops to a value less than 4.5, aluminium becomes increasingly soluble. Under strong evaporative conditions, like in the topsoil of raised beds during the dry season, the soluble Al^{3+} ions precipitate at the surface of aggregates as water-soluble aluminium sulphates (Van Breemen and Pons 1978). These alumi-

Table 3 Total acidities, in mmol (+) per sample, in the bypass flow from the soil columns

Sample	First shower		Second shower	
	Bp (1)	Ta mmol(+)	B (1)	Ta mmol(+)
A1	0.47	3.91	0.82	7.18
A2	0.49	5.26	0.85	6.17
A3	0.46	4.37	0.78	5.54
B1	0.94	0.87	0.94	1.22
B2	0.87	1.48	0.87	1.95
B3	0.80	4.04*	0.43	1.55
C1	0.95	0.23	0.92	0.34
C2	0.13	0.08	0.23	0.21
C3	0.57	0.58	0.67	0.90

* value is too high because of too much bypass flow

Table 4 Extractable acid in the topsoil of the three raised beds

Layer in cm	Ea, mmol(+)/100 g dry soil)								
	A1	A2	A3	B1	B2	B3	C1	C2	C3
0-3	10.25	12.44	12.27	18.46	17.13	18.35	18.06	16.26	16.85
12-15	11.87	10.88	11.81	18.06	18.17	18.35	15.74	17.83	17.08
Average	11.06	11.66	12.04	18.26	17.65	18.35	16.90	17.05	16.97

nium salts are easily dissolved and leached out from the topsoil when water is flowing through the macropores and cracks.

Table 4 shows the extractable acidities in the topsoil of the raised beds. It is remarkable that there is much more extractable acid in the older beds, while it was expected that the amount would be highest for the youngest bed, and slowly decreasing with age of the bed.

Two explanations are possible. Firstly, it is possible that the youngest bed was constructed at a location where the pyrite content was somewhat lower than in the surroundings (Hanhart, pers. comm.). Secondly, not all pyrite in the topsoil may have been oxidised at the moment of sampling. Oxidation of pyrite by oxygen is a slow process. Pyrite is much faster oxidised by Fe^{3+} ions (Van Breemen 1976). For this second type of oxidation it is necessary that the Fe^{3+} ions diffuse to the pyrite in the core of the peds. Since the bed was constructed at the start of the dry season, much of the soil solution was lost by evaporation. Diffusion of Fe^{3+} through the dry soil was hampered and pyrite was slowly further oxidised by oxygen. This second explanation is believed to be the main reason for the lower acid content in the topsoil of the youngest raised bed. Even if there was less pyrite at this location, it is plausible that it was not completely oxidised at the moment of sampling (about 100 days after construction).

Measurements showed that approximately 70 per cent of the extractable acidity consisted of aluminium (Al^{3+}). Dissolved Al^{3+} is toxic to plants. However, during the experiments, pineapple and banana grew well on the seven years old bed, and on the one year old bed young Eucalyptus trees were growing. Obviously, conditions for plant growth are acceptable when the aluminium is no longer present in soluble form in the soil moisture.

Table 5 shows calculated values per square metre of raised bed of both extractable acidity in the topsoil (0-22 cm) and the amounts of acid leached out from the topsoil with the bypass flow. The results show clearly that, although the leaching efficiency decreases sharply after a few years, the acid content of the soil remains high.

Table 5 Amount of acid leached out from the topsoil (0-22 cm) compared with remaining acid in the topsoil

Raised bed	Ea mol(+) m^{-2}	Ta mol(+)m^{-2}	
		1st shower	2nd shower
A	25.8	0.144	0.201
B	40.4	0.045	0.051
C	39.4	0.010	0.017

Conclusions

The leaching of acid from the topsoil of raised beds is mainly caused by bypass flow through cracks and other macropores. Leaching by matrix flow is very slow because of a low permeability of the soil matrix. Due to a loss of structure, the number of cracks in the topsoil of traditionally-constructed raised beds decreases with age of the bed. Consequently, the amount of bypass flow decreases, and more rainfall is lost to surface runoff.

The leaching efficiency decreases sharply with age of the bed. Seven years after construction, hardly any acid is leached out from the topsoil but the acid content in the topsoil does not show a sharp decrease. About 70 per cent of this remaining acid is aluminium, which is not soluble in the soil moisture but is bound to the clay minerals.

Acknowledgement

This research was carried out in the framework of the EEC STD2 Project 'Mise en valeur des sols acides du delta Mekong'.

References

Bouma, J., L.W. Dekker, and C.J. Muilwijk 1981. A field method for determining short-circuiting in clay soils. J. Hydrol., 52, 347-354

Bouma, J. 1986. Using morphological data for the simulation of water regimes in clay soils. In: Dost, H. (editor) 1986. Selected papers of the Dakar symposium on acid sulphate soils. International Institute for Land Reclamation and Improvement Publication No. 44, Wageningen

Breemen, N. van 1976. Genesis and solution chemistry of acid sulphate soils in Thailand. Agric. Res. Rep. (Versl. Landbouwk. Onderz.) 848, PUDOC, Wageningen

Breemen, N. van and L.J. Pons 1978. Acid sulphate soils and rice. In: IRRI, 1978. Soils and Rice, Los Baños, Philippines

Soil Survey Staff 1975. Soil Taxonomy: a basic system of soil classification for making and interpreting soil surveys. Agriculture handb. 436. U.S. Government Printing Office, Washington D.C.

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

M. Sylla[1], N. van Breemen[2], L.O. Fresco[2], C. Dixon[3] and A. Stein[2]

[1] Institut Sénégalais de Recherches Agricoles, Djibelor, P.O.Box 34 Ziguinchor, Sénégal
[2] Wageningen Agricultural University, Soil Science and Geology Department, P.O.Box 37, 6700 AA Wageningen, The Netherlands
[3] West Africa Rice Development Association Rokupr, Sierra Leone

Abstract

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

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

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

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

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

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

Introduction

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

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

Materials and methods

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

Site selection

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

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

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

Site characterization

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

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

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

Agronomic trials

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

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

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

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

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

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

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

Results

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

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

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

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

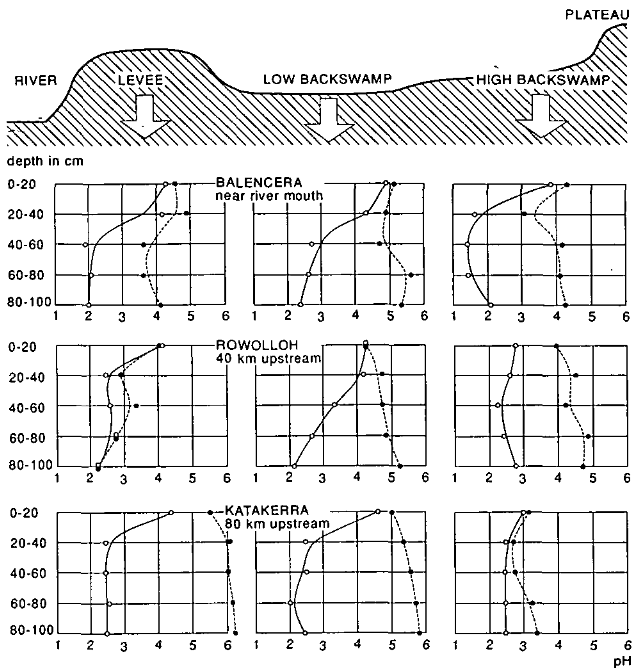


Figure 1 pH of the fresh soil (pecked lines) and pH after incubation (solid lines) along transects at each of the three sites

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

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

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

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

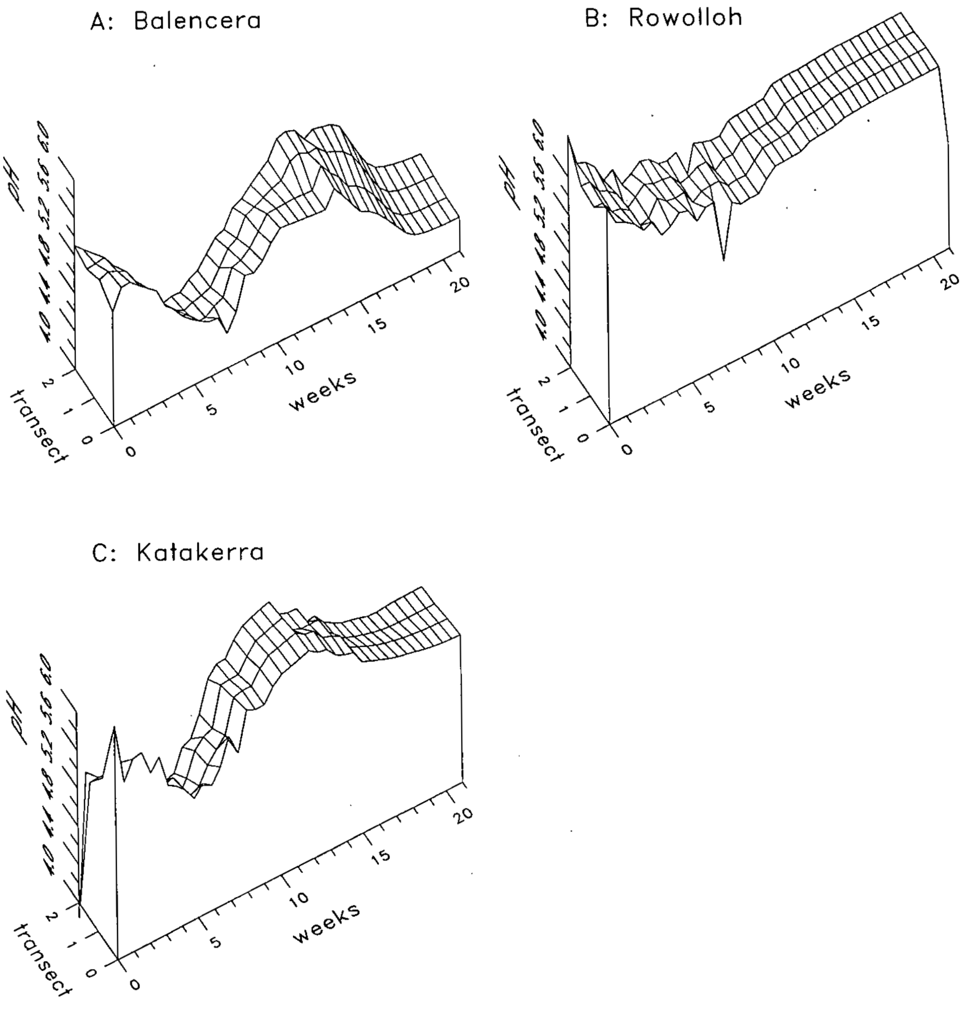


Figure 2 Temporal and spatial variability of pH of the soil solution at 0-25 cm depth in each of the three sites. Along each transect, 0 refers to the river levee, 1 to the low backswamp, and 2 to the high backswamp. Time is weeks after the start of monitoring

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

Results of the agronomic trials

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

T5> or = T4> T3> T2> or = T1 >T0.

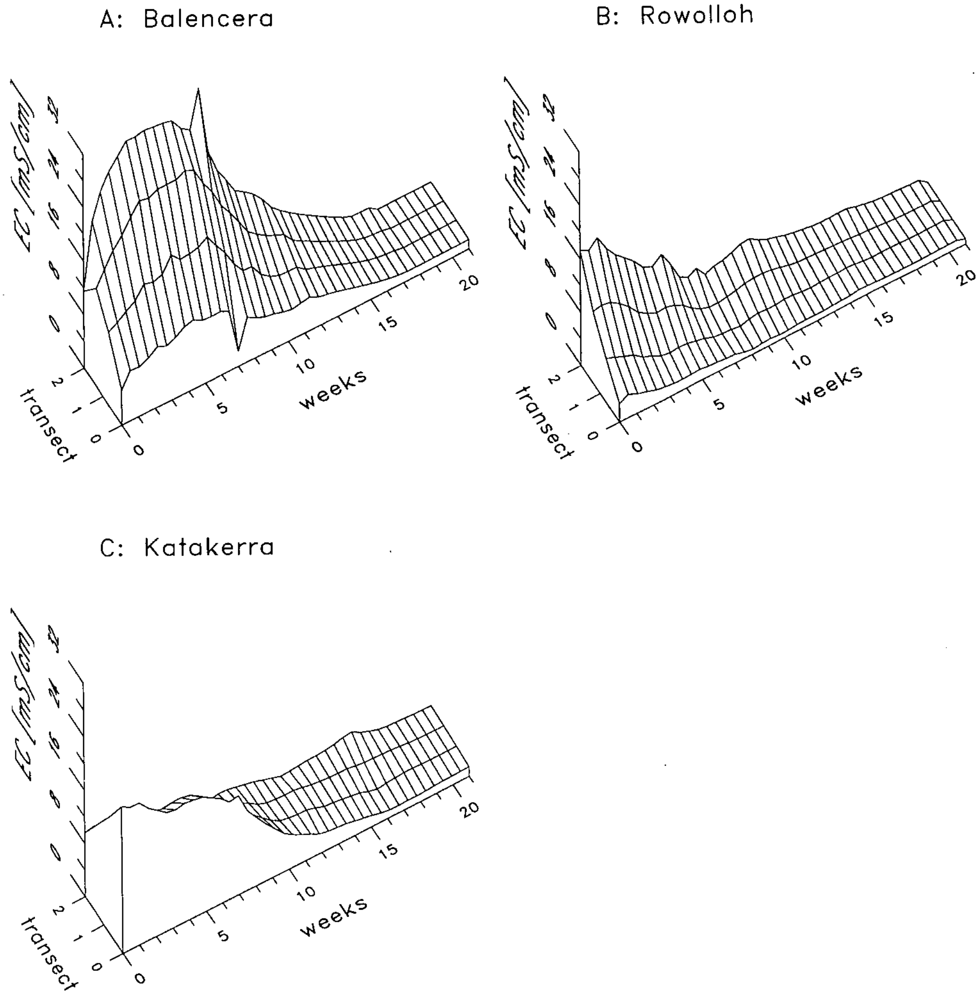


Figure 3 Temporal and spatial variability of salinity (expressed as electrical conductivity) of the soil solution sampled at 0-25 cm depth in each of the three sites. For explanation see Figure 2

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.

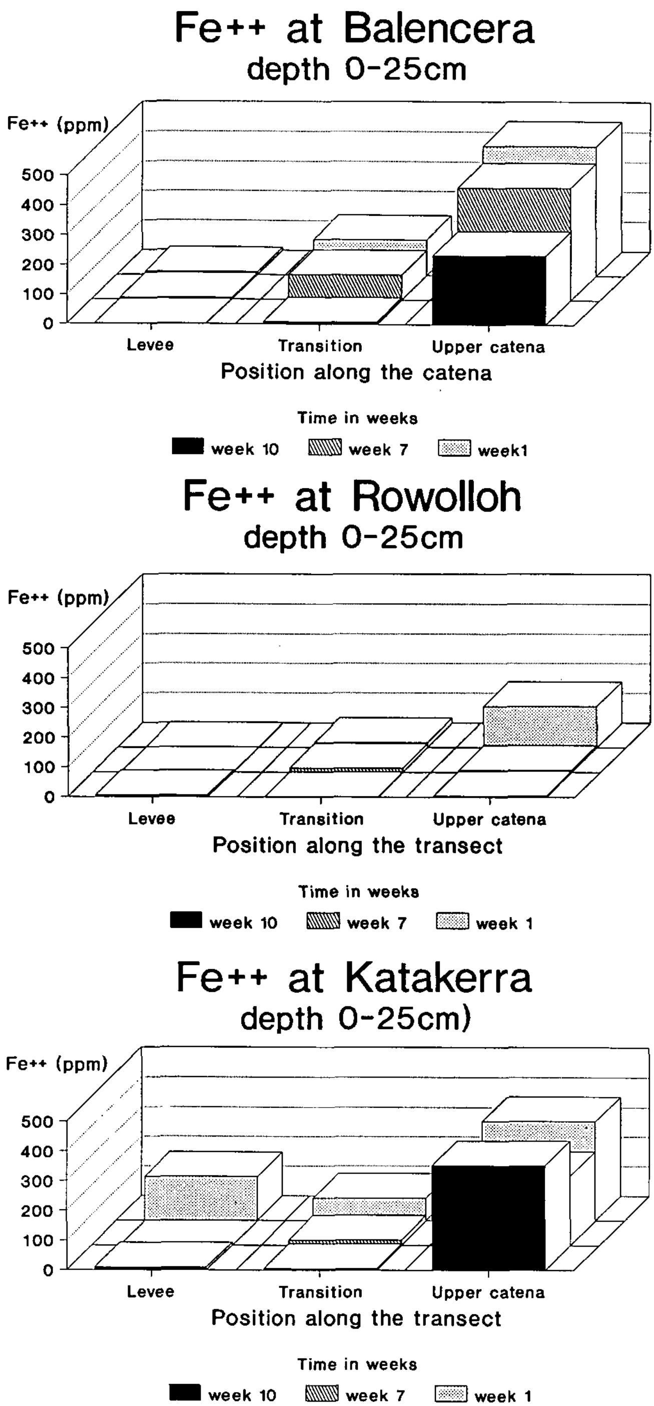
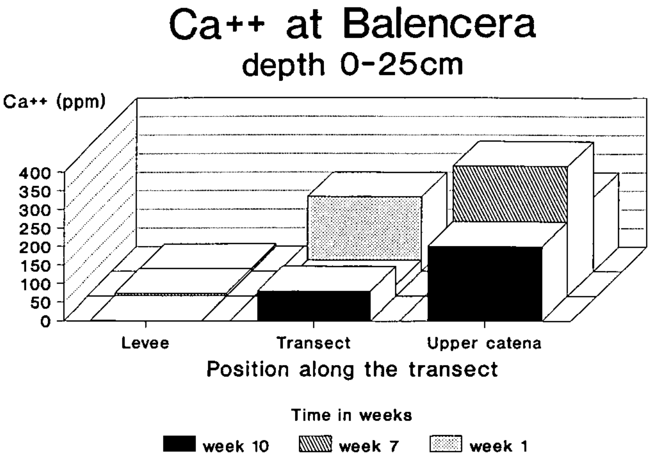
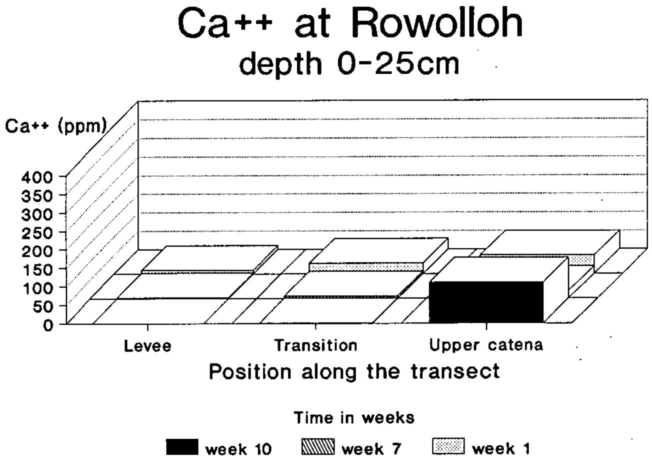


Figure 4 Concentrations of dissolved Fe^{2+} at 0-25 cm depth in each of the three sites, as a function of position in catena, at 1, 7 and 10 weeks after the start of monitoring





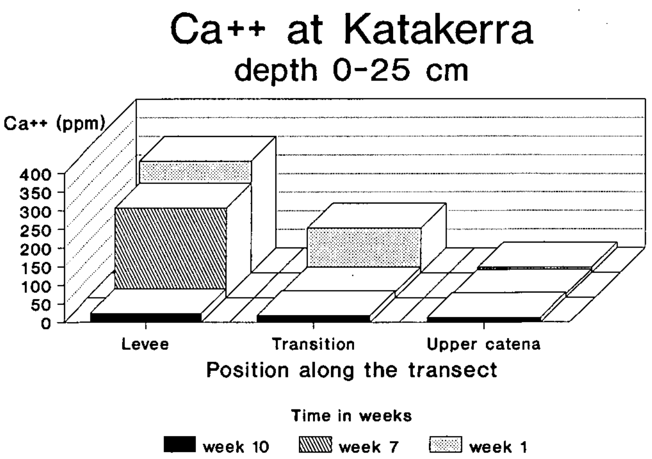


Figure 5 Concentrations of dissolved Ca^{2+} at 0-25 cm depth in each of the three sites, as a function of position in catena, at 1, 7 and 10 weeks after the start of monitoring

Table 2 Soil treatments and environmental effects on rice yield

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

References

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

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

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

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

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

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

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

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

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

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

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

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

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

Effect of fluoride on aluminium tocixity in rice

Tang Van Hai and B. van Parijs

Unité des Sciences du Sol, Université Catholique de Louvain, Place Croix du Sud, 2,
B. 1348 Louvain-la-Neuve, Belgium

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.

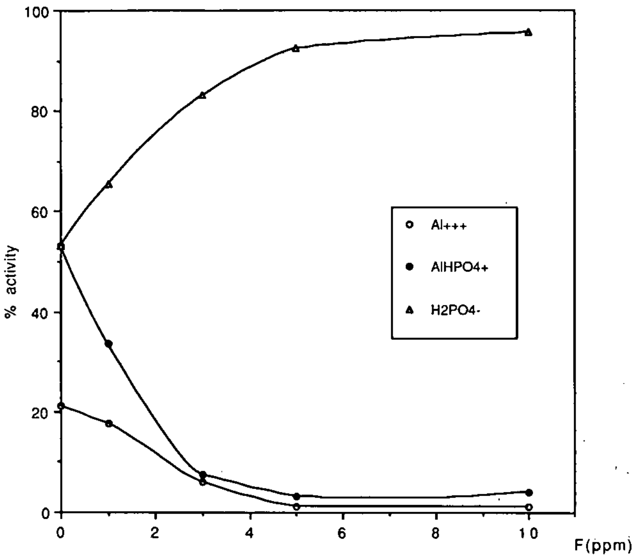


Figure 1 Evolution of relative activities (%) of Al^{3+}, $AlHPO_4^+$ and $H_2PO_4^-$ as a function of F^-concentration in nutrient solution with 5 ppm Al.

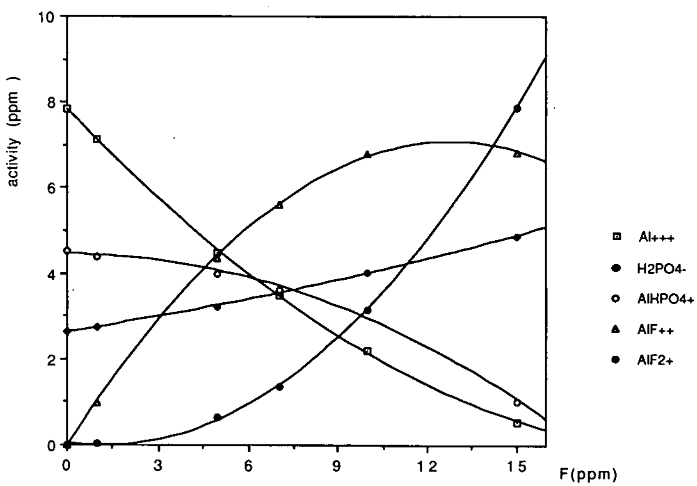


Figure 2 Evolution of the activities (ppm) of Al^{3+}, $H_2PO_4^-$, $AlHPO_4^+$, AlF^{2+} and AlF_2^+ as a function of F concentration in nutrient solution with 20 ppm Al.

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.

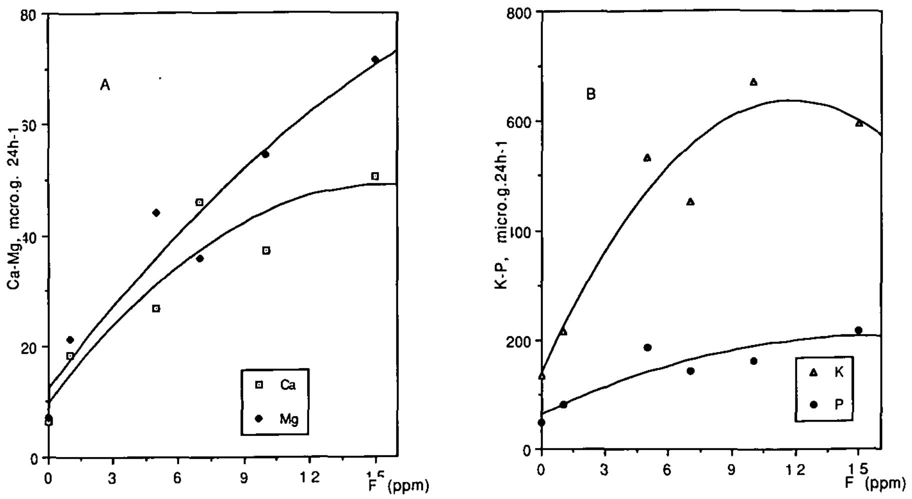


Figure 3 Evolution of the absorption of Ca, Mg (A) and K, P, (B) in µg during 24 hours by 5 plants as a function of F concentration for a nutrient solution with 20 ppm Al.

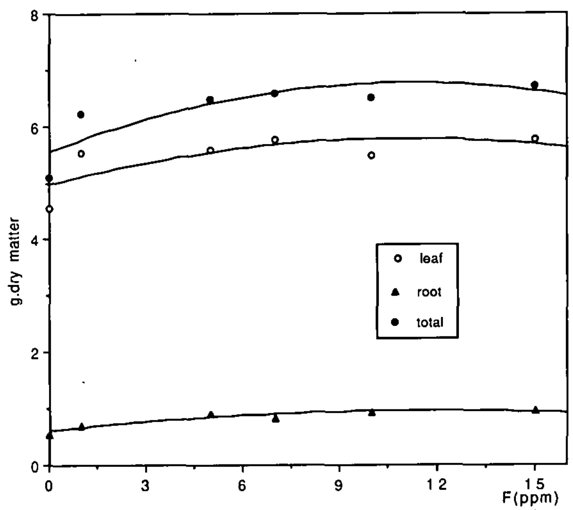


Figure 4 Evolution of dry matter (measured after 50 days) as a function of F^- concentration in nutrient solution with 20 ppm Al.

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).

References

Léon, L.A., W.E. Fenster and L.L. Hammond 1986. Agronomic potential of eleven phosphate rocks from Brazil, Colombia, Peru and Venezuela. Soil Sci. Soc. Am. J.50, 798-802

Lindsay, W.L. 1979. Chemical equilibria in soils. Wiley, New York

Ritchie, G.S.P., R.C. Cameron and C. Moore 1986. Aluminium toxicity to barley in the presence of fluoride ions. XIIIème Congrès Ass. Int. Science du Sol

Tang Van Hai, Truong Thi Nga and H. Laudelout 1989. Effect of aluminium on the mineral nutrition of rice. Plant and Soil 114, 173-185

An overview of water management of acid sulphate soils

To Phuc Tuong

IRRI, P.O. Box 933, Manila, The Philippines

Abstract

The paper addresses the issue whether water management is the key and the only practical way to reclaim and ameliorate a large area of acid sulphate soils. It reviews recent developments in water management practices with special emphasis on leaching, flushing and deacidification measures. Their success and failure is related to the critical role of water and its movement in initiating chemical and physical processes in the soil. Therefore, the choice of suitable practices depends strongly on the surrounding hydrological conditions of the environment and the physical properties of the soil. Labour, the amount of water needed, and possible environmental consequences may pose severe limitations to the application of water management measures for reclamation on a large scale.

Introduction

In most cases, severe acidity and the large areas of land involved prohibit reclamation of acid sulphate soils by chemicals (e.g. liming) because of the high costs. Appropriate water management has been identified by several authors (Dent 1986, Sen 1988a) as the only practical way to manage these soils. Water management is imperative because most acid sulphate soils are in extreme and hostile hydrological conditions, such as waterlogging during the rainy season and lacking water in the dry season. It is not surprising that many water control measures have been tried out by farmers, governmental and private agencies as one of the first steps in the process of reclamation. Their efforts have met with both success and failure, and it is not uncommon that mistakes have been repeated. This is an indication of the poor distribution of available knowledge on the reclamation of acid sulphate soils.

The purpose of this paper is to give a review of recent developments in water management in Southeast Asia and elsewhere in the world with special emphasis on (i) watertable management, (ii) surface water management and (iii) leaching, and on the analysis of their interaction and adaptability to different hydrological, environmental conditions and the soil physical properties.

Watertable management

Optimum watertable level

Detrimental effects of pyrite oxidation by lowering the watertable in coastal potential acid sulphate soils on crop yields were reported by Beye (1973), Kanapathy (1973), and Yin and Chin (1982). Such studies led to one of the general recommendations for management of potential acid sulphate soils: controlled high watertable to keep the sulphidic subsoil waterlogged (Dent 1986) and, hence, prevent acid formation.

This recommendation puts emphasis on the role of water in controlling the chemical processes in acid sulphate soils. Water is also a medium of transport of toxicities and nutrients in the soils. Watertable management should also be analyzed in its relation to evaporation by which toxins accumulate in the surface horizon through upward flux of solutes during a dry period. This is of particular importance in areas with a long dry season and with bad groundwater quality. Any attempt to check the oxidation of pyrite by keeping the watertable high is counteracted by an increased evaporation and transport of acidity to the surface horizon. Keeping the watertable high does not necessarily reduce the toxicities at the rootzone. Sen (1988b) reported that, regardless of the watertable levels, the average total acidity and pH over the upper 30 cm of potential acid sulphate soil columns did not show much variation (Table 1) though lower watertables enhanced the oxidation of pyritic materials.

Where the sulphidic horizon occurs near the surface, high watertable will impede leaching of the accumulated salts, the workability of the soils and reduce the aerated zone for root development of upland crops. This might be the reason for yield difference, as reported by Dent (1986), of about 8 t ha^{-1} of oil palm on normal, non-acid soils and on acid sulphate soils with high watertable management at 0.6 m.

For actual acid sulphate soils, few data exist on the effects of keeping the watertable above the oxidized horizon. Theoretically, there can be no further deterioration of soil properties resulting from exposure of a completely oxidized sulphuric horizon to the air because oxidation of pyrite has been completed. Konsten et al. (1990a) in Kalimantan detected no signs of further acidification when the watertable dropped and exposed the sulphuric horizon of acid sulphate soils to the air during the dry

Table 1 Averaged pH, EC, total acidity of the first 30 cm in the profile of different soil columns after different groundwater level treatments (Sen 1988b)

Column number	Groundwater level (cm)	pH	EC (mS/cm^{-1})	Average total acidity ($mol\ m^{-3}$)
1	65	4.05	0.95	0.75
2	65	3.90	1.05	0.89
3	–	3.92	0.76	0.38
4	65	4.00	1.15	0.99
5	40	3.59	1.24	1.27
6	65	3.49	1.16	1.19
7	40	3.54	1.08	1.13
8	65	3.51	1.36	1.77
9	65	3.31	1.50	5.57
10	65	3.10	1.98	13.88
11	40	3.37	1.26	2.94
12*	–	3.64	0.64	0.79
13	40	3.79	1.14	0.83
14	65	3.62	1.08	1.04

* control column

Table 2 Changes in chemical properties of the top soil layer of an actual acid sulphate soil due to capillary rise from different watertable depths (Tuong et al. 1993)

Water table depth (cm)	pH		Soluble acidity (cmol kg^{-1})[a]		Soluble Al^{3+} (cmol kg^{-1})[a]	
	(1)	(2)	(1)	(2)	(1)	(2)
30	3.6	3.4	12	46	13	24
60	3.1	3.1	15	51	11	22
90	3.5	3.5	13	35	7	11

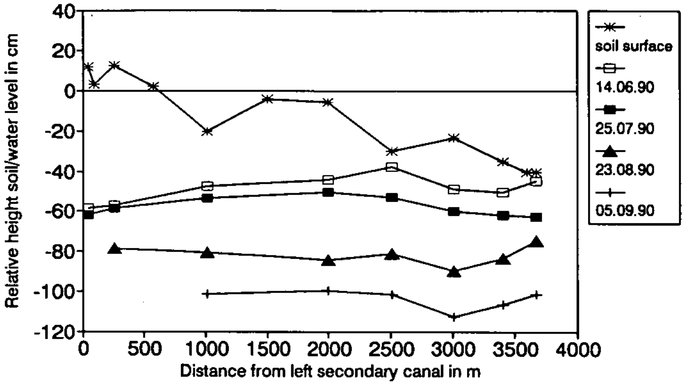
(1) initial value
(2) 90 days after start of the study
[a] Soluble acidity and Al^{3+} measured in saturation extracts

season. Likewise, not much will be gained by keeping the watertable high in these 'mature' soils because submergence of the jarosite layer is not followed by a lowering of the redox potential or an increase in pH (van Breemen 1976, Danh 1991). This is due to low content of organic matter and the extremely acid conditions in which iron-reducing bacteria are absent. In these soils, a deep watertable is recommended because it reduces capillary rise from the groundwater and the accumulation of acid salts at the top soil horizon as illustrated in Table 2. In practice, tangerine farmers in Nakorn Nayok province, Thailand, keep watertable levels at more than 1.5 metres in an acid sulphate soil where the jarosite layers start at 60 cm (Charoen and Maneewon 1989). Keeping watertable low is particularly important to avoid the upward transport of acid water to the rootzone when there is bad quality groundwater influx from surrounding areas (Kselik 1990).

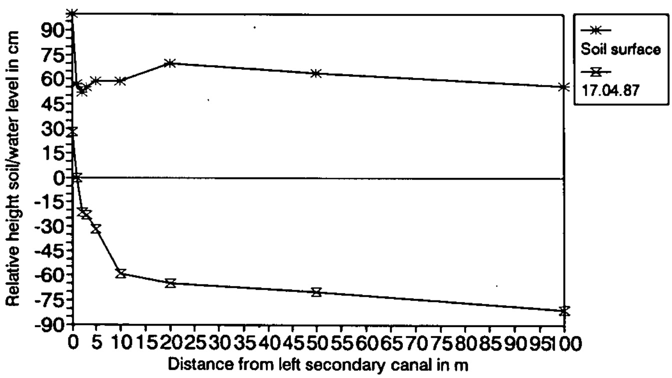
In recently-oxidized acid sulphate soils, pyrite may still exist in the inner cores of the soil peds of the sulphuric horizon and may be oxidized if the watertable drops for an appreciable time. This may be the reason for Xuan's recommendation (1987) that both the sulphidic and sulphuric horizons should be kept in submerged conditions. The determination of optimum water level in these soils requires further research to find an optimum balance between the rate of acidification and rate of toxicity accumulation on the surface layers.

Practical difficulties in watertable management

The success of a high watertable strategy for potential acid sulphate soils has been demonstrated for oil palm by Yin and Chin (1982) and for grassland in North Western Europe and New Zealand (Dent 1986). It is, however, important to recognize the practical difficulties in maintaining the watertable at the desired depths on a large scale. One of them is the spatial variation in depths of the sulphidic and sulphuric horizons. Sometimes they vary greatly at distances less than 50 m (e.g. Burrough et al. 1988). To be effective in preventing oxidation of pyrite, the watertable has to be kept at different levels at different parts of a water management scheme. This may complicate the management of the system to an impracticable level on a large scale. It is imperative to have detailed maps of depths of these diagnostic horizons and to plan and operate the hydraulic components accordingly. In most cases of opening up new areas, these maps are not available.



a) Groundwater fluctuation Transect 3 Belawang, South Kalimantan, Indonesia (Hamming et al. 1990)



b) Groundwater profile of a Transect Go Cong, Mekong Delta, Vietnam (Tuong et al. 1988)

Figure 1 Groundwater profiles in acid sulphate soil areas in Indonesia and Vietnam

Another difficulty is associated with the required density of canal networks to be compatible with the hydraulic conductivities (K), the transmissivity (T) of the soils and the climate. Watertable in areas with fairly high K and T can be controlled by manipulation of water level in the drainage canals spaced at reasonable distances. Such a situation prevails in South Kalimantan, Indonesia, where T is reported to be in order of hundreds of metres per day (Hamming et al. 1990) and as a consequence watertable varied only about 20 cm over a distance of few kilometres between the two main drainage canals (Figure 1a). Watertable cannot be controlled with the same ease in situations, like in Vietnam, where a long dry season exists and the hydraulic conductivity is in the order of 0.1 m day^{-1} (Thuan 1989). Results from a simulation run by Thuan indicated that the general groundwater level in the Plain of Reeds, Vietnam, at the end of the dry season is not affected by the provision of drainage canals at 200 m intervals. Field measurements (Tuong et al. 1988) showed that the groundwater level at the end of the dry season dropped sharply at the first 10 metres away from the canal, and steadily decreased with the distance away from the canal (Figure 1b). Obviously, high evaporative demand over a long dry season created a loss of water through capillary rise which was not adequately compensated by recharge from the surrounding canals through slowly-permeable soil. In this situation, if the water-table is to be controlled by canals, very dense networks at distances less than 20 m will be needed. High labour requirements would discourage such a solution on a large scale.

Surface water management

The rate of reduction in acid sulphate surface soils is known to be slow (Ponnamperuma et al. 1973, Van Breemen 1976). This is particularly true for ripe acid sulphate soils as further evidenced by recent experiments. Ritsema et al. (1991) indicated no spectacular pH effects for actual acid sulphate soils during prolonged submergence. Satawathananont et al. (1991) reported (Figure 2) no appreciable reduction in soluble aluminum after 6 months of submergence in two out of three ripe acid sulphate soils. Obviously, from the soil amelioration point of view, keeping these ripe soils under submergence is not a necessary measure, though the presence of the surface water will help suppress the capillary rise of toxicities to the rootzone.

In raw acid sulphate soils, surface layers are often rich in organic matter and iron. Reduction is much faster but prolonged submergence will not necessarily reduce water soluble Al concentration to a non-toxic level, even though the pH may have increased to higher than 4.4 (Satawathananont et al. 1991). It is commonly observed in raw acid sulphate soils that rice plants in the higher spots of waterlogged fields perform better than those in continuously-submerged locations. This may be attributed to 'side effects' of submergence: increase in dissolved iron II and/or H_2S and the acidification of the surface water (Van Breemen 1976). Hanhart and Ni (1991) proposed a compromise of intermittent drainage. They found that rice grown under intermittent drainage had healthier root systems, less empty grains, heavier weight per panicle. Rice in continuous submergence showed strong bronzing symptoms but had more tillers

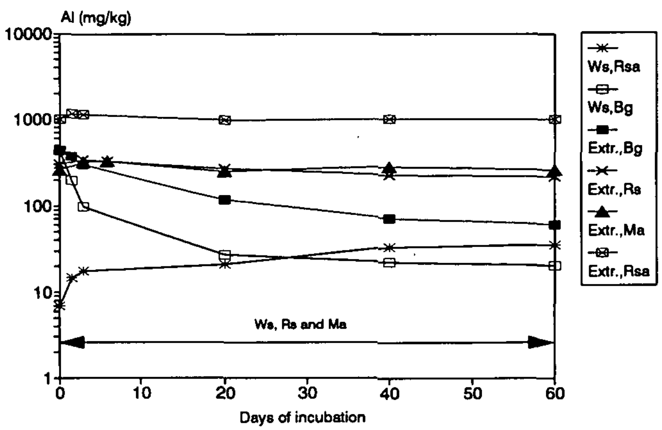


Figure 2 Changes of water-soluble and extractable Al with time in stirred suspensions of four acid sulphate soils under incubation in a closed system. Ma, Rs, Rsa are ripe acid sulphate soils. Bg is pre-oxidized potential acid sulphate soil (data from Satawathananont et al 1991)

Table 3 Plant development and yield of rice grown on a severe acid sulphate soil in Hoa An, under continuous submergence (Ic) and with wet/dry cycles (Ii). (Data from Hanhart and Ni 1991).

Treatment	Plant height at day 48, cm	Tiller number at day 48 per 0.45 m^2	Yield, ton ha^{-1}	Weight per panicle,	Empty grains, per cent
Ii	34.4*	200*	3.8	0.532	9.4*
Ic	39.5*	234*	3.6	0.453	14.3*

(Note: The values indicated by * are significantly different at a 0.05% interval)

(Table 3). Further research is needed to arrive at an optimum surface water management strategy for these raw acid sulphate soils.

Leaching

Positive effects of leaching of acid sulphate soils have been reported Ponnamperuma et al. (1973), Kivinen (1950), van Breemen (1976). However, most early studies were carried out in small, homogenized samples or in small pots where the water flow pattern and soil physical properties were greatly modified as compared to the real field conditions. This is unfortunate, because the rate of leaching and therefore its field applicability depend on those properties.

Undisturbed soil core and field experiments indicate that leaching of acid sulphate soils is a slow and water-demanding process. Table 4 gives a summary of findings on leaching of aluminum in the top 25 cm of undisturbed soil samples. Aluminum is chosen because it is likely to be the principal hazard for agricultural crops and can become toxic at concentration as low as 2 ppm in the solution (Dent 1986). Leaching aluminum from undisturbed soils is particularly difficult. Even one metre of water was not adequate to bring the aluminum concentration of the rootzone to a safe level for plant growth.

Field evidence indicates that leaching of undisturbed soils is not only a slow process but is limited to a fringe of about 10 m along the drainage canals where there is inadequate exchange of water between the canal and the soil body (Figure 3). The limited

Table 4 Effects of leaching on aluminum concentration in soil solution at depths 20-25 cm of undisturbed severe acid sulphate soils by various authors

Authors	Days of leaching	Water used cm	Al^{3+} in soil solution at depth 20-25 cm: Before leaching mmol(+) l^{-1}	After leaching mmol(+) l^{-1}
Sen 1988a	30	100-450	33	6-18
Tuong et al. 1993	15	500	10	4.5
	30	1300	10	4.5
SIWRR 1990	63	450	9.3	2.5
Konsten et al. 1991	200	> 1000	> 20	App. 2

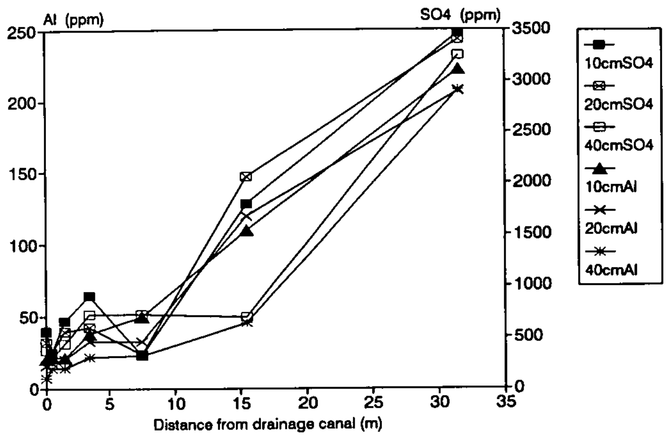


Figure 3 Variation of Al and SO_4^{2-} in soil solution at three different depths as function of distance from a drainage canal in the acid sulphate soil area of Cu Chi, Vietnam

effects of leaching and flushing of undisturbed soil in the field are also shown in Figure 4, which presents pH of the surface water of a fish pond in acid sulphate soil area at Cu Chi, Ho Chi Minh City, after a six-month effort of leaching with nearly neutral water at a rate of 20 mm day^{-1}. A large area in the middle of the pond, with pH lower than 3.5, appeared not to be affected by the leaching process. The findings help explain why areas subjected to annual overland flooding, like the Plain of Reeds, remain acidic for years.

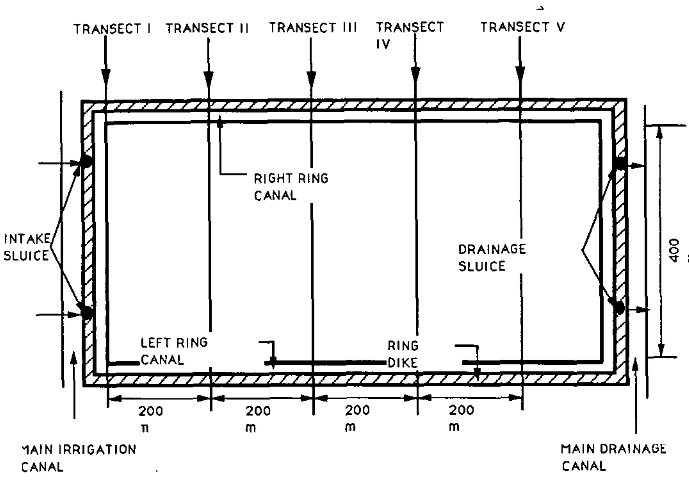
Konsten et al. (1990b) also reported slow leaching under natural conditions in Pulau Petak, Kalimantan where annual rainfall is about 2300 mm. They estimated that the annual leaching amounted to 1.3 per cent of the total acidity present in the upper 65 cm. At this rate it will take at least 80 years to get rid of the all acidity. In poorer drained areas it may take longer.

Some processes during leaching

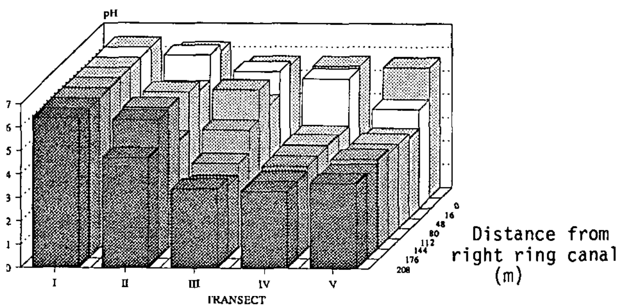
One of the reasons for the persistence of aluminum in the soil solution during the leaching process is that a portion of the aluminum in the soil complex is slowly released into the solution (SIWRR 1990, Konsten et al. 1991, Van Mensvoort et al. 1991). The greater part of leached aluminum over the initially present soluble aluminum in layer 0-5 and 0-25 cm in Figure 5 must have come from this release.

The release can be interpreted as a reestablishment of equilibrium of the soil-water system, which was upset by the leaching process. It is impossible to determine which of the processes of cation exchange, dissolution or desorption is responsible for the release of aluminum and sulphate into the soil solution. Possibly, it is the dissolution of jurbanite, as indicated by Van Breemen (1976) and Danh (1991).

Another important aspect affecting the leaching rate in heavy clay acid sulphate soils is the distribution of flow in the soil profile. Water percolating through the soil mainly passes round, rather than through, the peds. Solutes held within the peds are, therefore, protected against leaching until they diffuse to the ped surface. 'By pass' flow is responsible for the removal of solutes from the soil body but, at a later



A Layout of the fishpund



B pH of surface water

Figure 4 Layout (A) of a 900 x 400 m fish pond being reclaimed in an acid sulphate soil, Cu Chi with continuous water flow of approximately 20 mm/day. pH of surface water after six months along 5 transects and at various distances from the right ring canal is shown in (B).

stage of leaching, it is the intra-ped diffusion which controls the rate of leaching. This diffusion may be responsible for the increase of Al in the soil solution during the submergence following the leaching process in Figure 6. In this case, the rate of release of Al^{3+} into the solution appears to be very slow: after 90 days, the average concentration of Al^{3+} in soil solution layer 25-50 cm increased about 1.5 meq/l (Figure 6), equivalent to only about 1 per cent of the KCl-extractable aluminum in the layer.

The arrangement and sizes of macro-pores and aggregates will have a strong influence on both 'by pass' flow and the extent to which diffusion proceeds towards equilibrium and, therefore, on the leaching process. The initial distribution of solutes within soil aggregates is also important.

Enhancement of leaching via land preparation

Proper land preparation and its timing to form suitable soil aggregates and to influence the initial solute distribution can enhance the leaching rate. Tuong et al. (1993) showed

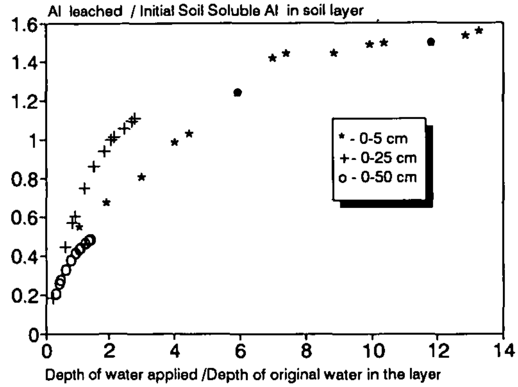


Figure 5 Al^{3+} leached out of three soil layers as compared with soluble Al^{3+} originally in the soil solution within the layers before leaching. Total leaching time: 63 days at 7 mm day^{-1} (SIWRR 1990)

that ploughing and drying the soil under the sun for two weeks before leaching improved the leaching rate and could reduce Al concentration in the soil solution considerably as compared to non-ploughed plots (Figure 7). It was postulated that, under the drying process, Al moved to the outside of the soil crumbs where it has better contact with the fast-moving water and, thereby, is removed more efficiently. The postulation was supported by consistently higher concentration of soluble ions in the outer 3 mm of the soil crumbs as compared to that of the inner cores (Figure 8).

Farmers in the Mekong Delta plough their land, then leave it fallow and submerged in flood water before taking advantage of the recession of the flood to flush the root zone of about 20 cm. The flushing process begins when the flood depth lowers to about 40 cm and is achieved in combination with land preparation: the field is harrowed and puddled before the water is drained out of the field. Flood water is readmitted and the cycle of flushing and puddling is repeated several times. Farmers claim

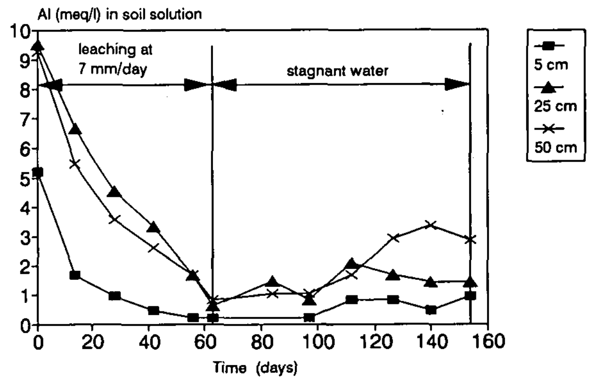


Figure 6 Changes in Al^{3+} in soil solution at sampling depths 5, 25, 50 cm of an undisturbed acid sulphate soil column. Data from SIWRR (1990)

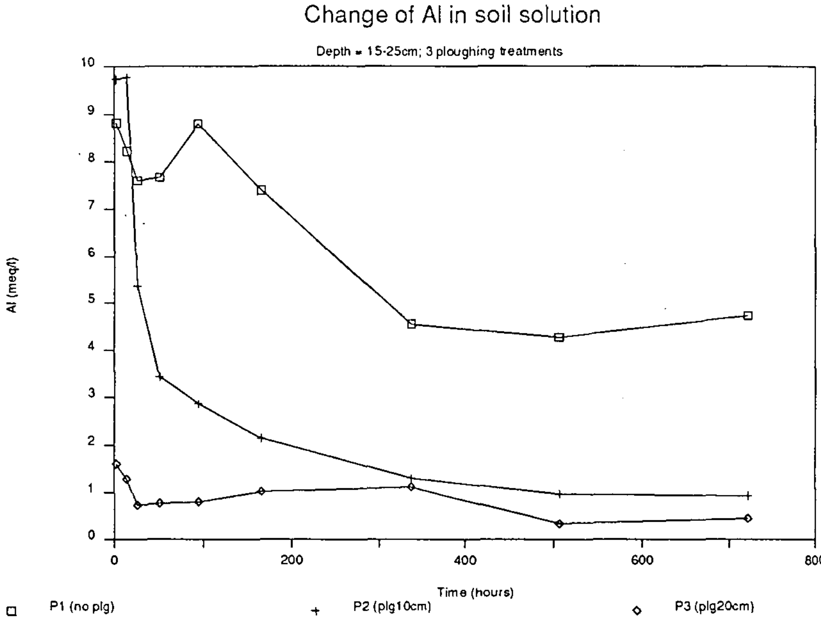


Figure 7 Changes of Al concentration in solution at depth 15-25 cm in a field leaching experiment of acid sulphate soil, Cu Chi.
P1: no ploughing before leaching, P2 and P3: soil was ploughed to depth 10 cm, 20 cm and dried before being leached (Tuong et al. 1993)

that the harrowing and puddling processes 'stir up' and dissolve the toxic elements which then can be removed with the water.

Other remarks on leaching

To sum up, the leaching process of acid sulphate soils involves many complicated mechanisms which are not yet fully understood. Further research is needed to arrive at quantitative expressions for the amount of water needed for the leaching process. It appears, however, that severe acid sulphate soils need water in the order of 1 m for the initial leaching to remove the free acid which is accessible to moving water, creating initial conditions suitable for root growth in macropores. A considerable quantity of acid still remains in the soil peds and in the exchange complex. If not properly managed, its subsequent release into the soil solution presents a risk of aluminum and other toxicities at a later stage to plants grown on leached soils. It was noticed (Van Mensvoort et al. 1991, Sen 1988a) that during the first 15-30 days after transplanting, rice grew well on newly leached soils but, then, the growth was retarded. In some cases (Tuong et al. 1993), the rice plants performed very well in the vegetative stage but produced only empty panicles. It is, thus, important to realize that leaching is not a once and for all measure of soil amelioration. In order to maintain soluble acidities of the macropores at a safe level for root growth, leaching (or flushing) should be continued during the plant growth cycle. Leaching may have to be repeated for many years before the soil can be said to be free of acidity.

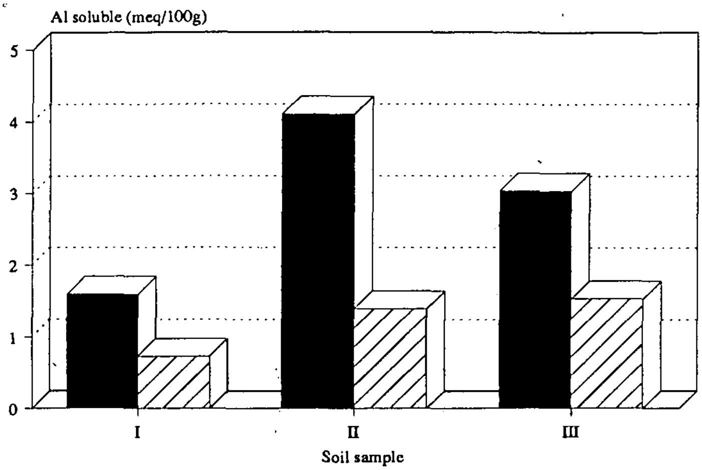


Figure 8 Soluble Al^{3+} in soil taken from the inner cores hatched and the outside 2 mm solid layers of soil crumbs after being dried in the sun for two weeks (Tuong et al. 1993)

Leaching also removes valuable basic cations which further worsens the already low nutrient status of most acid sulphate soils. Chemical amendment is imperative in leached acid sulphate soils.

