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Spatial variability of acid sulphate soils in the Plain of Reeds, Mekong delta, Vietnam

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Abstract

At all scales (delta-wide to individual fields) the acid sulphate soils of the Mekong delta show high spatial variability and closely intertwined soil types. Focusing on the field level in the Plain of Reeds, clear correlations are observed between soil physical and chemical characteristics, natural vegetation, groundwater table and microelevation. On ''high'' locations (higher than 85 cm above mean sea level), Typic Sulfaquepts are covered with *Ischaemum spp*. (grass). Highly organic and hydromorphic Hydraquentic Sulfaquepts are found in ''low'' locations (lower than 75 cm above mean sea level), where *Eleocharis spp.* (reeds) are dominant. In between, soils and vegetation present intermediate characteristics. These correlations, the high spatial variability and the soil patterns are explained by soil genesis. Because of longer and stronger evaporation on high locations as compared with low locations, small differences in elevation can lead to important differences in water table level and therefore redox condition. Over long periods, these differences greatly influence soil development and thus, soil types. Hydraquentic Sulfaquepts can be considered at an intermediate stage of development and are expected to develop into Typic Sulfaquepts upon further drainage. Rice growth is strongly influenced by soil characteristics and redox conditions. As a consequence, rice yields are correlated with microelevation. Correlations between elevation, soil characteristics and natural vegetation can facilitate mapping of these highly variable soils. Integration of soil and water variability in the research programmes and use of adapted

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methods not only increase research efficiency but also make it possible to use this variability to better understand soil genesis and agronomic processes.

Keywords: spatial variability; acid sulphate soils; Vietnam; elevation

1. Introduction

Worldwide, acid sulphate soils are estimated to cover 24 million hectares, mostly in coastal and river plains in South East Asia. (Van Mensvoort and Dent, 1997). In the Plain of Reeds, a depression located in the northern part of the Mekong delta, Vietnam, extensive tracts of acid sulphate soils (400 000 ha) are found. In 1992, one third of this area was still uncultivated, especially where acid conditions are most severe, but because of the high population pressure, these soils are being reclaimed for agricultural use.

Acid sulphate soils pose serious physical, chemical and biological problems (Dent, 1986). Oxidation of the pyrite leads to acidification and aluminium toxicity, while iron and hydrogen sulphide toxicity can be expected in case of any subsequent reduction. Crop performance on recently reclaimed acid sulphate soils depends on management techniques and soil characteristics. Therefore, it is important to develop and transfer to farmers agronomic practices that are adapted to the specific soil characteristics. However, technology development, technology transfer, and also land-use planning are made difficult by the very high spatial variability of these acid sulphate soils. Methodological problems are raised by (i) the high short-range variability of these soils, and (ii) the fact that variability shows at various scales.

Geostatistical tools make it possible to assess the optimal mapping scale in relation to variability, and allow us to present the uncertainty in the information by mapping conditional probabilities of exceeding a specified critical threshold (Bregt, 1992; Ahmed and Dent, 1996). Sylla (1994) conducted a multi-scale agro-ecological characterisation of mangrove ecosystems in West Africa, distinguishing different environments based on criteria adapted to the scale (from West Africa region to catena), but the short-range variability was not addressed in this survey and the variability at very small distance was reduced by bulking samples. This absence of characterisation of short-range variability is not an exception (Wilding and Drees, 1978). Although short-range variability of acid sulphate soils has been recognised (Bos and Van Mensvoort, 1983; Burrough et al., 1988; Bregt, 1992), agronomic research has ignored it, leading to inappropriate design of field experiments and errors in analyses (Van Mensvoort, 1996).

However, characterisation of significant variability in acid sulphate soil areas is not easy. Within the dynamic environments of flood plains and wetlands, patterns of soil texture, ripeness and, above all, acidity or potential acidity are not always clearly expressed by surface patterns. Furthermore, because each locality has a unique history, establishment of the relationships between landform and soil profile morphology, and between morphology and the key physical and chemical characteristics has to be undertaken independently in each locality (Van Mensvoort and Dent, 1997).

The objectives of this study are:

1. to characterise acid sulphate soil variability in the Plain of Reeds with special attention to short-range variability (intra- and inter-field levels, i.e. distances between 10 m and 2 to 3 km) of soil characteristics which can influence plant growth,
2. to explain this variability across the scales, and
3. to identify criteria that can be used for identification and characterisation of the different soil and cropping conditions in the Plain of Reeds.

2. Methods and study area

2.1. Study area

A multi-scale approach (Fresco, 1995) was applied for this study. Scaling down from the Mekong delta to the Plain of Reeds made it possible to identify a village representative of agro-ecological conditions where very detailed soil and water characterisation could be conducted. After validation of major results obtained at this level elsewhere in the Plain of Reeds, scaling up becomes possible.

At all scales, the various maps of the Plain of Reeds and the Mekong delta (Agro-Ecological Map of the Mekong Delta by NIAPP (1987) at scales 1:2 500 000 and 1:250 000; Map of land constraints to farming in the Mekong delta by Van Mensvoort et al. (1993) at scale 1: 2 500 000; Atlas of the Plain of Reeds at scale 1:250 000 by the National Centre for Scientific Research (1990); Soil Map of the Plain of Reeds by NIAPP at scale 1:100 000 (1985) and Soil Map of Tan Thanh District by Can Tho University (1994) at scale 1:25 000) show soil types that are intertwined in patches and stripes, and the variability within mapping units remains very high.

