SPATIO-TEMPORAL VARIABILITY OF ACID SULPHATE SOILS IN THE PLAIN OF REEDS, VIETNAM

Impact of soil properties, water management and crop husbandry on the growth and yield of rice in relation to microtopography

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Proefschrift
ter verkrijging van de graad van doctor
op gezag van de Rector Magnificus
van de Landbouwuniversiteit Wageningen,
Dr. C.M. Karssen,
in het openbaar te verdedigen
op vrijdag 11 september 1998
des namiddags te half twee in de Aula.

“Tram nghe không bàng môt thây”

“Listening one hundred times does not worth watching one time”

“Tram thây không bang môt lân thuc hành”

“Watching one hundred time does not worth doing one time”

STELLINGEN

1. As early as 1928, V. Delahaye stated that : "Toute étude de la Plaine des Joncs, étude géographique d'ensemble, étude de sa mise en valeur, suppose une connaissance précise de son nivellement et de sa cartographie". Unfortunately, this recommendation remained unused for over 60 years.

   Delahaye, V. (1928). La Plaine des Joncs (Indochine française) et sa mise en valeur. Impri. Ouest -Eclair, Rennes, France

2. Although found at very close range, Typic and Hydraquentic Sulfaquepts have very different properties, raise opposite agronomic problems and require opposite water management strategies.

   This thesis

3. Most recommendations for cultivation of acid sulphate soil are based on good water management. When water control is poor, as is common, these recommendations are useless. A more realistic approach consists in identifying the most favourable sowing period to cultivate when cropping conditions are optimal.

   This thesis

4. In the Plain of Reeds, farmers take very high risks. In such a situation, researchers should not try to express risks in term of an arbitrary threshold level, but should aim at rapidly providing farmers with recommendations adapted to their specific field conditions and reduce the risk they will always have to take.

   This thesis

5. Farmers in the Plain of Reeds rapidly and successfully reclaimed extensive areas of severely acid sulphate soils when most scientists thought it was not feasible nor recommendable. It shows that once again, indigenous knowledge has been underestimated and underused by scientists.

   This thesis

6. It seems to take long before the recommendation of Bart de Steenhuijsen Piters (1995) to "treat variation as an object of research, instead of as a statistical residue, in order to determine its objective importance and to derive essential information from it" will be commonly acknowledged, and that research sites will be selected for their high heterogeneity rather than for their relative homogeneity.

   De Steenhuijsen Piters, B. (1995). Diversity of fields and farmers. Explaining yield variations in northen Cameroon. PhD thesis, WAU. The Netherlands.

7. Fifteen years ago, Preece stated that biometry in the third world was often a ritual more than a science. This is still true, and not only for the developing countries.

   Preece, D.A.(1984). Biometry in the third world: science, not ritual, in Biometrics, 40, pp. 519-523.

Spatio-temporal variability of acid sulphat soils in the plain of reeds, Vietnam. Impact of soil properties, water management and crop husbandry on the growth and yield of rice in relation to microtopography. Olivier HUSSON. 1998. Ph.D. Thesis. Wageningen Agricultural University, The Netherlands.

8. Scientists should not satisfy themselves with linear mathematics and deterministic models when dealing with nature.

9. Users of Geographic Information Systems should be cautious with the beautiful spatial representation of information they are able to make, as they often give credibility to unreliable or erroneous data.

10. Major advances and changes in paradigms in the history of scientific research often came from confrontation of various disciplines. Such confrontations should be systematically seeked.

Kuhn, Th. (1962). The structure of scientific revolutions. University of Chicago Press, Chicago. USA.

11. The present system of scientists' evaluation, largely based on number of publications, raises important constraints to develop real inter-disciplinary and integrated studies.

12. Saigonese beauties lost their smile in 1993. It clearly coincides with the massive arrival in Vietnam of foreigners and consumption goods.

Spatio-temporal variability of acid sulphat soils in the plain of reeds, Vietnam. Impact of soil properties, water management and crop husbandry on the growth and yield of rice in relation to microtopography. Olivier HUSSON. 1998. Ph.D. Thesis. Wageningen Agricultural University, The Netherlands.

Foreword

The work presented in this thesis has been realised in the framework of the IAS (Institute for Agricultural Science, 121 Nguyên Bihn Khiêm, T.P. Hô Chi Minh, Vietnam) / FOS (Funds for Development Cooperation, Grasmarkt 105/ Bus 46, 1000 Brussel, Belgium) Farming Systems Research Project for the Plain of Reeds, from 1992 to 1997.