When adequate fresh water is available and properly managed, leaching can turn acid sulphate soils into productive soils, but the opportunity cost of water use should be analyzed critically when irrigation water is also in high demand for other areas. Techniques to enhance leaching efficiency by use of rainfall and flood water should be further investigated.

Environmental impact of leaching and drainage of acid sulphate soils

Reclamation, leaching and drainage of acid sulphate soils for agricultural cultivation affects the environment, especially the aquatic one. As an extreme example, Sterk (1991) calculated that a shower of 36.3 mm in 30 minutes could leach 143.6 mmol(+) m^{-2} of acidity from the topsoil of a new (three months) raised bed of acid sulphate soil. Figures calculated from changes in concentration of the soil and soil solution range from 1 to 3 mol(+) m^{-2} per cropping season (Konsten et al. 1990b, Hanhart and Ni 1991). It is not uncommon that the pH in tertiary canals and farm ditches of the reclaimed area remains less than 3, with aluminum concentration exceeding 3 mol(+) m^{-3} (Kham 1988, Chairuddin et al. 1990). The pollution is not confined to the reclaimed area. Through diffusion and mass transport, acidity concentration is diluted but contaminates a much larger surrounding area. Figure 9 illustrates such a contamination in the Plain of Reeds, Vietnam (Kham 1988) where pH of the surface water remained below 5 during the rainy season on almost all the 500 000 ha of the Plain. Higher pH values due to the mixing of the river water at high tides, was only possible along a belt of about 10 km from the Mekong river where pH is 7.5-8.0.

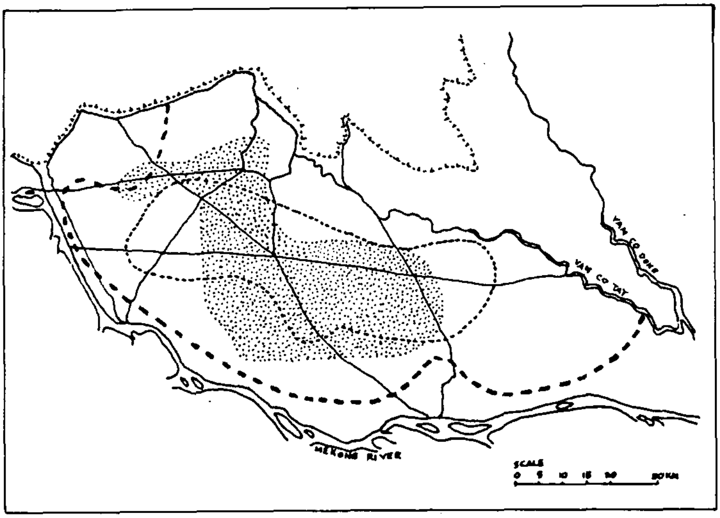


Figure 9 Acid pollution and its effects on benthic communities in the Plain of Reeds, Vietnam
Dotted area: 'depressed' situation of benthic communities, June 1987 (Grimas 1988).
Area within the fine pecked line: Al in canal water > 10 ppm, May 1987 (Kham 1988)
The bold pecked is the pH5 isoline, May 1985 (Kham 1988)

Similar contamination on a large area was reported by Chairuddin et al. (1990) for Pulau Petak, Indonesia.

Acid water contamination may have profound effects on the aquatic population of the area. Grimas (1988) reported a chronic 'depressed' benthic situation (both regarding the abundance of the benthic animals and the number of species) in the centre of the Plain of Reeds, approximately coinciding with the most heavily polluted area with aluminum concentration higher than 0.3 mmol(+) m^{-3} (Figure 9).

Fish production in the Plain of Reeds has not been studied quantitatively, but it is expected to be greatly affected by acid pollution of the water and/or by the decrease of food, for example the benthic communities. Elsewhere, strongly negative effects of flushes of severe acidity from reclamation of acid sulphate soils in coastal mangrove forests on shellfish, crustacea and fish was reported by Marius (1982) and from inland acid sulphate soils on fish population by Chairuddin et al. (1990). Both species diversity and abundance of fish population were approximately halved in the polluted area (Tabunganen) as compared to the surrounding, not-polluted areas of Pulau Petak, South Kalimantan. Somewhat paradoxically, the authors found that the amount earned by fishing was highest in the most acidified area. This was the result of a higher fishing effort and more time spent in selling the fish directly to the consumer rather than because of particularly good fishing grounds. This shows the importance of fisheries in providing extra income in areas where farming is less successful due to acidity problems.

The negative effects on the fish population of acidification of canal waters by leaching of acid sulphate soils, and the importance of fisheries for farmers' income and diet, make careful management of these resources imperative. Simulation techniques may offer a predictive tool to study the degree and extent of pollution from development plans and can, possibly, ensure that the negative effects are within the 'absorbing' capacity of the surroundings. Conservation of part of the swampy area is highly recommended. Another option in already-devastated areas is the restoration of swamp forests. This will not return the soil to its properties before acidification but will minimize the acid pollution to the surroundings. Such a method has been tried out in the Plain of Reeds by dikebuilding and tree planting for the establishment of more than 5 000 ha of wetland forest (Duc 1988, Rome 1990). After a few years, the wetland regained a resemblance of the original wetland forests in health and appearance and, once again, became a feeding ground for fish and suitable environment for the home-coming of once-driven-away red headed cranes (Rome 1990).

References

Beye, G. 1973. Acidification of mangrove soils after empoldering in Lower Casamance. Effects of the type of reclamation used. In: H. Dost (editor). Proceedings of the International Symposium on Acid Sulphate Soils, 13-20 August 1972, Wageningen, Vol II, 359-372. International Institute for Land Reclamation and Improvement Publication No. 18, Wageningen

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

Bronswijk, J.J.B. and J.E. Groenberg 1991. Validation of model using measurements from column experiments. In: AARD & LAWOO Simulation model of physical and chemical processes in acid sulphate soils to evaluate water management strategies (draft report), 115-132, Bogor

Burrough P.A., M.E.F. van Mensvoort and J. Bos 1988. Spatial analysis as a reconnaissance survey technique: an example from acid sulphate soil regions of the Mekong Delta, Vietnam. In: H. Dost (editor). Selected papers of the Dakar Symposium on Acid Sulphate Soils, 68-89. International Institute for Land Reclamation and Improvement Publication No. 44, Wageningen

Chairuddin, Gt., Iriansyah, O. Klepper and H.D. Rijksen 1990. Environmental and socio-economic aspects of fish and fisheries in an area of acid sulphate soils: Pulau Petak, Kalimantan. In: AARD & LAWOO Papers workshop on acid sulphate soils in the humid tropics, 20-22 November 1990, Bogor, Indonesia, 374-392

Charoen, C. and N. Maneewon 1989. Acid sulphate soils improvement project in Central Plain, Thailand: Physical features, socio-economic situation, problems and activities of development. Paper presented at the workshop on the expert meeting on development of integrated management models for rehabilitation of acid sulphate soils in Central Thailand. July 31 August 4, 1989, AIT Bangkok

Danh, Ngyuen Tan 1991. Influence of different water managements on variation of toxins in acid sulphate soils. In: Collection of papers presented at the Workshop on Management of Acid Sulphate Soils, Ho Chi Minh City, October 21-25 1991, International Mekong Committee, Bangkok

Dent, D.L. 1986. Acid sulphate soils: a baseline for research and development. International Institute for Land Reclamation and Improvement Publication No. 39, Wageningen

Duc, Le Dien 1988. Sen dau do (Red headed cranes, in Vietnamese). Centre for Resources Management and Environment Studies, University of Hanoi, Hanoi

Grimas, U. 1988. Water quality investigations in the Lower Mekong Basin, biological monitoring – an evaluation. Paper presented at the workshop of surface water quality in the Lower Mekong Basin, Ho Chi Minh City, 7-13 September 1988. International Mekong Committee, Bangkok

Hamming, A.F.J., K. Subagyono and T. Vadari 1990. Soil permeability aspects in Pulau Petak, Kalimantan. In: AARD & LAWOO Papers Workshop on Acid Sulphate soils in the Humid Tropics, 20-22 November 1990, Bogor, Indonesia, 295-323, Bogor

Hanhart, K. and D.V. Ni 1991. The effect of water management on the cultivation of an irrigated dry season rice crop on a severe acid sulphate soil in Hoa An station, Vietnam. Interim report of VH-10 Program, Department of Soil Science and Geology, Wageningen Agricultural University

Kanapathy 1973. Reclamation and improvement of acid sulphate soil in West Malaysia. In: H. Dost (editor). Proceedings of the international symposium on acid sulphate soils, 13-20 August 1972, Wageningen, Vol II, 381-388. International Institute for Land Reclamation and Improvement Publication No. 18, Wageningen

Kham, Tran Duc 1988. Water quality reclamation in the Plain of Reeds in the '80's. Paper presented at the workshop of surface water quality in the Lower Mekong basin, Ho Chi Minh City, 7-13 September, 1988. International Mekong Committee, Bangkok

Kivinen, E. 1950. Sulphate soils and their management in Finland. Trans. 4th Int. Congr. Soil Sci. Vol.2, 259-262

Konsten, C.J.M., S. Suping, I.B. Aribawa, C.J. Ritsema and K. Nugroho 1990. Field experiments in Southern Kalimantan. In: AARD & LAWOO Simulation model of physical and chemical processes in acid sulphate soils to evaluate water management strategies (draft report), 59-77, Bogor

Konsten, C.J.M., S. Suping, I.B. Aribawa and I.P.G. Widjaja-Adhi 1990b. Chemical processes in Acid sulphate soils in Pulau Petak, South and Central kalimantan, Indonesia. In: AARD & LAWOO Papers workshop on acid sulphate soils in the humid tropics, 20-22 November 1990, Bogor, Indonesia, 109-136

Konsten, C.J.M., S. Suping, I.B. Aribawa and I.P.G. Widjaja-Adhi 1991. Column experiments, Indonesia. In: Simulation model of physical and chemical processes in acid sulphate soils to evaluate water management strategies (draft report), 27-58. AARD & LAWOO, Bogor

Kselik, R.A.L. 1990. Water management on acid sulphate soils at Pulau Petak, South Kalimantan. In: Papers workshop on acid sulphate soils in the humid tropics, 20-22 November 1990, Bogor, Indonesia, 249-276. AARD & LAWOO

Marius 1982. Vegetation et ecology des mangroves. In: H. Dost and N. Van Breemen (editors). Proceedings of the Bangkok symposium on acid sulphate soils, 103-136. International Institute for Land Reclamation and Improvement Publication No. 31, Wageningen

Mensvoort, M.E.F. van, J. van der Schans and Duong van Ni, 1991. Chemical improvement of acid sulphate soils by leaching with salt and brackish water. In: P. Deturck and F.N. Ponnamperuma (editors). Rice production on acid soils of the tropics. Proceedings of an international symposium, 26-30 June 1989, 219-227. Institute of Fundamental Studies, Kandy

Ponnamperuma, F.N., T. Attanandana and G. Beye, 1973. Amelioration of three acid sulphate soils for lowland rice. In: H. Dost (editor). acid sulphate soils. Proceedings of the international symposium on acid sulphate soils, 13-20 August 1972, Wageningen, Vol. II, 391-406. International Institute for Land Reclamation and Improvement Publication No. 18,, Wageningen

Ritsema, C.J., K. Nugroho and K. Obstindie 1991. Column experiments, The Netherlands. In: AARD & LAWOO Simulation model of physical and chemical processes in acid sulphate soils to evaluate water management strategies 27-57, Bogor

Rome 1990. Coming home. In Vietnam, a majestic bird rises from the ashes of war. Sierea, 75,2

Satawathananont, S., W.H. Patrick Jr. and N. van Breemen 1991. Changes with time of redox potential, pH and chemical constituents of acid sulphate soils of Thailand. In: P. Deturck and F.N. Ponnamperuma (editors). Rice production on acid soils of the tropics. Proceedings of an international symposium, 26-30 June 1989, 59-64. Institute of Fundamental Studies, Kandy

Sen, Le Ngoc 1988a. Influence of various water management and agronomic packages on the chemical changes and on the growth of rice in acid sulphate soils. Thesis, Agricultural University, Wageningen

Sen, Le Ngoc 1988b. The evaporation and acidification process in an acid sulphate soil. In: H. Dost (editor): Selected papers of the Dakar Symposium on acid sulphate soils, 135-149. International Institute for Land Reclamation and Improvement Publication No. 44, Wageningen

SIWRR 1990. Progress report of management of acid sulphate soils. Southern Institute of Water Resources Research. International Mekong Committee, Bangkok

Sterk, G. 1991. Leaching of acidity from the top soil of raised beds on acid sulphate soils in the Mekong Delta, Vietnam. Technical paper No. 8, EEF Project STD-Vietnam. Department of Soil Science and Geology, Agricultural University, Wageningen

Thuan, Tran Minh 1989. A study of the lowering of the groundwater level. A case study in the Plain of Reeds, Vietnam. Unpublished Master of Science thesis, Agricultural University, Wageningen

Tuong, T.P., T.M. Chanh, T.M. Thuan and T.T. Tai 1988. Groundwater level profiles in acid sulphate soils as influenced by water level in the surrounding canals in Hau Giang Province. Interim Report VH-10 program. Department of Soil Science and Geology, Agricultural University, Wageningen

Tuong, T.P., L.V. Du and N.N. Luan 1993. Effects of land preparation on leaching of an acid sulphate soil at Cu Chi, Vietnam. In: D.L. Dent and M.E.F. van Mensvoort (editors): Selected papers of the Ho Chi Minh City symposium, 281-287. International Institute for Land Reclamation and Improvement, Publication 53, Wageningen

Tuong, T.P., L.Q. Minh, and T.P. Khanh 1991. Effect of watertable depth on evaporation and distribution of salts and moisture in a bare acid sulphate soil. In: P. Deturck and F.N. Ponnamperuma (editors).

Rice production on acid soils of the tropics. Proceedings of an International Symposium, 26-30 June 1989, 71-76. Institute of Fundamental Studies, Kandy

Xuan, Vo Tong 1987. Nutrient management in saline, acid sulphate and other problem rice soils in Vietnam. Paper presented at the International Rice Research Conference, 21-25 September 1987

Yin, T.P. and P.Y. Chin 1982. Effects of water management on performance of oil palm on acid sulphate soils in Peninsular Malaysia. In: H. Dost and N. Van Breemen (editors). Proceedings of the Bangkok symposium on acid sulphate soils, 260-271. International Institute for Land Reclamation and Improvement Publication No. 31, Wageningen

Effect of land preparation on leaching of an acid sulphate soil at Cu Chi, Vietnam

To Phuc Tuong[1], Le Van Du[2] and Nguyen Ngoc Luan[2]

[1] IRRI, P.O. Box 933, Manila, The Philippines
[2] University of Agriculture and Forestry, Ho Chi Minh City, SR. Vietnam

Abstract

A large part of the severe acid sulphate soil areas of the Mekong Delta, Vietnam is underlain at a depth of 15-30 cm, by a slowly-permeable layer which impedes water movement and reduces leaching. This paper reports an attempt to enhance the leaching in an aeric sulfaquept by breaking this layer. Three treatments are applied: (i) a control without preparation before leaching, (ii) hoeing to the depth of 10-15 cm followed by sun-drying for two weeks, and (iii) hoeing to the depth of 20-25 cm and sun-drying for two weeks before leaching. The effect of leaching was greatly enhanced by land preparation and sun-drying. Toxicities were removed faster and water was used more efficiently. In the non-hoed treatment, after four weeks and approximately 1300 mm leaching water, the toxicities remained high enough to inhibit rice growth while in other treatments they were reduced to a much lower level with less water and in a shorter period. The effects are explained by the movement of water through the soil profiles and the distribution of toxicities within the soil crumbs subjected to the drying process.

Introduction

The texture of most of the 1.6 million hectares of acid sulphate soils of the Mekong Delta is heavy clay (Mekong Delta Integrated Survey Program 1986). Its low permeability and structure impede water movement and inhibit leaching. Farmers invariably practice leaching in combination with various land preparation techniques. They claim that leaching can be greatly enhanced by ploughing and fallowing before leaching. This study aims at quantifying the effects and identifying possible mechanisms by which ploughing followed by fallowing modifies the leaching process.

Materials and methods

Soil and site of experiment

The experiment was carried out from March 6, 1989 and lasted for thirty days in an abandoned field of acid sulphate soil in Cu Chi district, 50 km Northeast of Ho Chi Minh City. This area is flooded from August to January, with a maximum flood depth up to 40 cm in September-November. Previously, the watertable in the dry season was more than 80 cm below surface. Seepage from an irrigation canal constructed in 1987, has raised the dry season watertable to about 40 cm and aggravated the waterlogging problem.

Table 1 Some chemical properties of soil in the experiment, Cu Chi

Depth cm	pH H_2O 1:5	pH KCl 1:5	EC mS cm^{-1}	Acid*	Al*	Ca	Mg mmol$_c$ kg^{-1}	Na	K	N Tot %	OM %	Am. Fe** %	Av. P*** mg/ 100 g
0- 5	2.9	2.8	2.5	223	183	7	44	37	2	0.36	12.4	0.24	1.77
5-15	3.4	3.1	0.8	161	145	1	21	23	1	0.36	11.7	0.22	1.22
15-25	3.5	3.2	0.7	179	145	2	23	09	1	0.38	11.7	0.15	0.82
25-35	3.2	2.9	0.9	185	153	1	26	26	2	0.30	8.9	0.24	0.61
35-45	3.2	2.8	0.8	160	131	2	30	18	2	0.12	2.1	0.20	0.55
55-65	3.2	2.8	0.8	135	114	2	30	5	2	0.10	2.1	0.17	0.24

* in a 1 M KCl extract
** iron extracted with ammonium oxalate
*** in a 0.01 M sulphuric acid extract

The soil is a Typic sulfaquept, with sulfuric horizon extending from 40 cm depth to the sulfidic material at 135 cm. The whole soil profile is characterized by very low pH and high exchangeable aluminum (Table 1).

Some soil physical properties are presented in Table 2. The original, unploughed soil had by low permeability, especially at depth 20-40 cm.

Treatments and experiment layout

The treatments were three levels of land preparation before leaching:
P1: Land was not prepared
P2: Land was hoed once to 10-15 cm and dried in the sun for two weeks
P3: Land was hoed twice to 20-25 cm and dried in the sun for two weeks

The treatments were arranged in a complete randomized block with three replications. Each plot was a 1.5 m x 1.5 m (Figure 1), with sides of wooden planks driven into the soil 20 cm. The wooden sides were designed to reduce the lateral seepage from the plot, which was further minimized by 2,5 m x 2.5 m 'buffer zones' where the water level was kept at the same level as in the inner plot. Leaching water was applied to

Table 2 Some hydraulic characteristics of soil in the experiment, Cu Chi

Depth	Vertical Saturated Hydraulic Conductivity (m day^{-1})			Horizontal Saturated Hydraulic Conductivity (m day^{-1})		
	P1	P2	P3	P1	P2	P3
0-10	0.15	1.79	–	0.18	0.21	–
10-20	0.30	0.13	3.70	–	0.47	0.48
20-31	0.03	–	–	0.03	–	0.52
31-42	0.16	0.16	–	0.05	–	–
42-53	0.65	0.65	–	0.1	0.10	–
53-65	0.04	0.04	–	0.05	0.05	–

Note: P1 = control
P2 = hoed to depth 10-15 cm
P3 = hoed to depth 20-25 cm

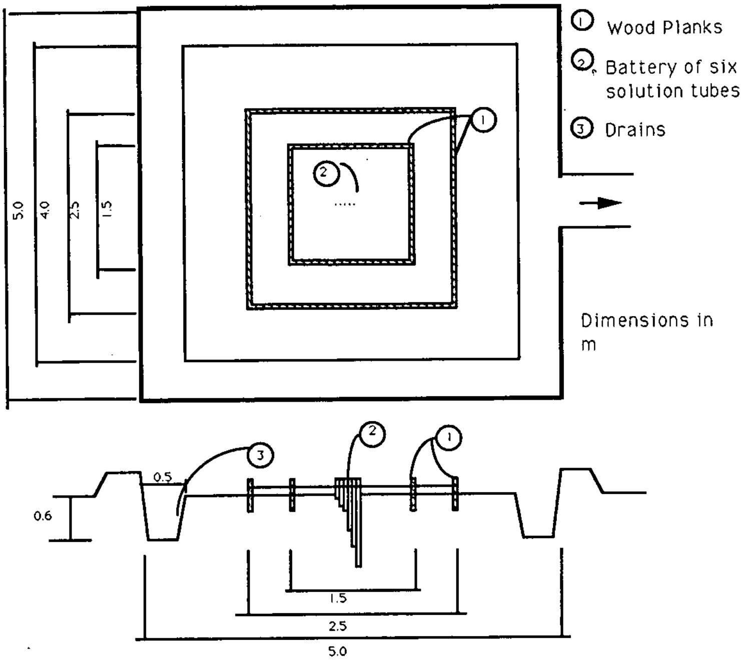


Figure 1 Schematic layout of an experimental plot

the experimental plots from a calibrated tank, leachate was collected from drains surrounding the experimental plots.

Sampling and chemical analyses

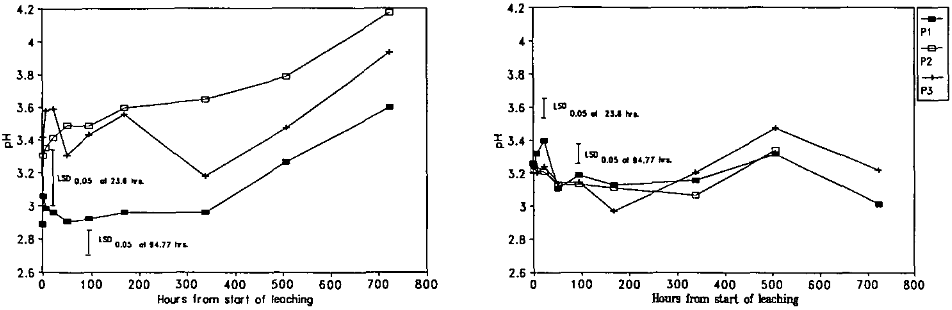
Each experimental plot was equipped with a battery of six tubes to extract soil solutions at depth 0-5, 5-15, 15-25, 25-35, 35-45 and 55-65 cm. The construction of soil solution tubes was similar to that described by van Breemen (1976) with some modification to avoid vertical leakage along the tube side and to enhance free flow of soil solution at the sampling depths into the tubes. Samples were taken by pre-vacuumed bottles at the start of the leaching treatment and 0.5, 1, 2, 4, 7, 14, 21 and 30 days thereafter.

The pH and electrical conductivity (EC) of the solution were measured within one hour after sampling. Other constituents were analyzed as described in Begheijn (1980). To stop oxidation of Fe^{2+} ions during the storage before the analysis, a small portion of soil solution was fixed with 0.1 M HCl.

Results and discussion

Soil solution chemistry

A significant positive correlation was found between EC, Al^{3+}, titratable acid and soluble SO_4^{2-} for all sampling times and depths. A significant negative correlation existed between pH and the above constituents for the two depths 0-5 and 5-15 cm but not for greater depths. No significant correlation was found for Fe^{2+} and other measurements.



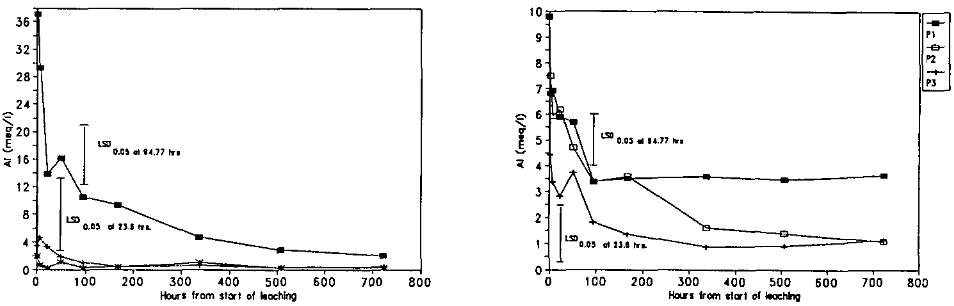
(a) (b)

Figure 2 Changes in pH of soil solution at sampling depths (a) 5-15 cm and (b) 55-65 cm during the leaching process as influenced by three land preparation treatments

The pH of the soil solution in the first two sampling depths (0-5 and 5-15 cm) was raised by the leaching process (Figure 2a), where the effects of land preparation were strongly felt at early sampling times. For deeper sampling depths, pH remained rather constant throughout the leaching period (Figure 2b) and no significant differences amongst treatments were found.

Figure 3 demonstrates that land preparation treatments significantly enhanced the leaching of Al^{3+}. Differences between the P2 and P3 treatments were noticeable even at greater depths at early sampling times but, as leaching proceeded, these effects diminished. After about one week, Al^{3+} concentration remained almost constant. In the non-hoed treatment, Al^{3+} concentration at all depths remained very high, far exceeding the tolerable level of rice, while in the hoed treatments it was brought down to less than 1 mmol(+) per liter. Variations in EC, titratable acid and soluble SO_4^{2-} were similar to that of Al^{3+}.

The behaviour of Fe^{2+} (Figure 4) was peculiar in that its concentration at the shallower depths increased within a few days after the start of leaching under the P1-treatment. This rise of Fe^{2+} was too fast to be attributed to the reduction process in which Fe^{2+} reaches its peak about 2 weeks after the soil submergence (Dent 1986, Ponnamperuma 1984). The phenomenon may be explained as the effect of a rising



(a) (b)

Figure 3 Changes in Al^{3+} of soil solution at sampling depths (a) 5-15 cm and (b) 55-65 cm during the leaching process as influenced by three land preparation treatments

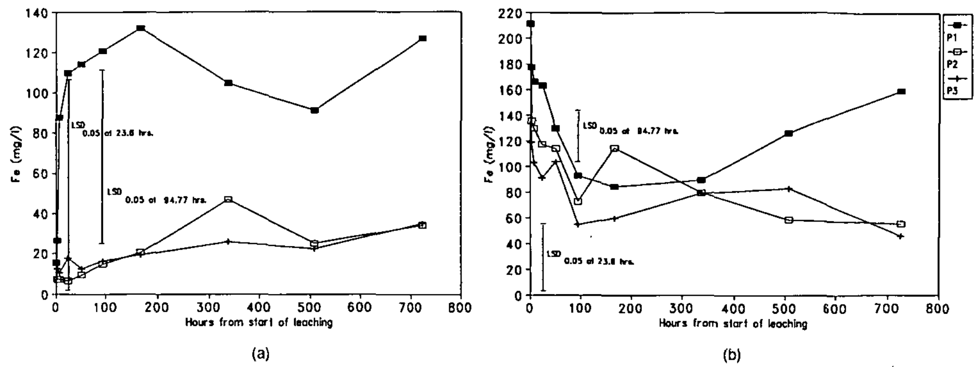


Figure 4 Changes in Fe^{2+} of soil solution at sampling depths (a) 5-15 cm and (b) 55-65 cm during the leaching process as influenced by three land preparation treatments

watertable which brought the Fe^{2+}-rich groundwater to the surface layers. In the hoed treatments, this mixing effect of the watertable was suppressed by the fast downward movement of water.

In deeper horizons, Fe^{2+} concentration decreased as a result of the simultaneous actions of leaching and dilution from water of better quality from above and was greatly influenced by land preparation treatments.

Leaching efficiency and the importance of soil structure

The faster rate of leaching achieved by land preparation can be explained by the

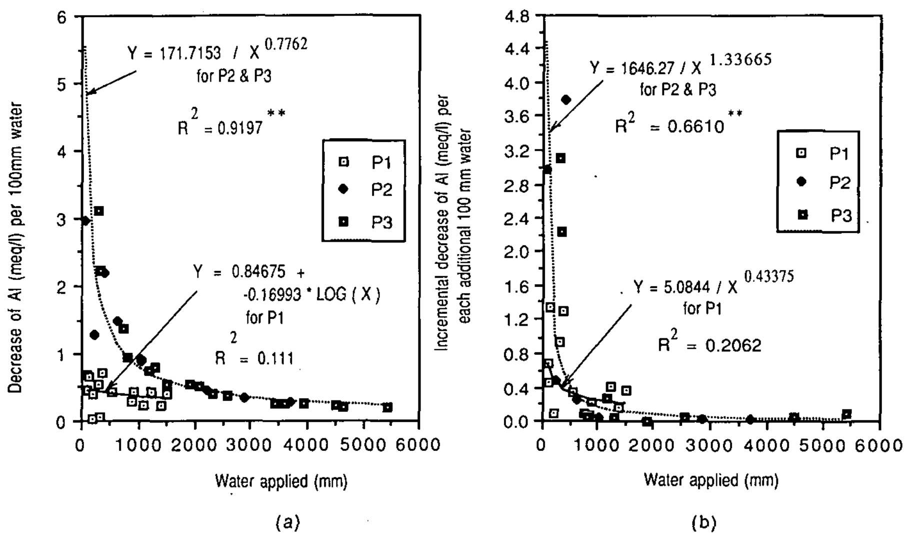


Figure 5 Leaching efficiency expressed as (a) decrease in Al^{3+} concentration (compared to original concentration) per 100mm cumulative water applied and (b) incremental decrease in Al^{3+} concentration per each additional 100 mm (sampling depth 15-25 cm)

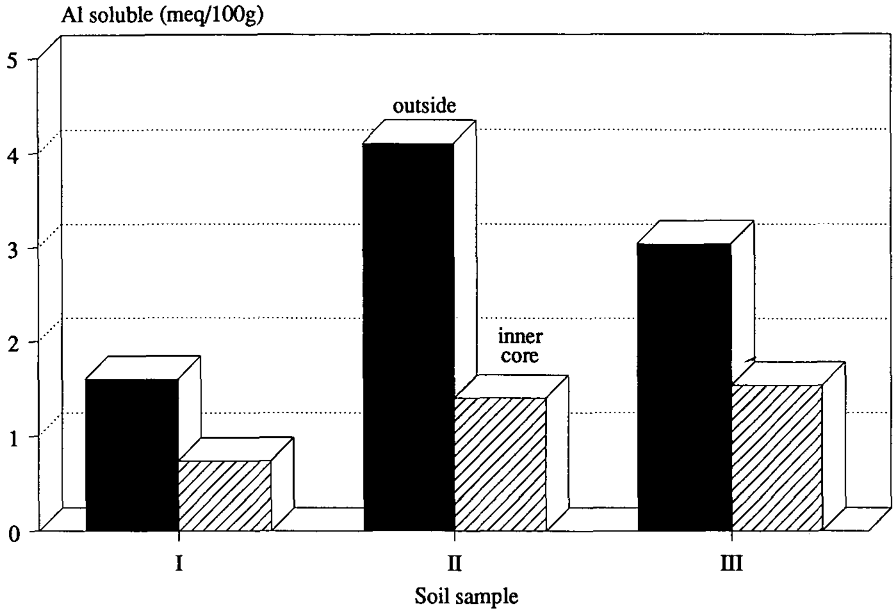


Figure 6 Soluble Al^{3+} in soil taken from the inner cores and the outside 2 mm layer of soil clods after being dried in the sun for two weeks

increase in infiltration rate of the profile and hydraulic conductivity of the most slowly permeable soil layers (Table 2). Land preparation causes more macropores between the soil crumbs. Despite of these 'by passes', leaching efficiency, in terms of its effect in removing Al^{3+}, of the hoed treatments was much higher than the non-hoed treatment (Figure 5). This is particularly clear when the amount of water applied was less than 1000 mm.

The higher leaching efficiency indicates the importance of land preparation in changing the structure of the clay soil into clods which have more surface contact with the fast-moving water through the macropores. Furthermore, under the drying process, toxic substances move to the outside of the soil crumbs where they are removed more efficiently. This explanation is supported by the consistently higher concentration of soluble ions in the outer 2 mm of the sun-dried soil clods as compared to that of the inner cores (Figure 6).

After the removal of the easily-accessible substances at the clod surface, leaching could only remove substances which move by diffusion from the inner cores to the clod surfaces. This is a slow process, so leaching efficiency decreased rapidly as more water is added. Beyond about 1500 mm, additional water does not further reduce the Al^{3+} concentration of the soil solution. It should be noted that the infiltration rates in the experiment were very high, even after 30 days of submergence, those of P3 plots approximated 100 mm/day. This might be attributed to the proximity of the plots to the surrounding drainage canals. In actual farmers' fields, the infiltration will probably be much lower and leaching would require more time.

Conclusions

Land preparation by hoeing and drying under the sun before leaching enhances leaching. Toxicities are removed faster and with less water. The enhanced leaching effects are attributed to the change from large structure elements to smaller clods and the movement of toxicities during the drying process to the sides of the clods where they are removed more efficiently by the fast-moving water through the macropores. Leaching effects decreased rapidly after the removal of these readily-soluble substances.

Acknowledgements

The study was carried out in the framework of IRRI-Vietnam Collaborative research in water management.

References

Begheijn, L.Th. 1980. Methods of analysing soil and water. Department of Soil Science and Geology. Agricultural University, Wageningen

Breemen, N. van 1976. Genesis and solution chemistry of acid sulphate soils. Agricultural report 848. PUDOC, Wageningen

Dent, D.L. 1986. Acid sulphate soils: a baseline for research and development. International Institute for Land Reclamation and Improvement Publication No. 39, Wageningen

Mekong Delta Integrated Survey Program 1986. Final report on the integrated survey of the Mekong Delta (in Vietnamese). State Sci. & Tech. Commission, Hanoi

Ponnamperuma, F.N. 1984. Effects of flooding on soils. In: T.T. Kozlowski (editor). Flooding and plant growth, 9-45. Academic Press Inc., Orlando

From land evaluation to land use planning

David Dent

School of Environmental Sciences, University of East Anglia, Norwich, England

Abstract

Sustainable development of acid sulphate soils requires integrated soil, water and cropping system management over whole landscapes. The various groups of managers and decision-makers need information at different levels of detail which is not provided by conventional soil survey and land evaluation.

To help bridge the information gap between soil specialists and decision-makers, a range of knowledge-based decision support systems may be built, making use of available computer software. An outline system is put forward.

The place of soil information in land use planning and management

The problems posed by acid sulphate soils that most concern most people are problems of land use, problems of management. Farmers, winning their daily bread from the land, are most concerned with day-to-day management of soil and water. They need very specific, detailed information: first, about the land use options open to them and, next, about the practical consequences of opting for one kind of management, rather than another, on their particular patch of land.

In the absence of specific information, land use evolves by trial and error. This is costly and, where acid sulphate soils are involved, the costs are borne not just by those who err but by the whole community. For acid sulphate soils, more than for most other soils, decision-makers need land information on a scale broader than the individual farm because production on any patch of land depends on the timing, amount and quality of water delivered, perhaps, from far beyond; while the quality of drainage and floodwater leaving the acid sulphate soil affects cropping, fisheries and other facets of the environment downstream. Soil-, water- and cropping systems are so closely dependent that sustainable production demands integrated management of the whole landscape.

Beyond the level of the farm or landscape, at regional and national level, decisions have to be made about the allocation of scarce resources not just land but also water, capital, research and management skills – for the common good. These decision-makers need information on the comparative advantages and disadvantages of different land use options on different tracts of land.

Land use planning at any scale needs land information, but there are lots of managers; they have different goals; they don't all need the same information and they don't all have the same capability to make use of soil information (Figure 1). Not being soil scientists, they find it difficult to specify just what soil information they need. On our part, not having been privy to the deliberations of government ministers, bankers, bureaucrats or farmers, we have produced information that is mostly unusable by any of the managers. At any rate, it has been mostly unused. In short, if the right information

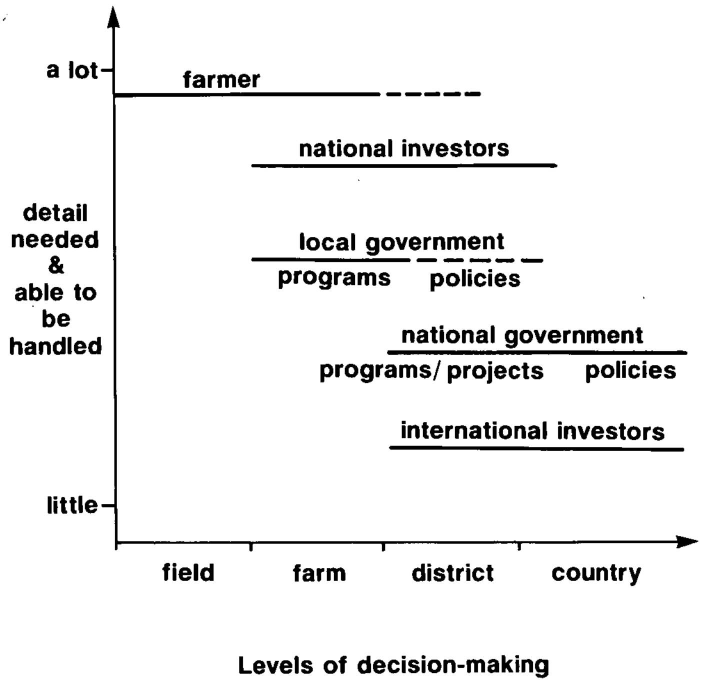


Figure 1 Levels of decision making and degrees of detail of information needed

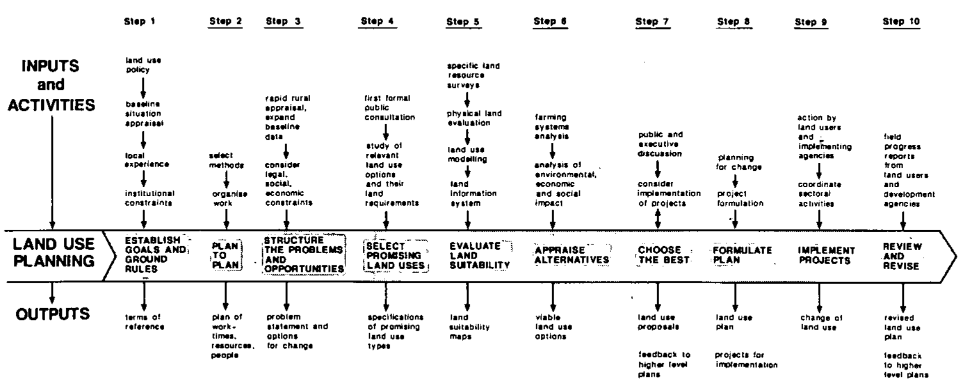


Figure 2 Ten steps of land use planning

is to be provided to the right people at the right time, both sides should know the place of different kinds of land information in land use planning.

Figure 2 presents an idealised sequence of steps in land use planning. The detailed inputs and outputs of each step refer to a large land development project but others can be substituted at any level of planning from local to national. Soil information is needed at increasing levels of detail from Step 1 (Establish goals), to Step 3 (Structure the problems and opportunities), to Steps 4 and 5 (Select promising land uses), and (Evaluate land suitability), to Step 8 (Formulate to plan, which may include a detailed management prescription) to Step 10 (Sort out what went wrong). By the time detailed technical information comes into play, the most important decisions – to develop or not, to drain or not, rice or fishponds, – have already been taken.

It is now 20 years since the First International Symposium on Acid Sulphate Soils. We have come a long way in our understanding of how these soils develop, their extent, distribution and variety. We have won a lot of technical knowledge about their reclamation and management. But most work has concentrated on details of the kind needed in Steps 8 and 10; much less on the kind of information that could be used in the more strategic earlier steps. Again, there is much information that can be used by technical specialists; hardly any that can be used by farmers, land use planners, or ministers. It is time to put our hard won knowledge to better use. A stitch in time saves nine. In terms of the Ten Steps, good land information at Step 1 can save a lot of trouble over the next nine.

Focus on land evaluation

Land evaluation addresses some of the more strategic questions – grading land from best to worst, predicting performance, and valuing this performance by comparing the outputs with the inputs. One great advance made by the FAO 'Framework for Land Evaluation' (1976) was to point out that you cannot evaluate land unless you know exactly what it is being evaluated for. So the step before land evaluation is to identify promising land use types for example subsistence production of rice by smallholders using manual labour and animal draught power, or commercial aquaculture based on milkfish, or prawns (see, for example, Le Quang Tri et al. 1993).

Having specified the land use type, you can establish its land requirements in terms of land qualities – attributes of land that directly determine its performance, for example, sufficiency of water or sufficiency of nutrients (Melitz 1986). Ways have to be found of measuring these land qualities and assessing their effect on performance. Then, evaluation can proceed by matching the requirements of the land use type with what the land has to offer.

Depending on how much we know about the requirements and how much we know about the land, we can make a qualitative assessment of which land is best and which worst. By transferring experimental data and experience from one area to similar soils elsewhere, land use opportunities and problems can be identified, crude estimates of performance can be made and, sometimes, useful management guidelines can be given.

But if we want quantitative predictions, we need quantitative models: models that take account of the inputs – land, water, power, fertilizer, labour – and which predict the outputs – not just crops, but other products that have value, like water that can be re-used, and acid and salts that bring costs either on site or elsewhere. We also need model farmers!

Modelling land qualities and land use types

Work on quantitative land evaluation (Beek et al. 1987, Bouma and Bregt 1989) has been very revealing. It has laid bare our ignorance of the requirements of even major crops, let alone farming systems; ignorance of their response to land qualities; and a lack of information at a useful scale about the variation (in space and time) of the key land qualities like sufficiency of water, sufficiency of nutrients, trafficability and workability of the land, intensity of aluminium and iron toxicity. This information is not given on conventional soils maps.

Soil surveys record characteristics that can be assessed in the field or by remote sensing, like soil texture, thickness of horizons and position in the landscape. Often, we find good local correlations between crop performance and one or other mapped characteristic. Often, we don't. And any correlation breaks down over a large area because the crop is not responding directly to the individual land characteristic but to a land quality that is determined by the interplay between several characteristics, for example depth to sulphidic material and water regime.

Figure 3 shows how yield might respond to the quality sufficiency of water and Figure 4 shows how sufficiency of water is a shifting balance between demand and supply with the crop appearing on both sides of the equation. It is obvious that land qualities cannot be mapped like individual land characteristics: 30 cm of rooting depth might supply enough water for a crop in New Zealand but not in Senegal, enough at an early stage in crop growth but not at full development, enough for pineapple but not for sugar cane. Land qualities can only be assessed by modelling. Simulation models of crop performance then have to combine several land quality models. Usually, they begin with a potential yield of the crop determined by sufficiency of energy. This potential yield is progressively downgraded according to sufficiency of water and, maybe, oxygen, nutrients or disease. With the aid of a computer, calculations are made daily or for each stage of growth so that the effects of variable weather or soils can be simulated (see, for example, van Diepen et al. 1989). This ability to simulate natural variability is important for decision-makers who must be able to assess the element of risk. So we need probability data for each land quality (Johnson and Cramb 1991).

Crop models have yet to address the special characteristics of acid sulphate soils but, in principle, we can take account of the physiological response to Al, Fe, and H_2S toxicity and to salinity, and the period of flooding needed to reduce acidity to a tolerable level. I hand this one over to the hairy-chested modellers, who also need to tackle the problem of building models that use the data we can realistically get.

Evaluation for farming systems

The question of farmers has to be dealt with separately (Driessen 1989). For one thing, you cannot stick an auger into a farmer. For another, farmers combine several crops, a range of soils, and more-or-less successful attempts to match land use with land and improve land qualities by management. Their success is not measured in terms of crop yield but in terms of profit, and security of food and income.

The information that farmers need is not for soil profiles but for management units; not just for single crops but for integrated cropping systems. Land use planners, working at district and national scales, need the same information for whole landscapes, not just for now but for a range of probable physical and economic conditions in the future.

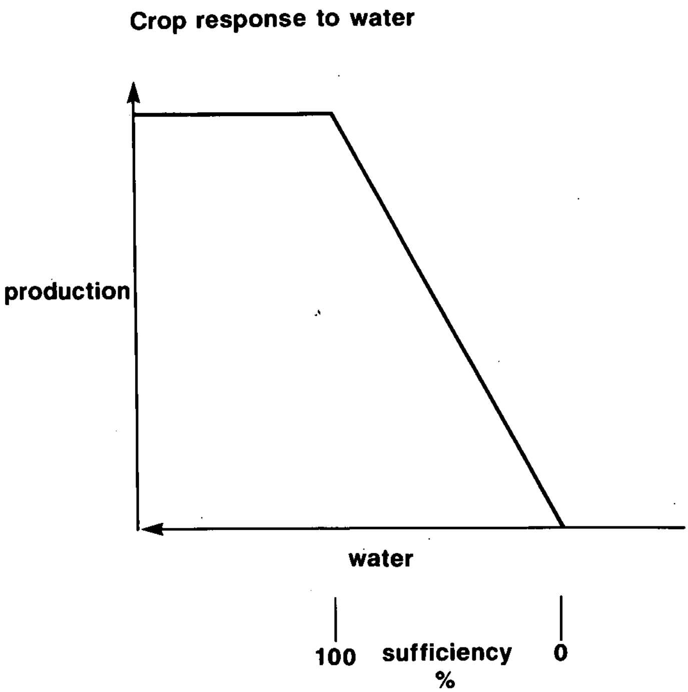


Figure 3 Yield response to sufficiency of water

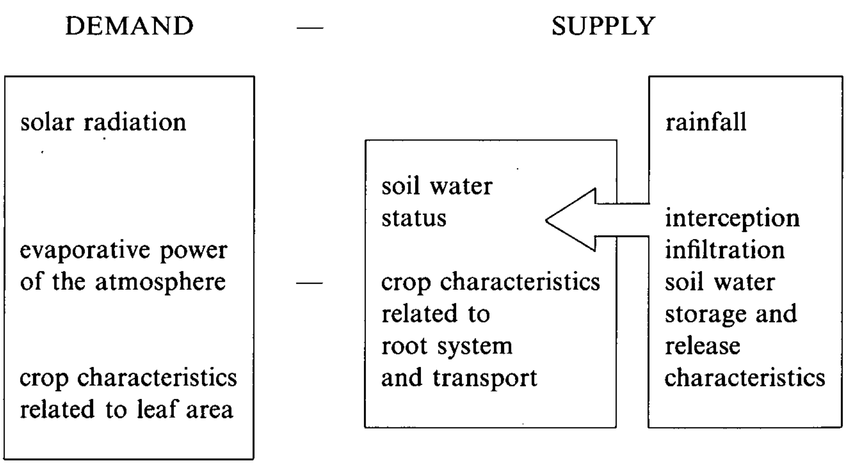


Figure 4 A model of water sufficiency

It is obvious that simulation models of whole production systems will be expensive in terms of expert time and data. But they are essential at national level for rigorous evaluation of the potential performance of different land use options on different kinds of land, acid or otherwise (McDonald and Brklacich 1992). For example, in the Mekong Delta the low flow in the dry season is the ultimate constraint on production. Inexorably, the water supply is being reduced as changing land use in the upper catchment leads to soil erosion and, hence, lower base flow, and as water is diverted to other uses upstream. In the near future, decisions will have to be made at national level about allocation of water resources, for water used to leach and irrigate acid sulphate soils is also someone else's water. What is the best use of this water? How much sulphuric acid can the downstream systems cope with?

In general, the best returns from any enterprise will be obtained from the best-suited land. Acid sulphate soils are rarely the best-suited soils. Whilst an individual farmer may have no alternative land in which to invest his skill and labour, governments do have a choice. Once the benefits and costs of different options have been assessed, land use policies needed to achieve development goals can be devised and physical infrastructure and services can be planned and financed.

Make decisions where the information is

It is equally obvious that, in the foreseeable future, neither simulation models nor soil maps at a useful scale will be available to small farmers, extension workers or district land use planners. The kinds of land evaluation maps produced so far are no use to farmers. Telling a farmer that his land is marginally suitable for rice is not very helpful.

When talking to groups of farmers about soil management, find that they are well informed about costs and prices, crop varieties, cultivation, fertilizers and pesticides. But they don't know a lot about what goes on beneath the plough layer, which is where many of their management problems lie. Once, I exclaimed 'Why don't you just dig a hole and look?'. Back came the reply 'We don't know what to look for'.

Out there is a legion of people who have the strongest possible interest in the land, and who are just waiting to be told what to look for. Within this room is most of the knowledge about acid sulphate soils that has been gathered over the last 30 years. Can't we tell them what to look for, and tell them in plain language?

Figure 5 is the skeleton of a decision-support system. It can be fleshed out by local soil scientists and advisers so that it can be used in the field by land users, by agronomists and by local planners. The soil scientists' expert knowledge is used to identify key attributes of the land that present opportunities and problems for the land user. What to look for is listed as a series of questions. Then we must show the user how to find the answers.

Depending on the answers, we can identify a range of land use options that, from experience in many parts of the world, we know to be viable. With local calibration, estimates of production and environmental impact can be provided. Equally, we can highlight those options that are not viable, and explain why they are not viable. Then the decision-maker can match the predicted outcome of each option with his or her goals, and can choose the best.

Figure 5b illustrates examples of the kind of decision trees that can be included. These could be published as colourful, illustrated posters to inform farmers and extension workers, or written as computer software for land use planners who have personal computers. Different programs can be written for different kinds of decision-maker. The advantage of this transparent presentation of facts and reasoning is that each step is open to challenge and to further development by the decision-makers; more so since they are involved in gathering the key information. This is important since 'expert' knowledge soon becomes out of date and, by using the system, the decision-maker will soon become more expert in his or her locality then any of us can be.

This is only a decision-support system. It doesn't tell the decision-maker what to do. But, if we do our work well, decision-makers will be able to gather, and make use of, land information they need to make wise decisions about land use.

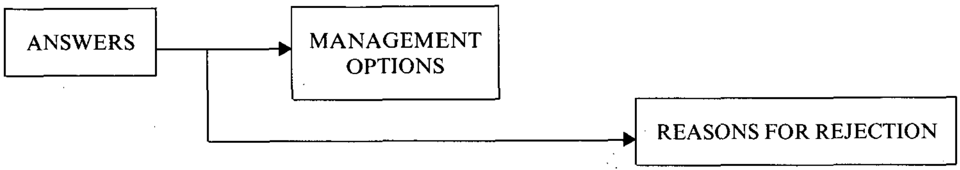
Figure 5 A knowledge-based decision-support system for acid sulphate soils

1 QUESTIONS	-> 2	ANSWERS	-> 3	MANAGEMENT OPTIONS	-> 4	REASONS FOR REJECTING ALTERNATIVE

5a)

QUESTIONS	*HOW TO FIND ANSWERS*
1.1 Is there severe acidity?	1.1 Field pH (paper) <4 or <4.5 flooded; yellow jarosite mottles or 'beurre marron' colour.
1.2 Is there potential acidity?	1.2 Bad eggs smell; dark grey colour and partly-decomposed organic matter; reaction with peroxide to pH <2.5. If there are rust mottles, there is no pyrite.
1.3 If so, how deep and how severe?	1.3 Measure thickness of non-acid/not potentially acid topsoil. Incubate sample for 3 months and test pH (simple lab backup by titrating acidity after peroxide treatment).
2.1 For how many months of the year can the watertable be kept above the sulphidic layer?	2.1 Position in the landscape; estimate soil permeability from soil texture and structure; length of dry season.
3.1 For how many months of the year is water available for the crop and for leaching	3.1 Length of wet season (range) and period of flooding (range).
3.2 What is the quality of the water?	3.2 Salty taste, acid taste (simple lab backup salinity measurement).
3.3 Where does the drainage water go?	3.3 Position in landscape, proximity of main channels and tidewater.
4.1 Is the soil ripe, ripe with unripe subsoil, or unripe?	4.1 Field test by squeezing.
5.1 Is lime available?	5.1 / 5.2 Realistic economic judgement for possible farming systems.
5.2 Is fertilizer available?	

5b) EXAMPLES OF DECISION TREES



IF

1.1 no
1.2 yes
1.3 < 25 cm,
very severe

THEN ->

DO NOT RECLAIM ->
Manage natural vegetation for: timber, natural products, fish, wildlife and tourism, coastal protection

OPTIONS SEVERELY LIMITED

Seek better land elsewhere

1. Anywhere else will be more economic
2. Unacceptable environmental impact
3. Lack of potable water

IF

1.1 yes
1.2 +
1.3 < 25 cm,
very severe
2.1 < 5 months
3.1 < 5 months
3.2 acid
3.3 to main drains
4.1 unripe

THEN ->
OPTIONS SEVERELY LIMITED ->
either abandon, or convert to low input Melaleuca forestry. Contain run-off or divert away from productive soils and fisheries

1. Cannot support any other viable use
2. Unacceptable environmental impact of further drainage and leaching
3. Lack of potable water

ANSWERS → MANAGEMENT OPTIONS

ANSWERS → REASONS FOR REJECTION

IF

1.1 yes
1.2 no
1.3 not severe, not potentially severe within 1m
2.1 8 months ± 2
3.1 7 months ± 1
3.2 good, fresh-water
3.3 outlet to major river
4.1 ripe
5.1 yes
5.2 yes

THEN -> MANY OPTIONS:

Low input options:	
• single crop, rainfed rice ->	Low, unreliable yield < 2 t ha^{-1}
• Casuarina, Eucalyptus, Melaleuca forestry ->	Low returns, yield class 2-8 over 8-12 year rotations
Labour-intensive options: ->	Viability depends on markets. Realistic benefit: cost analysis should compare with alternative investments elsewhere.
• reclamation package with raised beds, lime, fertilizer and irrigation for:	
– double cropped rice ($2 \times 3/4$ t ha^{-1})	
– sugar cane (30/65 t ha^{-1})	
– fruits	
– vegetable crops	
• DO NOT DRAIN POTENTIALLY ACID DEEP SUBSOIL ->	Costly environmental impact of acid drainage

References

Beek, K.J., P.A. Burrough and D.E. McCormack (editors) 1987. Quantified land evaluation procedures, ITC Pub. 6, Enschede

Bouma, J. and A.K Bregt (editors) 1989. Land qualities in space and time. Pudoc, Wageningen

Dent, D.L. 1992. Guidelines for land use planning. FAO Soils Bulletin, Rome, in press.

Diepen, C.A. van, J. Wolf, H. van Keulen and C. Rappoldt 1989. WOFOST: a simulation model of crop production. Soil Use and Management 5,1, 16-24

Driessen P. 1989. Quantified land evaluation: consistency in time and space. In: Bouma and Bregt loc cit.