The representative village (Tan Lap, in Tan Thanh District) is located in the central part of the Plain of Reeds, encompassing the western ‘‘high’’ part of the Plain, dominated by Typic Sulfaquepts and Sulfic Tropaquepts, and the low Bac Dong depression, to the East, with important areas of Hydraquentic Sulfaquepts (Fig. 1). The study area was chosen on the non-saline, severely acid Typic Sulfaquepts and Hydraquentic Sulfaquepts as they represent 180 000 ha, i.e. 45% of the area covered by acid sulphate soils in the Plain of Reeds (National Centre for Scientific Research, 1990). At the beginning of the survey, the area was still uncultivated.

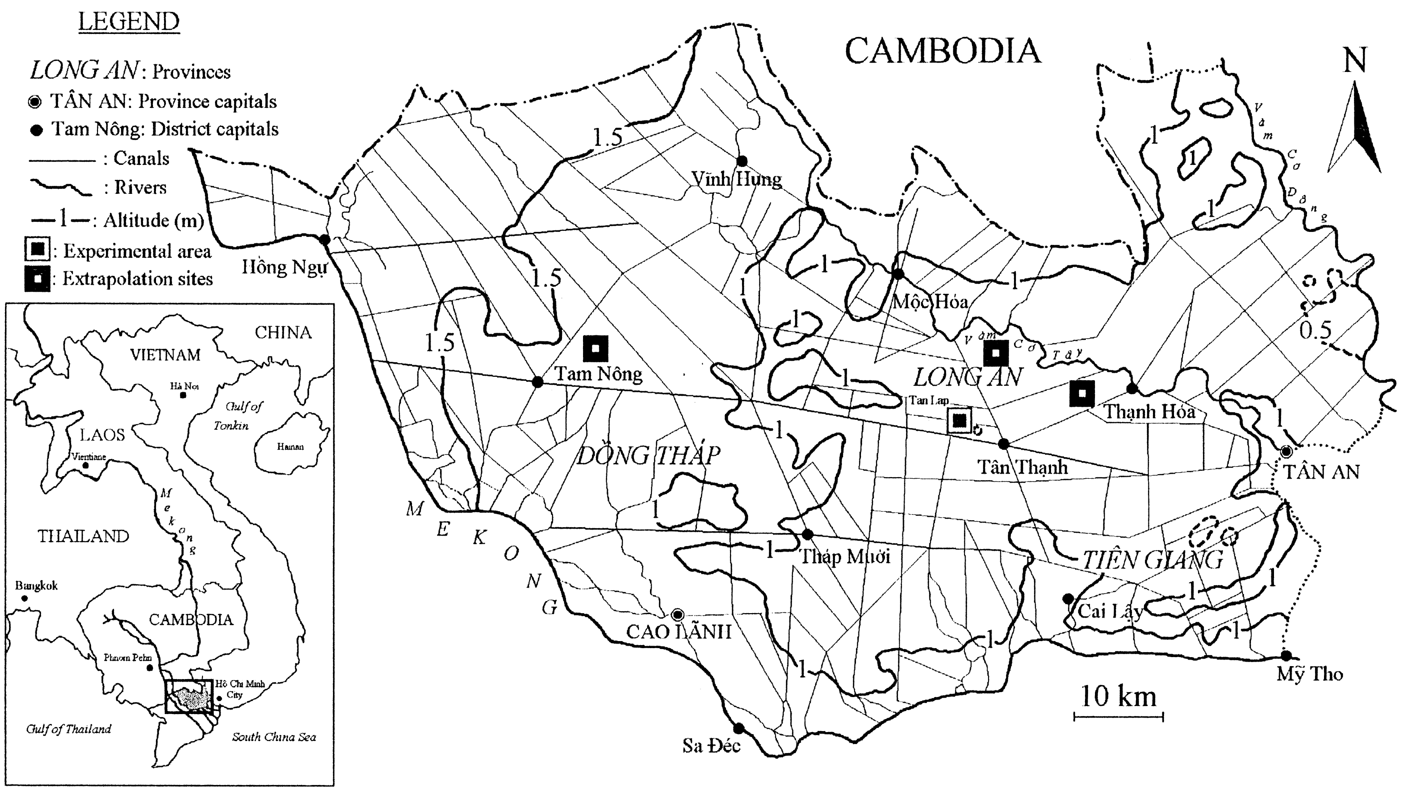

Fig. 1. Topographic map and location of study areas in the Plain of Reeds, Mekong delta, Vietnam.

The area enjoys a warm monsoonal climate, with a marked dry season (December to April) and a rainy season (May to November) with a total rainfall of about 1500 mm/year. High levels of rainfall in combination with high discharges of the Mekong river cause inundation of the land from July/September until December/February. In Tan Lap, inundation depth and duration are intermediate for the Plain of Reeds (about 1 m and 6 months), but vary from year to year.

In the study area, the canal network and water quality also present intermediate characteristics: the canal system has an average network density. There are more canals, thus better water quality than in the Bac Dong area towards the East, but fewer canals than in areas closer to the Mekong River in the West, where there is less acidic water throughout the year.

2.2. Data collection

Soil descriptions presented here are the result of a survey conducted in February–March 1994, at the end of the dry season (Verburg, 1994). Soils were classified according to Soil Taxonomy (Soil Survey Staff, 1996). On fallow land, 138 profiles were observed in auger holes in two transects of respectively 300 and 400 m length with approximately 5 m between augerings. Detailed soil profiles with chemical and physical analyses were made in three representative sites. Detailed soil maps of experimental fields were made before reclamation by augerings in 10 × 10 m (for fields in which experiments were conducted) or 25 × 25 m grids (for fields where farmer practices were monitored), with additional profiles when vegetation or topography suggested soil differences. All these observations (over 500 soil augerings and 20 detailed profiles and soil analyses) are in agreement with the measurements made in the two transects.