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Model of PhD Thesis build-up

Germination

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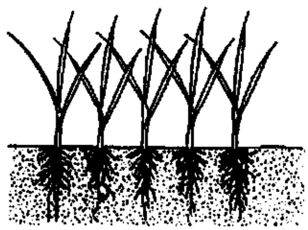
Mai Thanh Phung (IAS)

Plant density



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Chapter 1

General Introduction

The Plain of Reeds

The Plain of Reeds is a broad backswamp located in the north of the Vietnamese Mekong delta where 400 000 ha of acid sulphate soils are located. In the middle of the 1980s, a reclamation programme started by digging a network of primary and secondary canals. Local farmers and migrants were responsible for building tertiary canals and the reclamation of fields. They first settled down on slightly or moderately acid sulphate soils, which are less difficult to reclaim. Thus, by 1990, only severely acid sulphate soils, covering an area estimated at 150 000 ha, remained uncultivated. They posed tremendous problems for reclamation. Oxidation of pyritic material in those soils leads to strong acidification, thus to solubilisation of aluminium which rapidly reaches toxic levels. In reduced conditions, plants suffer from ferrous iron present in high concentrations, and from hydrogen sulphide, carbon dioxide and organic acids produced in these organic matter-rich soils. In addition, acid sulphate soils are known to be low in available phosphorus and other nutrients, and have low base status. They also present physical and biological problems: they are poorly structured and microorganisms can hardly develop in these adverse conditions (Dent, 1986).

Migrants and local farmers in the Plain of Reeds do not hesitate to take high risks to reclaim these soils. They are encouraged by the government, which regards reclamation of the entire Plain of Reeds as a national priority, and they are trying to seize a unique opportunity to increase their land area. As they usually have limited means, failure can have dramatic consequences, leading farmers into a dangerous vicious circle of indebtedness, with interest rates around 10% per month. This leads to very rapid social differentiation.

Initiated in 1992, the IAS/FOS (Institute for Agricultural Sciences, Vietnam / Funds for Development Cooperation, Belgium) Farming System Research Project for the Plain of Reeds logically set as its main objective the development of techniques for land reclamation of severely acid sulphate soils.

Research on acid sulphate soils

Knowledge on acid sulphate soils dramatically increased since the first symposium on acid sulphate soils held in The Netherlands in 1972 (Dost, 1973). A striking feature of research on these soils is a long focus on the soil alone, with strong emphasis on their identification, distribution and genesis (Van Mensvoort, 1996). With the increasing awareness of the high variability of acid sulphate soils, new research methods and topics appeared progressively. A major break in acid sulphate soils research occurred in the 1980s with the development of agronomic studies on these soils.

However, a large number of experiments was done in controlled (and as a consequence disturbed and not representative) environments, either in laboratories or in research stations. Farmers' knowledge remained under-used (Van Mensvoort, 1996), and the relevance of research results for application in real conditions was poor. The high variability of these soils greatly complicates their management and is still rarely integrated in agronomic surveys and experiments. Although Tuong (1993) recognised the practical difficulties in maintaining field water tables at desired depths, this is not considered in most research on water management, a key issue for cultivation of these soils.

Finally, the high complexity of acid sulphate soils is rarely tackled. Interactions between soils, water and plant growth are still poorly explained. Only recently, integrated studies of acid sulphate soils were published (Hanhart and Ni, 1993; Kselik et al., 1993), but high short-range variability, although often recognised, hardly was integrated into the research programme.

Thus, there is a serious lack of practical recommendations for cultivation of acid sulphate soils in actual field conditions. This lack is all the stronger for the Plain of Reeds where problems raised by acid sulphate soils are at their height immediately after land reclamation, before cropping conditions have been improved by cultivation.

Approach and objectives

The approach used at the IAS/FOS Project is largely derived from the "Création-diffusion" of cropping systems developed by L. Séguy at CIRAD-CA[1] (Séguy, 1994).

The choice deliberately is made to be close to farmers, working in actual conditions of production. Thus all the work is done by farmers (under supervision of researchers), in their own fields, with their own means. Protocols and research programmes are established jointly by researchers and farmers. This allows integration of researchers' and farmers' knowledge, and is a guarantee for the production of practical research results, that are meaningful to farmers. The traditional farmers' systems are used as a reference. Careful agronomic surveys allow the identification of bottlenecks and the ranking of factors limiting plant growth.

The approach is holistic, combining systems research conducted on a real scale, without replications and aiming at analysing processes and interactions between factors ("central core"), and thematic research conducted in classical experiments with replications ("satellites"). The main problems faced in each system can be studied in satellite trials, and the best results of satellites are tested at real scale in the central core during the following season. A common treatment applied in all experiments allows comparison between systems.