FAO 1976. A framework for land evaluation. Soils Bulletin 32, Rome

Johnson A.K.L. and R.A Cramb 1991. Development of a simulation based land evaluation system using crop modelling, expert systems and risk analysis. Soil Use and Management 7,4, 239-245

Le Quang Tri, Nguyen Van Nhan, H.G.J. Huizing and M.E.F. van Mensvoort 1993. Present land use as a basis for land evaluation in two districts of the Mekong Delta. In: Dent D.L. and M.E.F. van Mensvoort (editors): Selected papers of the Ho Chi Minh City symposium on acid sulphate soils, 299-320, International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen

McDonald, B. and M. Brklacich 1992. Prototype agricultural land evaluation systems for Canada. I) Overview and systems development, II) Selected applications and prospects. Soil Use and Management 8,2, 1-20

Melitz, J. 1986. The sufficiency concept in land evaluation. Soil Survey and Land Evaluation 6, 1, 9-19

Present land use as basis for land evaluation in two Mekong delta districts

Le Quang Tri[1], Nguyen Van Nhan[2], H.G.J. Huizing[3] and M.E.F. van Mensvoort[4]

[1] Soil Science Department, Can Tho University, Can Tho, Viet Nam
[2] National Institute of Agricultural Planning and Projection (NIAPP), 86 Hai Ba Trung Street, Ho Chi Minh City, Viet Nam
[3] ITC, PO Box 6, 7500 AA Enschede, The Netherlands
[4] Department of Soil Science and Geology, Agricultural University, PO Box 37, 6700 AA Wageningen, The Netherlands

Abstract

Land use systems are described and land use types are selected for land evaluation in two districts of the Mekong delta, Vietnam: Phung Hiep and Thanh Hoa. Phung Hiep has a wide variety of soils, ranging from fertile soils recently deposited by the Mekong river to severely acid sulphate soils. Thanh Hoa is strongly dominated by acid sulphate conditions.

Based on soil and hydrological characteristics, 27 land units are distinguished in Phung Hiep and 23 in Thanh Hoa.

The most important land and water management practices are the construction of raised beds for upland crops, and an optimal use of tidal movement for irrigation and drainage in both districts. In Phung Hiep, ditches are excavated for combined rice and shrimp cultivation.

Costs of inputs of present land use, gross incomes and recurrent costs are generally higher in non-acid and slightly acid areas than on acid land. There are exceptions: the promising land use type of cashew combined with pineapple, and sugar cane followed by rice have a high gross margin per year. Upland crops such as cabbage, ginger, sugar cane or yams, require very high investments but give greater gross margins than rice, except when rice is combined with shrimp.

The results of land suitability, indicate that in Phung Hiep the non-acid areas are highly suitable for vegetables followed by rice, but that this type of land use is not recommended for the acid areas. Land use types of sugar cane followed by rice, cashew intercropped with pineapple, double rice and Melaleuca are suitable for both the non-acid and the acid soil areas. In Thanh Hoa, double rice and upland crops such as yams and sugar cane are moderately suited for the acid areas and highly suited for the non-acid and slightly acid parts.

Introduction

The objective of land evaluation is to select the optimum land use for each area of land, taking into account both physical and socio-economic considerations and the conservation of environmental resources for future use (FAO 1983). The first formal land evaluation studies in Vietnam, carried out in the framework of a resource inventory of the Mekong delta (Tuong et al. 1991) concentrated on the physical conditions of the land. Little attention was paid to selection and description of land use types relevant to the physical and socio-economic conditions. In this study in Phung Hiep and Thanh Hoa, present land use is taken as basis for land evaluation. Phung Hiep has partly very fertile, partly acid sulphate soils. Thanh Hoa was chosen as an area representative of the severe acid sulphate soils of the delta.

Methods and materials

The study follows the FAO Framework for Land Evaluation (FAO 1976). It involves a study of the land, resulting in land units based on soil and hydrological differences, and a description of the land use types. Land use systems, i.e. land use types applied under certain soil and hydrological conditions, are next distinguished. Following the 'filtering system' described in FAO (1983) the most promising land use types are selected, based on (i) the benefits to the farmer, (ii) the development targets of the local gouvernment, (iii) the recurrent agricultural conditions in the area, and (iv) the potential increase in production of the farms in terms of employment, crop intensification and diversification, and production per hectare. The land use requirements of these promising land use types are established and, finally, a matching exercise determines to what extent a land unit meets those requirements.

Present land use types are used as basis for the land evalution exercise because they have been developed by trial and error, are adapted to the local conditions and have proved to be feasible and acceptable to the local farmers. It was felt too risky to propose completely new forms of land use, especially in hostile acid sulphate soil areas.

For both study areas, general and detailed soil and hydrological survey maps were available at scales varying from 1/250 000 to 1/25 000. All land use data were collected by farmer interviews, February/March 1990 for Phung Hiep, May/June 1991 for Thanh Hoa.

The study areas

Phung Hiep is a district of Hau Giang province, located west of the Bassac river, about 35 km southwest of Can Thò town (Figure 1). Its area is about 24 000 ha. Roughly 40 per cent consists of non-acid river clays, situated in the northern part of the area; the southern part has acid sulphate soils of various degrees of severity.

Except for the most acid part, the entire area has access to irrigation and drainage canals. Strong tidal movement is present throughout the district and water is fresh throughout the year. Floods in the wet season occur all over the district with a maximum depth of about 80 cm.

All land is used for agriculture with a wide variety of products. Phung Hiep is a densely populated district, especially the northern part and around the town of Phung Hiep.

Thanh Hoa district, covering 37 000 ha, is situated in the Plain of Reeds, about 30 km north of Long An town in An Giang province (Figure 1). Acid sulphate soils, floods in the rainy season and lack of fresh water in the dry season are severe con-

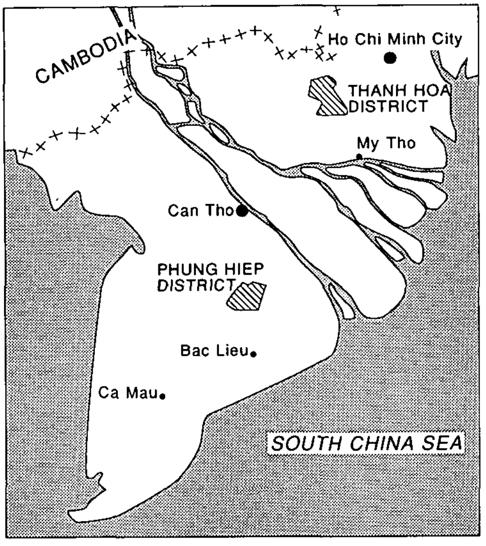


Figure 1 Location of Phung Hiep and Thanh Hoa districts.

straints for open land use. Only a quarter of the area is cultivated for rice and upland crops. Most of the cultivated areas are along the West Vam Co river and the main canals where there are favourable conditions for irrigation and drainage. Wetland covered with *Eleocharis spp* and *Cyperus spp* occupies about half the area, the remaining quarter consists of natural *Melaleuca spp* forest. The population density is 66 km^{-2}, low for the Mekong delta. Most people are poor farmers with a low education level, only 5 per cent of the farmers own tractors, buffalo or pumps. Apart from oil extraction from *Melaleuca* leaves, there are virtually no off-farm activities.

Land units

Land units are distinguished according to soil conditions and hydrological regimes which determine, to a large extent, the land use possibilities in the Mekong delta. Twenty-seven units are indentified in Phung Hiep. A description is given in Table 1. Phung Hiep has 40 per cent non-acid, 38 per cent slightly acid, 20 per cent moderately acid and 2 per cent very acid soils. The most extensive land units are numbers 1, 14, 16, 25.

Twenty-three units are identified in Thanh Hoa. The detailed description is given in Table 2. Thanh Hoa has 17 per cent non-acid, 43 per cent moderately acid and 40 per cent very acid soils. Most extensive land units are numbers 9, 10, 15 and 22.

Present land use

Present land use has been taken as a basis for land evaluation because land use types are already practised in the various physical conditions and provide basic information

Table 1 Land units and their characteristics in Phung Hiep district

Land unit	Soil types		Soil characteristics		Hydrological characteristics		
	Land Unit Code	Soil Taxonomy subgroups	Sulfuric horizon depth, cm	Sulfidic material depth, cm	Tide level relative to land surface		
					Av. Flood depth, cm	High tide March/April	Low tide Low tide
1	NA1 F1 H+/↓ L+	Typic Humaquept fluvic	–	> 150	< 40	at/below	at
2	NA1 F1 H↑ L+	Typic Humaquept fluvic	–	> 150	< 40	above	at
3	NA1 F2 H↑ L+	Typic Humaquept fluvic	–	> 150	40-60	above	at
4	NA1 F2 H↑ L↓	Typic Humaquept fluvic	–	> 150	40-60	above	below
5	NA1 F3 H↑ L+	Typic Humaquept fluvic	–	> 150	60-80	above	at
6	NA2 F3 H↑ L+	Typic Humaquept fluvic	–	> 150	60-80	above	at
7	SA1 F3 H↑ L+	Typic Humaquept fluvic	–	100-150	60-80	above	at
8	SA1 F3 H↑ L↓	Typic Humaquept fluvic	–	100-150	60-80	above	below
9	SA2 F2 H↑ L+	Sulfic Humaquept fluvic	100-150	> 150	40-60	above	at
10	SA2 F2 H↑ L↓	Sulfic Humaquept fluvic	100-150	> 150	40-60	above	below
11	SA3 F1 H↑ L+	Typic Humaquept	–	100-150	< 40	above	at
12	SA3 F2 H↑ L↓	Typic Humaquept	–	100-150	40-60	above	below
13	SA3 F2 H↑ L+	Typic Humaquept	–	100-150	40-60	above	at
14	SA4 F3 H+/↓ L+	Typic Humaquept	–	100-150	60-80	at/below	at
15	SA4 F1 H+/↓ L+	Sulfic Humaquept	100-150	> 150	< 40	at/below	at
16	SA4 F2 H↑ L+	Sulfic Humaquept	100-150	> 150	40-60	above	at
17	SA4 F2 H↑ L↑	Sulfic Humaquept	100-150	> 150	40-60	above	above
18	SA4 F3 H+/↓ L+	Sulfic Humaquept	100-150	> 150	60-80	at/below	at
19	SA4 F3 H↑ L+	Sulfic Humaquept	100-150	> 150	60-80	above	at
20	SA4 F3 H↑ L↑	Sulfic Humaquept	100-150	> 150	60-80	above	above
21	MA F1 H+/↓ L+	Sulfic Humaquept	50-100	> 100	< 40	at/below	at
22	MA F1 H↑ L+	Sulfic Humaquept	50-100	> 100	< 40	above	at
23	MA F2 H↑ L↑	Sulfic Humaquept	50-100	> 100	40-60	above	above
24	MA F3 H+/↓ L+	Sulfic Humaquept	50-100	> 100	60-80	at/below	at
25	MA F3 H↑ L+	Sulfic Humaquept	50-100	> 100	60-80	above	at
26	MA F3 H↑ L↑	Sulfic Humaquept	< 50	> 100	60-80	above	above
27	VA F3 H+/↓ L+	Typic Sulfaquept		> 50	60-80	at/below	at

Explanation of the codes:
NA = not acid; SA = slightly acid; MA = moderately acid; VA = very acid
F1,2,3 = average maximum flood depth
H = high tide level in the dry season relative to soil surface
L = low tide level at the end of the flood season relative to soil surface
↑ = above soil surface
↓ = below soil surface
+/↓ = at or below soil surface
\+ = at soil surface

Table 2 Land Units and their characteristics in Thanh Hoa district

Land Unit	Land Unit Code	Soil type	Soil characteristics		Hydrological characteristics				
		Vietnamese classification	Sulfuric horizon depth, cm	Sulfidic material depth, cm	Flood depth, cm	Flood time (from/to)	Salt intr. months	Possibility of gravity drainage	Fresh water in dry season
1	NA Fd3 Ft1 Su4 Wd1 Wf2	Alluvial	–	> 100	< 30	15Sep/15Dec	< 3	Good	Temporary
2	NA Fd1 Ft1 Su4 Wd1 Wf2	Soils	–	> 100	50-100	15Sep/15Dec	< 3	Good	Temporary
3	NA Fd1 Ft2 Su4 Wd3 Wf3	with	–	> 100	50-100	15Sep/30Dec	< 3	Very poor	No
4	NA Fd1 Ft1 Su5 Wd2 Wf1	deep	–	> 100	50-100	15Sep/15Dec	0	Poor	Permanent
5	NA Fd1 Ft1 Su5 Wd2 Wf2	sulfidic	–	> 100	50-100	15Sep/15Dec	0	Poor	Temporary
6	NA Fd1 Ft2 Su5 Wd3 Wf3	material	–	> 100	50-100	15Sep/30Dec	0	Very poor	No
7	MA1 Fd1 Ft2 Su4 Wd3 Wf3	Potential	–	50-100	50-100	15Sep/30Dec	< 3	Very poor	No
8	MA1 Fd1 Ft1 Su4 Wd1 Wf2	moderately	–	50-100	50-100	15Sep/15Dec	< 3	Good	Temporary
9	MA1 Fd1 Ft2 Su5 Wd3 Wf3	acid	–	50-100	50-100	15Sep/30Dec	0	Very poor	No
10	MA1 Fd1 Ft1 Su5 Wd2 Wf1	sulphate	–	50-100	50-100	15Sep/15Dec	0	Poor	Permanent
11	MA1 Fd1 Ft2 Su5 Wd3 Wf1	soil	–	50-100	50-100	15Sep/30Dec	0	Very poor	Permanent
12	MA2 Fd3 Ft1 Su4 Wd1 Wf2	Actual	50-100	> 100	< 30	15Sep/15Dec	< 3	Good	Temporary
13	MA2 Fd1 Ft2 Su4 Wd3 Wf3	moderately	50-100	> 100	50-100	15Sep/30Dec	< 3	Very poor	No
14	MA2 Fd1 Ft1 Su5 Wd2 Wf1	acid sul-	50-100	> 100	50-100	15Sep/15Dec	0	Poor	Permanent
15	MA2 Fd1 Ft2 Su5 Wd3 Wf3	phate soil	50-100	> 100	50-100	15Sep/30Dec	0	Very poor	No
16	VA1 Fd1 Ft1 Su4 Wd1 Wf2	Potential	–	0-50	50-100	15Sep/15Dec	< 3	Good	Temporary
17	VA1 Fd1 Ft1 Su4 Wd3 Wf3	severely	–	0-50	50-100	15Sep/30Dec	< 3	Very poor	No
18	VA1 Fd1 Ft1 Su5 Wd2 Wf1	acid sulphate	–	0-50	50-100	15Sep/15Dec	0	Poor	Permanent
19	VA1 Fd1 Ft2 Su5 Wd3 Wf3	soil	–	0-50	50-100	15Sep/30Dec	0	Very poor	No
20	VA2 Fd1 Ft2 Su4 Wd3 Wf3	Actual	0-50	> 50	50-100	15Sep/30Dec	< 3	Very poor	No
21	VA2 Fd1 Ft1 Su5 Wd2 Wf1	severely	0-50	> 50	50-100	15Sep/15Dec	0	Poor	Permanent
22	VA2 Fd1 Ft2 Su5 Wd3 Wf3	acid sulphate	0-50	> 50	50-100	15Sep/30Dec	0	Very poor	No
23	VA2 Fd1 Ft2 Su4 Wd3 Wf3	soil	0-50	> 50	50-100	15Sep/30Dec	< 3	Very poor	No

Explanation of the codes:

NA = not acid; MA = moderately acid; VA = very acid
Fd = flood depth
Ft = Flooded time
Su = Salt intrusion duration
Wd = Possibility for drainage by gravity
Wf = Fresh water availability in the dry season

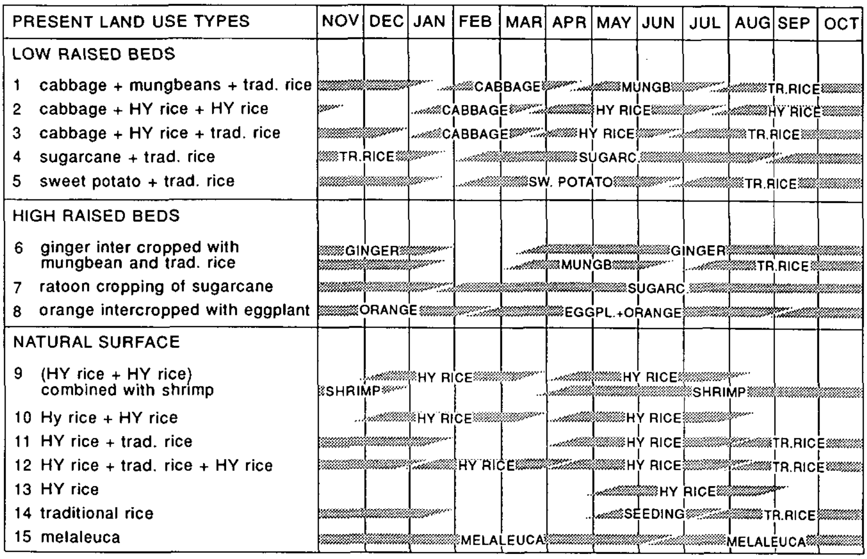


Figure 2 Cropping calendar of present land use types in Phung Hiep

needed to describe socio-economic, technical and management attributes. They are acceptable to the local population, and have often only been accepted after a long period of trial and error.

Phung Hiep

Figure 2 shows the cropping calendar of 18 major land use types practised in Phung Hiep. The way in which farmers apply these land use types varies strongly with differences in soil and hydrological conditions. Therefore it is important to distinguish land use systems, i.e. a land use type practised under specified soil and hydrological conditions. Table 3 shows the 28 land use systems present in Phung Hiep, grouped according to soils. In the non-acid part, seven land use systems are distinguished of which two can only be practised with pump irrigation or drainage. In the slightly acid part, eleven land use systems are practised, seven without irrigation and drainage, two are based on gravity irrigation and drainage, one has irrigation by gravity and drainage by pumping, and one uses irrigation and drainage by pumps. In the acid part, one system uses irrigation by gravity and drainage by pumps.

Land and water management, cultivation practices

Construction of raised beds is the most important land management practice. Low and high beds are constructed to avoid flooding in the rainy season and to improve the poor internal drainage of the heavy-textured natural soil. Vegetables and other upland crops are grown on the beds. Rice is grown on the natural soil surface, as is the case with *Melaleuca*. The way in which beds are constructed depends on soils and crops. In non-acid and slightly acid soils, temporary low raised beds are constructed for upland crops during the dry season and high raised beds for crops which grow all year round (Figure 3). In the moderately and very acid soils, precautions

Table 3 Present land use systems in Phung Hiep, Capital Intensity (i.e. initial investment (II) and recurrent annual costs (RAC), Gross Income per year (GI), Gross Margin/ha/year (GM) and Gross Margin/ha/manday in 1990

PRESENT LAND USE SYSTEMS		CAPITAL INTENSITY		GI	GM/HA/ YEAR	GM/HA/ MANDAY
		IIx1000 VND	RAC x1000 VND	x1000 VND	x1000 VND	x1000 VND
A.	*Non-acid Soil Zone:*					
1.	Cabbage + mungbean + traditional rice	410	3035	12320	9284	18
2.	Cabbage + irrigated HY rice + HY rice	410	3468	12050	8581	19
3.	Cabbage + irrigated HY rice + traditional rice	410	3258	11900	8641	21
4.	Orange intercropped with eggplant	5080	758*	26800	26042	**
5.	Irrigated HY rice + pump drained HY rice	660	1509	3450	1940	8
6.	Irrigated HY rice + traditional rice	410	1015	2700	1684	8
7.	Irrigated HY rice + trad. rice + pump drained HY rice	660	1873	4650	2776	9
B.	*Slightly Acid Soil Zone*					
8.	Sugarcane + traditional rice	2100	3223	7610	4386	12
9.	Sweet potato + traditional rice	200	1510	3000	1489	7
10.	Sugarcane (3 years)	3780	1610	8000	6389	21
11.	Ginger intercropped with mungbean and traditional rice	3980	3112	19074	15961	40
12.	Gravity irr. HY rice + gravity drained HY rice / shrimp	1010	1563	5820	4257	13
13.	Gravity irrigated HY rice + traditional rice / shrimp	1010	1512	7050	5537	19
14.	Gravity irrigated HY rice + gravity drained HY rice	660	1219	3150	1930	8
15.	Gravity irrigated HY rice + pump drained HY rice	660	1261	3000	1739	7
16.	Gravity irrigated HY rice + traditional rice	410	883	2550	1667	8
17.	Irrigated HY rice + traditional rice	410	923	2550	1627	8
18.	Irrigated HY rice + traditional rice + pump drained rice	660	1561	4050	2488	8
C.	*Acid soil zone:*					
19.	Sugarcane + traditional rice	2100	3182	7060	3878	10
20.	Eucalyptus	2100	198	4000	3801	**
21.	Cashew intercropped with pineapple	5040	316	6653	6337	31
22.	Sugarcane (3 years)	5040	1610	8000	6389	21
23.	Gravity irrigated HY rice + pump drained HY rice	660	1181	2280	1099	5
24.	Gravity irrigated HY rice + traditional rice	410	769	1830	1060	5
25.	Irrigated HY rice + traditional rice	410	827	1830	1002	5
26.	Irrigated HY rice	410	432	1200	767	6
27.	Traditional rice	0	120	720	600	7
28.	Melaleuca	760	61	5500	5448	**

US$ 1 = VN Dong 4 000 (02/1990)
(*) : no data available on hired labour
(**) : no data

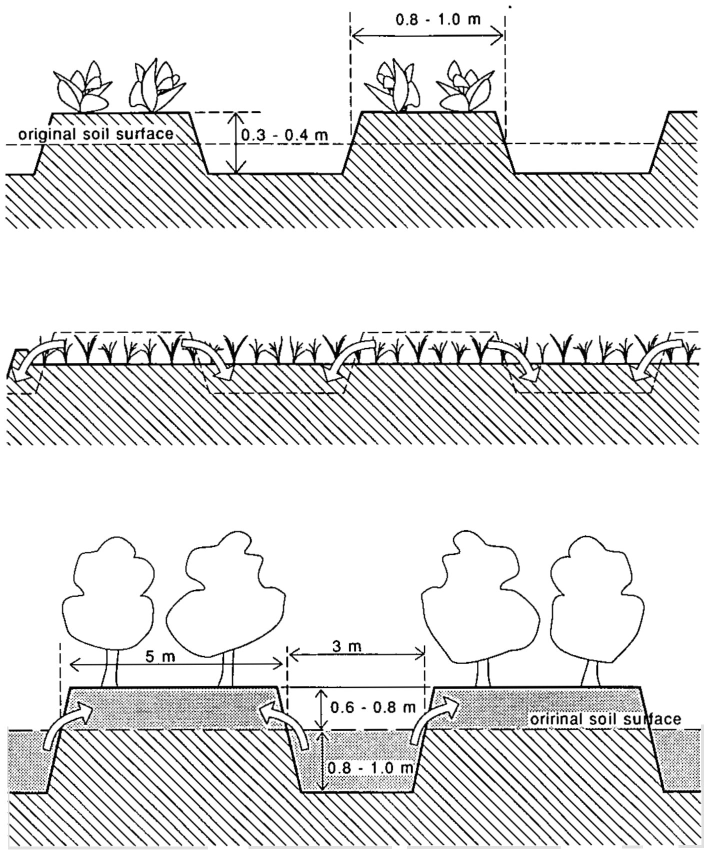


Figure 3 Types of raised beds in non-acid and slightly acid soils, Phung Hiep

are needed to avoid bringing the acid subsoil to the top of the bed (Figure 4).

Another land and water management practice is needed when applying the combination of rice on the fields and shrimps in the ditches surrounding the field. This system was recently introduced in Phung Hiep and requires (i) tidal water movement throughout the year, (ii) flood protection by means of high dikes surrounding the fields and (iii) gravity tidal irrigation and drainage facilities during the flood period. Rice/shrimp land use types are only found in the slightly acid area where tidal irrigation and drainage are possible throughout the year. A schematic design is given in Figure 5.

Ploughing on non-acid land is mainly done by tractors, on slightly and moderately acid land by buffalo. Land preparation for vegetables and upland crops is done by hand, as well as sowing, (trans)planting and fertilization. The use of fertilizers and pesticides is high in the non-acid and slightly acid areas, but low on acid soils. The quantity of seed used for high yielding rice is 200-300 kg/ha. This high quantity of seed is needed to control weeds and to give a high number of main panicles, a major factor to increase yields.

Family labour is the most important. In the double or triple rice land use systems of the slightly and non-acid areas, farmers use hired labour for land preparation,

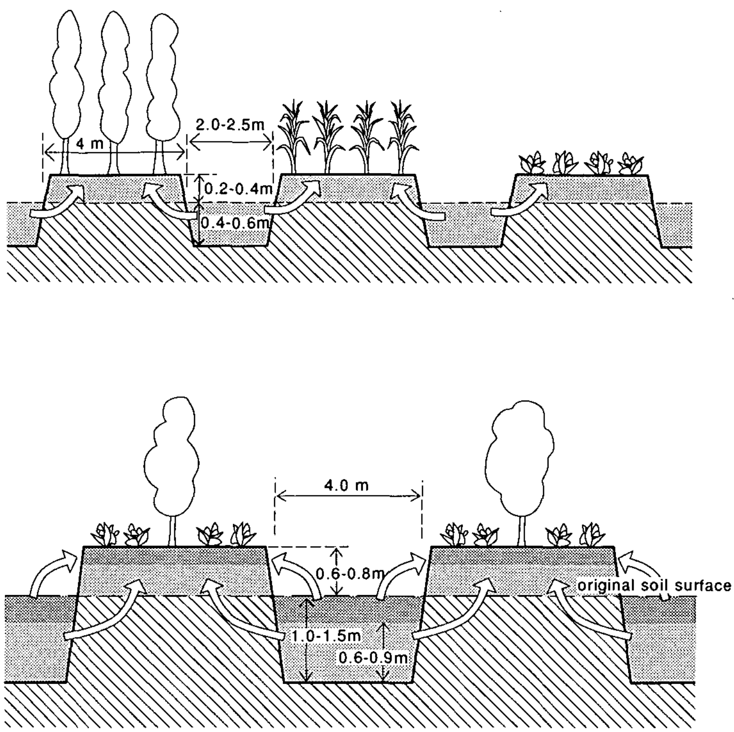


Figure 4 Types of raised beds in acid soils

(trans)planting of rice, irrigation of upland crops and the harvest. In the acid areas, family and exchange labour is mainly used. Only in peak labour periods of some crops, such as sugar cane or pineapple, is hired labour indispensable.

Yields are generally higher in the slightly and non-acid areas, and double or triple crops are cultivated much more extensively compared with the acid part.

Financial analysis

Table 3 shows that the recurrent costs and gross income in the slightly and non-acid areas are generally higher than in the acid part. Recently introduced systems (numbers 1-4, 8, 11-13, 19, 21, 23 and 28) gave much higher gross incomes in the slightly and non-acid part compared to the acid zone. Gross incomes from double rice differ little between soils.

Capital intensity refers to the levels of capital investment and the recurrent costs of a land use system. Gross margin/ha/year and gross margin/man-day can be used to analyze the profitability of a land use system for a farmer. Results are also shown in Table 3. Orange intercropped with eggplant, ginger intercropped with mung bean and traditional rice, ratoon sugar cane and cashew intercropped with pineapple require high capital investment, mainly due to the need to construct raised beds. At the same time, these systems have the highest gross income.

Recurrent costs are generally higher in the slightly and non-acid areas compared

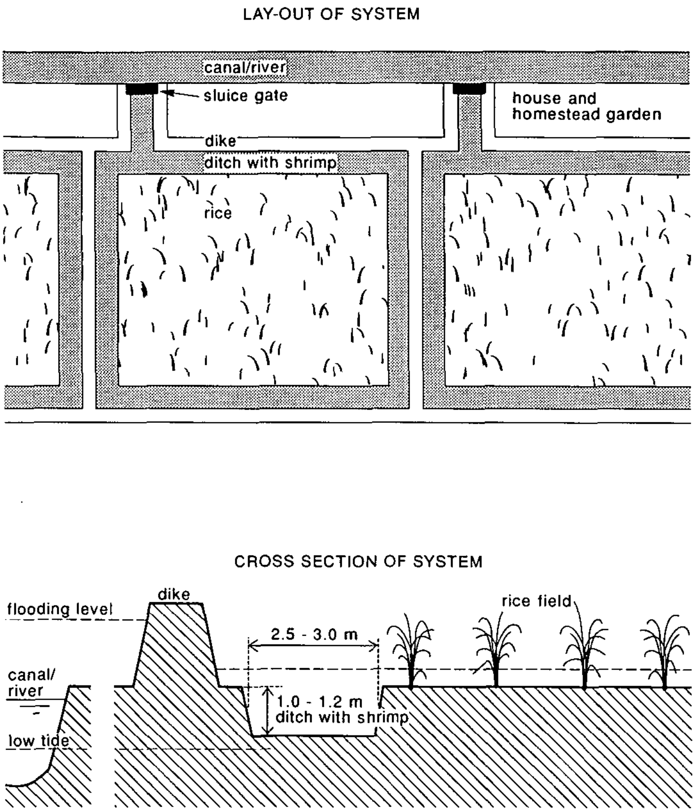


Figure 5 Ditch system for combined rice-shrimp cultivation in Phung Hiep

with the acid areas. Gross margin/ha/year varies within and between soil zones. Most systems have a low gross margin/ha/year in the acid area but this does not apply to some promising systems such as cashew intercropped with pineapple, sugarcane followed by rice and Melaleuca. The latter do, however, have high recurrent costs. Gross margin/manday is high in systems with cashcrops (cabbage, ginger, sugar cane, cashew) but low in all rice systems, regardless of the soil quality. The only exception is the system where rice is combined with shrimp cultivation.

Thanh Hoa

Present land use types and land use systems

Thirteen land use types were identified in Thanh Hoa, a surprising variety for recently cleared acid sulphate land.

The cropping calendar of the land use types is shown in Figure 6. Single, double and triple rice are most widespread. Upland crops (yams, sugar cane, cassava, cashew) are cultivated on small scale only.

In Thanh Hoa, 29 land use systems can be distinguished. They are shown in Table 4, and have been grouped according to soil conditions. Double rice systems and yams

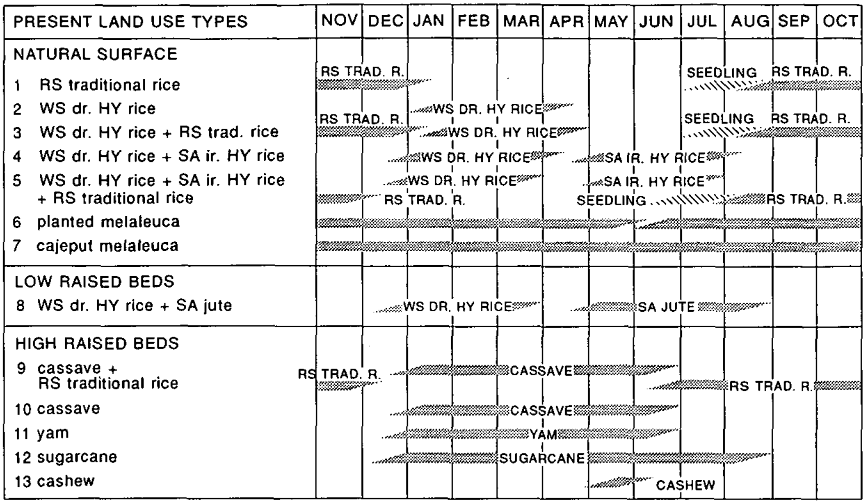


Figure 6 Cropping calendar of present land use types in Thanh Hoa

are cultivated in all soil conditions, even on a limited scale in the very acid soils. Triple rice is only found in a thin fringe along the Vam Co river which crosses the district. Cassava and sugar cane are not found in very acid conditions, Melaleuca is only cultivated (or exploited) on moderately and very acid soils.

Land/water management, cultivation practices

In order to cultivate HY rice, farmers must surround their fields with small dikes to enable the pumping out of flood water in December, at the end of the rainy season. In this way they can start the rice crop early and use floodwater surrounding the field for gravity irrigation. They also construct a shallow drainage system to remove soluble acidity from the topsoils in the early part of the rainy season (Xuan 1982).

High raised beds are needed to cultivate permanent upland crops (cassava, sugar cane, cashew) and low raised beds for mixed systems of rice and jute. Other new cultivation techniques which are not specific for the area are crop multiplication, zero-tillage between two rice crops (to gain time), irrigation, drainage and fertilizer application.

Financial analysis

The financial analysis of the 29 land use systems, shown in Table 4, indicates that double and triple rice, yams and sugar cane give the highest gross incomes. At the same time, these crops require the highest investments. Double or triple rice give a high gross margin per ha per year in non-acid areas. In the acid area, yams give the highest gross margins, even higher than the double or triple rice systems on good soils. Although economically attractive, it must be realized that yams are not a staple food in Vietnam and, therefore, have limited marketing and export possibilities.

The major part of the investment goes into the special soil and water management measures necessary to overcome the land constraints, i.e. the preparation of the land. Double-triple rice and upland crops have high labour requirements (150-300 mandays/

Table 4 Present land use systems in Thanh Hoa, Capital Intensity (i.e. initial investment (II) and recurrent annual costs (RAC), Gross Income per year (GI), Gross margin/ha/year (GM) and Gross margin/ha/manday, 1991

PRESENT LAND USE SYSTEMS	CAPITAL INTENSITY		GI	GM/HA/ YEAR	GM/HA/ MANDAY
	IIx1000 VND	RAC x1000 VND	x1000 VND	x1000 VND	x1000 VND
A. *Non-acid Soil Zone:*					
1. Traditional rice	220	1 383	2 000	595	5
2. Drained HY rice + irrigated HY rice	500	4 410	7 356	2 896	14
3. Drained HY rice + irrigated HY rice + traditional rice	800	4 582	10 000	5 338	18
4. Drained HY rice + jute	700	3 048	3 750	632	2
5. Cassava + traditional rice	450	1 649	5 330	3 607	36
6. Cassava	450	881	2 498	1 542	32
7. Yam	1 200	2 549	4 875	2 127	14
8. Sugar cane	640	2 489	6 150	3 554	24
B. *Moderately Acid Soil Zone*					
9. Drained HY rice + irrigated HY rice	630	4 304	7 327	2 959	14
10. Drained HY rice + irrigated HY rice + traditional rice	900	4 044	9 900	5 766	25
11. Drained HY rice	600	854	3 200	2 287	24
12. Cassava	520	1 648	2 664	929	8
13. Yam	1 500	3 589	6 825	2 986	16
14. Sugar cane	750	2 730	5 250	2 395	12
15. Cassava + traditional rice	840	1 790	5 172	3 242	17
16. Melaleuca forestry for timber	2 214	739	1 050	291	2
17. Melaleuca for cajuput oil	350	50	1 270	1 142	9
C. *Potentially Severely Acid Zone:*					
18. Drained HY rice + traditional rice	900	3 360	4 500	1 051	6
19. Drained HY rice + irrigated HY rice	950	4 331	6 262	1 836	9
20. Drained Hy rice + irrigated HY rice + traditional rice	1 130	4 044	9 400	5 243	21
21. Cassava	920	1 056	2 581	1 372	12
22. Yam	1 840	4 289	11 895	7 300	39
23. Sugar cane	1 840	2 816	8 875	5 753	37
D. *Severely acid soil zone:*					
24. Drained HY rice + irrigated HY rice	1 100	4 220	7 375	3 045	15
25. Drained HY rice + jute	1 550	3 100	4 000	745	3
26. Yam	2 400	4 523	12 350	7 427	39
27. Cashew	2 200	319	1 112	3 066	59
28. Melaleuca forestry for timber	2 214	739	1 050	291	2
29. Melaleuca for cajuput oil	350	50	1 270	1 142	9

US$ 1 = VN Dong 7 500 (05/1991)

ha/year) with peaks at land preparation and harvesting. Ploughing, irrigation and rice threshing with hired machinery significantly raise the inputs for double and triple rice crops.

Wide price fluctuations can have a significant effect on the calculations made here. This applies especially to sugar cane and jute, which showed a big price decrease in 1992.

Comparing land use types in Phung Hiep and Thanh Hoa

Phung Hiep data were gathered one year earlier than those from Thanh Hoa. Price increase has occured due to inflation. Initial investments for double rice crops, for instance, vary between 400 and 600 000 VN Dong in Phung Hiep, and between 500 and 900 000 in Thanh Hoa. The recurrent costs, however, are far higher in Thanh Hoa. The main reason is tidal irrigation during the dry season, which can be done in Phung Hiep, but not in Thanh Hoa. This means high pumping costs in Thanh Hoa.

In both districts, capital intensity usually increases with decreasing soil quality. When cultivating sugar cane, for instance, farmers need to construct higher raised beds because the acid soils are in low places, implying higher inital investments in labour and recurrent costs for maintenance.

Striking, also, is, the decrease in income by Melaleuca forestry when comparing Phung Hiep to Thanh Hoa. The market in Thanh Hoa is saturated, resulting in low prices.

Remarkably, the economically-most-interesting systems of one district are not found in the other. Phung Hiep has horticultural systems because the district has easy access to markets (Phung Hiep town, Can Tho, Ho Chi Minh City). Thanh Hoa is isolated. On the other hand, yams are not cultivated in Phung Hiep.

Selected land use types and their key attributes

Following the 'filtering' system of FAO (1983) and taking into account the development objectives of the local government, the agricultural conditions of the area, the present land use types, and the social and financial analysis, 11 land use types were selected for the land evaluation exercise. They are shown in Tables 5 and 6 with the key attributes: potential production, cultural practices, capital intensity (i.e. capital investment and recurrent costs), labour requirements and, maximal gross margin/ha/year. The tables also show the market orientation of the produce.

For Phung Hiep, the selected LUTs 1, 2, 3, 8 and 9 can help to increase the cash income of the farmer, will provide goods suited for export, create more employment and provide more subsistence food. The selected LUTs 4 and 5 will provide more subsistence and exportable rice. LUTs 6 and 7 will produce more raw material for the local sugar factories and provide employment. LUTs 10 and 11 will increase the productivity of the acid areas by raising the income of farmers, provide timber for local consumption and, possibly, for export.

For Thanh Hoa, the LUTs 1, 2, 3, 5 and 6 are attractive because they increase the cash income of the farmer, provide goods suited for export, create more employment and provide more subsistence food. Melaleuca has been chosen because it seems to be the only possible option for the severely acid areas, even though its economic outlook is not very promising.

Table 5 Selected land use types (LUTs) of Phung Hiep District and their key attributes

Selected LUTs	Maximum Production[1]	Capital intensity[2]		Labour requirements	Gross Margin per year[1]	Market orientation
	t/crop/ha	Initial investment	Recurrent costs	Manday/ha/year	x1000 VND/yr	
LUT 1: Vegetable + vegetable + rice	Cabbage: 23 HY rice: 4.5 Trad.rice: 4	Low	High	560	14 500	Cabbage: local cash crop Rice: subsistence
LUT 2: Vegetable + irrigated HY rice + rice	Cabbage: 23 HY rice: 5 Trad.rice: 4	Low	High	485	8 500	Cabbage: local cash crop Rice: subsistence and export
LUT 3: Irrigated HY rice + rice/shrimp	HY rice: 5-6 Trad.rice: 4.5 Shrimp: 0.2	Medium	Medium	330	5 500	Rice: subsistence and export Shrimp: export
LUT 4: Irrigated HY rice + drained HY rice	Irr.rice: 5 Dr.rice: 6	Low	Medium	210	2 000	Subsistence and export
LUT 5: Irrigated HY rice + traditional rice	HY rice: 5 Trad.rice: 4	Low	Low	250	1 600	Subsistence and export
LUT 6: Sugarcane + traditional rice	Raw Cane: 85 Trad.rice: 2.5	Medium	High	420	4 000	Rice: subsistence Cane: local cash crop
LUT 7: Ratoon sugarcane	Raw Cane: 100	High	High	335	6 000	Local cash crop
LUT 8: Fruit trees/eggplant	Orange: 270,000[3] Eggplant: 20	High	Medium	[5]	26 000	Local cash crop
LUT 9: Ginger/mungbean/traditional rice	Ginger: 15 Mungbean: 0.3 Trad.rice: 2.3	High	High	430	15 500	Ginger: export Mung and rice: local cash crop
LUT 10: Cashew/pineapple	Cashew: 3 Pineapple: 10	High	Low	200	6 500	Cashew: local cash crop Pineapple: export
LUT 11: Melaleuca (timber)	35 000 stem/ 6 years	Low[4]	Low	90	5 200	Local cash crop

[1] yields and gross margins of highly suitable land are mentioned
[2] capital intensity and recurrent costs classes are:
High: 3 000 000 – 6 000 000 VN Dong
Medium: 1 000 000 – 3 000 000 VN Dong
Low: below 1 000 000 VN Dong

[3] number of fruits per ha per year
[4] costs of planting not included
[5] no data

Table 6 Selected land use types (LUTs) of Thanh Hoa District and their key attributes

Selected LUTs	Maximum Production[1]	Capital Intensity[2]		Labour require-ments	Gross Margin per year[1]	Market orientation
	t/crop/ha	Initial investment[2]	Recurrent costs[2]	Manday/ ha/yr	x1000 VND/yr	
LUT 1: drained HY rice + traditional rice	HY rice: 3 Trad.rice: 2.1	Low	Medium	175	2262	Subsistence and export
LUT 2: drained HY rice + irrigated HY rice	Dr HY rice: 4.3 Irr HY rice: 3.3	Low	High	211	3305	Subsistence and export
LUT 3: drained HY rice + irr. HY rice + trad.rice	Dr HY rice: 5 Irr HY rice: 4.4 Trad.rice: 2.5	Low	High	235	5766	Subsistence and export
LUT 4: Melaleuca	Timber: 140 m^2 Honey: 15 kg Fish: 90 kg	High	Low	120	291	Subsistence and cash crop
LUT 5: Yam	Tubers: 19	High	High	191	7427	Cash crop
LUT 6: Sugarcane	Raw cane: 59	High	Medium	157	5743	Cash crop

[1] yields and gross margins of highly suitable land are mentioned
[2] Capital intensity and recurrent costs classes are:
High : over 3 000 000 VN Dong
Medium : 1 000 000 – 3 000 000 VN Dong
Low : below 1 000 000 VN Dong

Table 7 Land use requirements for selected LUTs in Phung Hiep

Land Use Requirements	Land Use Type										
	LUT1	LUT2	LUT3	LUT4	LUT5	LUT6	LUT7	LUT8	LUT9	LUT10	LUT11
1 Soil Acidity	+	+	+	+	+	+	+	+	+	+	+
2 Potential Soil Acidity	–	–	+	–	–	+	+	+	+	+	–
3 Flood hazard	+	+	+	–	+	+	+	+	+	+	–
4 Potential tidal irrigation	–	+	+	+	+	–	–	–	–	–	–
5 Potential tidal drainage	–	–	+	+	–	–	–	–	–	–	–

\+ Relevant land use requirement
– Irrelevant

When comparing similar selected LUTs in the two districts, it appears that the recurrent costs for double and triple rice (LUT 1-2-3 in Thanh Hoa, LUT 4-5 in Phung Hiep) are higher in Thanh Hoa than in Phung Hiep. This is because tidal irrigation can be practised at least part of the time in Phung Hiep, while in Thanh Hoa irrigation is needed throughout the dry season, raising the costs. Additionally, inflation has taken place (Thanh Hoa was surveyed one year after Phung Hiep). The higher price for rice in 1991 has also improved the gross margins in Thanh Hoa. The price of Melaleuca timber dropped dramatically. Gross margin was 5.2 million VN Dong during the Phung Hiep survey, a year later it had dropped to 0.3 million Dong in Thanh Hoa. The ratoon sugar cane of Phung Hiep is expected to give higher production and also a higher gross margin (LUT 7 Phung Hiep, LUT 6, Thanh Hoa).

Suitability classification

Tables 7 and 8 show the land use requirements of the LUTs selected. Soil acidity is important for all LUTs with the exception of Melaleuca forestry since Melaleuca does not seem to be affected by acidity. Potential soil acidity is relevant as soon as a LUT requires disturbance of the soil by construction of raised beds for dryland crops or ditches for shrimps. Floods are relevant for virtually all LUTs, except when traditional rice is cultivated. Double rice may easily suffer problems in years of early or very fast-rising flood. Deep floods also affect dryland crops and Melaleuca. The presence of fresh water in the dry season is imperative for all agricultural activities in that time of the year. In Phung Hiep, fresh water is available everywhere but possible tidal irrigation and drainage adds an extra dimension. Salt water intrusion may be relevant in Thanh Hoa when rice is cultivated in the dry season.

The requirements of each selected LUT have been expressed in terms of factor ratings. Tables 9 and 10 show two examples, one for selected LUT 3 (double crop rice and shrimps) in Phung Hiep, and one for selected LUT 6 (sugar cane) in Thanh Hoa. Similar ratings can be made for the other LUTs.

For soil acidity, the depth to the sulfuric horizon is used. A sulfuric horizon within 50 cm depth makes the land unsuited for rice and shrimp (Table 9) and for sugar cane (Table 10). The depth to potentially acid (sulfidic) material is important since

Table 8 Land use requirements for selected LUTs in Thanh Hoa

Land Use Requirements	Land Use Type					
	LUT1	LUT2	LUT3	LUT4	LUT5	LUT6
1 Soil acidity		+	+	–	+	+
2 Potential Soil Acidity	–	–	–	–	+	+
3 Flood hazard	–	+	+	+	+	+
4 Potential fresh water supply in dry season		+	+	–	+	+
5 Potential tidal drainage	–	+	+	–	–	–
6 Salt water intrusion	–	+	+	–	–	–

\+ Relevant land use requirement
– Irrelevant

Table 9 Factor Ratings for selected LUT 3 (Irrigated High Yielding rice + a second rice crop combined with shrimps) in Phung Hiep

Land Use Requirements		Factor Ratings			
Land Quality	Diagnostic factor	S1	S2	S3	N
Soil acidity (both rice and shrimps)	Depth sulfuric horizon (cm)	> 100	> 100	50-100	< 50
Potential soil acidity (both rice and shrimps)	Depth sulfidic material (cm)	> 100	> 100	50-100	< 50
Flood hazard (rice)	Maximum flood depth (cm)	< 60	60	60-80	> 80
Possibility of tidal irrigation (rice)	High tide level compared to soil surface	above	at/below	below	–
Possibility of tidal drainage (rice)	Low tide level compared to soil surface	below	at	above	above
Possibility of tidal irrigation (shrimps)	High tide level compared to soil surface	above	above/at	at	below
Possibility of tidal drainage (shrimps)	Low tide level compared to soil surface	below	below	at	above

Suitability ratings: S1 = highly suitable; S2 = moderately suitable; S3 = marginally suitable; N = not suitable

in both the rice/shrimps and sugar cane, excavations are necessary for construction of canals (shrimps) and raised beds (sugar cane). Sulfidic material within 50 cm makes the rice and shrimps system unsuitable, but sugar cane is still marginally suited. Inevitably, sulfidic material will be exposed when constructing the beds, especially in areas with deep floods. Deep sulfidic material (over 100 cm) will not be touched.

Floods and tides are of great importance in Phung Hiep. Floods less than 60 cm do not harm a traditional rice crop but floods of 60 cm deep or deeper depress rice yields. When flooding is deeper than 80 cm, traditional rice is not possible. A high tide above the soil surface combined with low tides below the surface offer the farmers optimal conditions for water management of both rice and shrimp. Yields will be reduced when tides are different.

Floods are also important in Thanh Hoa, but not so tides. Tidal movement is limited in the dry season, tidal irrigation is not possible. In the rainy season tides are absent. Floods deeper than 100 cm make sugar cane impossible; floods between 50 and 100 cm

Table 10 Factor ratings for selected LUT 6 (sugar cane) in Thanh Hoa

Land use requirements		Factor Ratings			
Land Quality	Diagnostic factor	S1	S2	S3	N
Soil acidity	Depth sulfuric horizon (cm)	absent	> 100	50-100	< 50
Potential soil acidity	Depth sulfidic material (cm)	> 100	50-100	< 50	–
Flood hazard	Maximum flood depth (cm)	< 30	30-50	50-100	> 100
Possibility of fresh water supply	Fresh water availability in dry season	permanent	temporary	no	–

Suitability ratings: S1 = highly suitable; S2 = moderately suitable; S3 = marginally suitable; N = not suitable will greatly reduce crop yields. A permanent supply of fresh water in the dry season guarantees a good crop. Where fresh water is only temporary because of saline intrusion during the dry season, yields are reduced.

Tables 11 and 12 show the land units of both districts, their suitability for the selected land use types and the limiting factors.

Land suitability

In Phung Hiep, land units in the non-acid part with shallow or medium floods are highly suited for land use types 1 (twice vegetables and rice), 7 (ratoon sugar cane), 9 (ginger and mungbean, followed by rice), 10 (cashew and pineapple) and 11 (Melaleuca). LUT 11 (Melaleuca) can be cultivated everywhere. Capital-intensive and profitable systems such as 1,2,3 and 8 (i.e. triple crops of rice and vegetables, rice and shrimp or fruits and vegetables) are marginally suitable or unsuitable for the moderately and very acid land. The moderately acid land units with favourable water management conditions (units 21-23) are moderately suited for double rice (LUT 4 and 5), sugar cane (LUT 7), ginger/mungbean and traditional rice (LUT 9) and cashew/pineapple.

In Thanh Hoa, non-acid and moderately acid units (units 1-11 and 16-19) are highly suitable for double rice cultivation of high yielding and traditional rice (LUT 1). In the other units, problems of fresh water availability and acidity make the land only moderately or marginally suitable. Twice high yielding rice (LUT 2) is more difficult, also in the non-acid and moderately acid areas, because of deep and long floods and acidity. Triple rice can be practised successfully only in unit 1, while unit 12 is marginally suited because of long and deep floods, problems of timely drainage at the end of the rainy season, and availability of water for irrigation.

Yams can be cultivated in all land units but the non-acid and moderately acid land is only moderately suitable, and the very acid land marginally suitable, because of floods and poor water availability. The deep flood is also a problem for sugar cane. On the acid land, the potential acidity is a problem because high raised beds need to be made, disturbing the potentially acid subsoil.

The entire Thanh Hoa area is moderately suited for Melaleuca. Deep floods prevent high suitability.

Conclusions

Taking present land use as a basis for the description and selection of relevant land use types, land evaluation studies of acid and non-acid land in the Mekong delta demonstrate large differences in level of investment, gross margins and labour requirements.

The most important land and water management practices for rice cultivation are the use of varieties and selection of growth periods adapted to the local flood depth and flood duration, and optimal use of the irrigation and drainage possibilities offered by tidal movement. For upland crops, the construction of raised beds to overcome floods and improve drainage is important. In Phung Hiep, a land and water management system for combined rice and shrimps cultivation has been developed.