Hydraulic conductivity was measured using the falling-head method (Black et al., 1965). Given values are averages of three replicates with 20-cm-long cylinders, 15 cm in diameter. EC, pH and Eh were measured with field pH/Eh and EC-meters.

Elevation was measured with a theodolite and calibrated to mean sea level on a reference point given by the Long An Province Hydraulic Services. Precision of measurements is estimated to be 1 to 2 cm within a field, and 2 to 3 cm between fields.

Aluminium concentration was determined by titration with dilute sulphuric acid with phenolphthalein as indicator, after complexation by NaF (Page et al., 1982). Ferrous and total iron were determined by colorimeter with *o*-phenanthroline as colouring agent. Hydrochloric and boric acid were added to samples to bring pH below 2 and create conditions that prevent fast oxidation or reduction. Total actual acidity and total potential acidity were measured as proposed by Konsten et al. (1988). Sulphates were determined by spectrophotometry at wavelength of 420 nm. (Page et al., 1982).

One day per week, water level was measured every hour in the secondary canal (6 m wide) in the study area.

2.3. Data analysis

Data were analysed at field level by means of scatter plots, multiple linear regressions and spatial statistics methods. Semi-variance analyses were made using GEO-EAS V. 3 software. Drawing the semi-variance of soil properties over a range of distance separations provides a description of the spatial relationships between any two points. These relationships can be used for prediction of values at unsampled locations and maps improvement. Maps of field characteristics have been made using kriging techniques (Isaaks and Srivastava, 1989).

3. Results

3.1. Soil types

3.1.1. ‘‘High’’ parts

On the highest parts with an elevation higher than 85 cm above mean sea level, soils are characterised by a ripe greyish brown (10YR5/2) sulphuric horizon with yellow brown and pale yellow mottles of respectively goethite and jarosite. Most often, the yellow brown goethite mottles are underlain by the pale-yellow jarosite mottles. The mottling abundance is greatest at highest locations. Around 85 cm above mean sea level, goethite and jarosite mottles are sometimes replaced by brown to dark brown (10YR4/3) mottles of organic matter fragments. At a depth of 1 m, the soil is permanently reduced, the organic matter content increases, wood remnants can be found and the colour is very dark grey (10YR3/1) to black. Below this level (1.25 m from surface) more fibrous organic matter without wood remnants can be found. The dark brown (7.5YR3/2 or 10YR4/3) colour turns black within a few minutes upon exposure to the air. The sulphuric horizon has a prismatic structure and many vertical old-root channels. Organic matter content is given for the various horizons in Table 1. At the driest period of 1994, the sulphuric horizon with jarosite mottles had a pH 2.8–3.0 and Eh varied from 590 to 670 mV. This soil is classified as a Typic Sulfaquept.

3.1.2. ‘‘Low’’ parts

When the land elevation is lower than about 75 cm above mean sea level, soils have a sulphuric horizon but without jarosite or goethite mottles. The sulphuric horizon has a brown (10YR5/3) matrix colour with brown to dark brown (10YR4/3) mottles, the colour of chestnut purée (‘‘beurre marron’’) as

Table 1
Organic matter content of three profiles

Typic sulfaquept (92 cm above m.s.l.)		Typic sulfaquept intermediate (80 cm a.m.s.l.)		Hydraquentic sulfaquept (70 cm above m.s.l.)	
Horizon	Organic matter content (dag kg^{-1})	Horizon	Organic matter content (dag kg^{-1})	Horizon	Organic matter content (dag kg^{-1})
Ah1	19.4	Ah1	15.9	Ah1	16.2
Ah2	10.2	Ah2	10.5	Bh	17.9
Ah3	5.3	AB	4.2	Cr	22.7
AB	3.1	Bjg	3.6		
Bg	3.0	Bj	3.8		
Bjg	3.7	Cr1	7.4		
Cr1	6.9	Cr2	16.1		
Cr2	7.3				

described by Marius (1984). In the lower part of the sulphuric horizon, very dark grey (10YR3/1) mottles can also be found. The subsoil contains a high percentage of fibrous organic matter without wood remnants. The dark brown (7.5YR3/2 or 10YR4/3) colour turns black within a few minutes upon exposure to the air. Structure development is weak and already at shallow depth the soil is unripe (a ‘‘buttery’’ consistency). Many recent root channels of *Eleocharis dulcis* reeds penetrate the sulphuric horizon. Organic matter content is very high in all horizons: from 16 to 23% by mass (Table 1). This high organic matter content and the lower topographic position probably explain the low Eh observed, even at the driest period of the year: Measurements in the sulphuric horizon conducted in 1994 a few days after the lowest watertable level of the year indicated Eh between 130 and 380 mV, pH from 3 to 3.2 and high ferrous iron concentrations (150–400 ppm). In the USDA Key to Soil Taxonomy (Soil Survey Staff, 1996), this soil type is classified as Hydraquentic Sulfaquept.

3.1.3. Transition zone

Between the high and low parts, a transitional type of soil can be characterised by a sulphuric horizon consisting of two parts. The upper part has mottling of goethite and/or jarosite. The lower part resembles the sulphuric horizon in the low parts and is not ripe. The subsoil is rich in fibrous organic matter (16% by mass). This soil is classified as Typic Sulfaquept.