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[1] CIRAD-CA : Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Annual Crops Department, Montpellier, France.

This approach has the advantage of giving a different perspective as compared to other research, integrating variability of, and interactions between, the different factors explaining rice growth. The relatively low values of R^2 as compared to those measured in "classical" research are explained by the high variability of acid sulphate soils and by the fact that factors are not isolated but studied in interactions. These low R^2 values are compensated by the high significance of the correlations and the large number of fields in which these correlations are measured.

In the Plain of Reeds, a detailed characterisation of experimental fields has been conducted in order to properly set up experiments. It allowed the integration of the high spatio-temporal variability of soils and water in the research programme, at various scales, using variability within and between fields as a source of information. Variability in soils and in rice growth and yield could be related to a simple, easily measurable criterion, the microtopography. Microtopography is understood as topographic level whose variations are measured in centimetres (the difference between the lowest and the highest points measured in the study area is less than 50 cm), even at considerable distances (a few kilometres). For agronomic surveys, microtopography is considered at two levels: (i) Within fields, as at this level topography determines soil types and characteristics, influences redox potential, and therefore greatly affects cropping conditions, and (ii) between fields, as water table levels and water control opportunities are a function of the average field topography.

With this holistic, integrated approach, the main objective of the IAS/FOS project was to rapidly produce recommendations for reclamation of severely acid sulphate soils in the Plain of Reeds. This required knowledge of cropping conditions and an understanding of processes and interactions. Thus, the objectives of this study are to:

* characterise and explain spatio-temporal variability of acid sulphate soils and water, at various scales, in the Plain of Reeds, Vietnam.

* assess impacts of soil and water variability on rice cultivation.

* develop a simple model of rice yield build-up, i.e. a theoretical model of biological functioning of a cultivated population of plants (Sebillotte, 1978; De Bonneval, 1993), in the conditions of land reclamation of severely acid sulphate soils as conducted in the Plain of Reeds.

* apply this model to identify and rank limiting factors, to precisely identify the optimal time window for cultivation and to develop optimal agricultural practices (in particular water management and fertilisation) for the main cropping conditions found in the Plain of Reeds.

Outline of the thesis

This thesis consists of a series of papers to be submitted separately to scientific journals.

Chapter 2 is a literature review on (i) the treatment of variability in land surveys and agronomic research, (ii) the evolution of research on acid sulphate soils and especially how research methods were progressively adapted to address the high variability of these soils, (iii) the agronomic problems raised by acid sulphate soils, and (iv) the growth of rice on these soils.

Chapter 3 gives a comprehensive characterisation of spatial variability of acid sulphate soils in the Plain of Reeds, with special attention to individual field levels.

Chapter 4 presents the temporal variability of soils and water in the Plain of Reeds and the research area. Favourable time windows for cultivation and associated cropping techniques are identified.

Chapter 5 focuses at field level on the effects of spatial variability of severely acid sulphate soils on rice yield. Careful monitoring of field characteristics, water management and yield components made it possible to develop a simple model of rice yield build-up, considering the effect of microtopography on soil and water characteristics and consequently on rice growth and yield.

In chapter 6 and 7, applications of this model are presented:

6. For water management: Different water management strategies are compared, for 3 major topographic levels and at different stages after reclamation.

7. For fertiliser experiments: Sources of variability of results in fertiliser experiments, are presented and research methods suitable for these highly variable conditions are proposed. Advantages of thermophosphate fertiliser as compared to Di-Ammonium Phosphate fertiliser are shown.

Finally, chapter 8 gives a synthesis of the main conclusions and a summary of the thesis.

Chapter 2

Literature review

Literature review

Introduction

In waterlogged soils that are both rich in organic matter and flushed by dissolved sulphate, as in tidal swamps with mangroves, pyrite (FeS_2) accumulates. Acid sulphate soils can develop when, upon drainage, pyrite is oxidised into sulphuric acid. Recent estimates suggest a total of about 24 million hectares where acid sulphate soils and potential acid sulphate soils are a dominant feature of the landscape (Van Mensvoort and Dent, 1996). Over half are located in South, Southeast and East Asia (Langenhoff, 1986), predominantly in densely populated coastal wetlands and river plains. In the Vietnamese Mekong Delta, these soils cover 1.7 million ha, or 47.2 % of the surface (NIAPP, 1987). Due to increasing population pressure and desire for land, these soils have been and are being reclaimed for agricultural purposes. This is the case in the Plain of Reeds, a low backswamp area in the North of the Mekong Delta, Vietnam, where acid sulphate soils are found on 400 000 ha. An analysis of satellite images of Tan Thanh district, in the central part of the Plain of Reeds (Coolegem, 1996) shows that between 1987 and 1995 the rice area more than doubled, while wasteland and Melaleuca forests decreased by more than 60%. This fast reclamation is the result of the conjunction between an important governmental programme and keen interest shown by local farmers and migrants. However, it doesn't reflect the difficulties faced when reclaiming acid sulphate soils.