There is a surprisingly wide variety of land use systems on acid soils. Eleven land

Table 11 Land suitability classification for Phung Hiep District

Land Unit	Land Unit Code *	Suitability classes S1	S2	S3	N
1	Na1 F1 H+/↓ L+	LUT 1,7,8,9,10,11	LUT 2,4,5 di	LUT 3,6 dfi	–
2	NA1 F1 H↑ L+	LUT 1,2,5,7,8,9,10,11	LUT 4 d	LUT 3,6 df	–
3	NA1 F2 H↑ L+	LUT 1,2,5,6,7,9,10,11	LUT 4,8 df	LUT 3 d	–
4	NA1 F2 H↑ L↓	LUT 1,2,3,4,5,6,7,9,10,11	LUT 8 f	–	–
5	NA1 F3 H↑ L↓	LUT 6,11	LUT 4 d	LUT 1,2,3,5,7,8,9,10 df	–
6	NA2 F3 H↑ L+	LUT 6,11	LUT 4 d	LUT 1,2,3,5,7,8,9,10 df	–
7	SA1 F3 H↑ L+	LUT 6,11	LUT 4 d	LUT 1,2,3,5,7,8,9,10 dfp	–
8	SA1 F3 H↑ L↓	LUT 4,6,11	–	LUT 1,2,3,5,7,8,9,10 fp	–
9	SA2 F2 H↑ L+	LUT 5,6,7,9,10,11	LUT 1,2,4,8 dfs	LUT 3 d	–
10	SA2 F2 H↑ L↓	LUT 3,4,5,6,7,9,10,11	LUT 1,2,8 fs	–	–
11	SA3 F1 H↑ L+	LUT 1,2,5,7,9,10,11	LUT 4,8 dp	LUT 3,6 df	–
12	SA3 F2 H↑ L↓	LUT 1,2,3,4,5,6,7,9,10,11	LUT 8 fp	–	–
13	SA3 F2 H↑ L+	LUT 1,2,5,6,7,9,10,11	LUT 4,8 dfp	LUT 3 d	–
14	SA3 F3 H+/↓ L+	LUT 6,11	LUT 4 di	LUT 1,2,3,5,7,8,9,10 dfip	–
15	SA4 F1 H+/↓ L+	LUT 7,9,10,11	LUT 1,2,4,5,8 dis	LUT 3,6 dfi	–
16	SA4 F2 H↑ L+	LUT 5,6,7,9,10,11	LUT 1,2,4,8 dfs	LUT 3 d	–
17	SA4 F2 H↑ L↓	LUT 5,6,7,9,10,11	LUT 1,2,8 fs	LUT 4 d	LUT 3
18	SA4 F3 H+/↓ L+	LUT 6,11	LUT 4 di	LUT 1,2,3,5,7,8,9,10 dfis	–
19	SA4 F3 H↑ L+	LUT 6,11	LUT 4 di	LUT 1,2,3,5,7,8,9,10 dfs	–
20	SA4 F3 H↑ L↑	LUT 6,11	–	LUT 1,2,4,5,8,9,10 dfs	LUT 3
21	MA F1 H+/↓ L+	LUT 11	LUT 4,5,7,9,10 dis	LUT 1,2,3,6,8 dfis	–
22	MA F1 H↑ L+	LUT 11	LUT 4,5,7,9,10 ds	LUT 1,2,3,6,8 dfs	–
23	MA F2 H↑ L↑	LUT 11	LUT 5,6,7,9,10 s	LUT 1,2,4,8 dfs	LUT 3
24	MA F3 H+/↓ L+	LUT 11	LUT 4,6 dis	LUT 1,2,3,5,7,8,9,10 dfis	–
25	MA F3 H↑ L+	LUT 11	LUT 4,6 ds	LUT 1,2,3,5,7,8,9,10 dfs	–
26	MA F3 H↑ L↑	LUT 11	LUT 6 s	LUT 1,2,3,5,7,8,9,10 dfs	LUT 3
27	VA F3 H+/↓ L+	–	LUT 11 s	LUT 10 fs	LUT 1,2,4,5,6,7,8,9

*: For explanation of the land unit codes in Phung Hiep see Table 1

Suitability classes: S1 = highly suitable; S2 = moderately suitable; S3 = marginally suitable; N = not suitable

Limiting factors:
- d = no possibility to drain land by tidal movement
- f = flood hazard
- i = no possibility to irrigate land by tidal movement
- p = potential acidity
- s = soil acidity

Table 12 Land suitability classification for Thanh Hoa District

Land Unit	Land Unit Code *	Suitability Classes S1	S2	S3	N
1	NA Fd3 Ft1 Su4 Wd1 Wf2	LUT 1,2,3,4,5	LUT 6 a	–	–
2	NA Fd1 Ft1 Su4 Wd1 Wf2	LUT 1	LUT 2,4,5 f	LUT 3,6 adf	–
3	NA Fd1 Ft2 Su4 Wd3 Wf3	LUT 1	LUT 2,4,5 f	LUT 3,6 adf	–
4	NA Fd1 Ft1 Su5 Wd2 Wf1	LUT 1	LUT 2,4,5 f	LUT 3,6 adf	–
5	NA Fd1 Ft1 Su5 Wd2 Wf2	LUT 1	LUT 2,4,5 f	LUT 3,6 adf	–
6	Na Fd1 Ft2 Su5 Wd3 Wf3	LUT 1	LUT 2,4,5 f	LUT 3,6 adf	–
7	MA1 Fd1 Ft2 Su4 Wd3 WF3	LUT 1	LUT 2,4,5 f	LUT 3,6 adfw	–
8	MA1 Fd1 Ft1 Su4 Wd1 Wf2	LUT 1	LUT 2,3,4,5 f	LUT 6 af	–
9	MA1 Fd1 Ft2 Su5 Wd3 Wf3	LUT 1	LUT 2,4,5 f	LUT 3,6 adfw	–
10	MA1 Fd1 Ft1 Su5 Wd2 Wf1	LUT 1	LUT 2,4,5 f	LUT 3,6 adf	–
11	MA1 Fd1 Ft2 Su5 Wd3 Wf1	LUT 1	LUT 2,4,5 f	LUT 3,6 adf	–
12	MA2 Fd3 Ft1 Su4 Wd1 Wf2	LUT 4	LUT 1,2,3,5 a	LUT 6 af	–
13	MA2 Fd1 Ft2 Su4 Wd3 Wf3	–	LUT 1,2,4,5 af	LUT 3,6 adfw	–
14	MA2 Fd1 Ft1 Su5 Wd2 Wf1	–	LUT 1,2,4,5 af	LUT 3,6 adf	–
15	MA2 Fd1 Ft2 Su5 Wd3 Wf3	–	LUT 1,2,4,5 af	LUT 3,6 adfw	–
16	VA1 Fd1 Ft1 Su4 Wd1 Wf2	LUT 1	LUT 2,4 f	LUT 3,5,6 afw	–
17	VA1 Fd1 Ft1 Su4 Wd3 Wf3	LUT 1	LUT 2,4 f	LUT 3,5,6 adfw	–
18	VA1 Fd1 Ft1 Su5 Wd2 Wf1	LUT 1	LUT 2,4 f	LUT 3,5,6 adf	–
19	Va1 Fd1 Ft2 Su5 Wd3 Wf3	LUT 1	LUT 2,4 f	LUT 3,5,6 adfw	–
20	VA2 Fd1 Ft2 Su4 Wd3 Wf3	–	LUT 4 f	LUT 1,2,3,5 adfw	LUT 6 a
21	VA2 Fd1 Ft1 Su5 Wd2 Wf1	–	LUT 4 f	LUT 1,2,3,5 afd	LUT 6 a
22	VA2 Fd1 Ft2 Su5 Wd3 Wf3	–	LUT 4 f	LUT 1,2,3,5 adfw	LUT 6 a
23	VA2 Fd1 Ft2 Su4 Wd3 Wf3	–	LUT 4 f	LUT 1,2,3,5 adfw	LUT 6 a

* For explanation of the land unit codes in Thanh Hoa see Table 2

Suitability classes: S1 = highly suitable; S2 = moderately suitable; S3 = margially suitable; N = not suitable

Limiting factors:
- a = acidity (actual or potential)
- d = no possibility to drain land at the start of the end of flood period in order to start HY rice cultivation on time
- f = flood (depth and/or duration)
- w = no availability of fresh irrigation water in dry season

use types in Phung Hiep and six in Thanh Hoa were selected for land evaluation. After matching the requirements of the selected land use types and the land qualities of the land units, we found that in Phung Hiep some land use types such as double rice, sugar cane and rice, cashew intercropped with pineapple and Melaleuca are highly or moderately suitable for the acid soil zone. In Thanh Hoa, double rice is also possible on acid land, as well as yams, sugar cane and Melaleuca. For both districts, limiting factors are acidity, flood hazard and lack of water for irrigation.

References

Beek, K.J. 1978. Land evaluation for agricultural development. ILRI Publ. 23, Wageningen, The Netherlands

FAO 1976. A framework for land evaluation. Soils Bulletin 32, Rome

FAO 1983. Guidelines: Land evaluation for rainfed agriculture. Soils Bulletin 52, Rome

Soil Survey Staff 1990. Keys to Soil Taxonomy (fourth edition). SMSS Technical Monograph 19, Cornell University, Ithaca, NY

Tuong, T.P., C.T. Hoanh and N.T. Khiem 1991. Agro-hydrological factors as land qualities in land evaluation for rice cropping patterns in the Mekong delta, Viet Nam. In: Rice Production on Acid Soils in the Tropics. P. Deturck and F.N. Ponnamperuma (editors). Institute of Fundamental Studies, Kandy

Vo Tong Xuan, Le Quang Tri and Nguyen Kim Quang 1982. Rice cultivation on acid sulphate soils in the Mekong delta. In: H. Dost and N. van Breemen (editors): Proceedings of the Bangkok symposium on acid sulphate soils. Publication 31, 251-259, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands

Coarse land evaluation of the acid sulphate soil areas in the Mekong delta based on farmers' experience

M.E.F. van Mensvoort[1], Nguyen van Nhan[2], Tran Kim Tinh[3], Le Quang Tri[3]

[1] Department of Soil Science and Geology, Agricultural University, P.O. Box 31, 6700 AA Wageningen, The Netherlands
[2] Sub-National Institute of Agricultural Planning and Projection (NIAPP), 86 Hai Ba Trung Street, Ho Chi Minh City, Vietnam
[3] Soil Science Department, Can Tho University, Can Tho, Vietnam

Abstract

Using the FAO Framework for land evaluation, a coarse land evaluation exercise is carried out for acid sulphate soil zones of the Mekong Delta. The Delta is divided into twelve physical zones based on soil constraints: severe, moderate/slight, or absent acid sulphate conditions; and hydrological constraints: deep or shallow flooding, surface water salinity in the dry season; and the availability of a fresh water source for irrigation.

Nine Land Use Types (LUTs) are described, four based on rice, four on upland crops, and one on forestry. The land requirements of these LUTs are expressed in terms of their tolerance to soil acidity and their hydrological requirements. The relative production in the Mekong Delta and the management practices of the farmers are used as key attributes of the LUTs.

For each soil zone, the present suitability for the nine LUTs is determined and, also, the conditional suitability after the most important constraint has been removed (if possible).

The land evaluation exercise indicates, that:

1) Fresh water availability is a crucial factor;
2) Making fresh water available in moderately and slightly acid sulphate soils improves unsuitable land to moderately suitable for irrigated rice and tolerant upland crops;
3) Severely acid land will only become marginally suitable for irrigated rice, but moderately suitable for tolerant upland crops, when fresh water is supplied for irrigation;
4) Well-constructed raised beds not only overcome the flood but, also, improve the soil. Moderately acid soils in areas with low floods become highly suitable for pineapples and sugarcane, provided the period of saline surface water is short or absent.

Introduction

So far, there have been few systematic land evaluation studies of acid sulphate land (Le Quang Tri 1989; Tuong et al. 1991). One of this main reasons is, probably, the complexity and our insufficient knowledge of the most typical land quality, the toxicity hazard. Certainly, the toxic properties of acid sulphate soils and the processes causing them have been studied extensively, but not as qualitative, let alone quantitative, ratings of land qualities. In this study, therefore, the land quality 'toxicity' will be characterized simply by the depth to the sulphuric horizon.

Water management is the key to the improvement of acid sulphate soils (Dent 1986), particularly in areas where lime cannot be applied on large scale. In the Mekong Delta, there are complicated, strongly contrasting but, also, well studied hydrological regimes which determine the possibilities for land improvement. Flood hazard, salt water intrusion and the availability of irrigation water are the most important land qualities used in the study.

When there is not enough reliable experimental data on crop performance, the best source of information is the farmers. The crops they now cultivate have been selected after trial and error. Each of the land use types dealt with here is practised by farmers on acid sulphate soils in the Mekong Delta.

The physical zones of the Mekong delta

For land evaluation, we must delineate a limited number of mapping units that: (i) differ from one another in important constraints for agricultural development; and (ii) are reasonably homogeneous in themselves. Soil and hydrological studies (Vê et al. 1989; Ton That Chieu et al. 1990; Tuong et al. 1991; Tran An Phuong 1990) have been used to distinguish 12 physical zones.

Soil constraints

The two dominating soil constraints are soil acidity and soil salinity. The salinity occurs in two ways. Soil salinity, i.e. a saline saturation extract of the soil, only occurs in a very narrow zone along the coast, and only in the dry season. More important is salinity in the surface water. In a broad zone, especially along the South China Sea, salt water intrudes. In this zone, even soils which are not saline cannot be used for agriculture in the dry season because there is no fresh water for irrigation. In this study, the salinity of the surface water is considered, not the soil salinity.

In the Mekong Delta, acidity and salinity may occur to such a degree that the land is unsuitable for crops. In other areas, the soil problems restrict agricultural use to some extent but do not make it impossible.

The depth to the sulfuric horizon (pH below 3.5 with, or without, jarosite mottles) is used to characterize the land quality toxicity. When it appears within the upper 50 cm soils are dubbed 'severely acid'; between 50 and 80 cm the soils are moderately acid; between 80 and 120 cm slightly acid; below 120 cm no acidity problems need be anticipated. When the groundwater is below 50-60 cm, even severely acid soils will no longer have capillary rise of toxic substances to the soil surface (Tuong et al. 1991), so moderately acid soils will not acidify by capillary rise in the dry season.

Hydrological constraints

A depth of flooding of more or less than 60 cm is thought to be an important boundary in view of agricultural possibilities. A flood over 60 cm strongly reduces the choice of rice varieties (too deep, even for most traditional rices) it also makes it impractical to construct raised beds for upland crops such as pineapples or sugarcane. The beds will need to be very high, a lot of land is lost to ditches and the risk of digging in potentially acid subsoil material is high.

Irrigation water is saline when the electrical conductivity is over 4 mS cm^{-1}. A distinction is made between non-saline, dry season saline (up to nine months of the year) and permanently saline ($>$ 9 months) areas.

The availability of fresh water (not meant as a contrast to saline water, but as the physical presence of a canal for irrigation in the dry season) determines the agricultural possibilities during that period. In many parts of the Mekong Delta an intricate canal system is present, leading fresh water to all fields. This is particularly the case near the rivers. In more remote areas or areas with unfavourable soil conditions, the system is less intensive. Often, only narrow strips of land along canals can be regarded as having fresh water available. It is impossible to draw this constraint on a map of the scale used in Figure 1, but it is taken into account in the evaluation.

The map

Figure 1 shows twelve physical zones, based on present soil and hydrological constraints. The constraints for each zone are indicated in the legend. In the south-western tip of the Delta, mean rainfall is more than 2000 mm $year^{-1}$, near Ho Chi Minh City

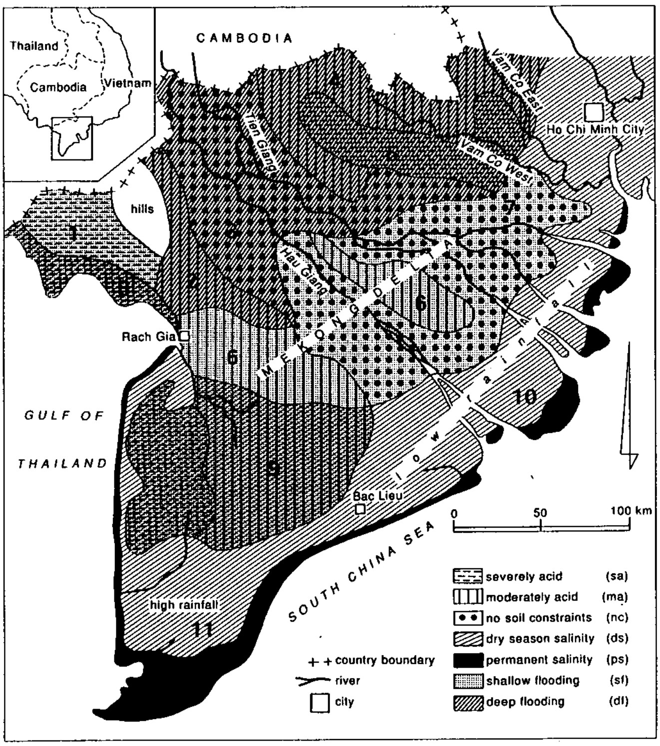


Figure 1 Map of land constraints to farming in the Mekong Delta

only 1500 mm year^{-1}, which falls in a comparatively short period. High and low rainfall separate zones 10 and 11 but these are zones without acid sulphate soils. In this paper, only zones having acid sulphate soils (1,2,4,5,6,8 and 9) are considered.

Land use types (LUTs)

The land evaluation exercise is carried out for the most important LUTs of the acid sulphate land in the Delta.

Rice LUTs
Naturally, rice LUTs are prominent, and the four most important rice cropping patterns in the Delta are taken into account: *Dong Xuan rice* (DX) – irrigated, dry season, high yielding variety rice, cultivated from about mid December to mid March; *He Thu rice* (HT) – mostly rainfed, high yielding rice, often with supplementary irrigation during dry periods, usually cultivated from May to August; *Mua rice* (MUA) – rainfed, commonly transplanted, traditional rice cultivated from May to December; *Deep Water rice* (DWR) – rainfed traditional rice cultivated in areas with a rainy season flood deeper than 60 cm, growth period from May to December.

Other LUTs
Sensitive Upland Crops (SUC) of which soybean, mungbean and maize are the most important. They are mainly cultivated as irrigated crops in the dry season. Recently, these crops, especially the beans, have been promoted by local governments because they are potential export products and can contribute to crop diversification, so they have been incorporated in the present study.

Tolerant Upland Crops (TUC) such as cassava, yam and sweet potatoes are generally planted after the recession of the flood (December) and harvested just before the flood (August). They need irrigation in the dry season. Only low raised beds are needed to increase the thickness of the good soil above the sulphuric horizon and to avoid waterlogging during heavy rains in the early rainy season.

Pineapple (PIN) and sugarcane (SUG) are tolerant of acidity, especially pineapples. They need high raised beds to overcome the flood period and, if well constructed, the beds can increase the depth to the sulphuric horizon. Irrigation is often not practised because of the high beds. Both crops are grown by individual farmers and, also, by large state farms, whereas the above mentioned crops are exclusively cultivated by individual farmers. Sugarcane cultivation discussed here is with ratoons. Some few farmers cultivate sugarcane as an annual crop.

Melaleuca leucodendron (FOR) is planted for constructional timber and firewood. The tree is native and very resistant to soil acidity.

Key attributes of the LUTs and their land requirements

Table 1 shows the key attributes used in this study. Only the crop production is used and management practices of the farmers. It is realized that others are very important too: economic profitability, environmental impact, water requirements, but these are

Table 1 Key attributes

1. Relative production in the Mekong Delta		
All crops (% of best yields)	DX rice t ha^{-1}	Suitability
80-100	4-5	high = S1
60- 80	3-4	moderate = S2
40- 60	2-3	marginal = S3
< 40	< 2	not = N
2. Management practices of farmers		

Table 2 Relevant land use requirements of 9 LUTs on acid sulphate soils

	LUTs								
	DX	HT	MUA	DWR	SUC	TUC	PIN	SUG	FOR
1 Soil acidity	+	+	+	+	+	+	+	+	–
2 Potential acidity	–	–	–	–	+	+	+	+	–
3 Flood hazard	–	+	+	–	+	+	+	+	+
4 Fresh water supply	+	+	–	–	+	+	+	+	–
5 Salt water intrusion	+	+	+	–	+	+	+	+	+

\+ = relevant
– = irrelevant

beyond the scope of this paper.

Table 2 indicates the relevance of five land use requirements for the nine LUTs discussed here. Soil acidity is important for all LUTs. Potential acidity is irrelevant for the rice LUTs because wetland rice keeps the potential acidity where it is. It is relevant for the upland crops because raised beds need to be made which might lead to acidification of potentially acid material. The flood is not relevant for DX rice because it is cultivated in the dry season and for DWR because it needs a deep flood. It is relevant for all others; even *Melaleuca* suffers impeded growth during a long, deep flood. Fresh water supply is important for all LUTs except rainy season traditional rices (MUA and DWR) and *Melaleuca*. Salt water intrusion is relevant for all except DWR, which is only cultivated in deep fresh water floods.

Tables 3 and 4 indicate the extent to which the land meets these requirements in the form of factor ratings for DX rice and sugarcane, respectively. These two crops were chosen as examples because DX rice is getting more widespread in the Delta with high investments for irrigation, fertilizers and crop protection. Sugarcane is chosen as an important tolerant upland crop needing high investment because of raised beds.

For DX rice, only toxicity (as reflected by the depth of the sulfuric horizon), fresh water availability (the crop is cultivated in the dry season) and salt water intrusion influence the yield. Potential acidity plays no role because DX rice does not disturb it. Flooding is not important because the crop is cultivated in the dry season.

Table 3 Factor ratings for Dong Xuan Irrigated rice

Land quality	diagnostic factor	S1	S2	S3	N
Toxicity	Depth sulphuric horizon	> 100 cm	50-100 cm	< 50 cm	–
Fresh water availability	Fresh water available in dry season	yes			No
Salt intrusion	Months saline surface water with EC > 4 mS cm^{-1}	0	<3	3-4	>4

Table 4 Factor rating for sugarcane

Land quality	Diagnostic factor	S1	S2	S3	N
Toxicity	Depth sulphuric horizon after construction of raised beds	not present	> 100 cm	50-100 cm	< 50 cm
Potential acidity	Depth sulphidic material before construction of raised beds	> 100 cm	50-100 cm	< 50 cm	–
Flood hazard	Flood depth before construction of raised beds	< 30 cm	30-60 cm	60-100 cm	> 100 cm
Fresh water availability	Fresh water available in dry season	permanently	temporarily	no	–
Salt intrusion	Months saline surface water with EC > 4 mS cm^{-1}	<3		3-4	>4

In the case of sugarcane, all land qualities need to be taken into account. With its deep roots, it will easily suffer from soil acidity. Potential acidity will be disturbed during construction of raised beds. Beds need to be over the flood to avoid waterlogging. A deep flood makes bedding impossible because of loss of land and costs of construction. Fresh water availability in the dry season for irrigation is important, without irrigation sugarcane will only perform marginally. Many farmers in the Delta, in fact, have no irrigation water for the sugarcane. When salt intrudes for a very short period (up to 3 months) it will not harm the crop, but when longer it strongly reduces crop growth, and with more than 4 months, sugarcane is not suited.

Similar factor ratings can be made for the other LUTs.

Land suitability

Tables 5-8 indicate the suitability of four acid sulphate soil zones in the Delta for the nine LUTs discussed. P/C suitability indicates the present and the conditional suitability, i.e. the suitability under the present conditions and the suitability when the most limiting constraint has been removed. This conditional constraint is indicated in the third column, while the last column indicates the limiting constraint that remains. Full tables are presented for West An Giang (zone 2), Central Plain of Reeds

Table 5 Zone 2, West An Giang

Crop	p/c suitability	Conditional constraint	Remaining constraints
HT	N/S2	fresh water	acidity
DX	N/S1	fresh water	none
MUA	N/N		deep flood
DWR	S2/S2		acidity
SUC	N/S3	fresh water	acidity
TUC	N/S2	fresh water	acidity
PIN	N/N		deep flood
SUG	N/N		deep flood
FOR	S1/S1		none

Table 6 Zone 5, Central Plain of Reeds

Crop	p/c suitability	Conditional constraint	Remaining constraints
HT	N/N		soil acidity
DX	N/S3	fresh water	soil acidity
MUA	N/N		soil acidity
DWR	N/N		soil acidity
SUC	N/N		soil acidity
TUC	N/S3	fresh water	soil acidity
PIN	N/N		acidity, flood
SUG	N/N		acidity, flood
FOR	S2/S2		acidity, flood

Table 7 Zone 6, Central Trans-Bassac, North Cuu Long

Crop	p/c suitability	Conditional constraint	Remaining constraints
HT	S2/S2		acidity
DX	S1/S1		none
MUA	S2/S2		acidity
DWR	N/N		shallow flood
SUC	S3/S3		acidity
TUC	S2/S2		acidity
PIN	N/S1	flood, raised beds needed	none
SUG	N/S1	flood, raised beds needed	none
FOR	S1/S1		none

Table 8 Zone 9, Central Ca Mau Peninsula

Crop	p/c suitability	Conditional constraint	Remaining constraints
HT	S2/S2		acidity, salinity
DX	N/N		salinity, acidity
MUA	S2/S2		acidity
DWR	N/N		low flood
SUC	N/N		salinity, acidity, flood
TUC	N/N		salinity, acidity, flood
PIN	N/S2	flood, raised beds needed	acidity, salinity
SUG	N/S3	flood, raised beds needed	acidity, salinity
FOR	S2/S2		acidity

(zone 5), Central Trans-Bassac and North Cuu Long (zone 6) and Central Ca Mau Peninsula (zone 9).

For zone 4, West and North Plain of Reeds, suitabilities are similar as zone 2. The difference between the two zones is mainly in the extent to which fresh water is, at present, available in the dry season. This is more developed in zone 2 than in zone 4. The suitability for DX rice is, with continued and skillful land and water management, increased to the S1 level.

Most of the suitabilities for zone 5 (see Table 6) are also applicable to zone 1, The Ha Tien Plain. The difference is the flood depth, which makes construction of raised beds possible in Ha Tien. The suitability for pineapples and tolerant upland crops, being the only crops tolerant to the extreme acidity, is only marginal. Another big problem of zone 1 is the difficulty of bringing fresh water there. Clearly, zones 1 and 5 are the most difficult and have few prospects.

Zone 6 consists of two areas which are, already, quite intensively used for agriculture. Water conveyance to most farms already exists, which explains why no clear change in suitability can be obtained for the rice crops. In those places where fresh water is not available, construction of secondary and tertiary canals can improve the suitability from N to S2 and, after some years of skillful use, probably to S1. Construction of raised beds is relatively easy and without much risk, because the layer of soil needed to construct the bed is not severely acid. Besides, construction of beds increases the thickness of the non-acid layer. Land becomes highly suitable for pineapples and sugarcane.

Table 8 shows suitabilities for the nine LUTs in the Central Ca Mau Peninsula. This is particularly heterogeneous area in view of all land qualities. Potential and actual acidity are very severe in a number of places, especially in the south-western part. Flooding is not deep. Salinity varies strongly in number of months and concentration. Land suitability is as varied as land conditions and, in general, the zone is a particularly difficult one. Conveyance of fresh water to the zone by large canals, and possibly, pumping stations is under study but needs careful consideration because of the intricate hydrological situation and the ecological vulnerability.

West Ca Mau Peninsula (zone 8), the area of the U Minh forest and surroundings, is very heterogeneous. In the centre is the U Minh peat dome, which is fast getting smaller. Immediately surrounding the peat dome is an area with severe, recently-developed acid sulphate soils, due to drainage and burning of the peat dome. Severe acidity, long periods of salt water intrusion and peat soils make agricultural use virtually impossible. The outer part of the zone consists of moderately acid soils having similar conditions as zone 9. This part is moderately suitable for HT and MUA rice (long rainy season) and moderately suitable for pineapple.

Some general remarks

There is a limit to the quantity of fresh water which can be made available in the dry season because of low flow in that period. Excessive irrigation upstream may lead to increased salt water intrusion near the coast.

Environmental aspects of the LUTs were not taken into account in this study. Only the possibilities of agricultural crop production are reviewed. Lack of data on the effects of the proposed LUTs is the reason for this. It is realized that the provision of fresh water in acid sulphate areas may lead to acidification of surface water from the dikes of the canals. The same applies to the unwise construction of raised beds. In severely acid areas, even rice fields release acid-related substances, such as soluble aluminium and iron into the surface water.

Conditions in the zones are often very variable. Locally, the suitability at farm level may be very different from what is predicted for the zone as a whole.

Conclusions

1) Making fresh water available in moderately and slightly acid sulphate areas improves unsuitable land to moderately suitable for irrigated rice and tolerant upland crops. Such areas can be given highest priority in development for agricultural use;
2) Severely acid land will become only marginally suitable for irrigated rice, but moderately suitable for tolerant upland crops, when fresh water is supplied for irrigation. Severely acid areas, such as the Central Plain of Reeds and Ha Tien Plain, should not have priority in development for agricultural use;
3) Well-constructed raised beds not only overcome the flood but also improve the soil. Moderately acid soils in areas with low floods become highly suitable for pineapples and sugarcane, provided that the period of saline surface water is short or absent.

References

Dent, D.L. 1986. Acid Sulphate Soils: a baseline for research and development. Publ. 39, International Institute for Land Reclamation and Improvement, Wageningen

FAO 1976. A framework for land evaluation. Soils Bulletin 32, Rome

Le Quang Tri 1989. Present land use as a basis for land evaluation, a case study of Phung Hiep District, Hau Giang Province Vietnam. Techn. Rep. nr. 6, VH 10 Project, Soil Science Dept., Agric. Univ. Wageningen, and ITC Enschede

Ton That Chieu, Tran An Phong, Nguyen Cong Pho, Nguyen Van Nhan, and Pham Quang Khanh 1990. Soil Map of the Mekong Delta. (NIAPP), Ho Chi Minh City

Tran An Phong 1987. Legend of the agro-ecological zones map of the Mekong Delta. National Institute of Agricultural Planning and Projection, Hanoi

Tuong, T.P., C.T. Hoanh and N.T. Khiem 1991. Agro-hydrological factors as land qualities in land evaluation for rice cropping patterns in the Mekong Delta, Vietnam. In: P. Deturck and F.N. Ponnamperuma (editors): Rice Production on Acid Soils of the Tropics. Institute for Fundamental Studies, Kandy

Tuong, T.P., L.Q. Minh and T.P. Khanh 1991. Effect of watertable depth on evaporation and distribution of salts and moisture in a bare acid sulphate soil. In: P. Deturck and F.N. Ponnamperuma (editors): Rice Production of Acid Soils of the Tropics. Institute of Fundamental Studies, Kandy

Vê, N.B. 1986. Soil map on the Trans Bassac area, scale 1:250 000. Soil Dept. Univ. Can Tho, Vietnam Soil Survey and Winand Staring Centre, Wageningen

Ways and means of modelling acid sulphate soils

J. Bouma[1], M.E.F. van Mensvoort[2] and Le Van Khoa[2]

[1] Department of Soil Science and Geology, Agricultural University, P.O. Box 37, 6700 AA Wageningen, The Netherlands
[2] Soil Science Department, Can Tho University, Can Tho, Vietnam

Abstract

Modelling seeks to explain and predict soil processes and properties. It can be realized at different levels of detail by farmers, field experts and by mechanistic simulation of processes. A case is presented for a broad approach, starting with a thorough analysis of farmers' experience and by applying expert knowledge. Mechanistic simulation of processes is attractive for predicting the effects of future soil or water management practices. However, acid sulphate soils present formidable barriers to simulation because of their heterogeneity and changing properties owing to ripening processes. Well focused field measurements, rather than simulation, of certain properties identified as being important by experts, should be considered as well. To allow mechanistic modelling, basic data have to be available.

A study was presented delineating major soil horizons in the Mekong delta which were characterized by physical data, allowing prediction of physical properties in identical horizons observed elsewhere.

Introduction

Modelling, as used in this paper, refers to a characterization of complex, interrelated, physical, chemical and biological soil processes with the objective to explain and predict agronomic and environmental soil processes and properties. Thus, it has a broad scope and includes attempts by farmers to interpret observed field phenomena in terms of failures and successes, taking into account site characteristics and types of soil and water management. It also includes knowledge gained by experts in their contacts with farmers, when making experiments and exchanging experiences with experts elsewhere, and by reading the scientific literature. The more traditional definition of modelling focuses on use of mechanistic, computer-simulation techniques which define, in quantitative terms, interrelated physical, chemical, and biological processes. Models can be relatively simple, including gross schematization of processes involved, or quite detailed. Obviously, the more detailed the model, the more basic parameters are needed to run it.

Which modelling approach should be followed? There is no simple answer to this question (e.g. Bouma et al. 1992). The selection will be a function of: (i) the type of problem being studied; (ii) the complexity of the soil system being studied; (iii) the data that are available; and (iv) the available time and finance.

Physical and chemical processes in acid sulphate soils are likely to be more complex than those in any other soil on this planet. Oxidation of pyrite, following ripening of clayey sulphidic soils, has quick and dramatic effects on chemical conditions but, mostly so in parts of the soil which are exposed by shrinkage cracks or old root channels. As ripening proceeds and more macropores are formed, soil physical conditions in the soil and the associated transport and diffusion parameters change constantly, and often irreversibly. To dynamically characterize these interacting processes with a deterministic simulation model is a formidable task indeed, as difficulties are still encountered when simulating much simpler water and solute processes in relatively stable and homogeneous sandy soils.

This paper will focus on examples from work in Vietnam on acid sulphate soils which has resulted in significant achievements. Acid sulphate soils in Vietnam are mostly well-ripened, heavy clays with illitic and kaolinic clays which are not very expansive. High aluminium contents add to their stability.

Considering project activities over more than a ten year period, the question as to which modelling procedure should be followed will be critically examined. An effort will be made to avoid presentation of material that has already been reported elsewhere.

Farmers' knowledge: the farmer model

Acid sulphate soils are very unfavourable for farming. Farmers have learned this the hard way and will not start farms in areas where raw acid sulphate soils have just been drained. However, in older soils where much acidity may have been leached, or at locations where pyrite occurred at greater depth in the soil, farming was started and farmers have devised innovative systems to improve conditions for crop growth. For example, raised beds have been introduced by farmers who found that crops could be grown better on the relatively well aerated beds than on the former soil surface which was closer to the groundwater level. Also, in acid sulphate soils, beds are leached more effectively.

In addition to using raised beds, shallow surface drainage systems have been applied successfully. These systems were originally devised for saline soils to accelerate surface leaching of salts. Later, they were also applied to the saline acid sulphate areas where a combined effect of desalinization and de-acidification was obtained. Local experts embraced the model and brought it to the acid sulphate areas where it proved successful (Xuan et al. 1982).

By growing acid-tolerant crops, like pineapple, surgarcane, cashew nuts and cassava, farmers have maintained an income that would have been elusive if they had aimed for crops that were not acid-tolerant. In areas with salt water influence, farmers have started mixed farming systems including breeding of shrimps.

Farmers' experience is usually limited to the area where they live and to observed effects of different management procedures. Underlying processes are often not understood but the farmers' model does reflect the observed effects of natural processes at different locations and has, therefore, a certain diagnostic character.

Expert knowledge: the expert model

Problem analysis

Acid sulphate soils have been studied for many years. International symposia on these soils have been held in 1972 in Wageningen (Dost 1973); in Bangkok in 1981

(Dost and van Breemen 1982) and in Dakar in 1986 (Dost 1988). Much is known about the occurrence of acid sulphate soils in different landscapes.

In Vietnam, two major questions regarding the use of acid sulphate soil areas had to be answered. The first, raised by the Government when it was obtaining information on the natural resources in the country, was: 'How can acid sulphate soil areas best be surveyed, and how can survey results be used to delineate areas where agricultural development would be feasible?'. Such a question requires a comprehensive analysis, for a large area of land, which focuses not only on soils but, also, on hydrological regimes and crop performance under different conditions. The second question, often asked by provincial and district authorities and their extension services, concerns the determination of optimal land use at the farm level, indicating land use type and detailed soil and water management packages for land improvement.

Soil mapping and land evaluation

Expert knowledge was used by initiating soil surveys, at different scales, which must be considered as an absolutely essential foundation for any study on soil and water management. Because acidification is a major problem in acid sulphate soils, maps have been prepared in the past that were based on pH values only. However, such maps are useless because continued soil development and flooding in the wet season may result in rapid changes of pH. By mapping the occurrence of soil layers with pyrite, and layers with jarosite and goethite (which represent increasing degrees of soil development) a more stable picture is obtained that also allows prediction of likely processes in future when soil development continues.

Such surveys can be used as a basis for determining relative suitabilities of different land units using the FAO framework for land evaluation (1976). Van Mensvoort et al. (1993), divided the Mekong Delta into soil-hydrological zones and indicated, for each zone, the present suitability for the most important land use types. They also defined conditional suitabilities provided that limiting factors were removed. Proposed suitabilities were based on expert judgement of actual suitabilities and of the expected effects of improvement measures.

The above examples indicate uncertainty as to the effects of several of the suggested soil and water management improvement measures. For example, what will be the effects of drainage on development of cracks and the associated aeration and oxidation processes? How can a raised bed be leached most efficiently using as little fresh water as possible? What are critical watertable levels for upward unsaturated flow carrying acids into the rootzone? Expert knowledge is not adequate to answer such specific questions and, often, field experiments cannot be made because of financial and time limitations. Because of this, use of computer simulation techniques is being advocated to characterize, dynamically, interrelated physical and chemical processes in acid sulphate soils. Also, specific on-site measurements can be made to solve such specific questions.

Computer simulation modelling

Simple and complex models

When using models, a distinction can be made between relatively simple models with a low data demand and more complicated models with a higher data demand. Wagenet et al. (1991) provided a review. A relatively simple model for describing the flow of water and solutes is the 'tipping bucket' capacity model, which considers the soil to consist of a rootzone until 'field capacity' is reached (often considered to correspond to a negative pressure of –10 kPa). More added water disappears to the subsoil. Water can be extracted by plants up to a pressure of –1500 kPa. This simple model can yield relevant data for crop production but is too schematic to allow an adequate representation of physical and chemical processes in acid sulphate soils.

The computer simulation model being developed for acid sulphate soils (SMASS) (Bronswijk and Groenenberg 1993) uses, therefore, a more complex model approach in which fluxes of water, solute and air are predicted using basic physical flow equations. These equations need parameters such as hydraulic conductivity and moisture retention for water flow; adsorption, desorption, dissolution and precipitation coefficients for chemical processes; and diffusion coefficients for gas transport.

The overall model integrates physical and chemical processes and consists of four sub models:

1 Two physical sub models that compute water and solute transport in the soil depending upon soil properties, water management and climate;
2 A physical sub model that describes the transport of oxygen in the soil in connection with water contents, soil structure and the oxygen consumption rate due to organic matter and pyrite oxidation;
3 A chemical sub model computing rates of oxidation/reduction, complexation, adsorption/desorption and precipitation/dissolution of the various compounds.

As main output, the model computes changes over time and depth of concentration in the soil solution and drainage water, and of the remaining contents of pyrite and other minerals in the soil. Periods during which iron and aluminum concentrations in the soil solution exceed levels toxic to crops can be predicted.

Feeding a complex model

Complex models have a high data demand. Before use of complex, mechanistic models can be recommended, there should be assurance that adequate basic data either are available or can be made available in time to be used in modelling. Working with a complex model while only estimated data are available with unknown accuracy is not acceptable from a scientific point of view.

Of particular interest are the soil physical parameters such as hydraulic conductivity and moisture retention, which are soil-specific. Chemical parameters, such as thermodynamic equilibrium constants, cation exchange constants, rate constants for precipitation/dissolution and redox reactions, have a general validity for each chemical compound and are not soil specific. The same is true for gas diffusion coefficients.

Many methods are available to measure soil hydraulic characteristics. Measurement at each site would be very expensive and would take too much time. Procedures have to be developed, therefore, to predict hydraulic characteristics using available soil survey data. The term: 'Pedotransferfunctions' has been used for functions that relate physical parameters needed for simulation to soil survey data, such as % clay, % organic matter or bulk density, or more integrated entities such as soil horizons occurring in particular soil types (e.g. Wösten et al. 1985). Data by Le van Khoa (1991) will be cited as an example of this approach, which also shows a direction in which soil survey work in future can go.

Major soil horizons

Le van Khoa (1991), studying acid sulphate soils in the Mekong delta, distinguished three major soil horizons: Pyrite C horizons, Jarosite B horizons, and Goethite B horizons which reflect successive stages of pyrite oxidation. They can be characterized as follows:

Pyrite C horizons

- Occur at a depth greater than 100 cm below surface;
- Soil matrix colour is grey to dark grey;
- No mottling;
- Soil structure is very weak, medium and coarse angular blocky/prismatic, or it is structureless;
- Half ripe to practically unripe.

Jarosite B horizons

- Occur at depths varying between 30 cm and 100 cm below surface;
- Soil matrix colour grey to greyish brown; is
- Mottling density changes from common to many and mottles are distinct, clear to prominent and yellow (2.5 Y 8/6);
- Soil structure is moderate medium blocky and weak medium prismatic breaking into moderate medium blocky;
- Half ripe.

Goethite B horizons

- Occur at depths varying from 30 cm and 100 cm below surface;
- Soil matrix colour grey to brownish grey; is
- Mottling density changes from few to common and colour is clear yellowish brown or brownish yellow;
- Structure is weak and moderate medium blocky;
- Half ripe to nearly ripe.

Physical properties of major soil horizons

By making physical measurements in well defined horizons, populations of physical data are obtained, including variability, which can be used to predict physical data in simular horizons elsewhere. Use of soil horizons as carriers of physical data is an application of a class-pedotransferfunction (e.g. Wagenet et al. 1991 and references therein). Some results of Le van Khoa (1991) are summarized in Table 1 which shows average values per horizon for bulk density and K-sat.

Statistical testing of values obtained showed that bulk densities of all horizons were significantly different (at 95 per cent probability) and that of the hydraulic parameters, only the K-sat values of the goethite and jarosite horizon were significantly different. Of particular interest are the results of the measurements with the one-step outflow method for measurement of the unsaturated hydraulic conductivity and moisture retention expressed in the equations of van Genuchten (1980):

$$S = \frac{\Theta - \Theta_r}{\Theta_s - \Theta_r} = 1 + /ah/^{n-m} \qquad (1)$$

Table 1 Some physical characteristics of acid sulphate soil horizons from the Mekong Delta. Standard deviations in parentheses

Type of soil horizon	Bulk density	K-sat	Hydraulic parameters				
	$g\ cm^{-3}$	$cm\ day^{-1}$	x	n	Θ_r	K-sat	m
Goethite B	1.18 (0.05)	0.03 (0.03)	0.05 (0.06)	1.17 (0.09)	0.10 (0.07)	0.85 (1.86)	3.71 (7.26)
Jarosite B	0.92 (0.06)	2.84 (1.61)	0.05 (0.04)	1.17 (0.06)	0.09 (0.06)	2.37 (2.29)	9.67 (8.62)
Pyrite C	0.78 (0.09)	1.49 (2.40)	–	–	–	–	–

$$K_s = K_{sat} \times S^1 = 1 - (1 - S^{1/m})^{m2} \qquad (2)$$

Average values for the parameters x, n, Θ_r (optimized residual water content); K-sat (optimized K-sat) and m are presented in Table 1 as derived from six goethite B and jarosite B horizons. Statistical testing indicated that the hydraulic characteristics of the three types of major horizons were significantly different, with only very few exceptions..

Expression of hydraulic characteristics in terms of the van Genuchten parameters allows rapid and effective input into the SMASS simulation model. Le Van Khoa's work demonstrates the use of soil survey expertise in defining major soil horizons which follow characteristic patterns in the landscape. When making measurements in these horizons, distinct populations of data are obtained. Availability of these data allows prediction of hydraulic characteristics in other areas within the Mekong Delta by determining the type of soil horizon and by extra polating physical data measured elsewhere. This, obviously, takes much less time than making new measurements.

Simulating fluxes of solute and gases in partly-ripened soils

Simulation techniques can be very helpful to predict physical and chemical soil conditions as a function of soil management (e.g. Van Wijk and Widjaja 1990). The alternative to simulation would be costly, long-term field experiments which are, often, not feasible.

When discussing simulation for acid sulphate soils, it should be recognized that processes in these soils are probably most complex of all soils. Generally clayey textures result in swelling and shrinkage of soil upon wetting and drying. Thus, pore patterns and, notably, the number and vertical continuity of cracks is continually changing. More important yet, most acid sulphate soils are not completely ripened, as was illustrated above for pyrite, jarosite and goethite horizons. Ripening upon drying implies permanent, not reversible, changes in basic hydraulic characteristics. Again, this was also demonstrated above for the three major horizons.

Simulation of water, solute and gas transport in acid sulphate soils cannot assume, therefore, presence of a relatively homogeneous, isotropic porous medium which is, theoretically, required to allow application of the Richards' equation for calculating fluxes. Progress is being made, however, in modelling solute movement in cracking clay soils using Coefficients of Linear Extensibility (COLE) to express effects of swelling and shrinkage on cracking patterns (Bronswijk 1988). An alternative procedure uses morphological analyses to observe the number of cracks and other macropores in cross section and their vertical continuity. Next, a flow system is defined that separates vertical flow into the matrix from infiltration into vertical macropores. This infiltration may occur when the matrix is unsaturated and this process has been called 'bypass flow'. The importance of bypass flow in acid sulphate soils was demonstrated by Sterk (1993) who showed that 80 per cent of rainwater was ineffective for leaching of raised beds, as it was part of bypass flow (50 per cent) or surface runoff (30 per cent). When free water accumulates at some depth in the soil in the bottom of vertically discontinuous cracks, the term 'internal catchment' (e.g. Bouma 1990, Booltink and Bouma 1991) can be used.

The SMASS model does not, so far, consider soil swelling, bypass flow and internal catchment while it does consider diffusion of air from cracks into the soil matrix. It assumes fixed hydraulic characteristics for horizons being considered in simulation runs. This is realistic when soil behaviour is characterized for a short period, in which it may be assumed that basic hydraulic soil characteristics do not change significantly due to ripening. Simulations for longer periods, say months or years are, as yet, very difficult to realize because of the complex and changing soil system.

Finally, it should be pointed out that relatively simple field experiments and measurements can be made to determine relevant aspects of physical behaviour in acid sulphate soils. For example, rates of bypass flow as a function of rain intensity and duration can be measured easily in the field (e.g. Bouma et al. 1981). Also, internal catchment can be quantified with relatively simple field measurements which include a morphological analysis of the macropore system in the soil (e.g. Van Stiphout et al. 1987). Such specifically focused measurements are to be preferred over the application of simulation techniques which could, in principle, also be used.

The field researcher should be alert to for natural soil conditions and should be prepared to devise new measurement methods if existing methods are bound to produce irrelevant results, for example when they operate on the assumption that soils are rigid, isotropic and homogeneous.

Evaluation of modelling

The success of the study program on acid sulphate soils in Vietnam has been based on the application of expert knowledge in close consultation with farmers and extension personnel. To do so, a very complex reality had to be schematized into simplified 'models' which expressed area-specific, interrelated, physical, chemical and biological processes, in terms of visible (or invisible) effects. Now, the introduction of simulation models offers the opportunity to focus on a quantitative analysis of several processes and their effects that are unknown and that cannot be derived from expert knowledge: the experts don't know either! The only alternative to modelling, as mentioned earlier, would be extensive field experimentation which is prohibitive in terms of cost and duration. Thus, effects of different management scenarios can be predicted by simulation modelling and this presents, in principle, a helpful tool for future work. However, simulation models should be applied with care because processes in acid sulphate soils are highly complex.

Instead of simulating soil processes, it is also possible to make specific field measurements of particular phenomena. For example, upward fluxes of water from the groundwater to the rootzone can be derived from hydraulic conductivity measurements. Bypass flow can be measured experimentally, which is more feasible than prediction by modelling. As discussed earlier for bypass flow and internal catchment, new methods may have to be devised for field measurements in clayey acid sulphate soils.

The overall objective of this paper is to emphasize the need for a broad research approach, starting with farmers' expertise and expert knowledge, and using either specific measurements for important problems identified by experts, or simulation modelling with mechanistic models. The ideal research procedure in our opinion is a central role for an expert with good local knowledge who communicates with farmers by learning about their experiences and by passing on to them expert knowledge gained elsewhere and results of scientific work in the area itself. At the same time, this expert communicates with scientists of various disciplines, advising them about the most relevant practical questions concerning soil and water management. Results of measurements or simulations, made by scientists, are fed back to the expert.

Literature cited

Booltink H.W.G. and J. Bouma 1991. Physical and morphological characterization of bypass flow in a well-structured clay soil. Soil Sci. Soc. Amer. J. 55, 1249-1254

Bouma J. 1990. Using morphometric expressions for macropores to improve soil physical analysis of field soils. Geoderma 46, 3-13

Bouma J., L.W. Dekker and C.J. Muilwijk 1981. A field method for measuring short – circuiting in clay soils. J. Hydrol. 52 (3/4), 347-354

Bouma J., M.S.C. Wopereis, J.H.M. Wösten and A. Stein 1992. Soil data for crop soil models. In: Systems approaches to agricultural development. Proc. int. symposium Bangkok. Kluwer publ. Co.

Bronswijk J.J.B. 1988. Modelling of water balance, cracking and subsidence of clay soils. Journal of Hydrology 97, 199-212

Bronswijk J.J.B. and J.E. Groenenberg 1993. A simulation model for acid sulphate soils, I: Basic Principles. In: D.L. Dent and M.E.F. van Mensvoort (editors). Selected papers of the Ho Chi Minh City symposium on acid sulphate soils. ILRI Publication 53, International Institute for Land Reclamation and Improvement, Wageningen

Dost H. (editor) 1973. Acid sulphate soils. Proc. First Int. Symposium Publication 18. International Institute for Land Reclamation and Improvement, Wageningen

Dost H. (editor) 1988. Selected papers of the Dakar Symposium on acid sulphate soils. Publication 44. International Institute for Land Reclamation and Improvement, Wageningen

Dost H. and N. van Breemen (editors) 1982. Proc. Bangkok Symposium on acid sulphate soils. Publication 31. International Institute for Land Reclamation and Improvement, Wageningen

FAO 1976. A framework for land evaluations. Soils Bulletin 32, Rome

Genuchten M.Th. van 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Amer. J. 44, 892-898

Le van Khoa 1991. Relationship between some soil physical characteristics and morphology in acid sulphate clays in Mekong Delta, Vietnam. Technical Report 5 NUFFIC Project VH-10. Dept. Soil Science and Geology, Agricultural University, Wageningen

Mensvoort M.E.F. van, Nguyen Van Nhan, Tran Kim Tinh and Le Quang Tri 1993. Coarse land evaluation of the acid sulphate soil areas in the Mekong delta based on farmers' experience. In: D.L. Dent and M.E.F. van Mensvoort (editors). Selected papers of the Ho Chi Minh City symposium on acid sulphate soils. Publication 53, 321-329, International Institute for Land Reclamation and Improvement, Wageningen

Sterk G. 1993. Leaching of acid from the topsoil of raised beds on acid sulphate soils in the Mekong Delta of Vietnàm. In: D.L. Dent and M.E.F. van Mensvoort (editors). Selected papers of the Ho Chi Minh City symposium on acid sulphate soils. ILRI Publication 53. International Institute for Land Reclamation and Improvement, Wageningen

Stiphout T.J.P. van, H.A.J. van Lanen, O.H. Boersma and J. Bouma 1987. The effect of bypass flow and internal catchment of rain on the water regime in a clay loam grassland soil. J. Hydrology 95 (1/2), 1-11

Wijk A.L.M., van and I. Putu Gedjer Widjaja-Adhi 1990. Modelling of physical and chemical processes in (potential) acid sulphate soils: objectives and outline of the research. In: Papers Workshop on acid sulphate soils in the humid tropics, 81-88. AARD and LAWOO, Bogor

Vo Tong Xuan, Nguyen Kim Quang and Le Quang Tri 1982. Rice cultivation on acid sulphate soils in the Vietnamese Mekong Delta. In: H. Dost and N. van Breemen (editors). Proc. Bangkok Symposium acid sulphate soils. Publication 31, 251-259. International Institute for Land Reclamation and Improvement, Wageningen

Wagenet R.J., J. Bouma and R.B. Grossman 1991. *Minimum data sets for use of soil survey information* in soil interpretive models. In: M. J. Mausbach and L.P. Wilding (editors). Spatial variability of soils and landforms. Special Publication 28, 161-183. Soil Science Soc. of Amer. Madison, Wisc.

Wösten J.H.M., J. Bouma and G.H. Stoffelsen 1985. The use of soil survey data for regional soil water simulation models. Soil Sci. Soc. Amer. J. 49, 1238-1244

A simulation model for acid sulphate soils, I: basic principles

J.J.B. Bronswijk and J.E. Groenenberg

DLO – Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), P.O. Box 125, 6700 AC Wageningen, The Netherlands

Abstract

A computer Simulation Model for Acid Sulphate Soils (SMASS) has been developed to predict effects of water management strategies, such as drainage or leaching, on acidification and de-acidification, and on release and movement of elements in including toxid elements acid sulphate soils.

SMASS consists of:
- A water transport sub-model;
- A pyrite oxidation and oxygen transport sub-model;
- A solute transport sub-model;
- A chemical sub-model.

The output consists of the soil water balance, the oxygen concentrations in the soil air, the solute concentration in the soil solution, and the amount of minerals, including pyrite, in the soil. Time steps for model simulations are in the order of hours. The output of SMASS and its sub-models is generally given on a daily basis. Model predictions can be done over periods of decades, so that long-term effects of various water management strategies can be predicted quantitatively.

Introduction

Adequate soil and water management is essential for sustainable agriculture in acid sulphate soil areas. Development of optimum water management strategies for new land reclamation projects, or for rehabilitation of existing projects, in coastal plains with acid sulphate soils requires knowledge about future consequences of the various possible water management options. Both the consequences for the soil quality in situ, i.e. inside the reclaimed areas, and downstream of the reclamation project (e.g. coastal mangrove forests) should be considered.

In acid sulphate soils, numerous complex physical and chemical processes determine the magnitude and rate of acidification and production of toxic compounds. Furthermore, chemical processes in acid sulphate soils may continue for a long time. For example, complete oxidation of all pyrite present in a soil may take decades. Long-term prediction of these complex chemical processes and their practical consequences is only feasible by using simulation models. Development of such models was recommended repeatedly (Dost and van Breemen 1982, Dent 1986, Dost 1988).

The objective of our study was to develop a computer simulation model, which can predict effects of water management strategies, such as drainage and irrigation, on acidification and de-acidification of acid sulphate soils under various conditions of soil and climate. To obtain such a model, a joint Indonesian/Dutch research project was set-up in Southern Kalimantan, Indonesia. Over a period of three years, extensive laboratory and field experiments for model development and validation have been conducted (AARD/LAWOO 1992). The resulting model combines physical processes such as transport of oxygen, water and solutes, and chemical processes such as oxidation/reduction, complexation, adsorption/desorption and precipitation/dissolution of chemical compounds. The model output includes the acidity and the chemical quality (toxicity) of soil, groundwater and drainage water. The model facilitates the evaluation of various water management strategies for land reclamation or project rehabilitation.

This article summarizes the basic principles of the model. A second article (Van Wijk et al. 1993) describes its validation and application.

General model principles

The Simulation Model for Acid Sulphate Soils (SMASS, Figure 1) consists of a number of sub-models in which the various physical and chemical processes occurring in acid sulphate soils are described using mathematical equations. In order to solve these equations, the soil profile has to be divided into compartments which may be of variable size (Figure 2).

The initial physical and chemical conditions in each compartment must be given as model input. For the complete simulation period, values for the boundary condi-

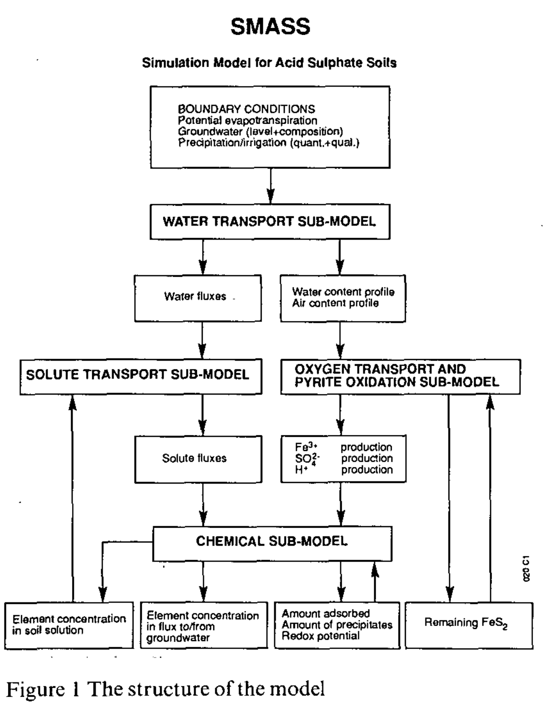


Figure 1 The structure of the model

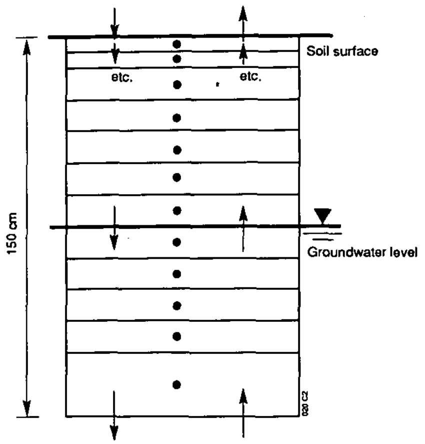


Figure 2 Schematization of a soil profile, as applied in the SMASS model. Arrows indicate water and solute fluxes

tions, as given in Figure 1, are required as input as well. The physical and chemical conditions in each compartment, together with the water and solute fluxes at the boundary of the soil system are computed at selected time intervals.