3.2. Short-range variability of acid sulphate soils

Soil surveys conducted before land reclamation showed that soils with very different characteristics could be found at very close distances (10 to 20 m). Geostatistical analysis on parameters such as depth to pyrite or jarosite, or

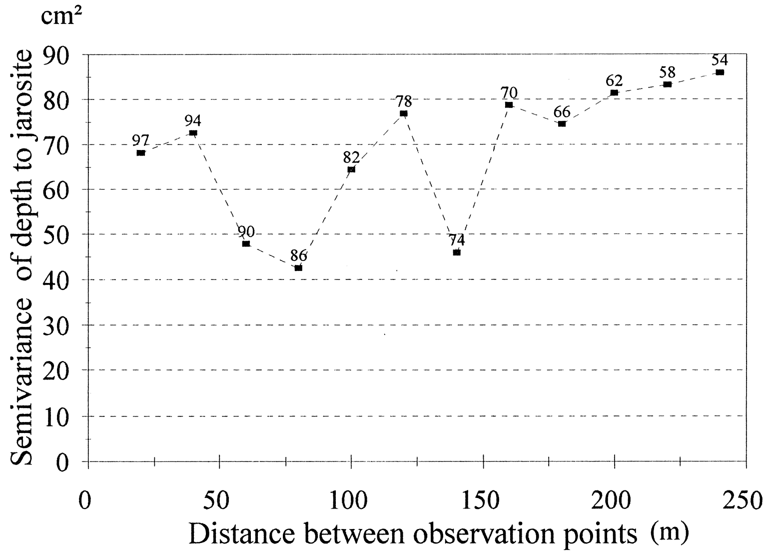

Fig. 2. Example of unidirectional semivariogram of depth to jarosite in the study area. Values indicate number of pairs for calculation.

presence/absence of jarosite showed variations at very short range (sometime less than 10 m), with a high anisotropy and a strong nugget effect (data not

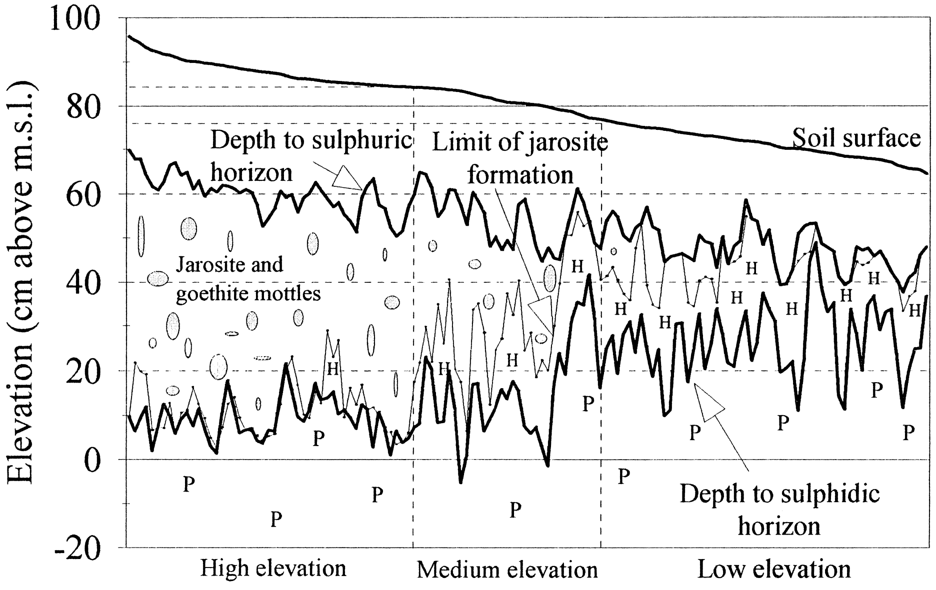

Fig. 3. Cross section of 138 soil profiles observed in two transects and expressed by decreasing elevation (in cm above mean sea level). Moving average of period 3. H indicates fragmentary organic matter. P indicates pyrite.

displayed). Semi-variograms are often trended, or cyclic (Fig. 2), suggesting a rippled and undulating pattern, probably reflecting the relationship between soil characteristics and microelevation.

3.3. Microtopography and soil characteristics

3.3.1. Soil profiles, water table and topography

The correlation between soil and microelevation is schematically shown in a cross-section (Fig. 3) based on 138 profiles observed on fallow land and sorted according to their elevation. On this graph, a transition between Typic Sulfaquepts and Hydraquentic Sulfaquepts is observed around 80 cm above mean sea level. The thickness of the sulphuric horizon is correlated to the microelevation. In high locations, a thicker, riper sulphuric horizon continues to greater depth, reflecting deeper and longer oxidation than in the low, waterlogged parts. This deeper and longer oxidation in high locations has been confirmed by measurement of the watertable level in piezometers during the dry season. The water table decreases faster and is lower in locations of a high topographic position than in those at low level (Fig. 4). As a consequence of this difference in oxidation, the depth to the sulphidic material is lower in low positions.