Figure 1 illustrates the sequence in which the various physical and chemical processes are computed within each time-step:

1) The *water transport sub-model* computes vertical water transport. This yields the water content profile in the soil and, as a corollary, the air content;
2) In the *oxygen transport and pyrite oxidation sub-model*, air contents are used to compute oxygen diffusion coefficients in the air-filled soil macropores. Oxygen consumption values in the soil are calculated from pyrite and organic matter contents. Subsequently, the oxygen content profile in the soil macropores is computed;
3) Depending on the oxygen concentration in a given compartment, the rate of pyrite oxidation in that compartment is now calculated in the *oxygen transport and pyrite oxidation sub-model*. The amount of pyrite it is converted into amounts of H^+, Fe^{3+} and SO_4^{2-} produced for each compartment. The amount of pyrite remaining in the soil is used for calculations in the next time step;
4) The *solute transport sub-model* computes solute fluxes between soil compartments, depending on the calculated water fluxes (step 1);
5) In the *chemical sub-model*, first the production/consumption terms for the non-equilibrium processes (such as iron reduction) are calculated. Then the total concentrations of each chemical component are calculated in the soil compartments by summing, for each component, the production/consumption terms, the inflow/outflow (from step 4), and the total amounts from the previous time-step. From these total concentrations, the equilibrium concentrations in the soil solution, the composition of the exchange complex, and the amount of minerals and precipitates are computed for each compartment.

Time steps for computations of the water and solute transport sub-models are in the order of hours. Pyrite oxidation, oxygen profiles and chemical equilibria are computed once for every day. The output of the model and its sub-models is generally given on a daily basis. If desired, each sub-model can be applied independently. Water transport can be simulated and validated first, for instance, before computing the chemical reactions. Model predictions can be carried out for one or more decades, so that the long-term effects of various water management strategies can be evaluated quantitatively.

Solute transport and chemical processes have been modelled independently: one step to solve the transport equations and a second step to solve the equations defining the chemical composition of the system.

Water transport sub-model

Schematization and modelling

The water transport sub-model is based on the SWATRE model (Feddes et al. 1978, Belmans et al. 1983). SWATRE calculates one-dimensional vertical transient water flow in soils. The basic flow equation of SWATRE is

$$\frac{\partial h}{\partial t} = \frac{1}{C(h)}\frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - \frac{S(h)}{C(h)} \tag{1}$$

in which

h = soil water pressure head (cm)
t = time (d)
C(h) = differential moisture capacity $d\Theta/dh$ (cm^{-1})
z = vertical coordinate (positive upwards) (cm)
K(h) = hydraulic conductivity (cm d^{-1})
S(h) = water uptake by roots (d^{-1})

Solving Equation 1 yields the flux of water through the upper and lower boundary of each soil compartment (Figure 2). For the top and bottom compartments, boundary conditions determine the flux at the upper and lower boundary of the soil profile. The complete set of equations is solved by an implicit finite difference scheme, applying a Thomas algorithm.

With respect to the boundary conditions at the top (precipitation/irrigation, evaporation, evapotranspiration) and the bottom of the soil system (groundwater level, pressure heads, free drainage, fluxes) various options are possible, which make the model flexible and generally applicable.

Input parameters and output

The required input parameters for the water transport sub-model are hydraulic functions of each soil horizon, boundary condition values (e.g. precipitation, potential evapotranspiration, groundwater level, flux-groundwater level relation) and crop parameters in the case of cropped soils. The output of the water transport sub-model consists of daily values of the water balance terms of the soil profile such as actual evaporation, flux through the soil surface and through the bottom of the soil profile, water flow between the various soil compartments, and water contents and pressure heads of each soil compartment.

Solute transport sub-model

Schematization and modelling

To model solute transport, the existing SWASALT model (Kroes 1991) has been extended for transport of more than one chemical component and for transport in the saturated zone. For the solute transport module, the soil profile has been divided into the same compartments that have been used in the water transport sub-model. Within these compartments complete mixing of the solutes has been assumed. For each compartment a mass conservation equation is formulated according to

$$V(n,t)\frac{dC(n,t)}{dt} + C(n,t)\frac{dV(n,t)}{dt} + q_{out}\cdot C_{out}(n,t) = q_{in}\cdot C_{in}(n,t) \tag{2}$$

in which

$C(n,t)$ = concentration of a solute in layer n at time t (mol cm^{-1})
$V(n,t)$ = volume of water in layer n at time t (cm)
q_{in} = incoming flux in layer n (cm d^{-1})
q_{out} = outgoing flux from layer n (cm d^{-1})
C_{in} = concentration of incoming flux (mol cm^{-1})
C_{out} = concentration of outgoing flux (mol cm^{-1})

The incoming fluxes and concentrations of layer n which are the outgoing fluxes and concentrations of the adjacent layer n-1 or n+1, depending on the direction of flow, have been assumed to be constant within one time step. The mean concentration of the adjacent compartment over the time step has been used for the concentration of the incoming flux. Since the calculations are done in the direction of flow, the concentration of the incoming flux is known. Assuming constant flow rates within one time step, the change in water contents will be linear with time

$$\frac{d\Theta}{dt} = \frac{\Theta(t) - \Theta(t-1)}{\Delta t} = a \tag{3}$$

Θ = water content ($m^3\, m^{-3}$)
a = differential water content (d^{-1})

The conservation equation can be rewritten as

$$\frac{dC(n,t)}{dt} + a\cdot\frac{q_{out}}{L(\Theta(t-1) + a\cdot\Delta t)} * C(n,t) = \frac{q_{in}\cdot C_{in}}{L(\Theta(t-1) + a\cdot\Delta t)} \tag{4}$$

in which:

L = thickness of the compartment (cm)

Solutions for equation 4 for different conditions are given in Berghuijs-van Dijk et al. (1985).

Input parameters and output

The required input data for the solute transport sub-model are initial concentrations of the solutes in the soil profile, concentrations of solutes in irrigation water, precipitation and groundwater, depending on the used boundary conditions and water fluxes between the compartments (output from the water transport sub-model).

The output of the solute transport sub-model consists of the incoming and outgoing flux of elements for the various soil compartments.

Oxygen transport and pyrite oxidation sub-model

Schematization

Oxygen plays a central role in the chemical processes occurring in acid sulphate soils. The concentration of oxygen at a certain depth in the soil determines the rate of pyrite oxidation at that depth (Dent and Raiswell 1982). The principles of the oxygen transport and pyrite oxidation sub-model have been outlined by Bronswijk et al. (1993). For steady-state conditions, the gaseous oxygen concentration profile in the air-filled pores of the soil is described by (e.g. Christensen et al. 1986)

$$\frac{\partial}{\partial x}\left(D_s(\varepsilon_g)\frac{\partial C_a(x)}{\partial x}\right) = \alpha_v \tag{5}$$

in which:

$C_a(x)$ = concentration of oxygen in air-filled pores (m^3 oxygen m^{-3} air)
$D_s(\varepsilon_g)$ = diffusion coefficient of oxygen in air-filled pores ($m^2\ d^{-1}$)
x = distance (m)
α_v = volumetric oxygen consumption rate in the soil (m^3 oxygen per m^3 soil per day)
ε_g = air-filled porosity

To solve this equation, the oxygen consumption term α must be quantified. A thin section (30-40 cm depth) of an acid sulphate soil from Barambai, Indonesia is pictured in Figure 3a. At the same depth, sites can be distinguished where pyrite is still present

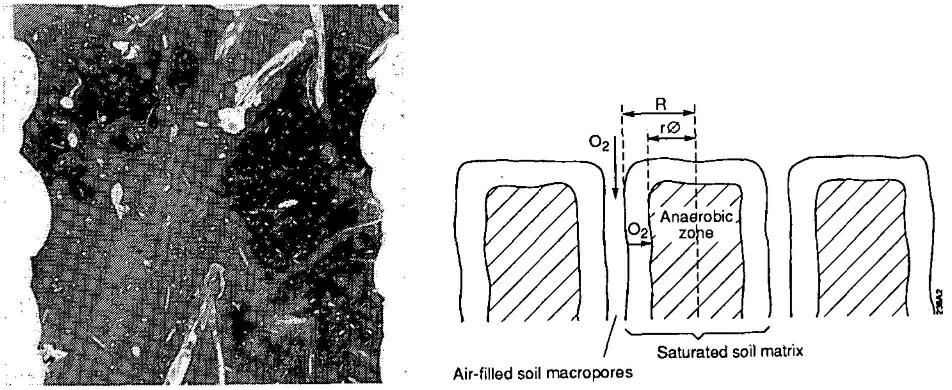


Figure 3 Two-dimensional distribution of oxygen in a structured acid sulphate soil
a. Thin section Barambai (30-40 cm depth). Pyrite is still present in the dark zones. In the grey zones all pyrite has been oxidized.
b. Model representation. R = radius of the soil aggregates (m), r = thickness of the anaerobic zone (m)

and sites where pyrite has been disappeared. The grey zones in Figure 3a, containing no pyrite, are relatively close to air-filled macropores. From these macropores oxygen has been diffused into the soil matrix, whereby pyrite has oxidized. The black zones, which still contain pyrite, are further from the macropores so that oxygen has not yet penetrated.

Figure 3b shows the schematization of such a structured acid sulphate soil, as applied in the model. In SMASS, an acid sulphate soil is considered as a configuration of relatively large, partly air-filled macropores, such as shrinkage cracks, and a wet soil matrix. In heavy clay soils, the soil matrix in between the macropores will remain saturated throughout the year (Bronswijk and Evers-Vermeer 1990).

In the model approach as pictured in Figure 3b, two main processes were distinguished: lateral diffusion of dissolved oxygen from the macropores into the saturated soil matrix and vertical diffusion of gaseous oxygen through the air-filled macropores. The two processes interact at the walls of the macropores where gaseous oxygen dissolves into the soil solution of the matrix. The equilibrium between dissolved and gaseous oxygen at the walls of the macropores has been described in our sub- model by Henry's law: $[O_2]_{air} = K_H *[O_2]_{water}$, in which K_H is Henry's constant. This constant is temperature dependent. At 20 °C, $K_H = 29.7$; at 30 °C, $K_H = 52$.

Modelling of diffusion of dissolved oxygen into the soil matrix

Oxygen is mainly consumed by two processes inside the soil matrix: decomposition of organic matter and oxidation of pyrite. Because oxygen consumption by organic matter decomposition is largely independent of local oxygen concentrations (e.g. Christensen et al. 1986), the oxygen consumption rate by organic matter decomposition (α^{om}) is described in the model by

$$\begin{aligned} \alpha^{om} &= Q, \text{ for } C_w > 0 \\ \alpha^{om} &= 0, \text{ for } C_w = 0 \end{aligned} \tag{6}$$

with Q being a constant (kg O_2 m^{-3} soil day^{-1}); C_w = local dissolved oxygen concentration (kg O_2 m^{-3} water).

Disappearance of pyrite crystals by oxidation is modelled by combining the equal diameter reduction model (Swartzendruber and Barber 1965) with the McKibben and Barnes rate expression for pyrite oxidation (McKibben and Barnes 1986). This yields

$$\frac{dm}{dt} = \frac{-0.311262\sqrt{C_w}}{\rho d} X_{FeS_2} \tag{7}$$

in which:

dm/dt = rate of disappearance of pyrite crystals (kg d^{-1} m^{-3} soil)
X_{FeS_2} = pyrite content (kg per m^3 soil)
ρ = density of pyrite ($kg.m^{-3}$)
d = average diameter of pyrite crystals (m)

Pyrite oxidation has been described in our sub-model by the chemical reaction equation

$$FeS_2 + 3\tfrac{3}{4}O_2 + \tfrac{1}{2}H_2O \rightarrow Fe^{3+} + 2\,SO_4^{2-} + H^+ \tag{8}$$

According to Equation 8, one kg of pyrite consumes one kg of oxygen. Therefore, Equation 7 also offers a quantitative expression for the mass oxygen consumption by pyrite oxidation inside the soil matrix, α_m. The steady-state equation for the dissolved oxygen concentration profile inside the soil matrix then reads

$$D_w \frac{d^2C_w(x)}{dx^2} = \alpha_m \tag{9}$$

in which:

D_w = diffusion coefficient of oxygen in the soil solution ($m^2\ d^{-1}$)

The oxygen consumption term α_m on the right hand side of this equation is equal to dm/dt from Equation 7.

Solving Equation 9 yields the dissolved oxygen concentration profile, $C_w(x)$ (kg O_2 m^{-3}) and the thickness of the aerobic zone inside the soil matrix (m). Furthermore, the total oxygen consumption β_m (kg oxygen m^{-3} soil per day) is computed by integrating $\alpha_m(x)$ over the thickness of the aerobic zone. This yields

$$\beta_m = \frac{A'C_b + Q'}{-\sqrt{B}} \left(\frac{1 - e^{2\sqrt{B}(R - r\phi)}}{1 + e^{2\sqrt{B}(R - r\phi)}} \right) . O \tag{10}$$

in which:

B	=	A'/D_w
A' and Q'	=	parameters in the linear approximation of the relationship between oxygen consumption and oxygen concentration: $\alpha_m = A'C_w + Q'$
C_b	=	dissolved oxygen concentration at the boundary between soil matrix and macropores (kg O_2 m^{-3} water)
O	=	the surface area of the soil matrix in one m^3 of soil (m^{-1})
R	=	radius of the soil aggregates (m)
$r\phi$	=	thickness of the anaerobic zone (m)

The oxygen consumption by organic matter within one m^3 of soil is equal to

$$\beta_m^{o.m.} = \frac{Q\,(R - r\phi)}{R} \tag{11}$$

and the oxygen consumption by pyrite equals

$$\beta_m^{FeS_2} = \beta_m - \beta_m^{o.m.} \tag{12}$$

Modelling of vertical diffusion of gaseous oxygen through the air-filled macropores

Equation 5 describes steady-state gaseous oxygen profiles in the soil macropores. After conversion into volumetric units, β_m from Equation 12 is equal to α_v in Equation 5. The relation between diffusion coefficient, D_s ($m^2\ d^{-1}$), and air content, ε_g ($m^3\ m^{-3}$), is described in the model by (Bronswijk 1991):

$$D_s(\varepsilon_g) = F(1 - (1 - \varepsilon_g)^{2/3})D_o \tag{13}$$

in which:

D_o = diffusion coefficient of oxygen in the atmosphere ($m^2\ d^{-1}$)

F = empirical tortuosity factor (–)

From the oxygen consumed by pyrite (Equation 12) we can calculate the amount of oxidized pyrite (Equation 8). This yields the production of Fe^{3+}, H^+, and SO_4^{2-}. Because the oxygen consumption rate depends on the oxygen concentration (Equation 7) and, reversely, the oxygen concentration depends on the oxygen consumption rate (Equation 5), an iterative procedure has been applied in the oxygen transport sub-model to solve Equation 5 (Berghuijs-Van Dijk et al. 1985).

Input parameters and output

The required input parameters for the oxygen transport and pyrite oxidation sub-model are:

- Average diameter of structural elements;
- Air content profile (output of water transport sub-model);
- Initial pyrite content and organic matter content;
- Initial average diameter of the pyrite crystals;
- Tortuosity factor.

The output of the sub-model consists of:

- Oxygen distribution in the soil macropores and matrix;
- Produced H^+, Fe^{3+}, SO_4^{2-} (input for chemical sub-model);
- Remaining FeS_2.

A typical example of a simulated oxygen distribution is presented in Figure 4.

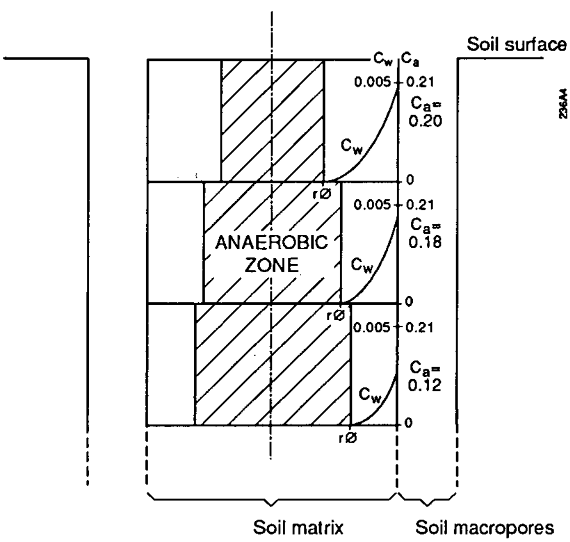


Figure 4 Example of a simulated two dimensional steady-state oxygen concentration profile in a structured acid sulphate soil. C_w = oxygen concentration in water (kg O_2 m^{-3} water), C_a = concentration of oxygen in air-filled macropores (m^3 O_2 m^{-3} air), rϕ = thickness of the anaerobic zone (m)

Chemical sub-model

Schematization

All important chemical processes for acidification and deacidification are incorporated in the model SMASS. Furthermore, processes which determine the concentrations of the toxic elements Fe^{2+},Al^{3+} and of the basic cations Mg^{2+},K^+ and Ca^{2+} in the soil solution are included. Table 1 gives an overview of the most important processes.

In the chemical sub-model, the same division of the soil in compartments has been used as in the other sub-models (Figure 2). Each soil compartment consists of a mineral phase, a cation exchanger phase and a solution phase.

Within each compartment, the solution is assumed to be completely mixed with uniform concentrations.The chemical sub-model computes, for each time step, the changes in chemical composition of each compartment. First, production and consumption due to oxidation and reduction processes is calculated. These data, together with data on the inflow and outflow of solutes from/to neighbouring compartments, and data taken from the previous time step on (i) the total quantity of adsorbed cations and (ii) mineral precipitates present will result in new total amounts for each compartment. From these total amounts, ion association, cation exchange and weathering/precipitation are calculated. This results in new concentrations of the soil solution, amounts of cations adsorbed and amounts of minerals for each compartment.

In order to describe the chemistry, a set of independent chemical components is chosen such that all the chemical species considered can be built up from this set. The components used within SMASS are: H^+, Na^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Al^{3+}, SO_4^{2-}, HCO_3^-, Cl^-, e^- (electron) and X^- (adsorption site). For the complete set of species see AARD/LAWOO 1992.

Oxidation processes

Pyrite oxidation has been described under Modelling of diffusion of dissolved oxygen into the matrix. Oxidation of adsorbed Fe^{2+}, which is much faster than the oxidation of aqueous iron (Ahmad and Nye 1990), in depyritized top layers can be a source of acidification. However, in the soils of Pulau Petak there is hardly any adsorbed Fe^{2+} in the oxidized non-pyritic top layers as a result of leaching (AARD/LAWOO 1992). This is expected to be the same in other acid sulphate soils in the humid tropics. In pyritic layers, adsorbed iron (II) can compete with pyrite for the available oxygen but pyrite oxidation is considered to be the dominant process. Therefore, oxidation of Fe^{2+} has not yet been included in SMASS, but could be important for soils in other regions.

Reduction processes

Because the concentrations of NO_3^- in acid sulphate soils are negligible and amounts of Mn(III/IV)-oxides are generally very low the most likely electron acceptor is Fe^{3+}. Reduction of $Fe(OH)_3$ is given by

$$Fe(OH)_3 + \frac{1}{4}CH_2O + 2H^+ \rightarrow Fe^{2+} + \frac{1}{4}CO_2 + \frac{11}{4}H_2O \qquad (14)$$

in which $Fe(OH)_3$ represents any reducable ferric oxide and CH_2O schematically represents organic matter. Because iron contents of oxidized topsoil layers in Pulau Petak

Table 1 Chemical processes and their effects in acid sulphate soils. Processes included in SMASS are indicated.

Process	Effects	Included in SMASS
Rate-limited Processes		
Pyrite oxidation	Acidification, produces Fe^{3+} and SO_4^{2-}	yes
Iron oxidation	Acidification, lowers Fe^{2+} concentration	no
Iron reduction	Deacidification, raises concentration of Fe^{2+}	yes
Sulphate reduction	Deacidification, raises sulphide concentration	no
Weathering of primary minerals	Produces basic cations, consumes protons	no
Weathering of secondary minerals/precipitates	Consumes protons, regulates Fe^{2+} and Al^{3+} concentrations	yes
Instantaneous Processes		
Cation exchange	Buffers pH and determines concentrations of Ca^{2+} and Mg^{2+}	yes
Ion association	Raises equilibrium concentrations, especially of Al^{3+}	yes

are generally low, iron reduction mainly occurs in recently oxidized pyritic layers that have undergone submergence again.

Reduction of sulphate may also occur. However at pH below 5 sulphate-reducing bacteria are inhibited and, also, the reduction of ferric oxides inhibits or prevents sulphate reduction. Therefore, sulphate reduction has not been incorporated into SMASS.

In SMASS, iron reduction starts when a soil layer is saturated with water. The model distinguishes two forms of Fe(III)-oxides: reducable ferric oxide and non-reducible ferric oxide. The transformation of reducible iron (III) into non-reducible iron (III) is described according to

$$\Delta[Fe(OH)_3{}^R] = -k_1(pH)\ [Fe(OH)_3{}^R] \cdot \Delta t \tag{15}$$

in which:

$[Fe(OH)_3{}^R]$ = the amount of reducable $Fe(OH)_3$ ($mol.kg^{-1}$)
$k_1(pH)$ = rate constant (h^{-1}).

Reduction of reducable ferric oxide is described by:

$$\Delta[Fe(OH)_3{}^R] = -k_2 \cdot \Delta t \tag{16}$$

in which:

k_2 = rate constant ($mol.kg^{-1}.h^{-1}$)

New amounts of reducable iron (III) oxide are calculated by combining Equations 15 and 16 and adding the amount of precipitated $Fe(OH)_3$ calculated in the precipitation/dissolution subroutine. From the amount of oxide reduced and the stoichiometry of Equation 14, the produced amounts of Fe^{2+}, OH^- and HCO_3^- are calculated.

Ion association

In acid sulphate soils, total concentrations of Al^{3+} and other cations in equilibrium with a solid phase can be raised by the complexation of these ions with anions (e.g. sulphate). Ion association has to be taken into account to calculate the activities of the chemical components since cation exchange and mineral equilibria are related to activities and not to total concentrations. Ion speciation is also of importance in relation to toxicity, as certain species of an element are more toxic than others.

Schematically, the formation of species B_j out of the components $[A_1.A_N]$ can be represented by

$$a_{1j} A_1 + ... + a_{ij} A_i + ... + a_{Nj} A_N = B_j \tag{17}$$

According to the Law of Mass Action, the concentration of each species B_j is given by

$$[B_j] = K_j \prod_{i=1}^{N} [A_i]^{a_{ij}} \tag{18}$$

in which:

K_j = the conditional equilibrium constant including activity corrections (AARD/LAWOO, 1992)

$[A_i]$ = the concentration of the free ionic component (mol l^{-1})

Weathering and dissolution of minerals

Weathering of minerals buffers the pH of the soil solution. Weathering of primary minerals such as felspars releases basic cations such as K^+, Mg^{2+} and Ca^{2+}. Because of high weathering rates in the humid tropics, soils in these areas contain little or no primary minerals. In general these soils contain mainly kaolinite. Therefore, weathering of primary minerals has not been incorporated in SMASS. Weathering of kaolinite is too slow to maintain equilibrium. Near-equilibrium concentrations of aluminium values with other aluminium bearing minerals and precipitates have been found in acid sulphate soils. In the soils of Pulau Petak, the concentrations of Al^{3+} at pH values around 5 and higher tend to equilibrium with amorphous $Al(OH)_3$. This was also found by Patrick and Moore (1991) for acid sulphate soils in Thailand. At a lower pH and high sulphate concentrations, Al^{3+} concentrations seem to be regulated by a basic aluminium sulphate, jurbanite (Nordstrom 1982). Van Breemen (1976) postulated the regulation of Al^{3+} concentrations by a basic aluminium sulphate for acid sulphate waters in Thailand based on activity calculations for Al^{3+} and SO_4^{2-} from which he found a linear relationship between $pAl(OH)_3$ and pH_2SO_4. This was also found for the soils in Pulau Petak (AARD/LAWOO 1992) and by Moore and Patrick (1991). At low pH and high SO_4^{2-} concentrations, jurbanite is more stable than gibbsite and amorphous $Al(OH)_3$. From the solubility products it can be deduced that jurbanite is stable over amorphous hydroxide below a pH_2SO_4 of 13.0 (AARD/LAWOO 1992). For activities of sulphate around 5 mmol l^{-1} jurbanite is more stable than amorphous aluminium hydroxide for pH values below 5.3, which is very general in acid sulphate soils. In the model equilibrium with jurbanite has been assumed.

The dissolution of jurbanite buffers one proton according to

$$Al(OH)SO_4 + H^+ \rightarrow Al^{3+} + SO_4^{2-} + H_2O \tag{19}$$

At pH values below 3, dissolution of iron oxides and iron hydroxides becomes important. The buffer intensity of this process depends on the solubility of the iron (hydr)oxide. From an examination of the data of the column and field experiments (AARD/LAWOO 1992) it is clear that various iron oxides determine the solubility of Fe^{3+}. In the model the solubility product of goethite has been used to calculate the iron concentration in the soil solution if ferric oxide is present.

The congruent dissolution of a solid phase B_j can be written as:

$$B_j \rightleftarrows a_{ij}A_1 + ..a_{ij}A_i.. + a_{nj}A_n \tag{20}$$

in which A_1 .. A_n are aqueous components. The concentrations of A_1 to A_n tend to equilibrium at which their activity product (Q_j) will be equal to the solubility product (K_j) of the particular precipitate. The activity product is defined as:

$$Q_j = \prod_{i=1}^{n} (A_i)^{a_{ij}} \tag{21}$$

If the rate is proportional to the difference between the activity product and the solubility product, the change in the total concentration of component A_i can be written as

$$\frac{d[A_i]^T}{dt} = \sum_{j=1}^{m} a_{ij}k_j\,[Q_j - K_j] \cdot \rho/\theta \tag{22}$$

in which:
k_i = rate constant
ρ = bulk density of the solid phase (kg m^{-3})

This equation can be approximated with finite differences according to

$$\Delta[A_i]^T = \sum_{j=1}^{m} \Delta t\, a_{ij}\, k_j\, [Q_j - K_j] \cdot \rho/\theta \tag{23}$$

Cation exchange reactions
Cation exchange can buffer the pH of the soil solution by the exchange of acidic cations such as H^+ and Al^{3+} against basic cations as Mg^{2+} and Ca^{2+}. Exchange reactions also control the concentrations of Ca^{2+} and Mg^{2+} in acid sulphate soils (Moore and Patrick 1989). Schematically, cation exchange can be written as

$$z_bA^{za+} + z_aBX_{z_b} \leftrightarrows z_aB^{zb+} + z_bAX_{z_a} \tag{24}$$

in which X denotes one adsorption site at the cation exchange complex, A and B are cations and z the valence of the cation. Cation exchange is included for Ca^{2+}, Mg^{2+}, Na^+, K^+, Al^{3+} and Fe^{2+}.

Cation exchange has been modeled with the Gaines-Thomas expression (see Bolt 1967).

$$K_{A/B} = \frac{E_A{}^{zb}\,(B^{zb+})^{za}}{E_B{}^{za}\,(A^{za+})^{zb}} \tag{25}$$

in which brackets denote activities in the solution, E stands for the equivalent fraction adsorbed, which is the amount adsorbed of a component in equivalents divided by the total adsorption capacity, and K is the exchange coefficient.

Cation exchange can be written as the sum of two half reactions which are similar to the equations for the ion association (AARD/LAWOO 1992).

Solution technique
For each component a mass balance can be formulated according to

$$[A_i]^T_{t-1} = \sum_{j=1}^{m} a_{ij}\, k_j \prod_{i=1}^{n} [A_i]^{a_{ij}} + \Delta [A_i]^T \tag{26}$$

in which:

$[A_i]_{t-1}^T$ = the total quantity of component i in solution and adsorbed at the previous time step (mol l^{-1})

$[A_i]$ = the concentration of the free ionic component (mol l^{-1})

$\Delta\, [A_i]^T$ = the change in the total concentration of A_i due to weathering/precipitation (mol l^{-1}), see equation 22.

This formula results in a set of n equations with n unknowns which is solved with a Newton Raphson iteration scheme (Groenendijk 1993).

Input parameters and output
The required input parameters for the chemical sub-model are:

System parameters
- Thermodynamic equilibrium constants;
- Cation exchange coefficients;
- Rate constants for precipitation/dissolution and redox reactions;
- Cation exchange capacity (CEC) of each compartment;
- Dry bulk density of each compartment.

Initial conditions
- Initial pH, pE and total concentrations of the elements for each compartment;
- Initial moisture fractions;
- Initial amounts of precipitates.

Variable conditions
- pH, pE and total concentrations of the elements for rainwater, irrigation water and groundwater;
- Produced amounts of H^+, Fe^{3+} and SO_4^{2-} (from the oxygen transport and pyrite oxidation sub-model);
- Incoming amounts of the chemical elements for each layer from the solute transport sub-model

The output of the model consists of the pH, pE and total concentrations of all the chemical components for the soil solution in the various compartments and the composition of the drainage water. Further, the model gives the amounts of adsorbed cations and precipitates.

Acknowledgement

This research has been carried out as part of the 'Research Program on Acid Sulphate

Soils in the Humid Tropics', which is a collaborative Dutch-Indonesian research project, by LAWOO (Land and Water Research Group), The Netherlands, and AARD (Agency for Agricultural Research and Development) Indonesia. This research was partly sponsored by the Netherlands Directorate General of International Cooperation (DGIS).

References

AARD/LAWOO 1992. Acid sulphate soils in the humid tropics. Volume 3: Simulation model of physical and chemical processes in acid sulphate soils to evaluate water management strategies. AARD, Jakarta

Ahmad, A.R. and P.H. Nye 1990. Coupled diffusion and oxidation of ferrous iron in soils. I. Kinetics of oxygenation of ferrous iron in soil suspension. J. Soil Sci. 41: 395-409

Belmans, C, J.G. Wesseling and R.A. Feddes 1983. Simulation of the water balance of a cropped soil: SWATRE. J. Hydrol. 63: 271-286

Berghuys-van Dijk, J.T., P.E. Rijtema and C.W.J. Roest, 1985. ANIMO, agricultural nitrogen model. ICW-note 1671, Wageningen

Bolt, G.H. 1967. Cation exchange equations used in soil science. A review. Neth. J. Agric. Sci. 15: 81-103

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

Bronswijk, J.J.B. 1991. Magnitude, modeling and significance of swelling and shrinkage processes in clay soil. PhD thesis, Agricultural University Wageningen

Bronswijk, J.J.B. and J.J. Evers-Vermeer 1990. Shrinkage of dutch clay soil aggregates. Neth. J. Agric. Sci. 38: 175-194

Bronswijk, J.J.B., K. Nugroho, I.B. Aribawa, J.E. Groenenberg, C.J. Ritsema 1993. Modeling of oxygen transport and pyrite oxidation in acid sulphate soils. J. of Environmental Quality

Christensen, T.H., B.L. Parker, and J.C. Refsgaard 1986. A model for the unsaturated zone; oxygen transport and consumption model. Report Danish Hydraulic Institute. Horsholm

Dent, D.L. 1986. Acid sulphate soils: a baseline for research and development. ILRI Publ. 39. International Institute for Land Reclamation and Improvement, Wageningen

Dost, H. (editor) 1988. Selected papers of the Dakar symposium on acid sulphate soils. ILRI Publ. 44, International Institute for Land Reclamation and Improvement, Wageningen

Dost, H. and N. van Breemen 1982. Proceedings of the Bangkok Symposium on Acid Sulphate Soils, January 1981. ILRI Publ. 31, International Institute for Land reclamation and Improvement, Wageningen

Feddes, R.A., P.J. Kowalik, and H. Zaradny 1978. Simulation of field water use and crop yield. Pudoc, Wageningen

Groenendijk, P. 1993. The calculation of complexation, adsorption, ion exchange, precipitation and weathering reactions in a soil-water system with the geochemical model EPIDIM. Staring Centre Report 70, DLO Winand Staring Centre, Wageningen

Kroes, J.G. 1991. Transol 2.1, A dynamic model for transport and transformation of solutes in soils. User's guide. Internal report 110, DLO Winand Staring Centre, Wageningen

McKibben, M.A., and H.L. Barnes 1986. Oxidation of pyrite in low-temperature acidic solutions: rate laws and surface textures. Geochimica et Cosmochimica Acta. Vol. 50: 1509-1520

Moore, P.A. and W.H. Patrick Jr. 1989. Calcium and magnesium availability and uptake by rice in acid sulfate soils. Soil Sci. Soc. Am. J. 53: 816-822

Moore, P.A. Jr. and W.H. Patrick Jr. 1991. Aluminium, boron and molybdenum availability and uptake by rice in acid sulfate soils. Plant and Soil 136: 171-181

Nordstrom, D.K. 1982. The effect of sulfate on aluminum concentrations in natural waters: some stability relations in the system Al2O3-SO3-H2O at 298 K. Geochim. Cosmochim. Acta 46: 681-692

Ritsema, C.J. Estimation of activity coefficients of individual ions in solution with ionic strengths up to 0.3 mol l^{-1}. Submitted to J. Soil Sci.

Swartzendruber and Barber, 1965. Dissolution of limestone particles in soil. Soil Sc. 100: 287-291

Wijk, A.L.M. van, I. Putu Gedjer Widjaja-Adhi, C.J. Ritsema and C.J.M. Konsten 1993. A simulation model for acid sulphate soils, II: Validation and Application. In: D.L. Dent and M.E.F. van Mensvoort (editors) Selected papers of the Ho Chi Minh City symposium on acid sulphate soils. Publication 53, 357-367 International Institute for Land Reclamation and Improvement, Wageningen

A simulation model for acid sulphate soils, II: Validation and application

A.L.M. van Wijk[1], I Putu Gedjer Widjaja-Adhi[2], C.J. Ritsema[1] and C.J.M. Konsten[1]

[1] The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen, The Netherlands
[2] Centre for Soil and Agroclimate Research, Bogor, Indonesia

Abstract

The Simulation Model for Acid Sulphate Soils (SMASS) was validated by comparing model predictions with measurements obtained during extensive laboratory and field experiments in acid sulphate soils from Southern Kalimantan, Indonesia. Using the model, pH and concentrations of major ions such as Al^{3+}, Mg^{2+} and SO_4^{2-} in the soil solution could be predicted at various depths for both actual and potential acid sulphate soils. Different water management strategies such as drainage, submergence and leaching were considered for both fresh and brackish water conditions. Subsequently, SMASS has been applied to evaluate various possible water management strategies for acid sulphate soils in the same area. It was shown that for an actual acid sulphate soil located in a backswamp with rainwater conservation and tidal drainage, that continuation of the current water management combined with leaching with good quality water could considerably reduce soil acidity. Moderate drainage at 40 cm depth and leaching with water of improved quality (to pH = ± 5) at the end of the wet season was found as a favourable water management option to improve an ill-drained potential acid sulphate soil with pyrite starting at 15 cm, also located in the same backswamp area. After 3 to 4 years the upper 35 cm is free of pyrite and subsequently shows a fast reduction of acidity and Al^{3+} concentrations.

SMASS can predict the long-term physical and chemical consequences of various water management strategies in areas with acid sulphate soils. The present water management practice in a certain area and possible alternatives can be evaluated with respect to their effects on soil and water quality.

Introduction

Simulation models that integrate main physical and chemical processes in a coherent system have been recommended as tools to evaluate water management in areas with acid sulphate soils (Dost and van Breemen 1982, Dent 1986). Therefore, the Simulation Model for Acid Sulphate Soils (SMASS) was developed to assist the selection of promising water management options. The principles of SMASS have been described by Bronswijk and Groenenberg (1993).

The present paper deals with the validation of the model and illustrates its capability for evaluating different water management strategies. Data required for the model validation were obtained from experiments with undisturbed acid sulphate soil columns from and monitored field plots in the Pulau Petak area of Southern Kalimantan, Indonesia. Also, the soil and water management options used in the model application were from Pulau Petak. A detailed description of the study area is given by Kselik et al. (1993).

Model validation

SMASS was validated by comparing model calculations with results from experiments with undisturbed soil columns subjected to controlled drainage, irrigation and leaching. In addition, model calculations have been compared with measurements from monitoring field plots located on both potential and actual acid sulphate soils in the different tidal land classes of Pulau Petak.

Column experiments

Materials and methods

Experiments with seven undisturbed soil columns of 1 m length and 25 cm diameter were carried out to study basic physical and chemical processes and to collect data for model calibration and validation. Four columns contained sulphidic clay soils and three columns ripe acid sulphate soils. The columns were subjected to the following hydrological conditions:

- Drainage to study oxidation of pyrite and subsequent acidification;
- Submerging/flooding to study reduction processes;
- Leaching with fresh and brackish water to study the removal of acidity and chemical compounds.

Every fortnight over two years, the complete water balance, oxygen concentration, redox potential, chemical composition of soil moisture at five depths and element concentrations in drainage and ponding water were measured. In addition, the initial and final hydraulic characteristics, texture, contents of organic matter, pyrite and $CaCO_3$ were measured. Four out of the seven columns, here indicated as the columns 1 to 4, were used for validation of the model. Columns 1 and 2 contained sulphidic (potentially acid sulphate) soil with pyrite from the soil surface downwards; while columns 3 and 4 were initially acid in the top (40 cm) and pyritic below. From day 1 until day 450, columns 1, 2 and 3 were subjected to drainage, keeping the groundwater table at 80 cm depth. During this period regular small irrigations with fresh (column 1) and brackish (columns 2 and 3) water were given to compensate for water losses by evaporation from the top and by soil moisture sampling. After day 450 the soil was submerged for one month with fresh (column 1) and brackish (columns 2 and 3) water. From day 480 onwards the columns were continuously leached with fresh (column 1) and brackish (columns 2 and 3) water, applying rates of 1 mm d^{-1} until day 500, 6 mm d^{-1} between days 500 and 715 and 6 mm d^{-1} from day 715 until 770.

Column 4 was subjected to fresh water submergence from day 1 until 480. After day 480, the soil was leached with fresh water with the same leaching rates as the other columns.

The model simulation was carried out over the same time span applying the same drainage, submergence and leaching/irrigation regimes as in the column experiment. The daily measured actual evaporation of the columns was given as top boundary condition in the model validation. This evaporation ranged from 1 to 1.7 mm d^{-1}. Furthermore, daily quantity and quality of irrigation water were used as top boundary condition. The daily groundwater level inside the column was given as bottom boundary condition together with the groundwater quality.

Various physical and chemical input parameters were available to run the model. An overview of the parameters needed, determination methods and values applied have been presented in AARD/LAWOO (1992a).

Results

During the validation some problems were encountered. First, due to drying of the upper layers of the columns during the drainage phase, it was not always possible to extract enough soil solution from the porous cups to carry out a complete chemical analysis. In that case, the pH was estimated with indicator paper which yielded only a very rough indication. Although great care was taken with the samples, a continuous series of measurements of high quality cannot be guaranteed. Especially pH, SO_4^{2-} and Al^{3+} were sensitive to erroneous measurements (Harmsen 1989, Supardi Suping 1990). Sometimes measured pH values of reduced bottom layers were low due to oxidation of Fe^{2+} in the sampling bottles. Samples with high ionic strength sometimes exhibit great differences between sum of cations and sum of anions; sum of anions often exceeds sum of cations, sometimes with a few hundred percent. SO_4^{2-} concentrations seemed to be too high, and aluminum too low (Supardi Suping 1990).

Figure 1 summarizes the results of the model validation. All data available on pH, Al^{3+}, Mg^{2+} and SO_4^{2-} from the four columns have been plotted against values computed for corresponding days using SMASS. Calculated and measured pH agree reasonably well within the range pH 2.5 to 7. The scattering of pH-values is obviously increased by the unreliable pH-paper measurements (which can be recognized as vertical columns of symbols at pH 3, 3.5, 4.5 and 5). Measured and calculated Al^{3+} concentrations exhibit more variability. Apart from uncertainties in measured data, other reasons may be:

- A relatively slight difference in measured and calculated pH results in a much more pronounced difference between measured and calculated Al^{3+} concentrations;
- In the model calculations, only the jurbanite equilibrium is assumed to take place while, in reality, Al-hydroxides are becoming important above pH 5;
- Constant exchange coefficients are used in the model simulations, sometimes leading to poor agreement between predicted and measured values, in particular during leaching.

The measured and predicted Mg^{2+} concentrations also indicate some dispersion. The main reason may be that the soil in the model is assumes uniform leaching, not accounting for macropore flow, leading to an overestimation of leaching efficiency. Measured and predicted SO_4^{2-} concentrations show a high similarity.

In conclusion, in spite of some noise, the relationship between the measured and computed major elements can be described by a 1:1 line over a very wide range of concentrations.

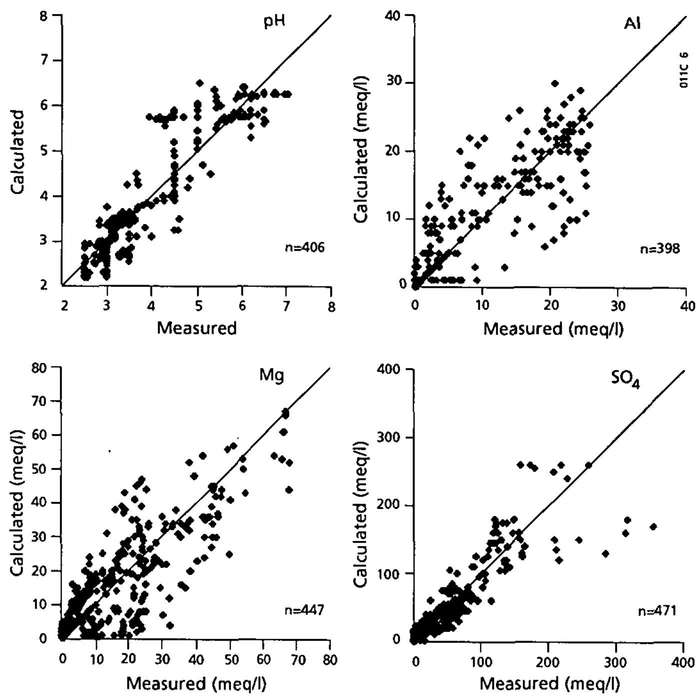


Figure 1 Comparison of model simulations of pH, Al^{3+}, Mg^{2+} and SO_4^{2-} concentrations with data measured at depths of 5, 45 and 85 cm in four columns with two undisturbed acid sulphate soils subjected to drainage, submergence and leaching with fresh or brackish water

Field experiments

Materials and methods

Conditions in the soil columns differ considerably from those in the field. Owing to rather extreme water management practices applied, the concentrations of some major elements (Al^{3+}, Mg^{2+}, SO_4^{2-}) were much higher in the columns than in the monitoring field plots.

To investigate the capability of the model under normal field conditions, SMASS was also validated by comparing model calculations with two year measurements (November 1988 to December 1990) from field plots on Pulau Petak. Five monitoring field plots were used, two on potential and three on actual acid sulphate soils. The plots were in four different tidal land classes. The following data were collected every fortnight: groundwater table depth, oxygen concentration, redox potential, chemical composition of soil solution at six depths and element concentrations in drainage and ponding water. In addition, the initial soil texture, hydraulic characteristics and contents of organic matter, pyrite, $CaCO_3$ were determined.

The validation of the model using measurements of each of these five plots has been described in AARD/LAWOO (1992a). Here, only the validation by the field plot at Tabunganen will be presented. Tabunganen is located in the coastal plain close to the sea. The soil is potential acid sulphate, with pyrite up to the soil surface, used for growing rice. The land is flooded daily with brackish water. Only during the dry period (two to three months a year), the groundwater table drops below the soil surface with a maximum depth of 15-20 cm below surface.

Groundwater levels measured at the field plot were used as the bottom boundary condition. The daily flooding regime and precipitation measured at the site were used as the top boundary condition. During flooding, brackish water of the same quality as measured in the nearby tertiary canal is infiltrating through the top boundary of the model with a rate of 10 mm d^{-1}. Potential evapotranspiration was obtained from open pan evaporation measurements and were completed with estimates from Doorenbos and Pruitt (1977) for missing periods.

Ionic concentrations, pH and redox potentials measured at the start of the monitoring period were used as initial condition for the different model compartments. Measured values of the cation-exchange capacity at different depths were used for model input. Other required input parameters and their values used have been given in AARD/LAWOO (1992a).

Results

Because groundwater levels at Tabunganen were high throughout the year, all chemical processes in Tabunganen occur in the upper 30 cm. Therefore, only the field observations and model computations for 5 and 25 cm depth will be presented.

SMASS computed the oxidation of pyrite upon aeration of the soil during the dry period in the first year of field measurements. The computed drop in pH around day 250 (Figure 2), and the corresponding rise in Al^{3+} and SO_4^{2-} concentrations, agreed with the field measurements. The leaching process in the successive wet period (starting around day 350) was shown by both computed and observed pH rise and decrease of SO_4^{2-} concentration. The model predicted aeration and pyrite oxidation in the dry period of the second year, starting around day 580 by a drop in pH, at 5 cm depth, and rise in SO_4^{2-} concentration.

In the second dry period, the model predicted a rise in SO_4^{2-} concentrations at 25 cm depth due to leaching of compounds out of the topsoil. In reality, however, concentrations at 25 cm depth were much more stable. Part of the SO_4^{2-} produced in the topsoil was, possibly, leached horizontally into the field ditches. As a result, the subsoil received less compounds from the topsoil than was computed with the one-dimensional model.

In general, however, there was a good agreement between modelled and actual conditions.

Model application to evaluate water management strategies

The model has been applied to predict the long-term effects of different water management strategies on soil properties and soil and drainage water quality for two acid sulphate soils in Pulau Petak, namely an actual acid sulphate soil (Barambai I) and a potential acid sulphate soil (Barambai II). Both soils are monitoring fields used for model validation (AARD/LAWOO 1992a).

Simulations were carried out for a period of ten years starting at the beginning of the field experiments (November 1988). To achieve a period of ten years, rainfall

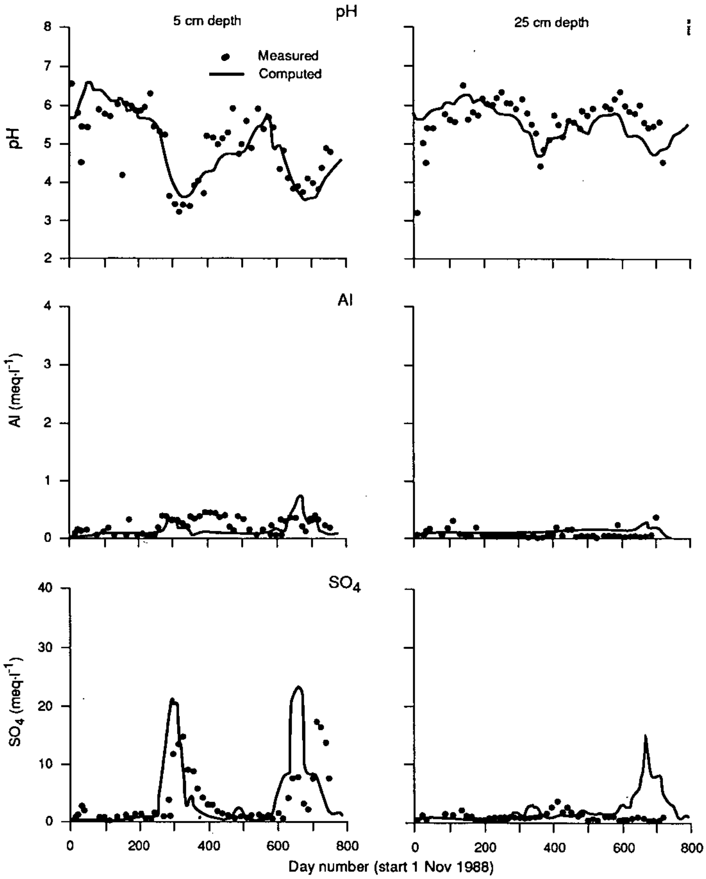


Figure 2 Comparison of simulations at pH, Al^{3+} and SO_4^{2-} concentrations at 5 cm (left-hand side) and 25 cm (right-hand side) depth with data obtained from field measurements of a potential acid sulphate soil (Tabunganen) subjected to daily flooding with brackish water

and groundwater level data collected in the period November 1988 to December 1990 were repeated five times because of lack of long-term daily weather records. Initial soil properties and other input parameters were similar to those used in the model validation.

Barambai I

Barambai I has actual acid sulphate soils (Sulfic Fluvaquents) with pyrite starting at 65 cm depth, used for growing rice. The site is located in a backswamp area in tidal land class C (Kselik et al. 1993). The current water management consists of tidal drainage and rainwater conservation. During the wet period the field is flooded for about four months. During the dry period the groundwater table falls to a maximum depth of 75 cm. Two water management strategies have been projected over ten years:

- Present water management;
- Present water management, extended with leaching in the wet season with irrigation water of good quality.

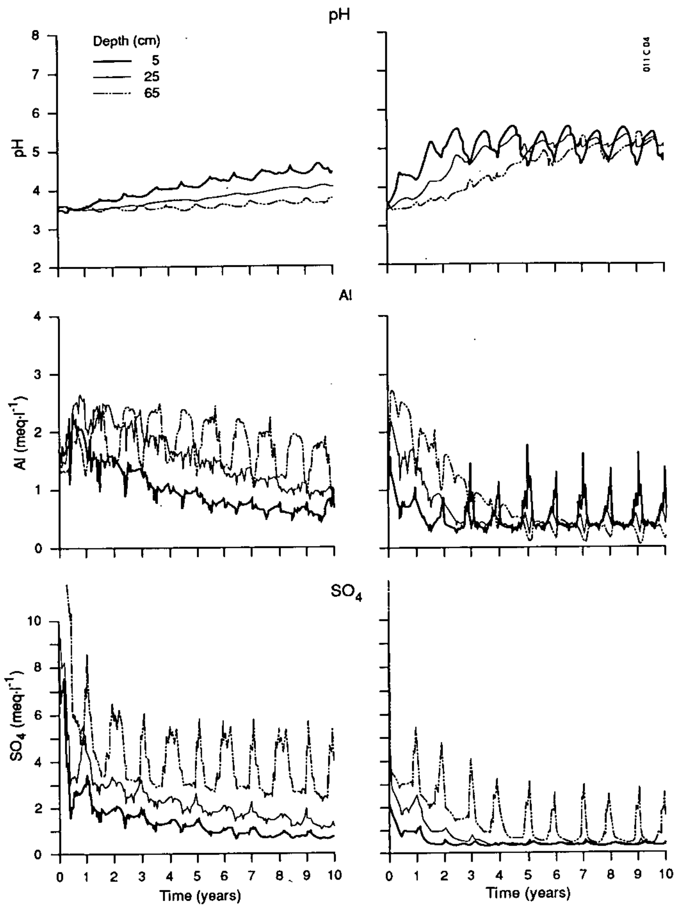


Figure 3 Model prediction of pH, Al^{3+} and SO_4^{2-} concentrations at depths of 5, 25 and 65 cm in an actual acid sulphate soil (Barambai I) for a period of ten years:
Lefthand side: present water management
Righthand side: present water management, extended with leaching with water of good quality during the wet season

Present water management

Continuation of the present water management system, with lowest groundwater levels around 75 cm depth, will not cause much pyrite oxidation because the pyritic layer starts at about the same depth (Figure 3, lefthand side). The fluctuations in pH, Al^{3+} and SO_4^{2-} are caused by dilution and leaching due to the seasonal influence of dry and wet periods. Acidity in the topsoil will be leached by rainwater, which can be seen from the very slow rise of the pH and decreasing concentrations of Al^{3+} and SO_4^{2-}. This slow improvement is only due to rainwater leaching, so continuation of the present water management does not lead to a rapid improvement of the soil.

Present water management and leaching with water of good quality

To improve an already acidified soil, the acidity must be removed. Simulations were done to evaluate the effect of leaching with water of good quality. Therefore, the soil was irrigated during the wet seasons (November to March, 30 mmd^{-1}, pH 5) over the 10 yearperiod considered. Figure 3 (righthand side) shows an increasing of pH within five years to values around 5. Also Al^{3+} and SO_4^{2-} concentrations will decrease due to the additional irrigation with good quality water.

Barambai II

Barambai II has potential acid sulphate soils (Typic Sulfaquents) with pyrite starting at 15 cm depth, used for rice cultivation. The experiment site is located within tidal land class C in the same backswamp area as Barambai I but it is outside the major influence of the drainage system. The present water management consists of rainwater conservation and restricted drainage. During the wet period the experiment site is flooded during six to seven months. The lowest groundwater levels in the dry period are around 60 cm, clearly below the pyritic layer, but reaches this depth for only 1-2 months. Besides, oxidation has only started recently, so Barambai II is in an initial stage of pyrite oxidation.

Two water management strategies have been projected over ten years:
- Continuation of the present water management;
- Drainage by keeping the groundwater level at 40 cm during the whole year to accelerate pyrite oxidation in the top 40 cm, combined with leaching with good quality irrigation water. At present this water is already available in the tertiary canals at the end of the wet season (March to May).

Present water management

Every dry season, the pH will to drop rapidly and Al^{3+}-concentrations will rise due to in situ pyrite oxidation (Figure 4, left-hand side). The reverse trend will occur in the wet season as a result of leaching and reduction. After ten years, the pyrite content of the soil profile is still high from a depth of 25 cm downwards, while soil conditions remain bad.

Combined drainage and leaching with water of good quality water

To remove pyrite from the topsoil, the effects of drainage throughout the year combined with additional leaching at the end of the wet season with good quality water from the tertiary canals have been studied.

At the end of the dry season (September to October), water in the tertiary canals has a very bad quality (pH between 2.5 and 3.5) and is not suitable for leaching purposes. At the end of the wet season (March to May), water quality in the tertiary canals is improving rapidly to pH values of around 5. Therefore, in the combined drainage – leaching scenario, irrigation was only applied during the period between March and May (30 mm d^{-1}).