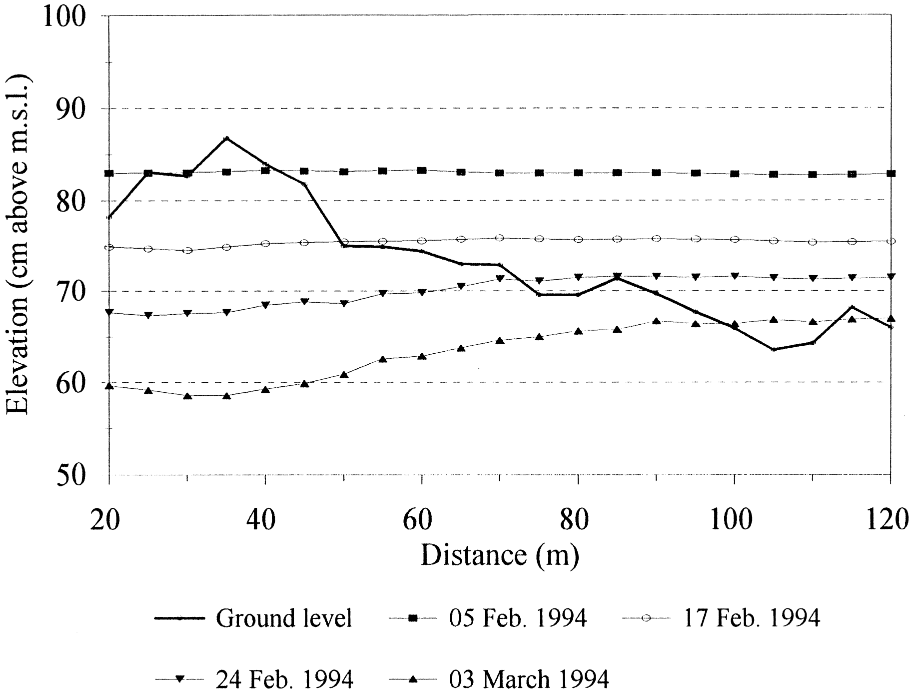

Fig. 4. Time series of water table level in relation to microelevation (adapted from Bil, 1994).

Another consequence is that soil maps are correlated to topographic maps at all scales. This can be observed over the Plain of Reeds where the proportion of Typic Sulfaquepts decreases from West to East, with a lower elevation. Fig. 5a and b show the relationship between soil and elevation at field level in the study area.

3.3.2. Vegetation and topography

On fallow land, natural vegetation can be used as an indicator of microelevation and soil types. Two main species are present in the area. On low parts, where highly organic soils are found, Eleocharis dulcis (reeds) dominates while high parts are mainly covered with *Ischaemum rugosum* grass (Fig. 6). Visual estimation of percentage of *Ischaemum* and *Eleocharis* was done on 1 m^2 plots, but R^2 is rather high at 0.58.

3.3.3. Soil physical characteristics and topography

Hydraulic conductivity was measured on fallow land in the survey area. Values were high and strongly variable, which can be explained by bypass flow

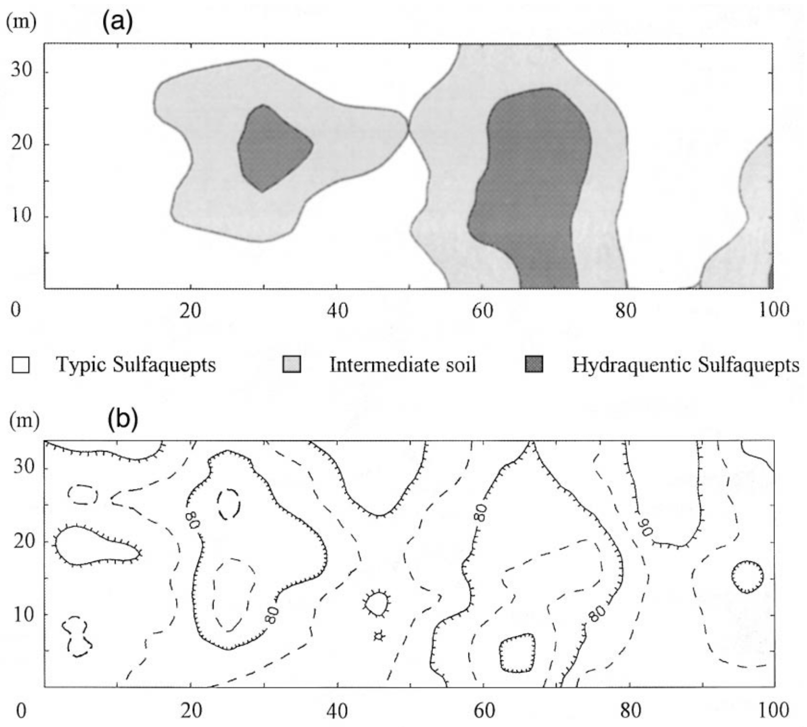

Fig. 5. (a) Soil map of experimental field no. 35. (b) Topographic map of experimental field no. 35. Contour intervals in cm.

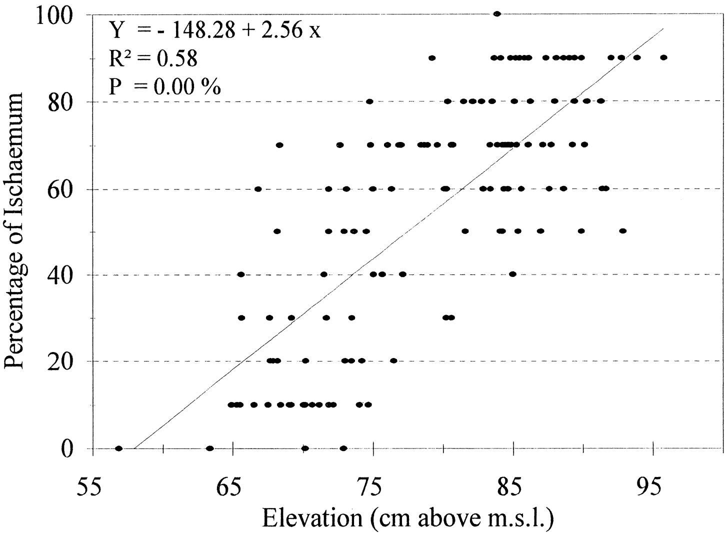

Fig. 6. Correlation between microelevation and percentage *Ischaemum rugosum* in vegetation.

through cracks. Hydraulic conductivity varies with horizons and microelevation. Surface horizons of Typic Sulfaquepts have a higher conductivity (> 5 m/day) than those in Hydraquentic Sulfaquepts, but in the C horizon the situation is reversed (Table 2).