Figure 4 shows that, initially, pyrite oxidation will accelerate by increased drainage giving rise to low pH and high Al^{3+} concentrations during the dry season. Leaching with good water in the following wet season improves the soil conditions considerably. The main objective of this scenario is fast removal of pyrite from the topsoil. After about three years, all the pyrite in the topsoil has been oxidized. Influenced by leaching with water of relatively good quality, soil conditions (pH, Al^{3+}) will begin to improve,

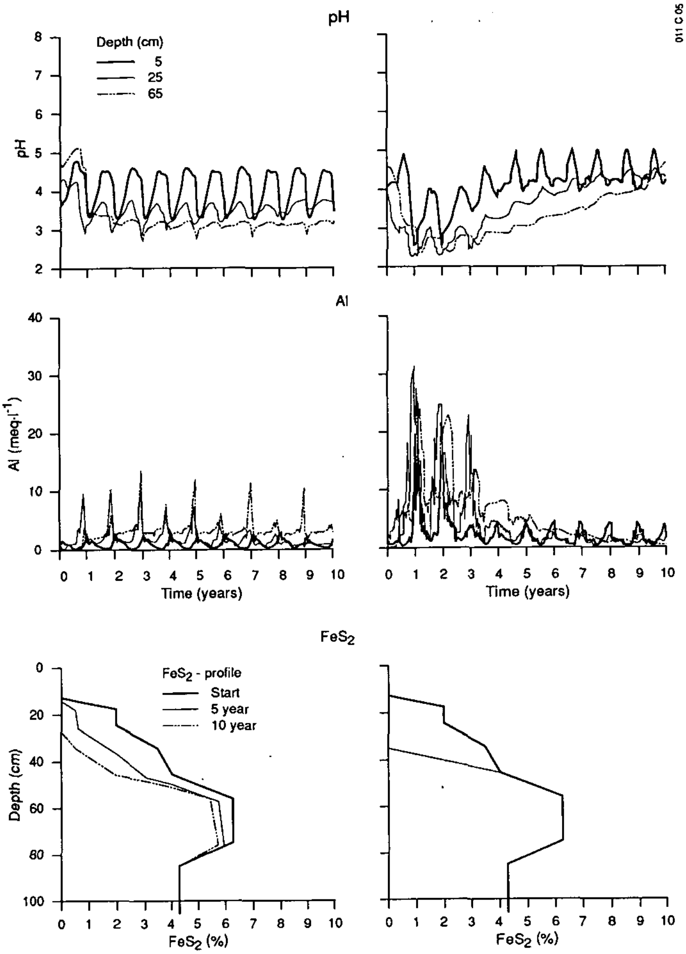


Figure 4 Model prediction of pH, Al^{3+} and SO_4^{2-} concentrations at depths of 5, 25 and 65 cm and resulting pyrite profiles (below) in a potential acid sulphate soil (Barambai II) for a period of ten years:
Left hand side: present water management
Right-hand side: drainage at 40 cm depth combined with leaching with water of good quality at the end of the wet season

because the pyrite has disappeared from the aerated zone. At the end of the period considered, the pH in the soil profile will be higher than when continuing the present water management. Moreover, the risk of acidification will be much smaller due to lowering of the top of the pyritic layer from 15 to about 40 cm below soil surface.

Conclusions

Using the SMASS model, pH and concentrations of major ions in the soil solution could be predicted at various depths for both actual and potential acid sulphate soils. Different water management strategies such as drainage, submergence and leaching for both fresh and brackish water conditions were applied.

The validation of the model by comparison of model calculations with measurements from column experiments and field plots showed a reasonably good agreement between measured and predicted pH, Al^{3+}, Mg^{2+} and SO_4^{2-} concentrations. Comparison of measured and predicted major ions yields a 1:1 relationship over a very wide range of concentrations. The greatest variability was found for Al^{3+} and Mg^{2+}, which can be ascribed partly to erroneous measurements and partly to some shortcomings of the model, related to our assumptions about leaching. The pyrite oxidation could be predicted. Resulting pH-decrease and rise in Al^{3+} and SO_4^{2-} were reasonably well predicted. SMASS offers the possibility of predicting the long-term physical and chemical consequences of various water management strategies in areas with acid sulphate soils. Present water management practices in a certain area and possible other strategies can be evaluated with respect to their effects on soil and water quality.

In the evaluation presented, the consequences of various water management strategies are predicted without discussing their implementation in practice. Implementation of promising water management strategies must be subsequently assessed by a technical and economic evaluation.

Acknowledgement

This research has been done as part of the 'Research Program on Acid Sulphate Soils in the Humid Tropics', which is a collaborative Dutch-Indonesian research project by LAWOO (Land and Water Research Group), The Netherlands, and AARD (Agency for Agricultural Research and Development), Indonesia. This research was partly sponsored by the Netherlands Directorate General for International Cooperation (DGIS).

References

AARD & LAWOO 1992a. Acid sulphate soils in the humid tropics. Volume 3: Simulation model of physical and chemical processes in acid sulphate soils to evaluate water management strategies. AARD, Jakarta

AARD & LAWOO 1992b. Acid sulphate soils in the humid tropics. Volume 4: Water management and soil fertility research in acid sulphate soils in Kalimantan, Indonesia. AARD, Jakarta

Bronswijk, J.J.B. and J.E. Groenenberg 1993. SMASS: a simulation model for acid sulphate soils, I: Basic principles. In: D.L. Dent & M.E.F. van Mensvoort (editors): Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils. Publ. 53, 341-355, International Institute for Land Reclamation and Improvement, Wageningen

Dent, D. 1986. Acid sulphate soils: a baseline for research and development. ILRI Publ. 39. International Institute for Land Reclamation and Improvement, Wageningen

Doorenbos, J. and W.O. Pruitt 1977. Crop water requirements. FAO Irrigation and Drainage Paper 24. FAO, Rome

Dost, H. and N. van Breemen (editors) 1982. Proceedings of the Bangkok Symposium on Acid Sulphate Soils, January 1981. ILRI Publ. 31. International Institute for Land Reclamation and Improvement, Wageningen

Harmsen, J. 1989. Report on a mission to South-Kalimantan for quality control of chemical analyses. Mission Report 26, Research on Acid Sulphate Soils in the Humid Tropics. International Institute for Land Reclamation and Improvement, Wageningen

Hendro Prasetyo, J.A.M. Janssen, and Alkasuma 1990. Landscape and soil genesis in Pulau Petak, Indonesia. In: Papers workshop on acid sulphate soils in the humid tropics, 18-29. AARD & LAWOO, Bogor

Kselik, R.A.L., K.W. Smilde, H.P. Ritzema, Kasdi Subagyono, S. Saragih, Mauliana Damarik and H. Suwardjo 1992. Integrated research on water management, soil fertility and cropping systems on acid sulphate soils in South Kalimantan, Indonesia. In: D.L. Dent & M.E.F. van Mensvoort (editors): Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils. Publ. 53, 177-194, International Institute for Land Reclamation and Improvement, Wageningen

Supardi, S. 1990. Problems of chemical analysis of water samples from acid sulphate soils. In: Papers workshop on acid sulphate soils in the humid tropics, 136-145, AARD & LAWOO, Bogor, Indonesia: 136-145

Modelling flow of water and dissolved substances in acid sulphate soils

Erik Eriksson

Division of Hydrology, University of Uppsala, Sweden

Abstract

Simulation of water flow is related to the particular properties of acid sulphate soils, in particular to the ongoing experimental work in the Plain of Reeds of the Mekong Delta. Simulated flow is used as input to the chemical part of the model. The time interval for the chemical transport is adjusted as to minimize the effect of numerical dispersion, allowing displacement of water commensurate with the thickness of layers considered. For unsaturated flow and a layer thickness of 10 cm, a time interval of up to ten days can be used. For saturated flow, e.g. during irrigation, the concepts of micropore and macropore space are used, a fraction of the total flow of water being diverted to the micropore space which also contains the storage and most of the dissolved matter. The size of this fraction depends on the contact area between micropore and macropore space, which is a function of the soil structure. The time interval used in this case is of the order of one day.

Sulphate adsorption is described by a Langmuir adsorption isotherm and cation exchange equilibria by Gapon equations, parameters being derived from experimental data. The saturated zone is regarded as a well-mixed reservoir considering outflow of dissolved substances. This is a fair approximation considering the pattern of flow between inflow and outflow areas. However, the diversion of flow through micropore space has also to be considered. Examples of simulations of chemical properties are compared to experimental results.

Background

Acid sulphate soils produce sulphuric acid through oxidation of pyrite. The rate at which this takes place depends on the rate at which oxygen enters the soil. In soil air, the diffusion of oxygen gas is fairly rapid while diffusion in water is slow and, by and large, rate-determining.

Water management practices can improve growing conditions for crops by controlling pyrite oxidation and by washing out from the root zone products which are toxic. Use of model simulation of physical and chemical processes in the soil seems to be a promising way to test the effect of various water management practices.

The present paper relates to soils in the Plain of Reeds in the Mekong Delta. An experimental area was designed for the study of the effects of different water management experiments in the Mekong Acid Sulphate Soils Project and reported in this symposium by Danh and Tuong. The data collected are most likely representative for acid sulphate soils in similar settings.

The physics of acid sulphate soils

The typical soil profile can be described as a set of layers labelled A, B1, B2, B3, and C from top to bottom. Unsaturated hydraulic conductivity varies with the water content in a normal manner. It shows a minimum in B1, at least in cultivated soils, usually attributed to tillage. At saturation, the hydraulic conductivity jumps to a value at least 10 times that expected from extrapolation of the unsaturated conductivity. This feature is important for the function of the soil as conductor for flowing water and is caused by the presence of permanent fissures which contribute what can be named the macroporosity of the soil. The macroporosity separates the structural elements, clods or peds, which contain the microporosity. Clods are found in the A-layer and often show a wide size distribution. The contact surface between macro- and microporosity is usually large in the A-layer. Below this layer, the peds become larger with a corresponding reduction in contact surface and are gradually taking the shape of columns with a relatively small contact surface between macropore and micropore space. In the C-layer, unripe structural features disappear and hydraulic conductivity becomes low.

The flow in unsaturated soil is confined to the micropore space, the flow direction being governed by the matric potential which is a function of water content. During dry spells, the flow direction is frequently directed upwards and can add up to considerable volumes.

In the saturated soil the flow direction is usually downwards, particularly during irrigation. The macropore space may carry more than 90 per cent of this flow.

The chemistry of acid sulphate soils

The sulphuric acid formed upon pyrite oxidation is partly neutralized when reacting with minerals in the soil, either by dissolution of clay minerals or by ion exchange. A fair part of the acid is adsorbed on mineral surfaces, primarily on gibbsite and goethite. The chemistry of the soil solution is characterized by low pH and fairly high concentrations of base cations and aluminium, the major anion being sulphate.

Table 1 gives some statistics on the chemistry of soil solutions at the experimental area of the Tan Thanh experimental farm, Plain of Reeds, Vietnam. The data are the 25, 50 and 75 per cent values of the frequency distributions obtained from 165 sets of analysis on samples taken in January, March and June 1991 at 20, 40, 80 and 120 cm depth.

The data indicate lognormal distributions of Fe^{2+}, Al^{3+} and sulphate while the rest is more or less normally distributed. The small variation in pH indicates a very high buffering capacity of the soil. A cluster analysis reveals the features shown in Figure 1 showing a close relation between the three variables mentioned above, the immediate result of the oxidation of pyrite in the soil when pH is below 5. Mg^{2+} and Ca^{2+} are related to this process, although in a somewhat looser manner. The rest of the ions seem to be only slightly related to the oxidation process. The correlation between sodium and chloride indicates a common origin – in all probability traces of sea water retained in ion exchange positions. A principle component analysis reveals that the first component accounts for nearly 50 per cent of the variance. Sulphate can form

Table 1 Data on frequency distributions of chemical properties of soil water in the Tan Thanh Farm Experimental Area

Property Unit Unit	pH	EC uS/cm	Fe^{2+}	Acid	Al^{3+}	SO_4^{2-}	Mg^{2+}	Ca^{2+}	K^+	Na^+	Cl^-
			mmol(+) l^{-1}								
25%	3.02	1425	5.11	10.6	3.7	26.0	9.5	3.1	0.13	3.25	0.18
50%	3.22	2160	7.99	17.3	7.6	40.2	14.1	4.4	0.18	5.00	0.27
75%	3.45	2890	12.31	29.2	14.4	62.1	19.0	6.7	0.22	6.25	0.52

basic sulphates and can also be adsorbed, particularly on gibbsite and goethite. The basic aluminium sulphates of interest here are jurbanite, $AlOHSO_4$, and alunite, $KAl_3(OH)_6(SO_4)_2$. The negative logarithm of the ion activity products of the ions in the formulae can be used to test experimental data against hypothetical minerals. For jurbanite, the equilibrium value is 17.8 according to Nordstrom (1982). Van Breemen (1973) found a value of 17.2 on chemical data from soil water in the acid sulphate soils of the Bangkok area but pointed out that this was no proof that jurbanite was present. In fact, nobody seems to have identified it in acid sulphate soils. Alunite is assumed to form very slowly. The equilibrium value, pK is given as 85.6 (Nordstrom 1982).

Accepting the two pK-values 17.2 and 85.6 for the two basic sulphates and a pK value of 32.65 for microcrystalline gibbsite, the stability regions of these three minerals can be illustrated as in Figure 2. Referring to $2pH + pSO_4$ as the sulphuric acid potential, SAP, jurbanite is stable for SAP below 8.7 and alunite (at $\log(K+) + pOH = 14.7$) for SAP from 8.7 to 14.5. Hence, if one starts at SAP equal to 7 and either adds alkali or removes hydrogen ions through leaching then the SAP-value of 8.7 is rapidly approached because of the reaction

$$3AlOHSO_4 + K^+ \rightarrow KAl_3(OH)_6(SO_4)_2 + 3H^+ + SO_4^{2-}$$

which means that both jurbanite and alunite can exist simultaneously. Adding more alkali converts more jurbanite but does not change SAP. Only when all jurbanite has

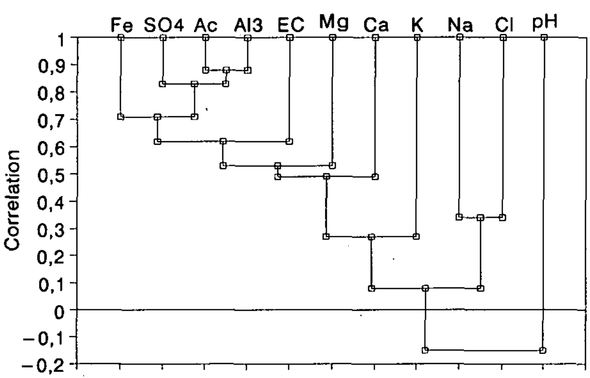


Figure 1 Dendrogram showing clustering of chemical properties of soil water sampled at the Tan Thanh Farm

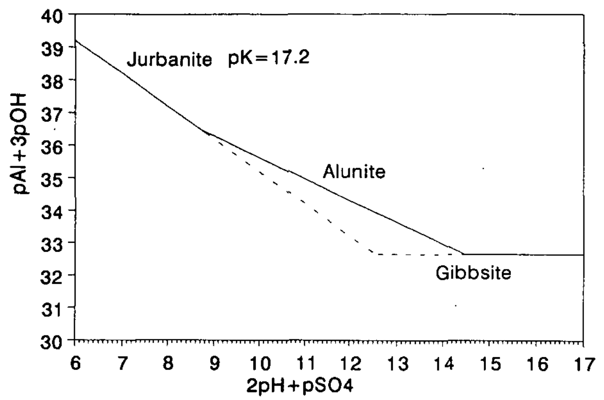


Figure 2 Stability diagram of basic aluminium sulphates. The dashed line could represent relatively rapid reactions if alunite forms slowly

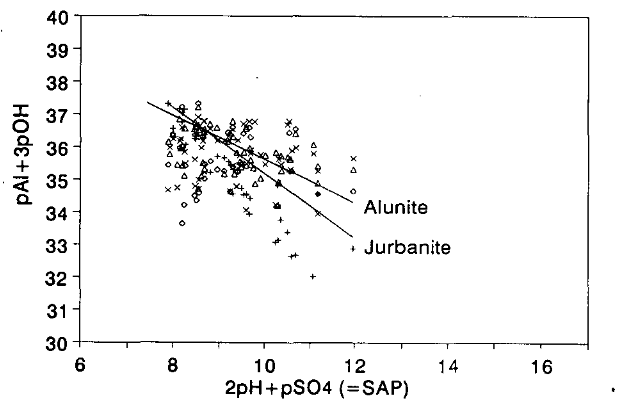


Figure 3 Experimental values of pAl + 3pOH plotted against 2pH + pSO_4, all in relation to the diagram in Figure 2. The symbols represent different water management practices

been consumed does SAP, the sulphuric acid potential, increase and this quite rapidly up to 14.5 where it will stay until all alunite is dissolved, forming gibbsite in the reaction

$$KAl_3(OH)_6(SO_4)_2 + 3H_2O \rightarrow 3Al(OH)_3 + K^+ + 3H^+ + 2SO_4^{2-}$$

It may be instructive to look at experimental data computing the -log(ion activity product) from chemical analyses of soil water samples. The data are from the same set as those in Table 1. Figure 3 shows the computed 'jurbanite' points, having pAl- + 3pOH and SAP as coordinates. The positions of the lines for jurbanite and alunite obtained from Figure 2 are also shown in this diagram. Although the spread of the points is considerable, they indicate the crossing of the two lines is within the cluster of points.

The deviations from expected equilibrium values can be explained by analytical errors, heterogeneous water samples being a mixture between micropore and macro-pore water, transpiration can have caused supersaturation, and so on. It seems at

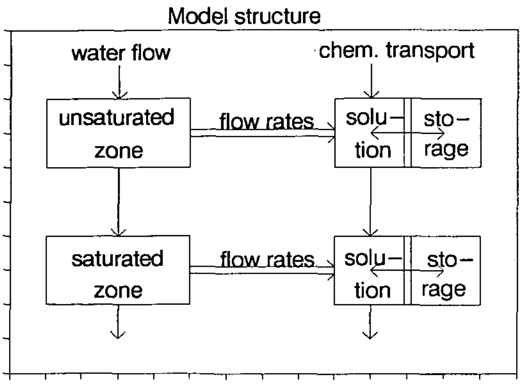


Figure 4 The structure of the model for simulating water flow and chemical transport. The flow rates from the water flow part are used as input to the chemical transport part

present useless to speculate further on this subject.

In the leaching experiments reported by Phan Thi Binh Minh (1991) it was found that the ionic activity product corresponding to jurbanite gave a pK-value close to 17.8. The leaching procedure used is, of course, rather drastic considering the rate of leaching. If the reaction rate is slow there will be a tendency for the SAP values to drift to the right of the equilibrium value, since the samples will appear diluted by water.

Maybe the concept of mineral components jurbanite, alunite and gibbsite controlling the system is too rigid in an environment like that of acid sulphate soils which also exhibit considerable heterogeneity. The surface areas of gibbsite and goethite are most likely large, favouring adsorption where the major binding mechanism may simulate formation of basic aluminium sulphates (Schindler and Stumm 1987). Adsorption introduces additional degrees of freedom for the equilibrium system. Phan Thi Binh Minh (1991) fitted the observed data from the leaching tests to Langmuir's adsorption isotherms and these seems to work well in the chemical transport model to be described later.

The water flow model

Figure 4 shows schematically the model structure used. The water flow is simulated in the left part of the diagram, flow rates being used in the right part for simulating chemical transport.

The water flow part of the model is conventional with one part for unsaturated flow and the other for groundwater flow. In the version developed by Phong (1991) presently used, the groundwater flow is treated as two-dimensional and horizontal, applying the Dupuit assumption, taking account of the drainage resistance due to the geometry of flow near the drainage channels. The inflow to and outflow from the groundwater surface is taken to be uniformly distributed over the area. It influences the groundwater level as, also, will horizontal flow from irrigation canals.

In the unsaturated part, evapotranspiration is computed from potential evapotranspiration and the root depth using a fairly sharp cutoff of flow rate close to the wilting point.

One problem is supersaturation of the surface layer during heavy rain. With the structure of cracks and fissures in the soil this is handled most easily using so-called bypass flow. This means that any excess moisture in a layer is diverted to the next layer below. This layer is then assumed to absorb the water up to saturation. Should there be any further excess this is transferred to the next layer and so on.

Saturated hydraulic conductivity was measured on 16 cm diameter cylinders of undisturbed soil. But the presence of wider cracks will cause large variations between duplicates, as was the case. Further, there is a high probability that the saturated hydraulic conductivities will be underestimated since the size of the samples may be very much smaller than the distances between major cracks. This is particularly important for the horizontal conductivity which should also be assessed by independent methods, i.e. by some form of pumping test.

The chemical model

Figure 5 shows schematically the flow of water and dissolved substances through a layer of soil, indexed j. Flow from the layer j-1 is divided into two fractions. One of magnitude alfa passes through the micropore space while the other, 1-alfa, passes through the macropore space.

The storage of ions as well as the major part of the dissolved ions are found in the micropore space. The return flow from this space is thus modified by the storage and other possible source and sink processes, attaining the concentration of the micropore space water. When it mixes with the fraction 1-alfa of water from previous layer, it attains the concentration described as co(j). As such it enters the layer j+1 where it again splits into two fractions.

This is now the basic flow model for chemical substances. Its concept is simple and congruent with the amount of information on the soil structure usually available for

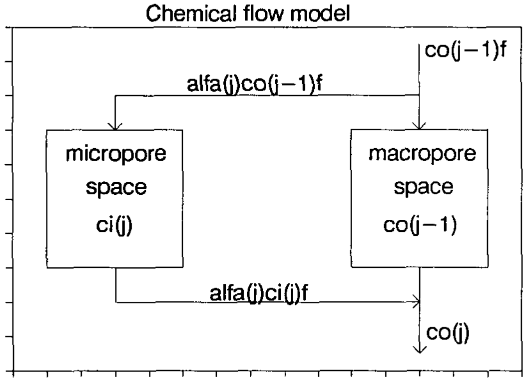


Figure 5 The chemical transport part of the model with differentiation into macropore and micropore space. Alfa is the fraction of total flow passing through the micropore space

a modeller. The real situation is certainly much more complicated. The present approach can be seen as a parameterization of the interactive physical processes – flow and diffusion – which occur in a soil. The parameter alfa will be uniform in the unsaturated soil since the flow is then confined to the micropore space. In saturated conditions, alfa can be estimated roughly from knowledge of the structure. In the surface layer the structure in a clay soil is commonly aggregates having a size distribution up to a few mm in diameter. This means that the flow paths for water in the micropore space are short. Even if the flux in the macropore space should be 90 per cent of the total, a great part of this can still pass through the micropore space. The important parameter here is really the contact surface between the micropore and macropore spaces. If this is large there will be a considerable exchange of water through micropore space by flow as well as by molecular diffusion. Because of this, alfa may well reach a value of 0.9 even if the macropore space is able to transfer 90 per cent of the flow. Deeper in the soil profile, at least of a clay soil, aggregates become larger and the contact surface between the two spaces smaller, particularly when the structural elements consist of columnar peds of 10 to 20 cm diameter. Under such conditions alfa may drop to 0.1.

Recalling Figure 4, the chemical environment consists of a solution phase and a storage phase. The storage, can be in crystalline state, as minerals in equilibrium with the solution, or as adsorption on surfaces or in cation exchange storage both of which can be regarded as being in equilibrium with the solution. In order to describe what happens chemically in the soil, it is necessary to formulate these processes in mathematical form. As an example of a mineral, jurbanite can be mentioned. Even if it should not exist, the aluminium and sulphate behave in a way which can be described as a mineral equilibrium engaging three important components, aluminium, sulphate and hydrogen ions. Storage of sulphate can be described as adsorption following the Langmuir adsorption equation, originally derived for monolayers of adsorbed gases. It may seem illogical to use jurbanite as a concept regulating the interaction between hydrogen ions, aluminium and sulphate and then use an adsorption process for sulphate alone but one may accept it for the time being. As to ionic exchange, this is a well-studied process for which several models of varying complexity exist. For the present purpose, a fairly simple model is the Gapon exchange equation.

Cation exchange involves the variable CEC_e, the effective cation exchange capacity, being a function of the pH of the soil. Within the range of pH values met with in the Plain of Reeds, it can probably be regarded as constant.

Cation exchange properties are described by selectivity coefficients. Since they depend primarily on the difference in valency of a pair of cations – the activity coefficients of the ions is the other part – one may simplify the presentation here by considering only aluminium, calcium and sodium as exchangeable cations (if calcium also includes magnesium and ferrous iron and sodium includes potassium). With this simplification, the exchangable cations can be expressed as fractions of the CEC_e by the variables E_{Al}, E_{Ca} and E_{Na}. The sum of E_{Ca} and E_{Na} is then the fraction of exchangeable base cations. For concentrations in the solution phase one can use C_{Al}, C_{Ca}, and C_{Na}. With this the necessary Gapon exchange equations, using mmol(+) l^{-1} as unit, are

$$E_{Al}/E_{Ca} = S_{AlCa} \cdot C_{Al}{}^{2/3}/C_{Ca} \qquad (1)$$

$$E_{Al}/E_{Na} = S_{AlNa} \cdot C_{Al}{}^{1/3}/C_{Na} \qquad (2)$$

The adsorption isotherm for sulphate reads

$$A_{SO4} = A_{max} \cdot b \cdot C_{SO4}/(1 + b \cdot C_{SO4}) \tag{3}$$

where A_{SO4} is adsorbed sulphate in $mmol_c l^{-1}$ of soil, A_{max} and b being constants.

Electroneutrality of the solution phase requires

$$C_H + C_{Al} + C_{Ca} + C_{Na} = C_{SO4} + C_{Cl} \tag{4}$$

where C_H is the hydrogen ion concentration also in mmol(+) l^{-1} and C_{Cl} the concentration of chloride ion. Using the assumption that the presence of jurbanite and alunite set a constant value of SAP, i.e. of $2pH + pSO_4$, another condition is

$$C_H = 10^{(-SAP+9.3)/2} * 1/(C_{SO4})0.5 \tag{5}$$

pH being computed from (SAP-9.3)/2 + 0.5*logC_{SO4}

Defining $X = C_{Al}^{\ 1/3}$

makes it possible to reformulate equation 5 as

$$X^3 + X^2 \cdot S_{AlCa} \cdot E_{Ca}/E_{Al} + X \cdot S_{AlNa} \cdot E_{Na}/E_{Al} - C_{SO4} - C_{Cl} + C_H = 0 \tag{6}$$

Solving this third degree equation yields a value for C_{Al} from which the rest of the concentrations can be computed. The solution of Equation 6 is best done with the regular false method.

As to the mass balance, Figure 5 indicates how it is approached. Since the volume of the macropore space is small compared to that of the micropore space, the mass balance of concern is that of the micropore space, i.e. of the sum of adsorbed/exchangeable and dissolved substances.

Provided the parameter set and initial conditions are properly selected, the simulation is obtained as response to addition of prescribed amounts of water to the top layer. This will then cause a displacement of the water in the soil approximately equal to the layer thickness. During the displacement, adjustment of equilibria between the added water and the solid and solution phases takes place, a process governed by the size of the fractions of added water which are diverted through the micropore space.

Model test

An important part of the project was experimental work on large undisturbed soil columns taken at the Tan Thanh Farm (Nguyen Tan Danh and To Phuc Tuong, 1993). Three of the columns were kept permanently at full saturation and, after a preliminary period, leached by adding water providing a preset drainage. Soil water was sampled at roughly 20 cm interval levels corresponding to the horizons A, B1, B2, B3 and C. Analyses included sulphate and aluminium and, on a few occasions, also Ca, Mg, K, Na and Cl. This set of data was used for comparison with simulated concentrations of sulphate, aluminium, and base cations in the water of the macropore space.

Table 2 Parameter data used in the simulation of the effect of leaching on chemical properties of soil water

Soil layer	A	B1	B2	B3	C	Unit
CEC_e	103	110	100	90	103	mmol (+) l^{-1} of soil
Exch. Al	62	70	60	50	58	,,
Exch. Ca+Mg	35	35	34	34	39	,,
Exch. Na+K	6	5	6	6	6	,,
S_{AlCa}	9.8	13.0	10.9	8.9	8.6	,,
S_{AlNa}	21.6	24.0	21.6	18.2	18.6	,,
Amax	20.8	20.8	20.8	20.8	20.8	,,
b	0.01	0.01	0.01	0.01	0.01	,,
alfa	0.9	0.6	0.1	0.1	0.1	,,

Most of the model parameters shown in Table 2 were obtained independently from the data set described. The importance of fractions for macropore space could be judged from the experimental data on hydraulic conductivity at different water contents and from the description of soil structure on these soils available in literature. Exchange capacities of the different layers were estimated from data obtained from a small program called batch experiments, designed for deriving these data as well as the selectivity coefficients needed. Sulphate adsorption equations of the Langmuir type were derived by Phan To Binh Minh (1991) from a set of leaching experiments on soil samples from the Tan Thanh Farm. There were no systematic variations in the adsorption parameters, hence the same values were used in each layer. The parameters which were adjusted to fit were the alfas, i.e. the fraction of flow diverted through micropore space. The set chosen is, however, well in agreement with the expected contact surface between macropore and micropore space in the layers.

The water saturated columns with preset drainage (after a short period of no drainage) called phase 2 lasted for 91 days. Initial concentrations used were those observed at the start. The daily drainage was far below free drainage. These flow rates were used as inputs to the model. The time interval was 1 day which in the macropore space should give a displacement equivalent to the layer thickness 20 cm. The output of the model was concentrations in the macropore space, the kind of properties which the chemical analysis should represent.

The results for aluminium and sulphate are shown in Figures 6 and 7. Each figure consists of five graphs, one for each layer. Simulated data are shown by full drawn lines, experimental data by crosses. During this simulation the C_H-term, Equation 5, was set to

$$C_H = 0.1/(C_{SO4})^{0.5}$$

which corresponds to a SAP value of 11.1 which is much higher than the expected value of 8.7.

Considering the scatter of experimental points, the simulation must be regarded as successful. It is obvious, though, that the alfa's chosen are quite powerful in determining the time development of concentrations. However, the set finally chosen can be regarded as unique in the sense that no alternative values could produce any better fit. The chosen values are also such that their variation with depth is supported by the evidence on soil structure at hand.

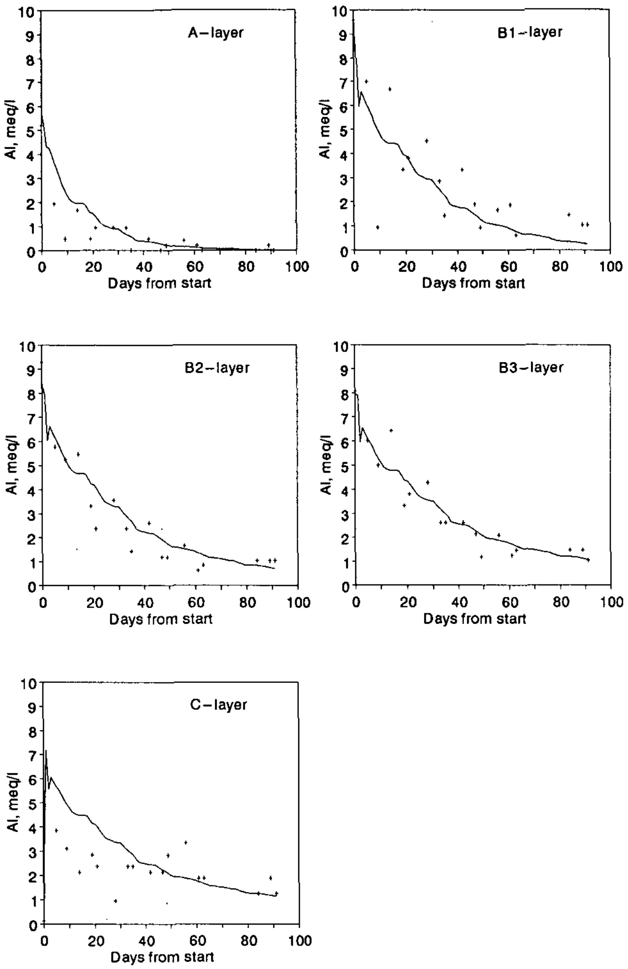


Figure 6 Simulated (fulldrawn) and experimental (crosses) values of aluminium in a soil column kept permanently water saturated during preset rate of leaching

The spread in experimental points is quite wide. This spread may be due to the heterogeneity of the soil and to the difficulty of sampling water from the macropore space when its volume is very small.

Alternatives to the Alfa-concept

The use of alfa in the present paper is a relatively crude way of weighing the influence of micropore space as a dynamic storage place of soluble material. A conceptually more satisfying way is to consider flow out of and into micropore space as a diffusion process. The intensity of this process is then proportional to the average gradient within clods, peds or other aggregates, and of the specific area of aggregates – area

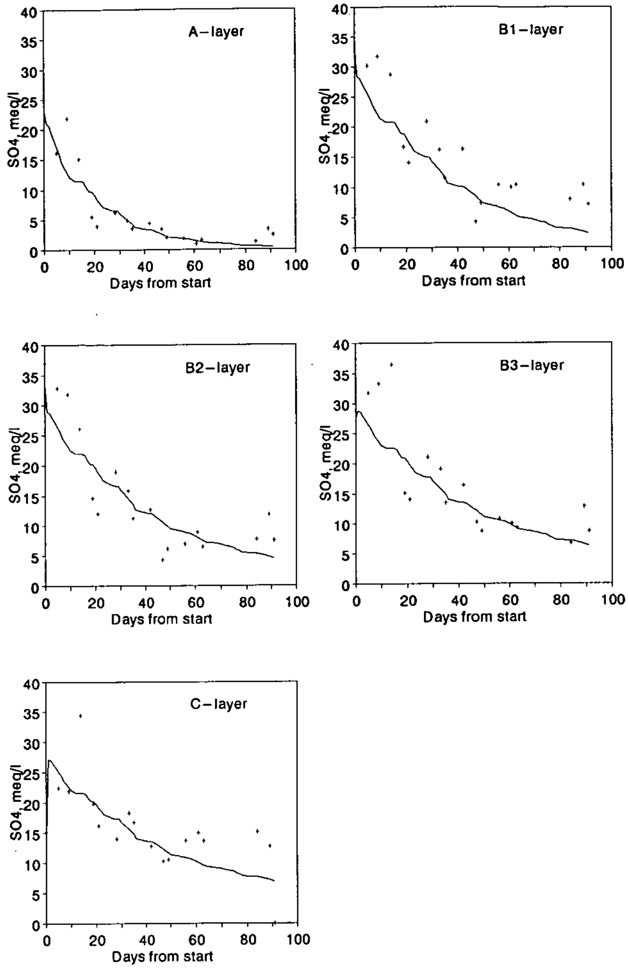


Figure 7 Simulated (fulldrawn) and experimental (crosses) values of sulphate in a soil column kept permanently water saturated during preset rate of leaching

per unit volume of soil. Geometry of macropore space also enters – the root channels may be quite effective in relation to their surface area. Research on these alternatives within the project is ongoing.

Acknowledgement

The present paper was prepared on request by the Secretariat of the Interim Committee for the Lower Mekong. I am indebted to the staff of the Southern Institute for Water Resources Research in Ho Chi Minh City who provided and helped to prepare the data needed, and to To Phuc Tuong, the International Rice Research Institute, for many inspiring discussions. To Phuc Tuong prepared the detailed study programme

for the MASS project and developed part of the model described by Phong. The model is nowadays also known as the Phong & Tuong model.

References

Ngo Dang Phong 1991. Modelling of water movement in acid sulphate soils. Paper presented at the Workshop on Management of Acid Sulphate Soils in Oct 21-25, held in Ho Chi Minh City

Nguyen Tan Danh and To Phuc Tuong 1993. Kenetics of soil solution chemistry in different leaching treatments of undisturbed columns of acid sulphate soils from the Plain of Reeds, Vietnam. In: D.L. Dent and M.E.F. van Mensvoort (editors). Selected papers of the Ho Chi Minh City symposium on acid sulphate soils. Publication 53, 381-390, International Institute for Land Reclamation and Improvement, Wageningen

Nordstrom, D.K. 1982. The effect of sulphate on aluminium concentrations in natural waters: some stability relations in the system $Al_2O_3 - SO_2$ at 298K. Geochimica et Cosmochimica Acta 46,681-692

Breemen, N. van 1973. Calculation of ionic activities in natural waters. Geochimica et Cosmochimica Acta 37, 101-107

Phan Thi Binh Minh 1991. The leaching experiments on acid sulphate soils from Tan Thanh. Experimental evidence. Report from the SIWRR, Ho Chi Minh City. The subject was also presented at the Workshop on Management of Acid Sulphate Soils in Oct 21-25 held in Ho Chi Minh City.

Schindler, P.W. and W. Stumm 1987. The surface chemistry of oxides, hydroxides and oxide minerals. In: W. Stumm (editor): Aquatic Surface Chemistry, 83-110. John Wiley & Sons

Kinetics of soil solution chemistry in different leaching treatments of undisturbed columns of acid sulphate soils from the Plain of Reeds, Vietnam

Nguyen Tan Danh[1] and To Phuc Tuong[2]

[1] Southern Institute of Water Resources Research, 2A Nguyen Bieu, Ho Chi Minh City, Vietnam
[2] IRRI, P.O. Box 933, Manila, The Philippines

Abstract

A long-term undisturbed soil column experiment was designed to simulate the effects of different leaching treatments and subsequent submergence of an acid sulphate soil in a monsoon sub-tropical area. Kinetics of toxic elements in soil solution of different treatments are compared. Major possible chemical processes during leaching are discussed. Continuous leaching seems superior to leaching with wet and dry cycles. While leaching is effective in reducing toxic elements, it is a slow process in undisturbed soil.

Introduction

Once the pyrite layer of potential acid sulphate soils is oxidized, it produces high degree of acidity that inhibits plant growth. Before any other remedies can be applied, toxicities have to be removed from the root zone, usually by leaching with water (Brinkman 1982).

The positive effects of leaching of acid sulphate soils were reported by previous investigators (inter alia Kivinen 1950, Ponnamperuma et al. 1973, and van Breemen 1976). While these studies indicated that leaching could remove toxins, they were not much help in designing appropriate reclamation measures in the field. Most of them were carried out in small, homogenized samples or in small pots where water flow patterns and soil physical properties were greatly modified as compared to the real field conditions. This is unfortunate because leaching is greatly dependent on the aforementioned properties.

By carefully monitoring the kinetics of soil solution chemistry, this experiment investigated the leaching process by using large undisturbed soil columns, aiming at addressing practical questions of farmers and planners in formulating appropriate strategies for reclamation of large tracts of acid sulphate soils. In particular, it (i) compares the effectiveness of leaching under continuous submergence to that when the surface layer is subjected to wet and dry cycles alternately, and (ii) investigates whether the effects of leaching are 'long lasting' i.e if they would be retained at a later stage when soil is submerged under more or less stagnant water during the subsequent flood season which usually takes place in inland acid sulphate soils areas such as the Plain of Reeds, Vietnam.

Table 1 Some chemical properties of the soil used in the experiments

Depth (cm)	pH H_2O 1:5	pH KCl 1:2.5	EC mS cm^{-1}	OM %	extr Al**	Total acid**	K+	Ca^{2+}	Mg^{2+}	Na^+
							mmol (+) kg^{-1}			
0- 15	3.87	3.37	0.90	7.48	140	146	1.6	4.2	37.7	3.5
30- 50	3.86	3.13	0.71	0.92	115	132	2.6	5.1	42.3	2.7
50- 80	3.45	3.02	0.87	1.27	117	146	2.7	5.8	42.9	3.0
80-115	3.61	3.09	1.05	1.89	140	148	3.5	6.5	55.3	2.8
> 115	2.95+	2.59+	4.00+	6.32	300+	475	0.1	7.1	85.9	0.8

** KCl extracts
+ pyrite was oxidized upon drying

Materials and methods

Soil and soil columns

Soil samples were taken from Tan Thanh farm, the Plain of Reeds, Vietnam. The profile was greyish brown in the upper 10 cm, and very dark between 10 and 50 cm. There was a sulphuric horizon with jarosite mottles at 50-115 cm. The texture was clay with medium structural development in the Bj horizon. Table 1 summarizes the chemical properties.

Undisturbed soil columns were collected in 1 m high steel drums with a diameter of 0.6 m, as described by Le Ngoc Sen (1982). Columns were transported to the central laboratory of the Southern Institute of Water Resources Research, Ho Chi Minh City and were instrumented for the control and measurement of water inflow, outflow and groundwater. Soil water sampling tubes and piezometers were also installed at mid-depth of each soil layer (Figure 1).

Treatments

Soil columns were subjected to three different leaching treatments from 19 October to 24 December, 1990.

T1: Soil columns were leached by drainage from the bottom at average rate 7 mm/day while being totally submerged under 5 cm water depth. The inflow from the water reservoir always compensated for the water loss due to drainage and to soil solution sampling.

T2: During a 14-day cycle, soil columns were also leached by drainage from the bottom at average rate 7 mm/day, the inflow was, however, stopped for the first 12 days so that the water table gradually dropped from +5 to –40 cm. The water level was brought back to +5 cm by a high rate of inflow over the next 2 days. This treatment simulated the conditions when farmers were able to irrigate their fields by gravity for a few days during a 14 day tide cycle. The wet and dry cycles of the surface soils may also help alleviate the 'side effects' of submergence such as the increase in dissolved iron and/or H_2S concentration and the acidification of surface water (van Breemen 1976).

T3: Soil columns were always submerged under 5 cm water and were not subjected to leaching.

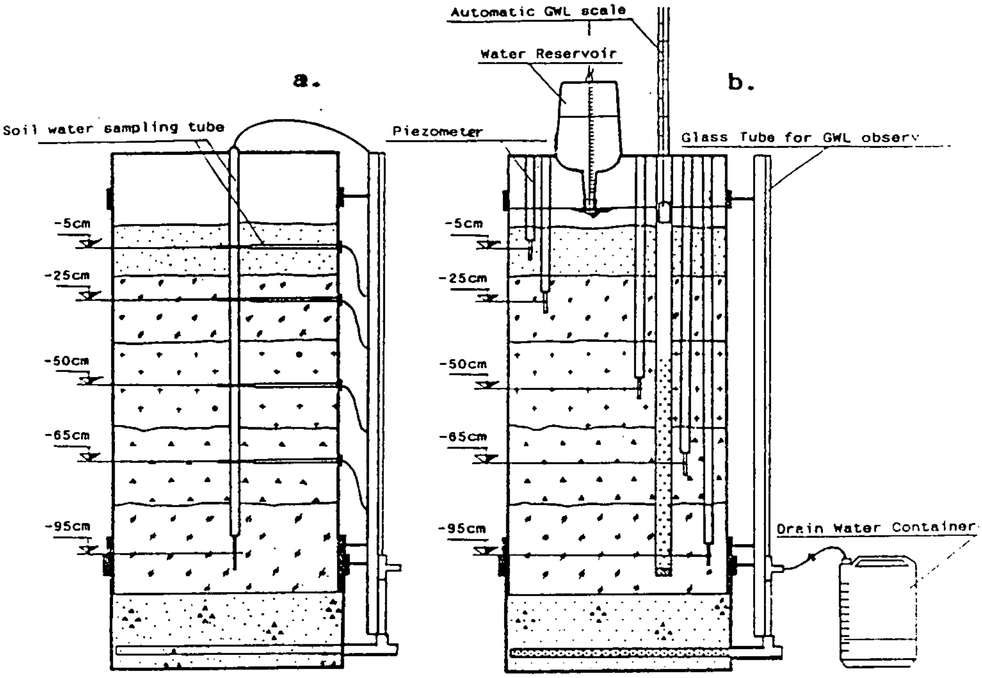


Figure 1 Apparatus: a) soil water sampling; b) water flow control and monitoring

After having been leached, all soil columns were subjected to submergence under 5 cm water depth for 5 months. This simulated the annual flooding following the growing season in the Plain of Reeds.

Three replications were planned but considerable leakage occurred in 4 columns. Results were analyzed based only on data of two replications of T1 and T2 and one for T3.

Sampling and chemical analyses

Soil solutions at depths 5, 25, 50, 65 and 95 cm were extracted three times during a 14 day cycle and analyzed for pH, EC, Al^{3+}, acidity, Fe^{2+}, SO_4^{2-}. Every month, Ca^{2+}, Mg^{2+}, K^+, Na^+ were also determined. Soil chemical composition was also determined before and after leaching and at the end of the flooding stage. To avoid the effects of oxidation of iron II during the storage before analysis, pH, EC, Fe^{2+} and SO_4^{2-} were measured within one hour after sampling.

All constituents were analyzed as described by Begheijn (1980).

Results and discussion

The soil solution was characterized by low pH and very high concentrations of basic cations and aluminum, with the main anion being sulphate. Table 2 gives some correlation coefficients amongst the main acidic parameters of the soil solutions at different

Table 2 Correlation coefficients between pairs of chemical parameters of the soil solution at different depths (150 observations)

	Depths (cm)	Fe^{2+}	pH	SO_4^{2-}	Ec	Acidity
	− 5	−0.105ns	−0.551**	0.939**	0.944**	0.968**
Al^{3+}	−25	−0.178*	−0.260**	0.816**	0.931**	0.968**
	−50	−0.112ns	−0.250**	0.817**	0.904**	0.964**
	− 5	−0.107ns	−0.581**	0.903**	0.927**	
Acidity	−25	−0.112ns	−0.291**	0.805**	0.918**	
	−50	−0.117ns	−0.318*	0.864**	0.899**	
	− 5	−0.120ns	−0.611**	0.943**		
Ec	−25	−0.122ns	−0.105ns	0.827**		
	−50	−0.109ns	−0.295**	0.911**		
	− 5	−0.093ns	−0.562**			
SO_4^{2-}	−25	−0.105ns	−0.238**			
	−50	−0.109ns	−0.249**			
	− 5	−0.120ns				
pH	−25	−0.152ns				
	−50	−0.225**				

Correlation coefficient marked with ** and * is statistically significant at 1 and 5 per cent respectively, ns is not significant

depths. Very strong correlation between aluminum and sulphate was expected because both are immediate results of oxidation of pyrite and form the major components of the soil solution chemistry. Very poor correlation of Fe^{2+} with other constituents reflected its dependence on the oxidation-reduction status of the soil, which varied with treatments, rather with the leaching effects. Low correlation coefficients between pH, Fe^{2+} and other constituents indicated that their kinetics have to be analyzed separately while those of sulphate, acidity, EC can be represented by that of aluminum.

Since differences between treatments revealed themselves most clearly at shallower depths, following discussions focus on sampling depths 5 and 25 cm.

Kinetics of pH

Changes of pH with time at 5 and 25 cm are shown on Figure 2. In treatment T3, initial decrease in pH may be attributed to the dissolution and hydrolysis of soluble salts such as $FeSO_4$, $Fe_3(SO_4)_2$, Al-sulphate, and $AlOHSO_4$ (van Breemen 1976). At the later stage of submergence, pH increased but not significantly, indicating that reduction of acidity of a mature acid sulphate soil cannot be achieved easily just by flooding as advocated elsewhere (van Breemen 1976, Dent 1986).

Leaching removed H+ and increased the pH of the surface layer (5 cm depth, Figure 2) considerably. Treatment T1 was superior to T2, most likely because it combined the removal effects of leaching and the increase in pH due to of reduction of the surface soil.

At greater depths, leaching was not effective in increasing pH of the soil solution. The initial decrease of pH in treatments T1 and T2 can be attributed to the dissolution

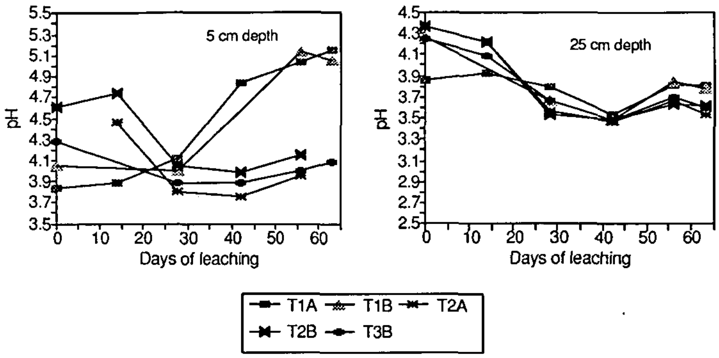


Figure 2 Changes of soil solution pH at two depths with time in three treatments (T1 = continuous leaching, T2 = leaching with wet and dry cycles, T3 = submergence without leaching, A and B are replications)

of soluble substances, as discussed above, or to addition of acid from the upper soil layer. Little change in pH may also indicate a high buffering capacity of the soil.

For all treatments, subsequent submergence after leaching hardly altered pH of the soil solution.

Kinetics of Fe^{2+} in solution

It has been well established that Fe^{2+} concentration will increase under reduced conditions (Ponnamperuma 1972). The increase of Fe^{2+} of treatment T3 (Figure 3) was anticipated and gave the evidence that reduced conditions actually prevailed under prolonged submergence.

Apart from being submerged continuously, treatment T1 was also subjected to leaching. Variations in Fe^{2+} in the topsoil indeed showed the combined influence of the two phenomena. As leaching proceeded, the removal effects became more predo-

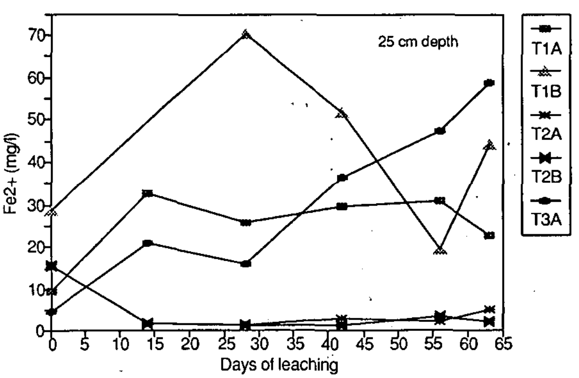


Figure 3 Changes of Fe^{2+} in soil solution at 25 cm depth with time in three treatments (T1 = continuous leaching, T2 = leaching with wet and dry cycles, T3 = submergence without leaching, A and B are replications)

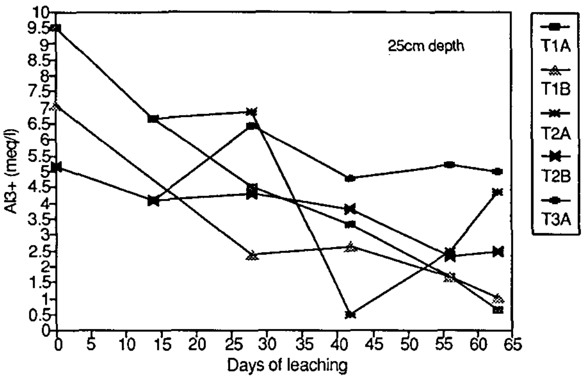


Figure 4 Changes of Al^{3+} in soil solution at 25 cm depth with time in three treatments (T1 = continuous leaching, T2 = leaching with wet and dry cycles, T3 = submergence without leaching, A and B are replications)

minant, resulting in a decrease of Fe^{2+} in the soil solution.

Under the wet and dry cycles in treatment T2, the surface soil was oxidized most of the time. The submerged periods at depths less than 25 cm were usually less than one week, not enough to start the reduction process. Consequently, Fe^{2+} concentration in the shallow depths under this treatment was particularly low (Figure 3).

During submergence following the leaching, Fe^{2+} concentration in all treatments increased steadily and attained values between 80 and 120 mg l^{-1}.

Kinetics of aluminum

Keeping the soil submerged has been recommended for reduction/alleviation of aluminum toxicity in acid sulphate soils (Dent 1986). This is possible because, in general, submergence creates a reduced condition which will be accompanied by proton consumption. The increase in Fe^{2+} in treatment T3 discussed above was an evidence that reduction conditions did, in fact, prevail when the soil under investigation was submerged. Mere reduction did not, however, affect the Al^{3+} concentration of the soil solution (Figure 4).

Soluble aluminum can be removed by the mass flow of the leaching process, resulting in sharp decrease in Al^{3+} in treatments T1 and T2, as presented for depth 25 cm in Figure 4. Differences between T1 and T2 were, most likely, created by differences in the flow regimes rather than the oxidation-reduction processes. Continuous and steady flow of treatment T1 resulted in a more steady and more effective removal of aluminum from the topsoil. In treatment T2, the sudden high flow rate following the dry period would favour higher by-pass through macro-pores and, hence, less effective leaching. Hanhart and Ni (1993) also found in field conditions that concentration of aluminum in the soil solution of a 'raw acid sulphate soil' under continuous irrigation was lower than that under intermittent irrigation with wet- and dry-surface soil cycles.

At the end of 64 days of intensive leaching, concentration of Al^{3+} at depth 25 cm in treatment T1 (about 1 mmol(+) l^{-1}) and T2 (4 mmol(+) l^{-1}) still exceeded the toxic level (2 mg l^{-1}, Dent 1986) for rice cultivation.

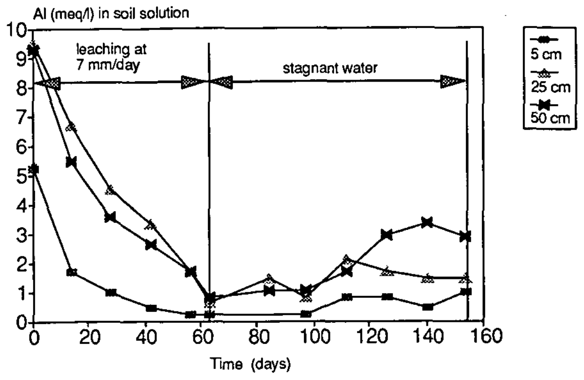


Figure 5 Changes in Al^{3+} in soil solution at sampling depths 5, 25, 50 cm during the leaching phase and subsequent submergence in soil column T1A

Figure 5 presents changes in Al^{3+} at three depths of sampling in the leaching phase and the subsequent submergence phase of soil column T1A. Other columns had similar patterns, with aluminium concentration increasing during the latter part of the submergence period. This is contrary to the commonly observed decrease in Al after submergence in natural conditions and, thus, cannot be explained simply by the oxidation-reduction status of the soil. One possible explanation for the increase was the diffusion of soluble Al^{3+} from the micro pores within the soil ped, which had not been leached by the moving water, to the macro pores from which the soil solution samples were taken for analysis. Another possible explanation might be the release of acidity from the soil complex to reestablish an equilibrium of the soil-water system which had been upset by leaching.

To investigate the processes possibly responsible for the release of aluminium and sulphate into the soil solution, the concentrations of Al^{3+} and SO_4^{2-} (both in mmol(+) l^{-1}) from the outgoing water samples of the surface soil layers were arranged in a cumulative sequence, i.e the extract concentrations were added consecutively, beginning with the last leaching extract ending with the first. These sequences are plotted for treatment T1 as cumulative SO_4 (cumSO_4) and cumulative Al (cumAl) in Figure 6.

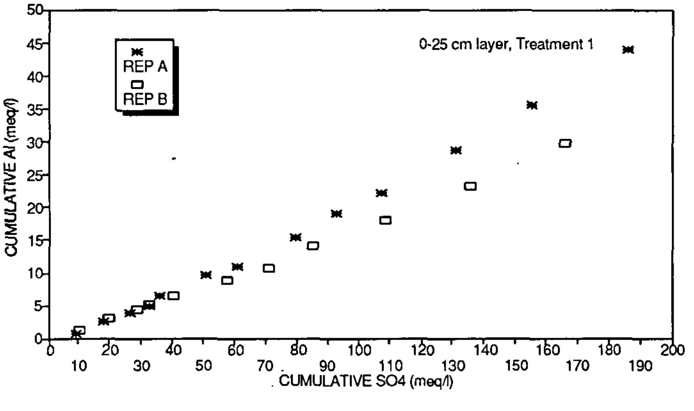


Figure 6 Al^{3+} versus SO_4^{2-} concentrations in cumulative sequence during the leaching phase of Treatment T1

Sulphate and aluminum can be stored in soil minerals like gibbsite and basic aluminum sulphates, of which jurbanite is most commonly referred to (van Breemen 1976), and also in adsorbed components. Leaching could initiate several reactions.

1. If present, jurbanite can participate in at least two reactions. One is its dissolution

   $$AlOHSO_4 = Al^{3+} + SO_4^{2-} + OH^-$$

   giving the slope of the cumAl versus cumSO_4 curve a value of 1.5. The second reaction is the conversion to alunite

   $$3AlOHSO_4 + K^+ + OH^- + 2H_20 = KAl_3(SO_4)_2\,(OH)_6 + 2H^+ + SO_4^{2-}$$

   producing sulphuric acid which cannot be distinguished from the product released from adsorbed sulphate as discussed in (2).

2) Adsorbed sulphate might be released as sulphuric acid. Some of the hydrogen ions would be exchanged for aluminum and other basic cations. Thus aluminum alone can not balance the sulphate components in the soil solutions and cumulative Al will be smaller than cumulative SO_4. Basic cations calcium and magnesium are also present in the soil solution and are, probably, very important in making up the equilibrium.

In Figure 6, the slope of the curve is in the order of 0.2, indicating that pure dissolution of jurbanite did not prevail. In fact, pK of $AlOHSO_4$ calculated from the experimental data were below that of jurbanite (about 15 as compared to 17.2, van Breemen 1973), indicating a supersaturation of jurbanite, or alternatively, the presence of adsorbed sulphate. The small slope of the curve indicated that dissolved sulphate was much higher than dissolved aluminum and suggested the release of adsorbed sulphate and/or conversion of jurbanite into alunite, both producing sulphuric acid and subsequent exchange of cations, as possible important mechanisms in the leaching process of undisturbed soils.

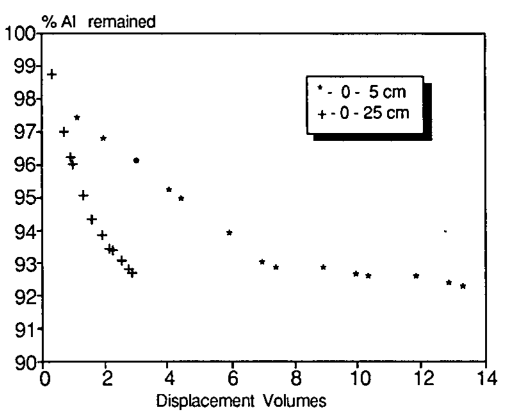


Figure 7 Amount of Aluminum retained in 0-5 and 0-25 cm soil layers, expressed as percent of the initial KCl-extractable Al before leaching, as related to the displacement volumes (ratio of the volume of leaching water applied to that of water contained in the soil layer)

How much aluminum can be removed by leaching?

A mass balance calculation of aluminum for the most effectively leached column, T1A, was carried out with results presented in Figure 7 where 100 per cent aluminum was taken as the initial KCl-extractable aluminum in the soil layers before leaching. The remaining aluminum was calculated by subtracting the leached amount being the product of the flow and the difference between the incoming and outgoing aluminum concentration of the soil solution. After 64 days of leaching with 440 mm of water, equivalent to 3 and 14 times the volume of water in 0-25 cm and 0-5 cm soil layers respectively, less than 10 per cent of aluminum was removed from the soil layers. As leaching proceeded, the rate of aluminum removal would be reduced further. It should be pointed out that the leached amount may have been overestimated since by-pass via macropores was not taken into account. The finding supported the earlier conclusion by Konsten et al. (1990) that leaching of undisturbed acid sulphate soils is a slow process.

Conclusions

Using undisturbed soil columns, only Fe^{2+} concentration was greatly affected by the oxidation-reduction status of the soil created by dry and submerged cycles. Other elements were more responsive to the movement of water during the leaching process. Continuous submergence without leaching did not reduce aluminum sulphate nor increase pH of the soil solution. Continuous leaching reduced toxic element concentrations at a faster rate than leaching with the soil surface soil subjected to wet and dry cycles. Most probably, this is due to higher by-pass through the macro pores in the later case. In all treatments, leaching of undisturbed soil was a slow and water-demanding process. After more than two months of leaching at 7 mm/day, aluminium concentrations in the soil solution at depth 25 cm were still higher than the toxic level for rice cultivation and less than 10 per cent of the initial KCl-extractable aluminum was removed. The release of adsorbed sulphate and/or conversion of jurbanite to alunite are possible mechanisms in the leaching process. Besides aluminum, basic cations (calcium and magnesium) in the soil might also be exchanged for hydrogen ions.

Acknowledgement

The study was carried out in the framework of the management of acid sulphate soils project, funded by SIDA, executed by the International Mekong Committee, Bangkok and implemented by the Southern Institute of Water Resources Research, Ho Chi Minh City, Vietnam. The University of Agriculture and Forestry, Ho Chi Minh City and the International Rice Research Institute, Los Baños provided technical support via the IRRI-Vietnam Collaborative project. The authors would like to thank Dr. Cu Xuan Dong, Director of the Southern Institute of Water Resources Research, for his enthusiastic support and Ms. Jovita Marquez, IRRI, for data analysis.

References

Begheijn, L. Th. 1980. Methods of chemical analyses for soil and water. Department of Soil Science and Geology, Wageningen Agricultural University, Wageningen

Breemen, N. van 1973. Soil forming processes in acid sulphate soils. In: Dost (editor): Acid Sulphate Soils. Proc. Int. Symp. Wageningen, Pub. 18,Vol. 1:66-130. International Institute for Land Reclamation and Improvement, wageningen

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

Brinkman, R. 1982. Direction for further research in acid sulphate soils. In: Dost and Van Breemen (Editors) Proceedings of the Bangkok symposium on acid sulphate soils. Publ. 31, International Institute for Land Reclamation and Improvement, Wageningen

Dent, D. 1986 Acid sulphate soils: A baseline for research and development. Publ. 39, International Institute for Land Reclamation and Improvement, Wageningen.

Hanhart, K. and D.V. Ni 1993. Water management on rice fields at Hoa An, Mekong Delta, Vietnam. In: D.L. Dent and M.E.F. van Mensvoort (editors): Selected papers of the Ho Chi Minh City symposium on acid sulphate soils, Publication 53, International Institute for Land Reclamation and Improvement, Wageningen

Kivinen, E. 1950. Sulphate soils and their management in Finland. Trans. 4th Int. Congr. Soil Sci. Vol. 2:259-262

Konsten, C.J.M, Supardi Suping, I.B. Aribawa and I.P.G. Widjaja-Adhi 1990. Chemical processes in acid sulphate soils in Pulau Petak, South and Central Kalimantan, Indonesia. Papers workshop on acid sulphate soils in the humid tropics, 20-22 November, Bogor Indonesia, AARD & LAWOO 109-136, Bogor

Le Ngoc Sen, 1982. A simple, low-cost method to collect undisturbed cores of acid sulphate soil profiles for the study of water and solute movement during reclamation and use for wetland rice. In: Dost and van Breemen (Editors) Proceedings of the Bangkok symposium on acid sulphate soils. ILRI Publ. 31:381-388

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

Ponnamperuma, F.N., T.Attanandana and G. Bye 1973. Amelioration of three acid sulphate soils for lowland rice. In. H. Dost (Editor) Acid Sulphate Soils. Proc. Int. Symp. International Institute for Land Reclamation and Improvement, Pub. 18, Vol. II:391-406, Wageningen

Environmental aspects of acid sulphate soils

N. van Breemen

Department of Soil Science and Geology, P.O.Box 37, 6700 AA Wageningen, The Netherlands

Abstract

The processes regulating the concentrations and emissions of the potentially harmful substances H_2S, H^+, SO_4^{2-}, Fe^{2+}, Al^{3+}, trace metals, and low-molecular weight organic acids in relation to acid sulphate soils are reviewed. Reclamation measures and management strategies are discussed briefly in relation to those processes. Conclusions:
- Pyrite oxidation can be curtailed efficiently only by waterlogging;
- Release of soluble trace elements (Ni, Co, Cu, Zn, Pb and As) and of gaseous SO_2 from drained pyritic marshes deserves more attention;
- Transport of dissolved $FeSO_{4(aq)}$ from oxidizing pyrite to surface soils and surface waters, followed by oxidation, causes further acidification as well as potentially harmful precipitation of FeIII oxides;
- Leaching of Fe^{2+} from highly organic acid sulphate soils in perhumid areas produces iron-poor acid sulphate soils which show little or no increase in pH upon flooding;
- H_2S and toxic organic substances may be particularly harmful to wetland rice in acid sulphate soils with little or no 'self-liming' upon flooding;
- Leaching with bypass flow after strong drying may be a cheap, effective way to improve raw acid sulphate soils;
- Adding amendments and preflooding are most efficient after leaching of watersoluble acidity;
- Leaching of raw acid sulphate soils must be limited to periods with high surface water runoff, so that the acidity in surface waters is diluted.

Introduction

This review deals with the dominant processes involved in chemical degradation or improvement of soil, water and air associated with the formation, use and reclamation of acid sulphate soils. The emphasis is on chemistry and on processes. This is, first, because the environmental problems associated with acid sulphate soils are distinctly chemical in nature and, secondly, because a good understanding of processes is the best basis for sound environmental management. The major chemical processes in acid sulphate soils and their practical applications have been reviewed (Bloomfield and Coulter (1973), van Breemen and Pons (1978) and Dent (1986, 1992), and can now be considered as 'textbook stuff'. However, recent research in Indonesia and Vietnam has thrown new light on several processes; some old questions still remain unanswered, while a few environmental aspects have so far not received proper attention. This paper will be fairly comprehensive in terms of the environmentally revelant chemical processes in acid sulphate soils. However, I will only brush over the better-known facts, and will emphasize points that appear to be little understood.

Not covered in any detail in this paper are dose-effect relations between harmful substances and biota. I will, rather uncritically, borrow information from other reviews about the substances that are assumed to be toxic, and about critical concentrations. The substances that will be considered here are: (i) H_2S, H^+, SO_4^{2-}, Fe^{2+}, Al^{3+}, trace metals, and low-molecular weight organic acids in surface water and soil solutions and groundwater; and (ii) SO_2 in the air.

No attention will be given to nutrients that may be in short supply, for example, P at low pH and Cu at high contents of organic matter, or to the problem of high salinity often associated with acid sulphate soils.

Reclamation measures and management strategies will be discussed briefly in relation to processes discussed. For a comprehensive overview of those technical aspects, see Dent (1992).

Chemical processes in soil, soil solution and ground water

Toxic effects in soils usually occur through contact with the aqueous phase, containing the toxic element in concentrations that are harmful to the receptor organism. An understanding of the solution chemistry is, therefore, a good basis to tackle the problem. Before discussing solution chemistry, however, physical soil properties important for transport of gas and water plus solutes will be considered briefly.

Permeability for water and gas

In spite of their normally high clay content, most pyritic tidal sediments in the tropics are very permeable, with hydraulic conductivities in order of 10^0 to 10^3 m/day (van Breemen 1976, Hamming et al. 1990). The high permeability of clayey mangrove soils is due to numerous biopores from crabs, roots, and decaying organic matter. After natural or artificial drainage, permeability may further increase due to crack formation.

In older acid sulphate soils used for rice cultivation, the permeability of the topsoil is often much lower (van Breemen 1976). Lower permeabilities may be due to puddling and traffic in wet conditions – the 'traffic pan' described by Moormann and van Breemen (1978). Acidified subsoils tend to maintain a high permeability. This may be due, in part, to stabilisation of pore walls and cracks by FeIII oxides, or by Al-saturated clay (Brinkman and Pons 1968, Kamerling 1974, Hanhart and Ni 1992).

Some pyritic sediments, however, have a very slow-permeability. Van Mensvoort and Tri (1988) describe clayey pyritic sediments with high contents of fragmented, fibrous organic matter, and with a very low macropososity, in the north-western part of the Mekong delta. They explain the genesis of these slowly permeable sediments by a sequence of erosion, reworking, mixing and redeposition of older pyritic clay and peat by marine action.

The differences in transport characteristics associated with these differences in permeability are of great environmental importance since they greatly influence the rates of oxidation and of leaching of oxidation products.

Oxidation processes

Oxidation of pyrite and its immediate environmental effects

Oxidation of pyrite produces sulphuric acid which causes low pH values and high levels of soluble Fe^{2+} in soils and waters when insufficient quick-acting neutralizing substances are present. Dissolved sulphate may turn into toxic H_2S under reduced conditions and, if present in excess of 200 to 500 mg/l, can damage concrete by formation of highly hydrated sulphates (van Holst and Westerveld 1972). Sulphuric acid is corrosive to metal (Prokopovich 1988) and concrete, and can have direct or indirect adverse effects on a range of biota. The indirect effects often involve the dissolution of potentially toxic metals from soil minerals.

Oxidation of pyrite has been reviewed several times in relation to acid sulphate soils. Here, a simplified summary of the process will be given, with emphasis on aspects important for an general understanding of its environmental effects, and of the possibilities to influence it. The first step in the oxidation of pyrite that markedly affects the soil solution chemistry can, probably, best be described as

$$FeS_{2(s)} + \tfrac{1}{2}O_{2(g,aq)} + H_2O_{(l)} \rightarrow Fe^{2+}{}_{(aq)} + 2H^+{}_{(aq)} + 2SO_4{}^{2-}{}_{(aq)} \quad (1)$$

This overall process proceeds rapidly at low pH (< 4), where pyrite is oxidized catalytically by dissolved Fe^{3+} (formed under the influence of *Thiobacillus ferrooxidans*)

$$FeS_{2(s)} + 14Fe^{3+}{}_{(aq)} + 8H_2O_{(l)} \rightarrow 15Fe^{2+}{}_{(aq)} + 16H^+{}_{(aq)} + 2SO_4{}^{2-}{}_{(aq)} \quad (2)$$

In the absence of pyrite, FeIII can persist and can be precipitated as FeIII oxide or jarosite, yielding still more acid. Complete oxidation of FeS_2 to SVI and FeIII and full hydroxylation of FeIII yields maximum acid formation, two moles of sulphuric acid per mole of pyrite

$$FeS_{2(s)} + 7/4O_{2(g,aq)} + 5/2H_2O_{(l)} \rightarrow FeOOH_{(s)} + 4H^+{}_{(aq)} + SO_4{}^{2-}{}_{(aq)} \quad (3)$$

Pyrite oxidation is more complex than suggested by equations 1-3. Different sulphur species of intermediate oxidation state (S0 to SIV) may be formed, and various autotrophic iron and sulphur bacteria are involved in different oxidation steps. With the possible exception of $SO_{2(g)}$, however, these intermediates are unimportant for most practical purposes.

The rate of pyrite oxidation tends to increase with decreasing pH. At low pH (<4) in soils, the process is usually limited by the rate of supply of O_2. This explains why dumps of pyritic material dredged from canals and ditches, exposed directly to atmospheric O_2, acidify much more rapidly than pyritic material in situ. When sufficient neutralizing substances are available to maintain near neutral pH values, pyrite oxidizes more slowly, presumably because reaction 2 cannot operate.

The magnitude of the pH decrease from pyrite oxidation mainly depends on (i) the quantity of pyrite, (ii) its oxidition rate, (iii) the rate of removal of soluble oxidation products, and (iv) the neutralizing capacity. Calcium carbonate and exchangeable bases are important for acid neutralization in the short term, their reaction with sulphuric acid being virtually instantaneous. $CaCO_3$ present in excess of potential acidity therefore prevents acidification except, perhaps, if it is very coarse-textured (shells). In potentially acid soils, pH rarely drops below 3 after drainage and aeration. Much lower pH values (< 2) are obtained in pyritic spoil and in aerated pyritic samples in the laboratory. These low pH values must be attributed to high rates of acid formation relative to the rates of removal of acid by diffusion-plus-leaching or neutralization by mineral weathering.

Release of trace metals

Several trace elements may accumulate together with Fe in sedimentary pyrite, either substituting for Fe in pyrite (notably Ni and Co), or in related sulfides (Cu, Zn, Pb and As) (Deer, Howie and Zussman 1965). These elements will be released during pyrite oxidation. Extreme acidification due to pyrite oxidation should also lead to release of trace metals from other minerals. Research on the release of potentially toxic heavy metals during acid sulphate soil formation is rare. Satawathananont (1986) observed concentrations of water-soluble Cu, Zn, Mo, Cd, Pb, Ni and As that were about an order of magnitude higher in an aerated pyritic soil (pH 2.9) than in three well-developed acid sulphate soils (pH 3.9-4.5) and one non-acid marine soil (pH 4.9) from the Bangkok Plain. Also, after incubation under controlled Eh-pH in acid oxidized conditions for two weeks, water-soluble trace metals were higher in the pyritic soil than in the older leached soils (Table 1). Palko and Yli-Halla (1988, 1990) observed similar contents of total Cr, Cu, Zn, Co, and Ni in acid sulphate soils and non-acid soils from Finland, suggesting that pyrite formation did not cause accumulation of heavy trace metals. Levels of soluble trace metals, however, were highest in the acid sulphate soils. These data indeed suggest that pyrite oxidation and associated acidification may release significant quantities of soluble trace metals.

Release of Al^{3+}

Interest in the concentration of dissolved Al^{3+} stems from its potential toxicity to plant roots and to fish at concentrations exceeding 0.02 mg l^{-1} to 10-50 mg l^{-1}, depending on variety or species and growth stage (Thawornwong and van Diest 1974, Singh et al. 1988). Virtually concurrent with the decrease in pH during acidification from pyrite oxidation, dissolved Al is released, presumably by dissolution of clay minerals. Over a wide range of conditions in Thai acid sulphate soils, from pH below 2 in oxidizing pyritic soil in the laboratory, to pH close to 5 in old leached acid sulphate soils in the field, activities of Al^{3+} obeyed the relationship $[Al^{3+}][SO_4^{2-}][OH^-] = 17.3$, suggesting control of dissolved Al by equilibrium with a basic sulphate $AlOHSO_4$ (van Breemen 1973). This relationship was confirmed for Thai acid sulphate soils (Moore and Patrick 1991) and for Indonesian acid sulphate soils (Groenenberg 1990). It could be explained by equilibrium with the mineral jurbanite, $AlOHSO_4.5H_2O$ (Nordstrom 1982). Jurbanite, however, has never been identified in acid sulphate soils. Nevertheless, the empirical relationship appears to be useful in predicting Al concentrations. Sulphate activities vary relatively little in most acid sulphate soils, so constant values of $[Al^{3+}][SO_4^{2-}][OH\text{-}]$ imply that the activity of Al^{3+} increases about tenfold

Table 1 Contents of water-soluble trace elements (mg l^{-1}) in stirred soil suspensions (200 g of soil, 800 ml of water) maintained at Eh = 400 mV and pH = 3.5 for two weeks. Bang Pakong is a pyritic soil, the others are surface soils of well developed acid sulphate soils. Data from Satawathananont (1986)

Soil	Zn	Cu	Cd	Pb	Cr	Ni	As
Rangsit very acid	16	0.55	0.29	2.1	0.35	3.0	2.8
Rangsit	19	0.34	0.15	1.2	0.30	4.1	2.4
Mahapot	18	0.89	0.23	1.9	0.46	7.3	2.1
Bang Pakong	42	1.12	0.75	6.6	0.69	10.5	9.9

with a one unit decrease in pH. At pH <4 the same relationship, approximately, holds also for the concentration of total dissolved Al. A roughly tenfold increase in the concentration of dissolved Al per one unit pH decrease, indeed, follows from data presented for acid sulphate soils by Satawathananont (1986) and by Hanhart and Ni (1991) in Vietnam.

It remains to be seen whether $[Al^{3+}][SO_4^{2-}][OH^-]$ remains constant under evaporative conditions, when highly soluble Al-sulphates (alum and pickeringite) precipitate, and in acidified surface waters. At least in open waters, Al^{3+} may simply behave conservatively, i.e. without regulation of its concentration by some solid phase, as shown by Nordstrom and Ball (1986) for acid mine waters.

Release of SO_2

Gaseous SO_2 is released during oxidation of sulphides and can be used in prospecting for sulphide ores. The distinct sulphurous odour that can be noticed, sometimes, in drained mangrove marshes may also be attributed to SO_2. There are indications from acid-base budgets for whole soil profiles that a very large fraction of the potential acidity present in pyritic sediments leaves the soil in unneutralized form as SO_2 (van Breemen 1976). If this were true, oxidation of pyritic sediments is a source of air pollution, and could contribute to 'acid rain'. In view of increasing SO_2 emissions from industrial sources e.g. in South East Asia (Rohde and Herrera 1988), a study of the background SO_2 concentrations and the possible contribution of acid sulphate soils is relevant.

Oxidation of FeII

The reactivity of FeIII with pyrite (Equation 2) accounts for a high mobility of iron in zones of active pyrite oxidation, and for a failure of solid FeIII to precipitate adjacent to pyrite, except at high pH or at exceptionally high rates of oxidation. Where $FeSO_{4(aq)}$ derived from pyrite (Equation 1) is transported before being oxidized to hydrated FeIII oxide, further acidification takes place at some distance from the pyritic zone

$$\begin{aligned} &Fe^{2+}{}_{(aq)} + SO_4^{2-}{}_{(aq)} + 1/4O_{2(g,aq)} + 3/2H_2O_{(l)} \rightarrow \\ &\quad FeOOH_{(s)} + 2H^+{}_{(aq)} + SO_4^{2-}{}_{(aq)} \end{aligned} \tag{4}$$

Such 'delayed' acidification can be observed in shallower soil horizons, in ponded fields where $FeSO_{4(aq)}$ diffuses upward through cracks from the pyritic subsoil, in tube drains and in open waters.

Rapid oxidation of Fe^{2+}, especially at low pH, is mainly due to autotrophic iron bacteria. In addition to acidification, clogging of drain tubes (Bloomfield and Coulter 1973) and of fish gills (Singh et al. 1988) by FeIII(hydrous)oxide may be among the unwanted effects of reaction 4.

In not-too-deeply-drained, highly organic acid sulphate soils in perhumid climates, oxidation of Fe^{2+} according to equation 4 seems to be hampered (Konsten et al., in preparation). Restricted oxidation of Fe^{2+} may be due to insufficient aeration or to protection of Fe^{2+} from O_2 by dissolved organic substances. Leaching of most of the iron derived from pyrite would explain the formation of acid sulphate soils with little or no mottling from FeIII oxide or jarosite. Such iron-poor acid sulphate soils differ from Fe-rich acid sulphate soils in their behaviour after flooding and reduction, as discussed below.

Reduction processes
Reduction of redox elements that are common in soils, such as Fe, Mn, S, and N, consumes protons and is responsible for the increase in pH commonly observed in acid soils after waterlogging. Increased pH upon flooding is the main reason why wetland rice cultivation is succesful on acid sulphate soils. While the increase in pH and associated decrease in dissolved Al^{3+} are favourable for the crop, other changes following reduction are not. These include the formation of other potentially toxic substances, such as Fe^{2+}, organic acids and H_2S, in the course of soil reduction. Moreover, soil reduction or pH increase following soil reduction are often limited in acid sulphate soils.

Reduction of FeIII and its chemical consequences
In most moderately acid soils (pH 4-6), waterlogging causes an increase in pH to a value between 6 and 7 after several weeks of flooding. Usually, reduction of Fe(III) to Fe(II) is quantitatively the most important process involved in this rise in pH (Ponnamperuma 1972, Patrick and Reddy 1978).

Equation 5 illustrates that protons are consumed in the reduction of Fe(III) oxides, with organic matter ('CH_2O') as the electron donor

$$Fe_2O_{3(s)} + 1/2CH_2O_{(s,l)} + 4H^+_{(aq)} \rightarrow 2Fe^{2+}_{(aq)} + 1/2CO_{2(g,aq)} + 5/2H_2O_{(l)} \qquad (5)$$

Hypothetical changes in pH and the concentration of Fe^{2+} upon reduction of soils with various proton donors are indicated in Figure 1. In acid sulphate soils, these protons can be derived from free sulphuric acid and desorption of adsorbed sulphate, producing soluble ferrous sulphate, according to pathway **d**. In acid soils with little free acidity and sulphate, hydroxylation of exchangeable Al^{3+} during reduction of FeIII produces Al hydroxide plus exchangeable Fe^{2+} (pathway **a**). In slightly acid to near neutral conditions, CO_2 may serve as a proton donor, producing HCO_3^- plus soluble Fe^{2+} (pathway **c**), part of which may be exchanged for other cations (pathway **b**). The increase in pH and in the concentration of dissolved Fe^{2+} stops when saturation with '$Fe(OH)_2$' [1] has been reached. By that time, acid sulphate soils have a somewhat lower pH and much higher levels of dissolved Fe^{2+} (pathway **d-c**) than acid 'non-sulphate' soils (pathway **a-c**), and than slightly acid soils with appreciable amounts of exchangeable bases (pathway **b**). Sulphate reduction, which may follow reduction of FeIII, produces H_2S and HCO_3^-. This causes a further increase in pH but tends to decrease dissolved Fe^{2+} by precipitation of FeS so that, ultimately, pH and dissolved Fe in flooded acid sulphate soils may reach the same values as in 'normal' flooded soils.

In most moderately acid wetland rice soils, the pH rises to equilibrium values between 6.5 and 7 within a few weeks of flooding. The same is true for many very young acid sulphate soils, where an increase in pH from 3-3.5 to 5.5-6 is associated with

[1] '$Fe(OH)_2$' is a proxy for the unknown FeII-containing hydroxide precipitates which form the bulk of solid FeII in most seasonally-reduced soils, with an apparent solubility product of about 10^{-18} (van Breemen and Moormann 1978)

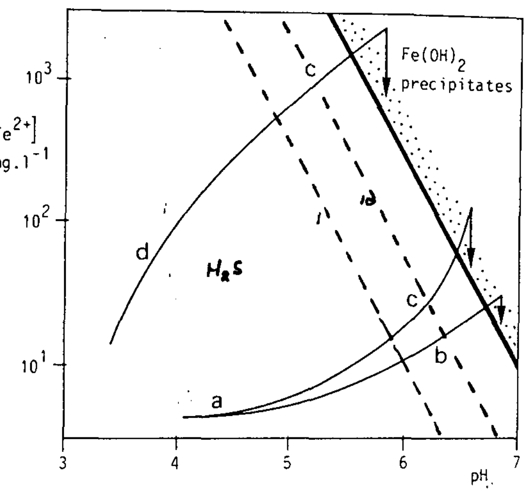


Figure 1 Hypothetical changes in the concentration of dissolved Fe^{2+} and pH in the course of soil reduction (van Breemen 1988). Dotted lines refer to H_2S concentrations (mg l^{-1}) in equilibrium with Fe^{2+}. Maximum concentrations Fe^{2+} are determined by the solubility of '$Fe(OH)_2$', as indicated by the bold line. Different arrows refer to different proton donors (exchangeable Al, CO_2 and adsorbed SO_4), with and without formation of exchangeable Fe^{2+}, as follows:

a $FeOOH + 1/4CH_2O + 2/3\,Al^{3+}{}_{(exch)} + 1/4H_2O \rightarrow$
$Fe^{2+}{}_{(exch)} + 2/3Al(OH)_{3(s)} + 1/4CO_2$

b $FeOOH + 1/4CH_2O + 7/4CO_2 + M^{2+}{}_{(exch)} + 1/4H_2O \rightarrow$
$Fe^{2+}{}_{(exch)} + M^{2+}{}_{(aq)} + 2HCO_3^-{}_{(aq)}$

c $FeOOH + 1/4CH_2O + 7/4CO_2 + 1/4H_2O \rightarrow$
$Fe^{2+}{}_{(aq)} + 2HCO^-{}_{3(aq)}$

d $FeOOH + 1/4CH_2O + SO_4^{2-}{}_{(ads)} + 1/4H_2O \rightarrow$
$Fe^{2+}{}_{(aq)} + SO_4^{2-}{}_{(aq)} + 1/4CO_2 + 2OH^-{}_{(ads)}$

a steep rise in dissolved Fe^{2+}. In most older acid sulphate soils, however, the pH increases very slowly after waterlogging and, sometimes, does not reach the values between 5.5 and 6.5 indicated in Figure 1 (Ponnamperuma 1972, van Breemen 1976). The reasons for this behaviour have not been studied explicitly. A slow rise in pH can be attributed to (i) slow reduction or (ii) appreciable reduction (fermentation) in the absence of inorganic reducable substances, e.g FeIII oxides (Ponnamperuma 1972, van Breemen 1976, Munch and Ottow 1982). In case (i), neither Eh nor pH will change much after flooding. In case (ii), the Eh will drop without concomittant increase in pH. Slow reduction has often been observed, and has been attributed to a low content of metabolizable organic matter (Kawaguchi and Kyuma 1968, Ponnamperuma 1972, Van Breemen 1976), and/or to adverse effects of low pH, high dissolved Al, and poor nutrient status on the activity of anaerobes (Kawaguchi and Kyuma 1968, van Breemen 1976). The strong reduction, and associated increase in pH upon flooding of very young acid sulphate soils, suggests that the presence of relatively undecomposed organic matter from the original mangrove vegetation and high nutrient status may be more important for strong reduction than a low pH by itself.

Some acid sulphate soils in Kalimantan, Indonesia, show or no increase in pH after reduction following flooding. This has been attributed to low contents of FeIII oxides relative to the base neutralizing capacity of the soil (mainly exchangeable acidity associated with organic matter) (Konsten et al., in prep.). Apparently, the combination of highly organic parent material and perhumid climate limits oxidation of FeII and accumulation of appreciable quantities of FeIII oxides and jarosite. This would explain why the acid sulphate profiles typical of monsoonal climates, with horizons of accumulation of FeIII oxide and jarosite at increasing depth as soils become older (van Breemen and Pons 1978), are lacking in Kalimantan, as well as in other highly organic acid sulphate soils perhumid climates. The strong leaching of iron thus appears to have important consequences, agronomically as well as for soil genesis.

Reduction of sulphate and fermentation reactions

Sulphate reduction also consumes protons and helps to increase soil pH

$$SO_4{}^{2-}{}_{(aq)} + 2CH_2O_{(s,aq)} + 2H^+{}_{(aq)} \rightarrow H_2S_{(aq)} + 2CO_{2(aq,g)} + 2H_2O_{(l)} \qquad (6)$$

Sulphate reduction is generally absent or very slow at pH values below 4 to 5 (Baas Becking et al. 1966, Connell and Patrick 1966, Nhung and Ponnamperuma 1966). Yet sulphate reduction often occurs in waterlogged young acid sulphate soils, and upon prolonged flooding in older acid sulphate soils. In acid sulphate soils, sulphate reduction is, probably, mainly a very local phenomenon, e.g. immediately adjacent to concentrations of fresh decomposing organic matter (Hanhart and Ni 1992). H_2S is highly toxic: 0.1 mg l^{-1} of H_2S may be toxic to rice in water culture (Mitsui 1964). Amorphous FeS probably regulates the concentrations of H_2S in flooded soils (van Breemen and Moorman 1978). Fig. 1 shows that high concentrations of both H_2S and Fe^{2+} can coexist in the presence of FeS at relatively low pH, which illustrates the potential danger of sulphate reduction in acid sulphate soils. Hanhart and Ni (1992) attributed the positive effect of regular shallow drainage of acid sulphate soils that had been flooded for a long time to the oxidation of H_2S.

A number of organic acids that form by fermentation in highly organic flooded soils can be harmful to rice at concentrations in the order of 0.1-1 mmol l^{-1}. High concentrations of reducing organic substances are common in peaty soils and chemically poor, sandy soils low in active iron, where the pH stays low after flooding (Okazaki and Wada 1976). Possibly, such substances are important, too, for rice growing on acid sulphate soils with a low pH during flooding.

Measures to decrease acidification

Curtailing pyrite oxidation

Pyrite oxidation can be decreased by limiting the supply of O_2 or by influencing the rate of one or more of the intermediate steps in pyrite oxidation. For example, oxidation rates can be limited by decreasing the concentration of Fe^{3+}, so that reaction 2 is hampered. Pulford et al.(1988) slowed down oxidation of pyrite in coal mine waste in the laboratory by (i) decreasing the rate of oxidation of Fe^{2+} to Fe^{3+} (through adding bacteriacide or a ligand that complexes Fe^{2+}), and (ii) complexing or precipitating Fe^{3+} (through addition of organic chelators or phosphate). By depressing soluble Fe^{3+}, liming would have a similar affect. Such amendments to decrease pyrite oxidation will be prohibitively expensive in most field situations.

The only sure way to curtail pyrite oxidation is cutting the supply of O_2, by waterlogging. One should realize, however, that even in the absence of O_2 pyrite oxidation may continue by FeIII, formed and precipitated nearby pyrite during a preceding phase of aeration.

Leaching

Soluble and exchangeable acidity should be removed as much as possible by leaching before applying amendments. In principle, leaching with fresh water is efficient in removing free H_2SO_4, and efflorescences of soluble Fe and Al salts from the soil. Data by van Mensvoort et al. (1991) suggest that continuous leaching with fresh water removes Al but does not affect exchangeable Al. The Al removed may well be Al^{3+} in equilibrium with '$AlOHSO_4$' or jurbanite. Leaching of jurbanite would have little effect on the chemistry of the soil solution and, hence, on the chemical environment of organisms exposed to the soil, as long as some '$AlOHSO_4$' remains present.

By leaching with salt or brackish water, exchangeable Al can be replaced by Na, Ca and Mg from the water added. Leaching with brackish water is efficient in removing exchangeable Al if done under oxidized conditions, but less so in reduced conditions, when part of the exchangeable Al^{3+} is precipitated as $Al(OH)_3$ or, perhaps, $AlOHSO_4$ (van Mensvoort et al. 1991).

The possibilities for leaching depend, among other things, on the structure of the soil. Water may percolate easily through a highly permeable soil, and bypass the interior of soil aggregates, which tends to decrease leaching efficiency. The contact between leaching water and soil could be increased by ponding and puddling, followed by surface drainage. However, as shown by van Mensvoort et al. (1991), reduction resulting from stagnant waterlogged conditions decreases the amount of acidity that can be leached. On the other hand, where soluble Al and Fe sulphates effloresce on the surface of aggregates, bybass flow in permeable soils can be very efficient (Sterk 1991). Leaching after strong drying may therefore be recommended in many cases.

While leaching can be a relatively cheap and effective measure to improve soils, it also removes nutrients from the soil, and it pollutes surface waters.

Liming

The amount of base to neutralize the acidity produced by oxidation of one per percent of oxidizable sulphur is in the order of 30 tons of $CaCO_3$ per ha per 10 cm of soil of bulk density $10^3 kg\ m^{-3}$. Exchangeable cations provide a neutralizing capacity equivalent to between 3 and 30 tons of $CaCO_3$ on the same basis, depending on clay content and mineralogy (Dent 1986). Any oxidizable sulphur in excess of that can be removed only by leaching or liming. Considering that contents of oxidizable sulphur are commonly between 1 and 5 per cent, this illustrates the huge amount of lime that would be needed if reclamation of acid sulphate soils depended on it. In practice, liming is efficient only after most of the water-soluble acidity has been leached. At least in case of lowland rice, applications of 2 to 10 ton of $CaCO_3$ ha^{-1} on leached acid sulphate soils often have a distinct beneficial effect, while larges doses are rarely economical.

'Self-liming' by reduction of FeIII oxides

The pH increase in acid soils undergoing soil reduction is one of the potential advantages of growing wetland rice on acid sulphate soils. However, there is a trade-off: high contents of toxic dissolved aluminium are being replaced by high contents of toxic soluble Fe^{2+}. Exchangeable acidity, on the other hand, is effectively neutralized by reduction of FeIII oxide, without an increase in dissolved Fe^{2+}. As when liming with $CaCO_3$, prior leaching of soluble acidity increases the efficiency of self-liming by reduction of FeIIIoxides. When the pH remains low after flooding because of insufficient reduction or because of low FeIII contents, application of organic matter or FeIII oxide (e.g. red earth) might help. However, the adverse effect of adding FeIIIoxide (higher Fe^{2+} concentrations in solution) may be greater than the advantages of an increased pH, as shown by Nhung and Ponnamperuma (1966). Small additions of $CaCO_3$ may also intensify reduction after flooding while at the same time depressing dissolved Fe^{2+} (Nae Joung Park et al. 1971).

Flooding has the beneficial side effect of transfering acidity from soil to surface water by oxidation of $FeIISO_{4(aq)}$ at the soil-water interface, followed by precipitation of FeIIIoxide on the soil surface and release of H_2SO_4 into the surface water (van Breemen 1975).

Negative side-effects of reduction, in addition to elevated concentrations of Fe^{2+}, include the formation of harmful organic substances and H_2S. These are especially bothersome at the relatively low pH typical of many flooded acid sulphate soils. Hanhart and Ni (1992) succesfully steered between aluminium toxicity in oxidized conditions and H_2S-induced Fe toxicity in flooded conditions by judicious water management involving alternate submergence and drainage of a strongly acid sulphate soil growing rice.

Surface water

Decreasing soil acidity by leaching necessarily involves transfer of acidity and associated toxic substances from the soil to the water. Because the buffering capacity of waters is generally low and, moreover, toxic threshold concentrations are often lower for aquatic organisms than for plant roots, leaching of severly acid ('raw') acid sulphate soils may have serious consequences. Apart from experience with fishponds (Singh et al. 1988), acidification of surface water has been little studied. No research has been done on the mechanisms controlling concentrations of toxic substances in acid sulphate surface waters. In the absence of such knowledge, its seems judicious to limit leaching, as much as possible, to periods with high surface water runoff, so that acid and often toxic products are diluted as much as possible.

References

Baas Becking, L.G.M., I.R. Kaplan and D. Moore 1966. Limits of the natural environment in terms of pH and oxidation-reduction potentials. J. Geol. 68: 243-284

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

Breemen, N. van 1973. Dissolved aluminium in acid sulfate soils and in acid mine waters. Proc. Soil Sci. Soc. Amer. 37, 694-697

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

Breemen, N. van 1976. Genesis and soil solution chemistry of acid sulphate soils in Thailand. Agric. Res. Rep. 848, Pudoc, Wageningen

Breemen, N. van 1987. Effects of redox processes on soil acidity. Neth. J. Agric. Sci. 35, 271-279

Breemen, N. van 1988. Effects of seasonal redox processes involving iron on the chemistry of periodically reduced soils. In J.W.Stucki et al. (editors) Iron in Soils and Clay Minerals, D Reidel Publ Co, Dordrecht 797-809

Breemen, N. van, and F.R. Moorman 1978. Iron-toxic soils. In: International Rice Research Institute: Soils and Rice. Los Baños 781-800

Breemen, N. and L.J. Pons 1978. Acid sulphate soils and rice. In: International Rice Research Institute: rice and soils. Los Baños 739-761

Brinkman, R. and L.J. Pons 1968. A pedogeomorphological classification and map of the Holocene sediments in the coastal plain of the three Guyanas. Soil Survey Papers 4, Soil Survey Inst. Wageningen

Connell, W.E. and W.H. Patrick 1969. Sulphate reduction in soil: effect of redox potential and pH. Science 159, 86-87

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

Dent, D.L. 1986. Acid sulphate soils: a baseline for research and development. Publ. 39, International Institute for Land Reclamation and Improvement, Wageningen

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

Dost, H. editor 1973. Acid sulphate soils: proceedings of the international symposium, Wageningen. Publication 18, International Institute for Land Reclamation and Improvement, Wageningen

Dost, H. editor 1988. Selected papers of the Dakar symposium on acid sulphate soils. Publication 44, International Institute for Land Reclamation and Improvement, Wageningen

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

Hamming, A.F.J., Kasdi Subagyono, and Tagus Vadari 1990. Soil permeability aspects in Pulau Petak, Kalimantan. In: AARD & LAWOO: Papers Workshop on Acid Sulphate Soils in the Humid Tropics, Bogor: 295-332.

Hanhart, K. and Doung Van Ni 1991. The effect of water management treatments on the cultivation of an irrigated dry season rice crop on a severe acid sulfate soils in Hoa An Station, Viet Nam. VH 10 Reprt, in prep.

Holst, A.F. van and G.J.W. Westerveld 1973. Corrosion of concrete foundations in (potential) acid sulphate soils and subsoils in the Netherlands. In H.Dost (ed.) Acid sulphate soils. Proceedings of the international symposium Wageningen. Publication 18, II, 373-382, International Institute for Land Reclamation and Improvement

Kamerling, E. 1974. Bodemfysisch en agrohydrologisch onderzoek in de jonge kustvlakte van Suriname. Versl. Landb.k. Onderz. 825. Pudoc, Wageningen

Kawaguchi, K. and K. Kyuma 1968. Fertility characteristics of the lowland rice soils in some Southern Asian countries. Transact. 9th Int. Congr. Soil Sci., Adelaide, Intern. Soc. Soil Sci. & Angus and Robertson, vol IV, 19-31

Konsten, C.J.M., N. van Breemen and Supardi Suping, I.B. Aribawa and J.E. Groenenberg. Factors limiting the rise of pH upon flooding in acid sulphate soils used for lowland rice in Kalimantan, Indonesia (in preparation)

Mensvoort, M.E.F. van, Duang Van Ni and J. van der Schans 1991. Improvement of acid sulphate soils by leaching with salt or brackish water. In: P.Deturck and F.N.Ponnamperuma (editors). Rice production on acid soils of the tropics. Inst. Fundamental Studies, Kandy p 219-224

Mensvoort, M.E.F. van, and Le Quang Tri 1988. Morphology and genesis of actual acid sulfate soils without jarosite in the Ha Tien Plain, Mekong Delta, Viet Nam. In H.Dost 1988. 11-15

Mitsui, S. 1964. Inorganic nutrition, fertilization and soil amelioration for lowland rice. 2nd ed. Yokendo, Tokyo

Moore, P.A. and W.H. Patrick 1991. Aluminium, boron and molybdenum availability and uptake by rice in acid sulphate soils. Plant and Soil 136, 171-181

Moormann F.R. and N. van Breemen 1978. Rice: soil, water, land. IRRI, Los Baños

Munch, J.C. and J.C.G. Ottow 1982. Einfluss von Zellkontakt und Eisen(III)-Oxidform auf die bakterielle Eisenreduktion. Z. Pflanzenernaehr. Bodenk. 145, 66-77

Nae Joung Park, Joung Sun Park and Yung Sup Kim 1971. Effect of lime on growth of rice and changes in pH, Eh, Fe^{2+} and Al in an acid sulfate soil. J. Korean Soc. Soil Science and Fertilizer, 4:167-175

Nhung, M.M. and F.N. Ponnamperuma 1966. Effects of calcium carbonate, manganese dioxide, ferric hydroxide and and prolonged flooding on chemical and electrochemical changes and growth of rice in a flooded acid sulphate soil. Soil Sci. 102, 29-41

Nordstrom, D.K. 1982. The effect of sulfate on aluminum concentrations in natural waters: some stability relations in the system Al_2O_3-SO_3-H_2O at 298 K. Geochim. Cosmochim. Acta 46, 681-692

Nordstrom, D.K. and J.W. Ball 1986. The geochemical behaviour of aluminum in acidified surface waters. Science 232, 54-56

Okazaki, M. and H. Wada 1976. Some aspects of pedogenic processes in paddy soils. Pedologist 20, 139-150

Palko, J. and M. Yli-Halla 1988. Solubility of Co, Ni and Mn in some extractants in a Finnish acid sulphate soil area. Acta Agric. Scand. 38, 153-158

Palko, J. and M. Yli-Halla 1990. Solubility of Al, Cr, Cn, and Zn in soils from a Finnish acid sulphate soil area. Acta Agric. Scand. 40, 117-122

Patrick, W.H. and C.N. Reddy 1978. Chemical changes in rice soils. In: Soils and Rice. IRRI, Los Baños 361-379

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

Prokopovich, N. 1988. Engineering aspects of acid sulfate deposits in California, USA, In H.Dost (editor) Selected papers of the Dakar symposium on acid sulphate soils. Publ. 44, 49-58. International Institute for Land Reclamation and Improvement, Wageningen

Pulford, I.D., C.A. Backes and H.J. Duncan 1988. Inhibition of pyrite oxidation in coal mine waste. In H.Dost (editor) 1988, 59-67

Rohde, H. and R. Herrera (editors) 1988. Acidification in tropical countries. Scope 36. John Wiley & Sons

Satawathananont, S. 1986. Redox, pH and ion chemistry of acid sulfate rice soils in Thailand. PhD Dissertation. Louisiana State University

Singh, V.P., T. Poernomo and R. Brinkman 1988. Reclamation and management of brackish water fish ponds in acid sulphate soils: Philippine experience. In H.Dost (editor) 1988, 214-228

Sterk, G. 1991. Leaching acidity from the topsoil of raised beds on acid sulphate soils in the Mekong Delta, Vietnam. Techn. Rept. no 8, EEC Project STD-Vietnam, Department of Soil Science and Geology, WAU, Wageningen

Thawornwong, N. and A. van Diest 1974. Influence of high acidity and aluminum on the growth of lowland rice. Plant and Soil 41, 141-159

Seasonally recurrent fish mortalities and ulcerative disease outbreaks associated with acid sulphate soils in Australian estuaries

R.B. Callinan[1], G.C. Fraser[1] and M.D. Melville[2]

[1] NSW Fisheries, Regional Veterinary Laboratory, Wollongbar Australia
[2] School of Geography, University of NSW, Kensington, Australia

Abstract

Acid sulphate and potential acid sulphate soils are now known to be widespread on the coasts of Australia, particularly in northern and eastern areas. The onset of heavy rain in these areas causes a 'first-flush' runoff and drainage of phytotoxic water with properties including low pH and high concentrations of dissolved aluminum. These waters have caused massive fish kills. Recently, a new ulcerative fish disease, epizootic ulcerative sÿndrome (EUS), has shown a pattern of seasonal recurrence in Eastern Australia also relating to these onset rains. However, the pattern of this disease's spread through Australia and Southeast Asia strongly suggests involvement of an exotic infectious agent. The oomycete fungus, *Aphanomyces* sp. has been consistently isolated from ulcers but it is unable to invade the intact skin of healthy fish. Early indications suggest that chemical properties associated with water draining from acid sulphate soil areas cause sublethal skin damage that can allow fungal invasion. There is a clear spatial and temporal association between onset rains, drainage from acid sulphate soil areas and outbreaks of EUS, although the details of the disease process have yet to be established.

This disease threatens a major protein resource for human consumption in the Asia-Pacific region, where population growth pressure and need for economic development are great.

Our ongoing research intends to establish, through field and laboratory studies, the role of water quality and hydrological parameters in the pathogenesis of EUS. This will allow better management of acid sulphate soil areas, thereby enhancing sustainability of estuarine fisheries.

Introduction

Acid sulphate soils and potential acid sulphate soils are widely distributed in tidal river flood plains in eastern and northern Australia. The sulphidic layers in these soils acidify periodically under natural conditions, as in prolonged periods of dry weather, or following changes to flood plain hydrology, when backswamps and freshwater lagoons are drainend by natural processes or human intervention.

Recent studies in Australia have demonstrated probable causal relationships between major rain events, the presence of significant areas of acid sulphate soil in river floodplains and certain seasonally recurrent fish mortalities. Studies of epizootic ulcerative sydrome (EUS), a new disease of freshwater and estuarine fish in Australia, have suggested similar water quality changes may be involved in its pathogenesis.

In this paper we briefly review the findings of these studies and discuss possible mechanisms responsible for death or ulceration in fish exposed to water derived from areas of acid sulphate soil.

Seasonally recurrent fish mortalities

A fish kill may be defined as any unusual increase in mortality and morbidity, due to infectious or non-infectious causes, in a fish population.

There have been several reports of seasonally recurrent fish kills in the Magela Creek system, part of the East Alligator River system in northern Australia. These fish kills typically occur during the transition from the dry to wet season, when 'first-flush' water enters lagoons and other permanent water bodies. Brown et al. (1983) described a major fish kill in a freshwater lagoon on Magela Creek which they attributed to high levels of toxic aluminum (up to 0.5 mg l^{-1}), a consequence of natural acidic water runoff. Hart et al. (1987) studied water quality in the Magela Creek system during a dry-to-wet season transition and found that 'first-flush' water flowing across the floodplain was acidic (pH about 4-5) with high conductivity (about 750 μS cm^{-1}) and high sulphate concentrations (about 200 mg l^{-1}). They concluded that the source of the acidity, dissolved salts and sulphate, as well as high concentrations of metals, particularly aluminum, was groundwater brought to the surface by rising watertables in acid sulphate soil areas of the floodplain.

Massive fish kills following major rain events have also been associated with acidic water and high concentrations of aluminum in major sections of the Tweed River in northern New South Wales. The acidic water is derived from runoff or drainage from the extensive areas of potential acid sulphate soil in the floodplain. In 1987, a fish kill on the Tweed River was associated with pH values as low as 3.6 and dissolved aluminum concentrations of 2.5 mg l^{-1} in major sections of the main stream (Fraser, unpublished).

Low pH, below 3-4, is directly lethal to most fish species, causing disturbances to water and ion regulation, as well as to oxygen transport mechanisms (Wendelaar Bonga and Dederen 1986). However, elevated concentrations of inorganic, cationic aluminum species (less than 0.1-5 mg l^{-1}) are thought to be primarily responsible for injury and death of fish in naturally acidified waters. These increased aluminum concentrations result, under acid conditions, from mobilisation of aluminum from watershed minerals (Driscoll et al 1980, Langdon 1988). In acidic water, inorganic aluminum accumulates in, and injures, fish gills, causing reductions in enzyme activity and lethal osmoregulatory disturbances (Staurnes et al 1984, Witters et al 1990). Other water quality attributes modify the toxicity of inorganic aluminum to fish; there is evidence that high calcium and silicon concentrations protect fish against aluminum toxicity (Brown 1983, Ingersoll et al 1990a, Birchall et al 1989). Humic substances (the end products of biological degradation of organic material) are also protective, binding aluminum in a non-toxic, organic form (Witters et al 1990).

In response to toxic acid/aluminum exposure, some fish species are able to acclimatize, via physiological changes, or undergo longer-term adaptation, via genetic selection (Mount et al 1990). These workers showed, however, that exposure to a 6-day 'pulse' of acid water with high inorganic, monomeric aluminum and low calcium concentrations, caused significant mortalities in brown trout fry not previously acclimatized to these conditions. It is likely that fish exposed to acid 'first-flush' water in Australian rivers are similarly unprepared, and that similar toxic mechanisms operate.

Epizootic ulcerative syndrome

Epizootic ulcerative syndrome (EUS), known colloquially in Australia as 'red spot disease', is an ulcerative skin disease affecting estuarine and freshwater fish. EUS was first reported in Australia from the Burnett River on the central Queensland coast in 1972 (McKenzie and Hall 1976). Since then, seasonally recurrent outbreaks have been recorded in many rivers on the East coast, from northern Queensland (Rodgers and Burke 1981) to southern New South Wales (Callinan, unpublished). Outbreaks have occured in southwest Western Australia since 1983 (Pass, unpublished) and in the Northern Territory since 1986 (Pearce 1990). Serious outbreaks of the disease have also occurred in Southeast and South Asia during the past decade (Anon 1991).

Losses due to EUS, primarily in cultured freshwater fish, were estimated at A$ 2.5 million in Indonesia in 1980, A$ 10.9 million in Thailand in 1982 and A$ 4.2 million in Bangladesh in 1988-89. EUS costs commercial estuarine fisheries on Australia's East coast approximately A$ 1 million in discarded fish annually.

Studies in North America have examined the possible long-term effect of 'ulcerative mycosis', a disease of estuarine species similar to EUS, on fishery sustainability (Merriner and Vaughan 1987). Results suggested that an incremental decline of 0.5 per cent per year in survival of young fish over a 30-year period would result in a reduction of 60 per cent of the normal expected biomass. Loss caused by EUS in Australian estuaries have not been accurately quantified but; assumming that up to 10 per cent of young fish of susceptible species die as a result of EUS outbreaks occuring once every 3 years, a similar long-term decline in biomass may result.

The sudden appearance and pattern of spread of EUS in Australia and Asia is consistent with the involvement of an exotic infectious agent. Studies examining possible primary causative roles for viruses, bacteria and metazoan parasites have, to date, produced negative results. However, in a study of the pathology of EUS, Callinan et al (1989) showed that massive invasion of the skin by oomycete fungi plays a central role in the induction of ulcers. Recently, Fraser et al (1992) recovered the oomycete fungus *Aphanomyces* sp. in apparantly pure culture from 27 of 28 early ulcers on 3 estuarine fish species from 3 widely separated river systems in Australia. Histologically indistinguishable fungi are also consistently present in lesions of fish affected with EUS in Asia (Roberts et al 1989).

These findings indicate that an *Aphanomyces* sp. is the causative infectious agent of EUS. However, attempts to induce typical lesions by exposing fish experimentally to fungal spores were successful only when skin was abraded prior to exposure (Callinan and Fraser, unpublished). This finding suggests that factors other than simple exposure to the fungus are necessary for EUS outbreaks to occur in wild fish populations.