These soils show another difference when cultivated. Through intensive land preparation, an impermeable plough pan is created which can be felt when walking in the fields. It develops rapidly in soils on high topographic positions (Typic Sulfaquepts), but very slowly on low Hydraquentic Sulfaquepts.

3.3.4. Soil chemistry and topography

Chemical characteristics of the topsoil, which influence crop growth, are correlated to elevation, especially in the dry season. Fig. 7 gives exchangeable ferrous iron, extractable aluminum, soluble sulphates, EC, and pH measured in April 1995 in a recently reclaimed field, as a function of microelevation. At that time, sulphates, aluminium and EC increase with elevation, while ferrous iron and pH decrease when elevation increases.

Table 2
Vertical hydraulic conductivity (m/day) in acid sulphate soil horizons (average of three replications)

Horizon (soil type)	Typic sulfaquept	Intermediate	Hydraquentic sulfaquept
A	5.3	11.0	1.4
B	2.5	1.6	0.4
C	0.8	1	1.6

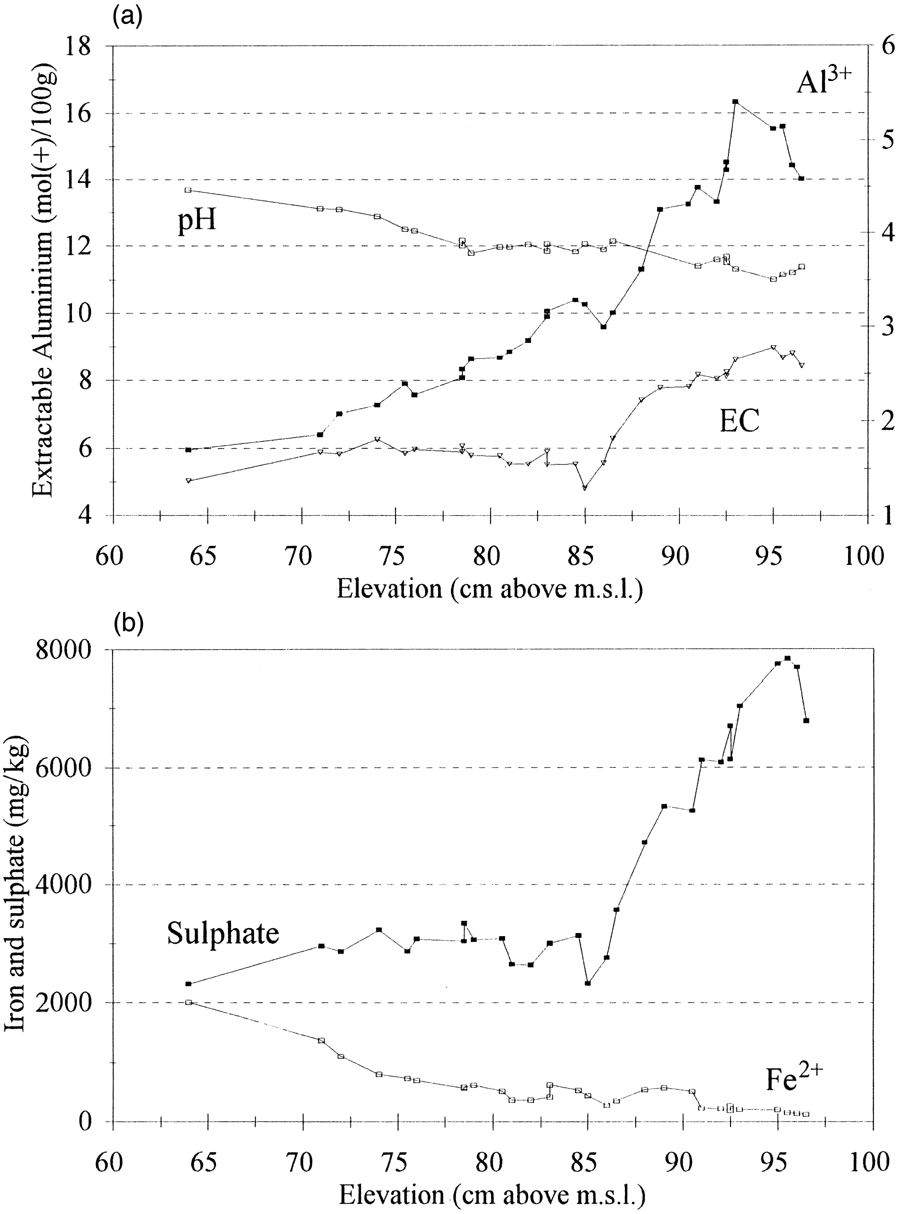

Fig. 7. Chemical characteristics of topsoil as a function of microelevation. Moving averages of period 3. (a) pH, EC (mS/cm) and extractable aluminium (mol(+)/100 g). (b) Sulphates (mg kg^{-1}), ferrous iron (mg kg^{-1}).

Elevation not only affects topsoil characteristics but, also, those of deeper horizons. The total sulphidic acidity of two soil profiles in the Plain of Reeds is presented in Table 3. The Typic Sulfaquept has lost most of its potential acid

Table 3
Total sulphidic acidity (mmol(+)/100 g) of two different soil profiles

Typic sulfaquept			Hydraquentic sulfaquept		
Horizon	Depth	Total sulphidic acidity	Horizon	Depth	Total sulphidic acidity
Ah	0–30	58.1	Ah	0–12	95.6
Bg	30–62	18.3	AB	12–23	72.2
Bjg	62–70	19.7	Bh	23–59	290.6
C1	70–88	28.1	C2	59–72	512.8
C2	88–107	162.2	C3	72–120	692.3
C3	107–120	325.3			

substances up to a depth of 85 cm from the surface. The sulphuric horizon without jarosite (Bh) of the Hydraquentic Sulfaquept still contains potentially acid substances, although less than the underlying sulphidic materials.

3.4. Soil spatial variability and rice cultivation

3.4.1. Microelevation and rice yield

Soil spatial variability has a very strong impact on rice yield in the years following land reclamation. In the Plain of Reeds, rice yield is correlated with microelevation. In 83% of the 61 farmers' fields studied between 1992 and 1996, significant correlation between microelevation and rice yield was observed (Husson et al., 1997a). Within-field variability of rice yield can be dramatic, as shown by the very high coefficient of correlation measured (up to 150 kg/ha/cm). The correlation between rice yield and microelevation is usually quadratic (Fig. 8), but can be linear in low fields sown too early (positive linear correlation between yield and elevation) and in high fields sown too late or poorly irrigated (negative linear correlation).

Between fields, correlation between average yield and mean field level is also observed. The lower Hydraquentic Sulfaquepts are the most difficult soils to reclaim.

3.4.2. Depth to jarosite and rice yield

An important criterion often used for classification of acid sulphate soils is the depth to jarosite. However, relation between depth to jarosite and plant growth seems weak. In our study area of the Plain of Reeds no significant difference could be observed on yield of rice grown on Typic Sulfaquepts and Sulfic Tropaquepts when depth to jarosite varied from 30 to 70 cm, i.e. 20 cm on each side of the threshold value of 50 cm used when classifying acid sulphate soils. On the other hand, considerable differences in soil characteristics and rice

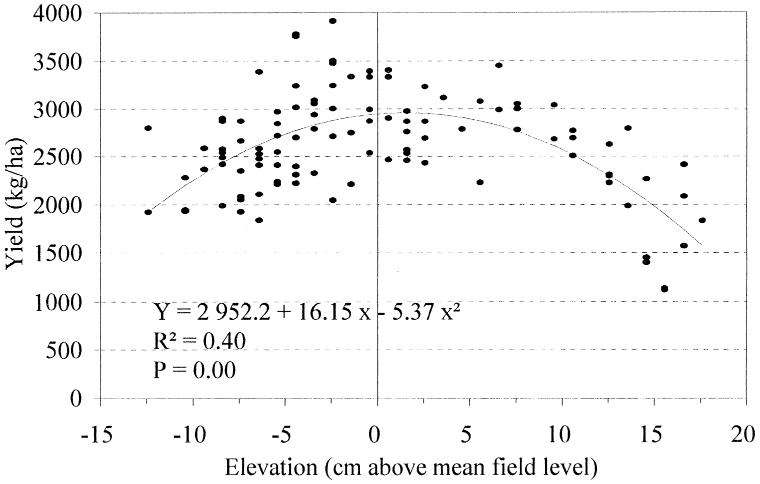

Fig. 8. Rice yield (kg/ha) as a function of microelevation. Field representative of 61 experimental fields cultivated between 1992 and 1996 ($n = 108$).

yield have been observed, and explained, in relation to the presence or absence of jarosite.

4. Discussion

4.1. Water table level and topographic level

Measurements of the water table along two transects indicate that the groundwater level in the dry season remains higher in the lower parts of the area (Fig. 4). Differences in ground water table at short distance can be maintained due to relatively low horizontal saturated hydraulic conductivity in these particular soils (0.5 to 1 m/day). The yearly lowest water table is mainly determined by the duration of the dry period, when water entering the soil (from rain and tidal irrigation through small canals and creeks) does not compensate for losses by evapo-transpiration and drainage (Bil, 1994). The length of this period is mainly determined by topography, in the two ways found below.

- Flood water recedes by natural drainage, at the end of the rainy season. High locations emerge first. Highest soils, at 100 cm above mean sea level, dry out 30 to 60 days earlier than soils only 30 cm lower. This water recession below the soil surface increases the rate of fall in groundwater level with a factor 5 to 10 compared to a fall caused by evaporation only.
- During the dry season, low places regularly receive water through tidal movements in rivers, creeks and canals (Fig. 9). Soils higher than 85 cm above mean sea level are too high to benefit from these water movements in the dry

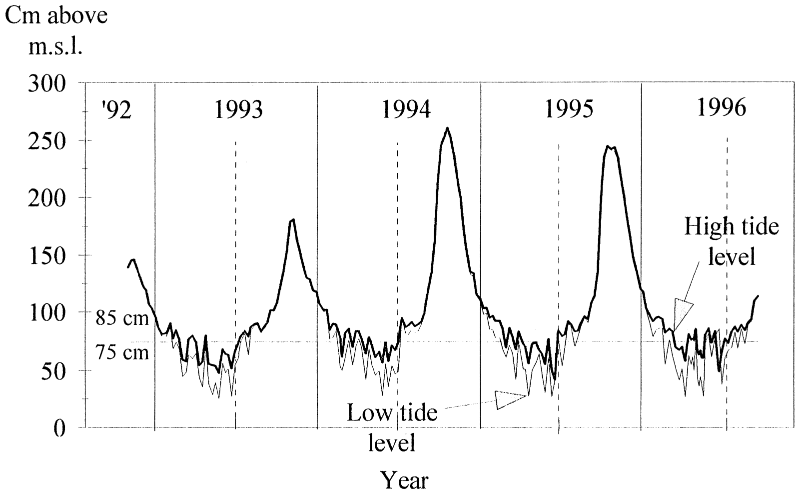

Fig. 9. Water level at low and high tides in secondary canal of the study area, 1992–1996.

season, whereas below 75 cm soils never stay more than 30 days without flooding by tides.