EUS outbreaks in eastern Australia typically begin about 2 weeks after periods of prolonged heavy rainfall in lower river catchments. There is a growing body of evidence suggesting that these outbreaks occur only when susceptible fish are exposed to both *Aphanomyces* sp. propagules (spores and/or hyphae) and water having specific attributes. Further, there is an association between these water quality attributes and the presence of significant areas of acid sulphate soils in the lower floodplains of affected rivers. Such areas are known to be present in floodplains of most rivers in Australia from which EUS has been reported.

Studies on the tidal floodplain of the Richmond River system in northern New South Wales have demonstrated some relationships between major rain events and several water quality parameters. A submersible automatic water quality data logger, programmed to measure pH, dissolved oxygen concentrations, conductivity, temperature and depth at 15-minute intervals, was placed in a tributary of the Richmond River immediately downstream of a typical, drained backswamp containing significant areas of acid sulphate soils. Water quality changes associated with a major rain event are shown in Figure 1.

The low pH of the water after the rain event was probably due to acidity leached from acid sulphate soils in the catchment. The cause(s) of the low dissolved oxygen concentrations are more difficult to explain; they may be associated with microbial decomposition of suspended organic matter or from soil water from the active root zone, but the clear temporal association between reductions in both pH and dissolved oxygen concentrations suggests a common mechanism. One such mechanism involves the oxidation of iron II (from pyrite oxidation) to ferrihydrite. Concentrations of toxic aluminum species were not measured but, given findings elsewhere, were likely to have been high. Following the pH decline, a moderate fish kill occurred at the study site.

Related studies on the Richmond and Clarence Rivers have shown that, during the 2 weeks after major rain events, significant falls in dissolved oxygen concentrations consistently occur in most representative floodplain tributaries and at some main-

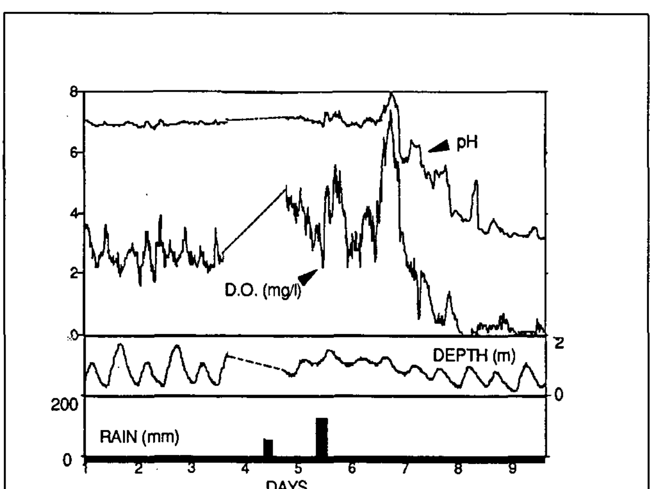


Figure 1 Changes in pH, dissolved oxygen (D.O.) concentrations and depth in a tributary of the Richmond River, New South Wales, downstream of an acid sulphate soils area. Data were recorded at 15-minute intervals by a submersible automatic data logger. Rainfall at the site is also shown.

stream sites. Falls in pH at mainstream sites may also occur. For example, on the Richmond River in May 1987 at Site 4 (Figure 2), dissolved oxygen concentrations fell from 5.8 mg l^{-1} to 3.3 mg l^{-1} and pH fell from 7.2 to 5.6 within 9 days of a major rain event. However, at Site 4 in April 1988, dissolved oxygen concentrations fell from 5.0 mg l^{-1} to 1.2 mg l^{-1} but pH fell only marginally, from 6.6 to 6.2, within 10 days of a major rain event.

Clearly, runoff or drainage from acid sulphate soil areas contributes to these changes, to an extent dependent on a complex of factors including rainfall patterns preceding the major rain event and the distribution of rainfall over the catchment during the major rain event. However, it is likely that a 'pulse' of acidic, deoxygenated water is discharged from these areas during the early stages of most major rain events.

Experimental exposure of fish to water with low pH (Daye & Garside 1976, Linnenbach et al 1987) and high aluminum concentrations (Ingersoll et al 1990b, Tandjung et al 1982) results in alterations to epidermal structure and, in extreme cases, epidermal necrosis. Low concentrations of dissolved oxygen may also injure fish epidermis. Plumb et al (1976) described apparantly sterile haemorrhagic and necrotic lesions in skin and skeletal muscle of channel catfish *Ictalurus punctatus*, exposed to dissolved oxygen concentrations of less than 1 mg l^{-1} for several days. They suggested that this epidermal damage allowed subsequent bacterial invasion and septicaemia. It is likely that, in some sections of lower river systems, and for varying periods after major rain events, 'first-flush' runoff water from acid sulphate soil areas causes sublethal water

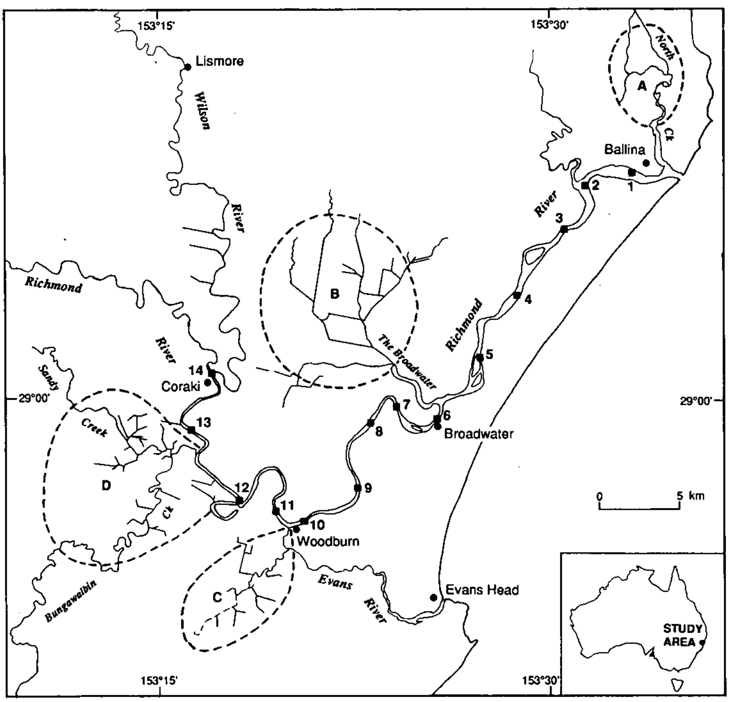


Figure 2 Location on the lower Richmond River of mainstream sampling sites for EUS prevalence (1-14) and known areas of acid sulphate soils (A-D)

Table 1 Prevalence of EUS in yellowfin bream (*Acanthopagrus australis*) and sand whiting (*Sillago ciliata*) sampled at 14 mainstream sites on the Richmond River at 3-monthly intervals on 7 occasions during 1988/89. Location of sites is shown in Figure 2

Site	Yellowfin Bream			Sand Whiting		
	Total examined	No. with EUS	Prevalence %	Total examined	No. with EUS	Prevalence %
1	271	6	2.2	–	–	–
2	1423	181	12.7	23	8	34.8
3	2019	231	11.4	40	18	45.0
4	1015	227	22.4	47	20	42.5
5	619	173	27.9	35	12	34.3
6	963	216	22.4	29	9	31.0
7	800	26	3.2	–	–	–
8	194	8	4.1	–	–	–
9	334	8	2.4	–	–	–
10	220	13	5.9	–	–	–
11	223	32	14.3	–	–	–
12	31	2	6.4	–	–	–
13	15	0	0	–	–	–
14	7	0	0	–	–	–

quality changes in tributaries and some mainstream sites. Epidermal structural changes may occur in exposed fish. Such changes may act in a manner similar to experimental abrasion and allow invasion by *Aphanomyces* sp. propagules, leading to development of typical EUS lesions.

The hypothesis that runoff or drainage from acid sulphate soil areas has a causal relationship to EUS is supported by the findings of a survey in which EUS prevalence in two relatively sedentary estuarine fish species, sand whiting (*Sillago ciliata*) and yellowfin bream (*Acanthopagrus australis*), was measured at 3-monthly intervals, on 7 occasions, at specific mainstream sites on the Richmond River during 1988/89. Findings of the survey are summarised in Table 1.

There are several acid sulphate soil sites in the lower Richmond River floodplain; the total distribution of such areas remains to be determined. EUS prevalence in yellowfin bream was highest in the section of river between Sites 2 and 6, where the cumulative effects of run-off from known acid sulphate soil areas should be at their greatest (Figure 2). Prevalence in this river section was also high in sand whiting, which have a more restricted distribution in the estuary. Given that the species examined are relatively sedentary, it is likely that the EUS lesions were induced at these sites. At Site 1, buffering and dilution with sea water during tidal exchanges would occur, and it is noteworthy that EUS prevalence at this site was low.

A similar association between EUS outbreaks and acid sulphate soils has been noted at a coastal study site in the Philippines (Reantaso, Paclibare, Callinan and Singh, unpublished). Acid soils, including acid sulphate soils, are widespread in Southeast and South Asia and may play a similar role in EUS induction in those regions. Studies in Southeast Asia have associated EUS outbreaks with water having low hardness (the characteristic of water which represents the total concentrations of calcium and magnesium expressed as calcium carbonate equivalent), low alkalinity (the buffering capacity of water expressed as calcium carbonate equivalent) and fluctuating pH (Anon 1989, Anon 1990a, Phillips 1992). Fish exposed to these conditions are highly susceptible to injuries caused by low pH and toxic metal ions (Anon 1990b).

Conclusions

While there is a clear causal association between fish kills and 'first-flush' run-off water from acid sulphate soil areas in some Australian estuaries, a similar causal association for EUS remains to be established. There is, however, experimental evidence that water quality attributes such as low pH, high concentrations of inorganic aluminum and low concentrations of dissolved oxygen which are present in this 'first-flush' water, may injure skin of sub-lethally exposed fish; the putative infectious cause of EUS, an *Aphanomyces* fungus, may then be able to invade these damaged areas and produce the characteristic ulcers.

In view of the potential of seasonally recurrent EUS outbreaks, as well as fish kills, to cause long-term damage to the sustainability of estuarine fisheries in the Asia-Pacific region, it is essential that major causal factors are identified and appropriate control measures, such as ameliorative drainage management practices, are put in place. However, given the complex interactions between rain events, acid sulphate soil areas, river flow patterns, populations of susceptible fish and distribution of the pathogenic *Aphanomyces* sp., considerable research effort will be required to elucidate thoroughly the possible relationships.

Acknowledgements

We thank R. West and G. McLennan for kind permission to include EUS prevalence data and water quality data respectively. We also thank C. Peak for generously assisting in the preparation of figures and A. Parrington for typing the manuscript. These studies were funded, in part, by Land and Water Resources Research and Development Corporation.

References

Anon 1989. A report on the NACA workshop on the regional research program on ulcerative syndrome in fish and the environment. Network of Aquaculture Centres in Asia-Pacific, Bangkok

Anon 1990a. Regional research program on relationships between epizootic ulcerative syndrome in fish and the environment. Network of Aquaculture Centres in Asia-Pacific, Bangkok

Anon 1990b. Water quality management for aquaculture and fisheries. Institute of Aquaculture, University of Stirling, Scotland

Anon 1991. Fish health management in Asia-Pacific. Report on a regional study and workshop on fish disease and fish health management. Asian Development Bank Agriculture Department Report Series No. 1, Network of Aquaculture Centres in Asia-Pacific, Bangkok

Birchall, J.D., C. Exley, J.S. Chappell and M.J. Phillips 1989. Acute toxicity of aluminum to fish eliminated in silicon-rich acid waters. Nature 338, 146-148

Brown, D.J. 1983. Effect of calcium and aluminum concentrations on the survival of brown trout (Salmo trutta) at low pH. Bulletin of Environmental Contamination and Toxicology 30, 582-587

Brown, T.E., A.W. Morley, N.T. Sanderson and R.D. Tait 1983. Report of a large fish kill resulting from natural acid water conditions in Australia. Journal of Fish Biology 22, 335-350

Callinan, R.B., G.C. Fraser and J.L. Virgona 1989. Pathology of red spot disease in sea mullet, *Mugil cephalus* L. from eastern Australia. Journal of Fish Diseases 12, 467-479

Daye, P.G. and E.T. Garside 1976. Histopathologic changes in surficial tissues of brook trout, *Salvelinus fontinalis* (Mitchill), exposed to acute and chronic level of pH. Canadian Journal of Zoology 54, 2140-2155

Driscoll, C.T., J.P. Baker, J.J. Bisogni and C.L. Schofield 1980. Effect of aluminum speciation on fish in dilute acidified waters. Nature 284, 161-164

Fraser, G.C., R.B. Callinan and L.M. Calder 1992. *Aphanomyces* species associated with red spot disease, an ulcerative skin disease of estuarine fish from eastern Australia. Journal of Fish Diseases. In press.

Hart, B.T., E.M. Ottaway and B.N. Noller 1987. Magela Creek System, Northern Australia. I. 1982-83 Wet-season quality. Australian Journal of Marine and Freshwater Research 38, 261-288

Ingersoll, C.G., D.R. Mount, D.D. Gulley, T.W. LaPoint and H.L. Bergman 1990a. Effects of pH, aluminium and calcium on survival and growth of brook trout embryos (*Salvelinus fontinalis*). Canadian Journal of Fisheries and Aquatic Sciences 47, 1580-1592

Ingersoll, C.G., D.A. Sanchez, J.S. Meyer, D.D. Gulley and J.E. Tietge 1990b. Epidermal response of pH, aluminium, and calcium exposure in brook trout (*Salvelinus fontinalis*) fry. Canadian Journal of Fisheries and Aquatic Sciences 47, 1616-1622

Langdon, J.S. 1988. Investigation of fish kills: I. History and causes. In: Fish Diseases Proceedings 106, 168-194. Post Graduate Committee in Veterinary Science, University of Sydney

Linnenbach, M., R. Marthaler and H. Gebhardt 1987. Effects of acid water on gills and epidermis in brown trout (*Salmo trutta* L.) and in tadpoles of the common frog (*Rana temporaria* L.). Anales de la Société Royale de Belgique 117, 365-374

McKenzie, R.A. and W.T. Hall 1976. Dermal ulceration of mullet (*Mugil cephalus*). Australian Veterinary Journal 52, 230-231

Merriner, J.V. and D.S. Vaughan 1987. Ecosystem and fishery implications of ulcerative mycosis. In: Proceedings of the Workshop on Fishery Diseases for the Albemarle-Pamlico Estuarine Study, 39-46. University of North Carolina Water Resources Research Institute, Raleigh

Mount, D.R., M.J. Swanson, J.F. Breck, A.M. Farag and H.L. Bergman 1990. Responses of brook trout (*Salvelinus fontinalis*) fry to fluctuating acid, aluminium and low calcium exposure. Canadian Journal of Fisheries and Aquatic Sciences 47, 1623-1630

Pearce, M. 1990. Epizootic ulcerative syndrome technical report, December 1987 – September 1987. Northern Territory Department of Primary Industry and Fisheries No. 22, Darwin

Phillips, M.P. 1992. Techical review of epizootic ulcerative syndrome. Network of Aquaculture Centres in Asia-Pacific, Bangkok. In press.

Plumb, J.A., J.M. Grizzle and J. Defigueiredo 1976. Necrosis and bacterial infection in channel catfish (*Ictalurus punctatus*) following hypoxia. Journal of Wildlife Diseases 12, 247-253

Roberts, R.J., R. Wootten, I. MacRae, S. Millar and W. Struthers 1980. Ulcerative disease survey, Bangladesh. Final report to the Government of Bangladesh and the Overseas Development Administration. Institute of Aquaculture, Stirling

Rodgers, L.J. and J.B. Burke 1981. Seasonal variation in the prevalence of 'red spot' disease in estuarine fish with particular reference to the sea mullet, *Mugil cephalus* L. Journal of Fish Diseases 4, 297-307

Staurnes, M., T. Sigholt and O.B. Reite 1984. Reduced carbonic anhydrase and Na-K-ATPase activity in gills of salmonids exposed to aluminium-containing acid water. Experientia 40, 226-227

Tandjung, S.D., D.V. Rottiers and R.L. Herman 1982. Histopathological studies on the effects of acid stress to brook trout *Salvelinus fontinalis* (Mitchill) in the presence of sublethal concentrations of aluminium. In: Johnson R.E. (Ed.). Acid rain/fisheries. Proceedings of an international symposium on acidic rain and fishery impacts on Northeastern North America, 357. American Fisheries Soc., Bethesda

Wendelaar Bonga, S.E. and L.W. van Dederen 1986. Effects of acidified water on fish. Endeavour. New Series 10, 198-202

Witters, H.E., S. van Puymbroek, J.H. Vangenechten and O.L. Vanderborght 1990. The effect of humic substances on the toxicity of aluminium to adult rainbow trout, *Onchorhyncus mykiss* (Walbaum). Journal of Fish Biology 37, 43-53

Assessment and management of acidity release upon drainage of acid sulphate soils in Finland

Jukka Palko[1] and Markku Yli-Halla[2]

[1] Water and Environment District of Oulu, Box 124, SF-90101 OULU, Finland
[2] Department of Applied Chemistry and Microbiology, Viiki, University of Helsinki, 00710 Helsinki, Finland

Abstract

Cultivated acid sulphate soils cover an area of over 160 000 ha in Finland. Their maximum sulphur content seldom exceeds 1 per cent of soil mass. Due to the cool and humid climate, the rate of oxidation of sulphide is determined by the length of the dry period in summer. In drainage of acid sulphate soils, measures are taken to prevent excessive acidification of the recipient waters. The percentage of acid sulphate soils in the drained area and the dilution of the drainage waters are used to assess the acidification expected and the lime requirement of acid waters. Equations and graphs used in the management of acid drainage waters are presented.

Introduction

Along the coasts of Finland, especially along the Gulf of Bothnia, there are 160 000 ha of cultivated sulphidic soils (Palko et al. 1988), tentatively classified as Sulphic Cryaquepts. Their total S content seldom exceeds 1 per cent by mass (Purokoski 1958), which allows the soils to be used for cultivation after liming and drainage. The quantities of acidity produced after drainage may, however, be large enough to cause serious acidification of drainage waters which may become lethal to fish.

Sulphide layers are oxidized in the summer when the groundwater table goes down. There are two periods during the year when the acidity reaches the rivers: during the fall rains, from September to November; and in the following spring, when waters from melting snow and thaw leach the soil. Outside these two periods there is no drainage water since the soil is dry or frozen. The fish killings occur during the runoff peaks when the quantity of water leaching the soil profile is highest.

Most fields of acid sulphate soils are poorly drained and, from the agricultural point of view, require additional drainage. The aim of the present work was to determine the relationship between the occurrence of acid sulphate soils in the catchment and the acidity of drainage waters. Guidelines for the planning and management of drainage projects in acid sulphate soils areas in Finland are also presented.

Materials and methods

The material consists of three parts:

1) A drainage basin experiment on three small catchments containing acid sulphate soils;

2) Results of a survey of four river catchments containing acid sulphate soils and subsequent monitoring of the river waters;
3) A polder experiment.

In the small drainage basin experiment, the effect of the percentage of acid sulphate soils in the catchment and the effect of annual hydrology on the acidity of runoff water were studied. The observations made in the small catchments were compared with those made on larger river catchments. The objective of the polder experiment was to compare the effect of open drainage and pipe drainage on the acidity of drainage waters from an acid sulphate soil.

Small catchment experiment

Three catchments (T7, T8, T9) were selected from Liminka, near Oulu:

	T7	*T8*	*T9*
Drainage area, km^2	2.8	2.2	6.6
Percentage of acid sulphate soils	13	73	64

Results of soil analyses of this area have been published by Purokoski (1958) and Erviö and Palko (1984). The area is completely cultivated and the soils are mainly silty in texture.

The land was originally drained in 1955 with 0.7 m deep open ditches. In 1984, the major ditches were deepened by 0.5 m. During 1986-1991, water samples were taken twice a week during four months (15 April to 15 June, and 1 Sept. to 30 Oct.) when the quantity of drainage water exceeded 10 $dm^3\ s^{-1}\ km^{-2}$. The samples were analyzed for pH and titratable acidity. The daily runoff was measured at Tuuranoja measuring weir, 50 km from the basins.

Larger river catchments

Four larger river catchments (Table 1) by the Gulf of Bothnia were surveyed for the occurrence of acid sulphate soils by at an intensity of one auger boring per 0.5 ha of the cultivated fields. 850 augerings were examined. The pH of the soil profile was measured down to 200 cm at intervals of 10 cm. The soil was classified as an acid sulphate soil if the pH in the profile had a typical gradient and the pH of the subsoil (0.5 m deep) was below 5.0. Water samples were taken from each river mouth twice a week during three periods: 1 Sept. to 30 Oct. 1986; 15 April to 15 June 1987; and 1 Sept. to 30 Oct. 1987. The water samples were analyzed for pH and titratable acidity. From each river, 16, 13 and 11 samples were taken in fall 1986, spring 1987, and fall 1987, respectively.

Table 1 Data on the river basin surveyed for acid sulphate soils

River	Drainage area, km^2	Field area km^2	Acid sulphate soils	
			km^2	%
Ähtävänjoki	2030	49.7	34.5	1.7
Kruunupyynjoki	767	36.5	18.9	2.5
Purmonjoki	830	88.2	49.3	5.7
Kovjoki	293	44.0	17.6	6.0

Polder experiment

In 1984, an experimental field of 2.5 ha (140 × 180 m) was established on a virgin acid sulphate soil at Ruhko-oja polder near the drainage basins described above. The surface soil (0-20 cm) was peat with a silty subsoil. The upper limit of the black, reduced subsoil was at 30 cm, and this sulphide-containing layer extended at least to a depth of 4 m. The pH of the surface soil ranged from 4.4 to 5.0, and the content of SO_4-S extracted with an ammonium acetate solution, from 420 to 540 mg dm^{-3} of soil. The total S content of the soil at depth 30-45 cm was 0.2 per cent.

In the polder were 12 pipe-drained plots (15 m × 35 m each; depth of the pipes 1.13 m) and eight plots (9 × 50 m) drained with open ditches which were 0.75 m deep. The pipe drainage applied is the standard drainage practice in Finland. The groundwater level was measured in three vertical pipes in both drainage areas in the spring and fall of 1986. Water samples were collected 2-5 times a week in spring and fall when the quantity of drainage water exceeded 10 dm^3 min^{-1}. In the field, pH and electrical conductivity (EC) of water were measured. The acidity was titrated in the laboratory.

Results

Small catchments

The drainage waters of the two catchments containing 73 per cent (T8) and 64 per cent (T9) acid sulphate soils had a lower pH and contained larger quantities of titratable acidity than the basin containing only 13 per cent (T7) acid sulphate soils (Table 2). During the five years when both spring and fall were observed, the mean acidity of fall flood was always greater than that of spring flood, and the runoff acidity in fall varied greatly from year to year (Table 3).

Table 2 Average pH and titratable acidity in spring and fall flood in three drainage basins in 1986-1991

Drainage basin	A.S. soils, per cent	pH		Acidity, mM dm^{-3}	
		Spring	Fall	Spring	Fall
T7	13	5.8	5.9	0.61	1.01
T8	73	4.1	3.6	2.89	4.93
T9	64	4.1	3.7	2.60	4.52

Table 3 Length of the dry period in summer and runoff period and mean runoff acidity during the fall flood in three drainage basins (T7, T8, T9)

Year	Dry d	Runoff d	Mean runoff acidity, mM dm^{-3}		
			T7	T8	T9
1986	72	13	1.88	8.54	7.70
1987	0	30	0.80	5.26	4.44
1988	42	14	1.19	6.45	5.26
1989	27	9	0.85	3.41	4.15
1990	30	0	0.50	2.07	2.14
1991	38	16	0.83	3.81	3.43

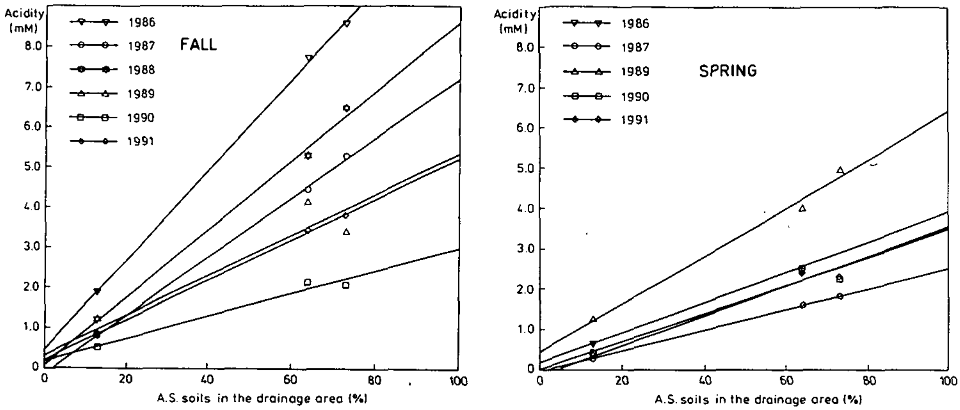


Figure 1 Correlation between the mean runoff acidity and the relative amount of acid sulphate soils in three catchments during fall and spring floods in 1986-1991

The duration of the dry summer period was defined as the number of days when the runoff was less than 1.0 $dm^3\ s^{-1}\ km^{-2}$. To some extent, the acidity measured in the fall runoff of a given area was dependent on the duration of the dry period in the preceding summer. When correlations between the titratable acidity (mM) and the duration of the dry period in days (S) were calculated, the results of 1989 and 1990 were excluded due to very short runoff periods. The regression equations for the three drainage basins were as follows:

T7:	Acidity = 0.015 S + 0.88	$R^2 = 0.92$
T8:	Acidity = 0.048 S + 5.29	$R^2 = 0.68$
T9:	Acidity = 0.046 S + 4.41	$R^2 = 0.86$

The relationship between the mean runoff acidity and percentage of acid sulphate soils in the catchment for spring and fall floods is presented in Figure 1. The minimum and maximum lines represent the range of mean runoff acidities during six years.

Larger river catchments

The titratable acidity and the pH in the recipient water are eventually dependent on the degree to which the acid drainwaters are diluted. Within the larger river catchments studied, the relative amount of acid sulphate soils in the whole catchment was substantially smaller than in the small catchments. Therefore, the acidity measured in river waters was lower as well (Table 4). However, the quantity of titratable acidity in the river waters was still dependent on the extent of acid sulphate soils in the catchment (Figure 2). The first fall when the acidity of river waters was measured (1986), followed a long dry summer. The year 1987, in turn, was exceptionally wet. The acidities measured after these contrasting summers very likely give the range within which the acidities of other years will vary.

Reproduction of fish is hampered where the pH of water is below 5.5 (Lakso et al. 1989). Regression analyses of the results of pH and titratable acidity in the rivers of the area concerned have shown that an acidity of 0.30 mM dm^{-3} corresponds to

Table 4 Titratable acidity (mM dm^{-3}) in samples taken from four rivers

River	Fall 1986		Spring 1987		Fall 1987	
	Mean	Range	Mean	Range	Mean	Range
Kruunupyynjoki	0.34	0.26-0.48	0.23	0.16-0.37	0.27	0.12-0.47
Ähtävänjoki	0.24	0.12-0.36	0.19	0.08-0.39	0.14	0.08-0.41
Purmonjoki	0.46	0.38-0.58	0.32	0.25-0.44	0.34	0.28-0.50
Kovjoki	0.59	0.48-0.68	0.41	0.32-0.65	0.44	0.27-0.70

pH 5.5. Therefore, the value of 0.30 mM was taken as the level which should not be exceeded in the river water. Figure 2 shows that acidity in Purmonjoki and Kovjoki exceeded the critical level in both falls, while in Kruunupyynjoki the critical level was exceeded in 1986 after the dry summer, but not in 1987 which was less favourable for sulphide oxidation.

Polder experiment

The depth of groundwater was monitored one year after drainage operations in the experimental polder were completed. During the spring and fall floods, the ground-

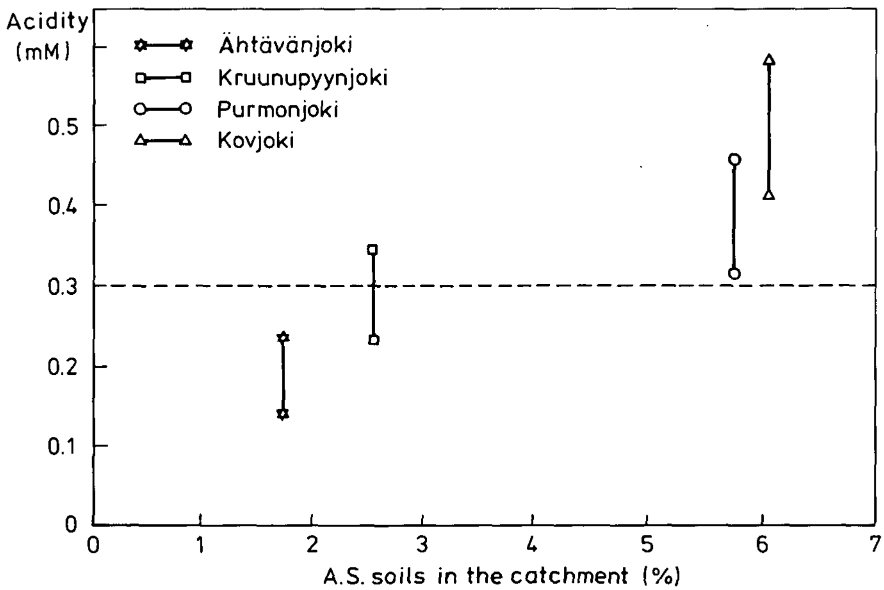


Figure 2 Variation of the mean acidity during the fall flood in four rivers with different proportions of acid sulphate soils in their catchments. The higher acidity value was obtained in 1986 after a long dry period (72 d) in summer and the lower value in 1987 when there was no dry period in the preceding summer. A concentration of 0.3 mM dm^{-3} represents the maximum tolerable level of acidity

Table 5 Indices of the quality of water obtained from subsurface pipes and open ditches

	Drainage		Significance of difference
	Pipe	Open	
Spring 1987:			
pH	4.4	3.9	**
Acidity, mM m^{-3}	9.3	4.3	**
EC, mS m^{-1}	391	188	**
Fall 1987:			
pH	4.3	4.1	n.s.
Acidity, mM m^{-3}	13.8	4.9	**
EC, mS m^{-1}	614	250	**

** significant at 1 per cent level; n.s. = not significant

water level was lower in the pipe-drained areas, as compared with the open-drained ones, as follows:

Period	*Pipe drainage*	*Open ditches*
23 May – 9 June 1986	60 cm	24 cm
3 Sept – 6 Nov 1986	60 cm	15 cm

Between the spring and fall floods, the depth of groundwater exceeded 160 cm in all plots and the profiles of all plots were exposed to oxidation. As compared with the standard pipe drainage, the runoff from the open drainage had a lower titratable acidity and EC, but also a lower pH than the runoff from the pipe-drained area (Table 5).

Practical applications

In 1988, instructions were given that the increase of the acidity in the recipient river water needs to be estimated before drainage operations are carried out in agricultural land containing acid sulphate soils. The evaluation is based on three variables:

1) Relative amount of cultivated acid sulphate soils in the area to be drained;
2) Mean runoff acidity of the recipient river water before drainage;
3) Dilution of waters from the drained area.

The relative amount of acid sulphate soils in the area to be drained is used to estimate the mean runoff acidity of drainage water (Figure 1), obtained from the results of the three small catchments. The maximum and minimum acidities expected are used in the calculations. The dilution of the drainage waters is determined as the ratio of the areas of the catchments of the recipient and the drained area. The acidity of the recipient river water is obtained by monitoring the water course before drainage of the acid sulphate soil area. The equation combining the factors is as follows

$$A_a = A_b + A_d * D$$

where

A_a = acidity after drainage in recipient
A_b = acidity before drainage in recipient
A_d = acidity of the drained waters
D = dilution factor = ratio of the drained area and the area of the recipient

For simplicity, it is assumed that, before drainage, the area to be drained does not contribute to the acidity of the recipient. If the predicted mean runoff acidity of the recipient exceeds 0.30 mM dm^{-3} after drainage, acidity needs to be taken into account in the drainage operations. The most common method to prevent rapid acidification of the recipient is to divide the drainage into several parts, and to drain each part separately at intervals of at least 10 years. Damming of drainage ditches immediately after flood is also used to prevent a fast drop of the groundwater table in drainage areas. The most expensive means to prevent problems caused by acidity is to lime the acidic runoff waters. The reduction of the acidity required is calculated as follows

$$A_r = A_d - 0.30$$

where

A_r = reduction of acidity required (mM dm^{-3})
A_d = acidity after drainage (mM dm^{-3})

Calcite is commonly used as the liming material. For example, a decrease of acidity by 2.2 mM dm^{-3} requires approximately 200 g of $CaCO_3$ per 1 m^3 of water. A large quantity of $CaCO_3$ is poorly soluble due to the precipitation of iron hydroxide on lime particles. Therefore, very acid runoff waters ($>$ 2.2 mM) are limed with CaO which dissolves rapidly in water. The quantity of liming material is determined from the quantity of runoff to be limed and the reduction of acidity required. The addition of lime is done in stream water in order to be certain of effective dissolution. After liming, the pH should be 5.5. The actual liming rate required is determined by a continuous pH measurement 200 m below the site of lime addition.

The rivers in the acid sulphate soil area along the Gulf of Bothnia have been classified by their acidity. In the rivers from catchments with a low percentage of acid sulphate soils (class I; e.g. Ähtävänjoki), the mean runoff acidity is not expected to exceed 0.30 mM dm^{-3}. In class II rivers (e.g. Kruunupyynjoki), the acidity exceeds 0.30 mM dm^{-3} after summers favourable for sulphide oxidation. Class III rivers (e.g. Purmonjoki and Kovjoki) are considered too acid to be rehabilitated at a reasonable cost. Classes II and III both consist of 12 rivers. Liming is carried out in class II rivers. Presently, there are liming stations operating in three rivers, including Kruunupyynjoki.

Discussion

The rough models presented for the management of acidity in drainage projects use the relative amount of acid sulphate soils in determining the acidifying potential of the drained area. The use of this variable in the assessment of expected acidity, without taking into account the sulphide content in the soil, is facilitated by the fact that the acid sulphate soils on the coasts of the Gulf of Bothnia are rather homogeneous in terms of S content, vertical distribution of S in the profile and hydrology. The use of the relative amount of acid sulphate soils as the factor determining the acidity of drainage waters seems to be justified also at the river level because the measured acidity correlated with the proportion of acid sulphate soils in the catchment. The importance of soil surveys to the planning drainage projects in areas containing acid sulphate soils is obvious from our experience.

In the cool and humid climate of Finland, the sulphidic layers are slowly oxidized after artificial drainage. It was, indeed, observed in the three small drainage basins that the mean runoff acidity is dependent on the duration of the dry period of the preceding summer. The length of the dry period determines the upper limit of acidity which is generated from the sulphide. In late summer, this variable can be used to assess the expected runoff acidity from a given acid sulphate soil area in the following fall.

Leaching intensity during the runoff period is another factor determining the actual quantity of acidity reaching the recipient rivers. However, the quantity of runoff need not necessarily be taken into account when calculating the acidifying effect of the drainage water in the recipient, because the runoff from the drained area correlates with the runoff of the whole catchment of the river. This is probably because the rivers in the area concerned are rather small and weather conditions are uniform within the whole catchment.

The polder experiment showed that open drains are less efficient than standard pipe drainage. This was directly measured as the level of groundwater, and indirectly as differences in the quality of drainage water. Even though measurements on the research field were carried out only over a very limited period of time, they show that by open drainage it was possible to reduce the rate of oxidation of sulphide layers of an acid sulphate soil, as compared to pipe drainage. Therefore, pipe drainage cannot be recommended in the acid sulphate soils as the first means of drainage.

References

Erviö, R. and J. Palko 1984. Macronutrient and micronutrient status of cultivated acid sulphate soils at Tupos, Finland. Ann. Agric. Fenn. 32:121-133

Lakso, E., S. Lindroos and K. Weppling 1989. Neutralointiohjeet happamien sulfaattimaiden valumavesille (Neutralization recommendations for acid sulphate waters). National Board of Waters and Environment. Publication 34. Helsinki

Palko, J., E. Merilä and S. Heino 1988. Maankuivatuksen suunnittelu happamilla sulfaattimailla (Land drainage planning for acid sulphate soils). National Board of Waters and Environment. Publication 21, Helsinki

Purokoski, P. 1958. Die schwefelhaltigen Tonsedimente in dem Flachlandgebiet von Liminka in Lichte chemischer Forschung. Agrogeol. Publ. 70, 1-88, Helsinki

Acid drainwaters from potential acid sulphate soils and their impact on estuarine ecosystems

I.R. Willett[1], M.D. Melville[2], I. White[3]

[1] Australian Centre for International Agricultural Research, GPO Box 1571, Canberra, ACT 2601
[2] University of NSW, PO Box 1, Kensington, NSW 2033
[3] CSIRO Centre for Environmental Mechanics, GPO Box 821, Canberra, ACT 2601, Australia

Abstract

There has been only limited recognition in Australia of the existence of actual or potential acid sulphate soils and their associated problems. Drainage of coastal areas for a variety of land uses has been undertaken in ignorance of the hazards posed by pyrite oxidation and dramatic degradation of estuarine ecosystems has occurred.

Several spectacular fish kills have occurred in the estuary of the Tweed River. Sugar cane production occupies most of the floodplain of this river and at least part of it is underlain by potential acid sulphate sediments. Drainage to improve sugar production has been carried out and it has been suspected that acid sulphate drainage water is at least partly responsible for the fish kills. Observations to support this include the timing of the fish kills in relation to dry periods for oxidation, wet periods for transport of oxidation products to the river, and the rapid clarification of the river which appears to be due to flocculation of the suspended load by dissolved aluminum.

Preliminary results identify the drained sugar cane land as the source of acidity and dissolved aluminum. The results are consistent with acid sulphate oxidation products and associated elevated concentrations of aluminum as contributors to large fish kills in the estuary.

Introduction

Until recently, little attention has been paid to acid sulphate soils in Australia. This may be related to the lack of major developments on the floodplains of coastal rivers in this country. Large areas of extremely acidic acid sulphate soils have been identified on the floodplains of the Macleay and Shoalhaven rivers of New South Wales (Willett and Walker 1982, Willett and Bowman 1990) and these may be associated with shallow drainage for dairy farming. Large areas of naturally occurring acid sulphate soils also occur, particularly on the floodplains of rivers of the Northern Territory (Willett et al. 1989). During the last few years it has been recognized that the disturbance of potential acid sulphate materials for urban and tourist developments, coastal sand mining, aquaculture and sugar cane growing are causing acidification of soils and adjacent water bodies.

Further attention was directed to acid sulphate soils of floodplains during the search for the causes of spectacular fish kills in the Tweed and some other coastal rivers of northern New South Wales. In addition to fish kills, there appears to have been a decline in catches and increases in the incidence of epizootic ulcerative syndrome

(EUS) in fish caught in the estuaries (Callinan et al. 1993). The estuaries and the sea grass beds that they support are particularly important for commercial fisheries as they provide essential habitats for the juvenile stages of many commercial fish species of the open sea as well as habitats for fish which are entirely estuarine.

Acidic water from drains in sugar cane fields has been suspected as the cause of both lethal and sub-lethal effects on the fishes in estuaries. Observations linking acid drainage water with fish kills include the association of several kills with heavy rains following prolonged dry spells and with rapid clarification of the water. It has been assumed that acidic products formed by oxidation of sulphidic subsoils during dry periods are flushed into the rivers during rainy periods. The clarification of the river appears to be related to flocculation of the suspended sediment by dissolved aluminum.

In this paper, we present preliminary results on the impact of sugar cane production on the acidification of drainage water and its transfer to the river.

Experimental

This study was conducted on Macleods Creek which is a right bank tributary of the Tweed River near the Queensland-New South Wales Border (Figure 1). The Creek has been widened and straightened as part of a drainage system. Drainage for sugar cane production is provided by several large lateral and numerous small field drains (Figure 1). A soil survey of the area is not available but most soils of the former backswamp area would be described as humic gleys in the Australian great soil group classification. Typically, they consist of dark (10YR 2/1) organic loam topsoil (0-35 cm) overlying mottled clay loam to light clay (35-90 cm). Jarositic mottles are found in the latter horizon and are at a maximum in the middle part of the horizon.

Organic fragments increase with depth. Below 90 cm, the material is dark (N 4/1), unripe pyritic marine clay.

Surveys of the pH of the Creek water were made on two occasions. The first during February 1990, after heavy rain and low level flooding associated with a cyclone. At this time, the Creek was flowing rapidly. The second was made during November 1991, after a prolonged dry period when there was no flow in the Creek. At each time, pH measurements were made of the Creek water at up to 20 locations ranged over about 3.5 km, from the Tweed River, across the backswamp areas and as far as the uplands not affected by marine sediments (Figure 1). At each location, the pH of the surface (5 cm) water was determined with a portable pH meter and a freshly standardized, combined glass-calomel electrode.

Samples of the surface water were also collected for analysis; 5 were obtained in 1990 and 16 in 1991. The samples were filtered (0.45 μm) in the laboratory and analyzed as soon as possible. Iron was determined by atomic absorption spectrophotometry, and sulphate and chloride by ion chromatography. The 1991 samples were analyzed for sulphate by a turbidimetric method. Total aluminum was determined by atomic absorption spectrophotometry and, for the 1990 samples, 'uncomplexed' aluminum was determined by an ion chromatographic method (Willett 1989). The latter analysis gives results for Al in the hydroxo- and sulphato-complexes, but excludes more stable complexes with fluoride or organic compounds.

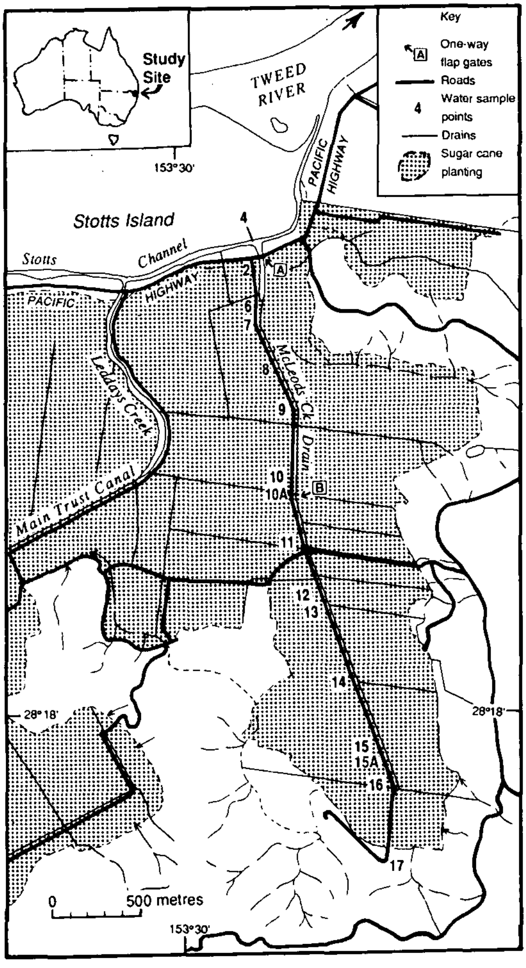


Figure 1 McLeods Creek caneland study site on the Tweed River, northern New South Wales, Australia

Results

The pH of the Creek water determined on four occasions during two days in 1990 is shown in Figure 2. During this period water was flowing through flap gates from the Creek into Stotts Channel (location 4). The pH of the water decreased from location 4 to those located in the cane fields on the backswamp. On approaching the uplands beyond the backswamp the pH rose, and was 6 or greater in the hillslope interceptor drain (location 17). The results clearly show that the backswamp areas are contributing acidity to the drainage water. During the 1990 sampling period, the pH values of the Creek water decreased with time while water ponded on the surface of the cane field remained above pH 5.0. This suggests that the acidity is being leached out of the soil with time and that the source of the acidic water is water draining from the profile rather than surface drainage water.

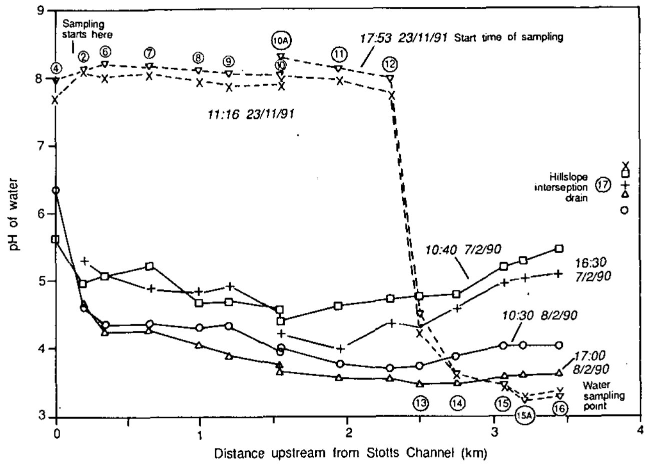


Figure 2 transects of McLeods Creek: 1990, during low-level flood recession; 1991, after prolonged dry conditions

The data for the chemical analyses of the water collected in 1990 are shown in Table 1. The results generally reflect those expected from the pH values shown in Figure 2 in that the products of pyrite oxidation and soil acidification are highest where the water pH was lowest.

The results for the chemical analyses obtained during the dry period in 1991 are shown in Table 2. Fe and Al were barely detectable by atomic absorption spectrophotometry near Stotts Channel but increased markedly at location 14, well into the backswamp area, where pH values were less than 4. The concentrations of sulphate were highest near Stotts Channel and indicate where estuarine water leaked into the Creek. At the hillslope interception drain (location 17) the pH was higher and the sulphate concentration much lower than in the samples downstream in the backswamp areas. These data correspond with the fact that location 17 is upstream of the acid sulphate materials. The concentrations of sulphate in the acidic samples from the backswamp area were less than those in samples affected by leakage of estuarine water but greater than the fresh water not in contact with acid sulphate subsoils.

The ratio of Fe:S in the acidic backswamp samples was considerably less than the 1:2 expected from pyrite oxidation. This may reflect precipitation of Fe as ferric hydroxyoxides, in the soil or in the Creek water, leaving an excess of sulphate. Ferric

Table 1 Analytical results for Creek water collected in 1990, expressed in mmol per litre

Sample Location	Cl^-	SO_4^{2-}	Fe	Al*
2	1.42	0.58	0.063	0.044
8	1.29	1.13	0.054	0.081
10	0.99	1.90	0.061	0.196
10A	1.48	2.76	0.100	0.230
15	1.20	1.71	0.154	0.070

* 'uncomplexed' Al by ion chromatography

Table 2 Analytical results for Creek water collected in 1991

Sample Location	pH*	SO_4^{2-} (mmol l^{-1})	Fe (mmol l^{-1})	Al** (mmol l^{-1})
3	7.25	14.2	0.003	0.028
2	7.16	20.4	0.003	0.017
6	7.43	21.1	0.003	0.017
7	7.44	15.3	0.004	0.017
8	7.37	10.2	0.004	0.021
9	7.37	19.0	0.003	0.021
10	7.33	18.7	0.003	0.027
10A	7.24	8.9	0.003	0.020
11	7.09	8.9	0.001	0.025
12	6.92	10.9	0.001	0.024
13	4.49	8.4	0.003	0.062
14	3.82	8.9	0.007	0.097
15	3.63	6.6	0.011	0.126
15A	3.46	6.6	0.016	0.165
16	3.52	9.5	0.060	0.164
17	6.33	0.1	0.042	0.058

* pH in laboratory
** Total dissolved Al by atomic absorption

hydroxyoxide films and scum were observed in the Creek. Jarosite accounted for only a small fraction of the total free Fe and S in acid sulphate soils of southern New South Wales (Willett and Walker 1982) and precipitation of sulphate in jarosite may not immobilize all the sulphate released by pyrite oxidation. The concentrations of total dissolved Al were very low except in the most acidic samples, and generally lower than those for 'uncomplexed' Al in the 1990 samples (Table 1).

Discussion

The backswamp areas that have been partly drained for sugar cane cultivation were identified as sources of acid sulphate oxidation products and aluminum. During a rainy period, acidic drainage water was transported from the soils of the backswamp by the Creek to the Tweed River. Pumping during drier periods allowed oxidation of pyritic subsoils but transport of oxidation products was limited. It appears that partial drainage and pumping during drier periods causes oxidation of pyritic subsoils and that acidity, iron and aluminum are transported to the Creek and River during wet periods.

The concentrations of sulphate, iron and aluminum in the Creek water were well above those normally found in freshwaters. The pH values were lower than those associated with acidity induced fish kills, whereas the aluminum concentrations greatly exceeded values known to be toxic to freshwater fish (Driscoll et al. 1980, McCahon et al. 1989, McCormick et al. 1989). In addition iron^{III} hydroxyoxides were being precipitated in the water at intersections between the Creek and the lateral drains. This precipitate, and possibly aluminum hydroxide, may be expected to kill fish by accumulation in the gills (McCahon et al 1989).

When sampled during a dry period in 1991, the pH measurements of the first 2.5 km of the Creek were similar to those of the river (Figure 2). There was no flow in the Creek at this time but the flap gates at 'A' and 'B' leak, allowing estuarine water into lower reaches of the Creek causing the high pH values in the lower reaches of the Creek.

The influence of the estuarine water extended upstream as far as sample location 12. The sharp change in pH between locations 12 and 13 is a result of pumping of water from the eastern end of the lateral drain running off the Creek at that point. After rain raises drain water levels, the water from this lateral drain is pumped into the hillslope interceptor drain. Initially this drain water flows northward and, then, into the lateral drain that enters the Creek immediately downstream of flap gates 'B'. This pumping activity causes drainage from the subsoils upstream of location 13 and corresponds with low pH values in the Creek at these upstream locations. The pumping activity also causes some upstream flow of water through flap gates 'B', and this has an important effect of mixing the acidic subsoil drainage and estuarine waters.

Beyond 2.5 km, the pH values were around 3.4 and indicate the effects of acid sulphate drainage from the soil on the Creek water. It would appear that the transport of acidic oxidation products from the soil to the Creek is limited to the far backswamp areas during dry periods but pumping is an important factor in its transport.

The sequence of a dry period, for oxidation, and a wet period, for transport of oxidation products, corresponds well with observations of the timing of fish kills in the River. Furthermore, it has been observed that fish kills are more severe, and flocculation more widespread, when wet periods follow prolonged dry periods. This may be related to the extent of oxidation that occurs in the subsoils during the dry periods.

To ensure survival of the sugar cane crops, the drainage system and pumping by the farmers allows removal of surface water within several days. The Tweed River has a relatively small catchment and the flood peak passes rapidly. Incidents of river degradation, as shown by fish kills and flocculation, occur during the latter part of the flood recession, usually about five to seven days after the flood peaks. This is the time when drain water egressing from canefields contains high concentrations of pyrite oxidation products but, at this time, the River is predominantly freshwater rather than seawater. The oxidation products are therefore being discharged to the River when its water has low buffering capacity and when flow rates are well below their peaks. Fish kills in the River may follow a combination of large inputs of pyrite oxidation products and aluminum from cane field drains, with low buffering capacity in the river water and when it has low dilution capacity.

Another factor affecting the likelihood of fish kills is the timing of the inputs of acidic water in relation to the tide at the time. It appears that some fish species and age classes are able to escape from the approaching acidic water, whereas others are trapped and killed.

Episodic inputs of acidity to freshwater systems, as well as chronic acidity, have marked effects on fish survival, breeding and non-lethal effects such as reduced feeding rates (McCahon et al. 1989). In some flood events in the Tweed River, such as those in 1987 described by Easton (1989), a large proportion of the total fish population and benthos organisms (such as crustaceans and annelids) were killed in up to 15 km of the River. The longer term impact on the estuary ecosystem has not been determined. However, the series of floods in 1987 and associated fish kills almost certainly precluded recruitment of many offshore-dwelling fish species as well as killing the fish and benthos species which live in the estuary. In periods with less extreme flooding than 1987, up to 20 per cent of fish caught by commercial fishers was rejected because of lesions caused by epizootic ulcerative syndrome (C. Copland, NSW Fisheries, personal communication).

Although the flap gate and pumping systems used in the study area and elsewhere on the eastern coast of New South Wales have been effective in flood control, there is now evidence that they are allowing oxidation of pyritic subsoils and contributing to the degradation of estuaries and fisheries. Further work is underway to relate the management of the drainage systems to its effects on the estuaries and fisheries with the aim of devising practices which reduce the impact of the escape of acidic water whilst maintaining adequate water control for sugar cane production.

Acknowledgements

This work received financial support from the CSIRO-University of NSW Collaborative Research Funds and the Australian Research Council.

References

Callinan R.B., G.C. Frazer and M.D. Melville 1993. Seasonally recurrent fish mortalities and ulcerative disease outbreaks associated with acid sulphate soils in Australian estuaries. In: D.L. Dent and M.E.F. van Mensvoort (editors). Selected papers of the Ho Chi Mhi City symposium on acid sulphate soils. Publication 53, 403-409 International Institute for Land Reclamation and Improvement, Wageningen

Driscoll T.D., J.P. Baker, J.J. Bisogni and D.L. Schofield 1980. Effect of aluminum speciation on fish in dilute acidified waters. Nature, 284: 161-164

Easton C. 1989. The trouble with the Tweed. Fishing World, March 1989. pp. 58-59

McCahon C.P., A.F. Brown, M.J. Poulton and D. Pascoe 1989. Effects of acid, aluminum and lime additions on fish and invertebrates in a chronically acidic Welsh stream. Water, Air, and Soil Poll., 45: 345-359

McCormick J.H., K.M. Jensen and L.E. Anderson 1989. Chronic effects of low pH and elevated aluminum on survival, maturation, spawning and embryo-larval development of the fathead minnow in soft water. Water, Air and Soil Poll., 43: 293-307

Willett I.R. 1989. Direct determination of aluminum and its cationic fluoro complexes by ion chromatography. Soil Sci. Soc. Am. J., 54: 1385-1391

Willett I.R. and G.M. Bowman 1990. Acid sulfate soil conditions near flood mitigation drains of the lower Macleay River. CSIRO, Australia, Report to Kempsey Shire Council

Willett I.R., M.D. Melville and B.N. Noller 1989. Acid sulphate soils research in Australia. Acid Sulphate Soils Newsletter, 2: 2-3

Willett, I.R. and P.H. Walker 1982. Soil morphology and distribution of iron and sulphur fractions in a coastal flood plain toposequence. Aust. J. Soil Res., 20: 283-294