4.2. Hypothesis of soil genesis: the development of Hydraquentic Sulfaquepts into Typic Sulfaquepts

Oxidation products of pyrite are a function of pH and redox conditions. Where the pH remains above 4, iron III oxides and hydroxides precipitate directly by oxidation of dissolved iron II, derived from initial oxidation of pyrite (FeS_2). The net result of pyrite oxidation can be expressed as:

$$FeS_2 + 15/4\,O_2 + 7/2\,H_2O \Rightarrow Fe(OH)_3 + 2\,SO_4^{2-} + 4\,H^+$$

Under strongly oxidising, severely acid conditions (Eh greater than 400 mV, pH less than 3.7), characteristic pale yellow deposits of jarosite ($KFe(SO_4)_2(OH)_6$) precipitate as pore fillings and coatings on ped faces (Dent, 1986).

In the Plain of Reeds, soils in low locations, which are waterlogged most of the time, have a parent material characterised by a high content of organic matter with a fibrous structure, and a brown to dark brown matrix (10YR5/3 or 10YR4/3). Field observations lead us to believe that this organic matter with its spongy structure helps keeping the soil almost saturated most of the time. In these conditions, it is probable that oxidation is slow as oxygen diffuses slowly in water-saturated sediments, while microbial decomposition of organic matter keeps the redox potential low. Upon (partial) drainage, the Eh rises to a level, which permits the oxidation of sulphide to sulphate, but not the oxidation of ferrous iron. Occasional measurements indicate that in the study area the redox potential stays below 400 mV in the oxidised sulphuric horizons without goethite/jarosite. In these conditions, oxidation of pyrite occurs according to:

$$FeS_2 + 7/2O_2 + H_2O \Rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^-$$

and jarosite cannot be formed (Van Mensvoort and Le Quang, 1988).

Upon prolonged oxidation of the organic sulphuric layer without goethite/jarosite, organic matter will further decompose and the redox potential will increase slowly. At a certain moment, jarosite will be formed in the most oxidative places, i.e. around root channels, while the matrix still contains the brown organic matter mottles. This is the intermediate soil type observed at medium elevation. Further drainage and oxidation will lead to further mineralisation of organic matter, and the brown matrix will turn into a greyish brown (10YR5./2) while more jarosite will precipitate.

Therefore, it appears that Hydraquentic Sulfaquepts develop into Typic Sulfaquepts and that the brown ‘‘beurre marron’’ horizon is only an intermediate stage which will develop into a sulphuric horizon with jarosite and goethite upon prolonged drainage (as also postulated by Dent, 1986).

4.3. Factors explaining the large short-range variability of soils in the Plain of Reeds

Van Mensvoort and Le Quang (1988) reported occurrence of extensive tracts of acid sulphate soils without goethite or jarosite mottles in the north-west of the Mekong delta. A striking feature of the Plain of Reeds is that soils with and soils without goethite and/or jarosite mottling are found close to each other. The occurrence of these two soil types in the same area has been explained mainly by redox conditions, which are greatly influenced by the relative soil/water level.

Now, two factors cause the redox potential to be extremely variable. The first one is the sensitivity of the water table level to the soil microelevation. Small differences in elevation lead to great differences in oxidation and mineralisation, and as a consequence to considerable differences in soil development. Furthermore, the redox potential varies greatly on each side of a threshold topographic level. The second cause of high variability in the Plain of Reeds is that this threshold topographic level happens to be the mean level of soils. This threshold is often crossed, leading to the high short-range variability observed in the fields.

4.4. Soil patterns

Bos and Van Mensvoort (1983) and Burrough et al. (1988) in the Mekong delta, and Ahmed and Dent (1996) in The Gambia related the cyclic soil pattern they observed to tidal creeks. In the Plain of Reeds, the system of creeks and banks of mangrove environments in which pyrite develops is reflected in the microtopography of the area, and as a consequence of the strong impact of elevation on soil formation, in the pattern of soil types. This pattern explains the non-stationarity and the anisotropy of soil characteristics in the study area. It also explains that variograms observed in this area are trended or cyclic (Fig. 2), and that soil maps at all scales (1:2 500 000 to 1: 2000) resemble one another, with closely intertwined soil patterns evoking former river branches, creeks and depressions.

5. Conclusions and recommendations

Geostatistics are problematic in soils varying so strongly at short distance, as in the Plain of Reeds. However, once variability has been explained and correlations established, simple mathematical tools as multiple regressions and covariance analysis are helpful in explaining variability.

5.1. Mapping

Mapping can be eased by the use of correlations between microelevation, soil characteristics and natural vegetation. As this vegetation still covers about 100 000 ha of severely acid sulphate soils in the Plain of Reeds and differences between plant covers can be observed on aerial photographs and satellite images, these field relationships can be used to produce precise mapping of wide areas at low cost.

5.2. Control and use of variability for agronomic research

The high variability of acid sulphate soils can cause dramatic variability of crop yields, greatly perturbing experiments when intra-treatment variability is higher than inter-treatment differences. The detailed characterisation and understanding of field-scale variability can be used to integrate variability of soils and water factors into the design and implementation of experiments. In our case, careful location of experiments in long and narrow plots (7–10 × 100–150 m) crossing heterogeneities and use of covariance analysis with microelevation as covariate greatly reduced CVs. It proved to be a highly efficient tool to take into account and control the high short-range variability of acid sulphate soils (Husson et al., 1997b).

5.3. Extension of results

Understanding the soil–water–plant interactions leads to a simple distinction between fields at ‘‘low’’ (lower than 75 cm above mean sea level), ‘‘medium’’ (between 75 and 85 cm above mean sea level) and ‘‘high’’ (higher than 85 cm above mean sea level) elevation. This distinction makes it easy for every farmer in the Plain of Reeds to classify his field as high, medium or low and thus adapt his cultural practices.

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