These soils are nearly unique in that their problems are so severe that they can dominate most other aspects of land development: from engineering works (including the kind of concrete or steel required, design of roads, embankments and drainage systems), to agricultural systems (including the choice of crops, disease, lime and fertiliser requirements), to economic and social planning at regional and local level, to the environmental impact of reclamation (Dent, 1986). Considering only the aspect of crop cultivation, these soils raise important chemical, physical and biological problems.

But Pons (1973) stresses that even if acid sulphate soils have to be considered as problem soils, they are at the same time scientifically extremely interesting. By the very dynamic character of their processes of formation, they come within reach of human control much more than other soils and therefore can help us to understand general soil genesis.

Another important feature of acid sulphate soils is their very high variability in space and time which raises serious methodological and practical problems. The evolution of methods and topics of research on acid sulphate soils reflects the struggle of researchers, and farmers, with this variability.

The first section of this chapter shows the evolution of the perception of variability by researchers and reviews methods developed to address this problem for land survey and agricultural research. The second section presents the history of research on acid sulphate soils, shows how it reflects the struggle of researchers with variability, and how they applied and adapted methods to take it into account. This section also gives an overview of present knowledge of these soils in various domains. The third section concentrates on agronomic problems raised by acid sulphate soils. Finally, the last section presents adaption of rice to these soils and requirements for cultivation in these difficult conditions.

Part I
Variability and methods for land survey and agricultural research

The recognition of variability

De Steenhuijsen Piters (1995) gives a synthesis of the evolution of perception of variability in agricultural research and methods developed to deal with it. The recognition of variability, which started one century ago, has passed through several stages and is still evolving. During the colonial time, the quest for farm homogeneity prevailed, based on the assumption that the production function was similar for all farms of the same type in a region. In the late 60's and 70's various Farming Systems Research (FSR)-labelled approaches were developed. The principle was to define small entities which could serve as more uniform units of diffusion. The notions of recommendation domain and agro-ecological zone, and methods like rapid rural appraisal and on-farm research (Mettrick, 1993) were disseminated and now are widely used. However, limitations of FSR appeared: It is essentially static, ignoring dynamic processes which take place in space and time (Fresco, 1986), and it assumes the intrinsic homogeneity of the systems.

In the past 10 years, new ideas have emerged. Heterogeneity is now regarded as more likely than homogeneity (De Steenhuijsen Piters and Fresco, 1994), and it is viewed as a key environmental attribute, a crucial soil property, rather than a nuisance (Dobermann, 1995; Finke, 1992). Variability, which previously was seen as having a negative impact on production, can now be seen as an opportunity of risk reduction (Brouwer et al., 1993). In addition, variability is at the core of one of the new development in agricultural management: precision farming. Here, management is varied within fields as a function of spatial variability, rising modeling information technology (Bouma, 1997)

Spatial variability, which has long been acknowledged at the macrolevel, but not at the microlevel (Wilding and Drees, 1978), is now acknowledged to be scale-specific. It is also regarded as property-specific, site-specific and not consistent in time-specific terms (Dobermann, 1995). Furthermore, it is recognised that in the natural environment some structures and organisations exist that show on certain scales. Failing to identify these structures and to study them at the optimal scale level, at which variability is minimal (but not necessarily zero), leads to the collection of highly variable and apparently spatially disorganised data, difficult to interpret (Bourgeon and Bertrand, 1983; Boivin et al., 1991; Fresco, 1995).

Based on this recognition of spatial and temporal variability at various scales, new tools and approaches have been and are being developed, especially in the domain of land survey and mapping, but also for agricultural research and production.

Variability, land survey and mapping

Sampling strategies

Since the 1960's, sampling strategies, densities and patterns have been extensively discussed in literature (Hammond et al., 1958; Leo, 1963; Martel and Zizka, 1978; Burgess et al., 1981; Russo, 1984; Ruelle et al., 1986; Di et al., 1989; Wopereis et al., 1992; Gascuel-Odoux et al., 1993; and Starr et al., 1995). A leitmotive in all these works is that sampling density and strategies are a function of the variability of the measured data, desired precision and map scale and costs.

Mapping methods

To cope with spatially related data, deterministic interpolation methods first were developed (Stein, 1991). However, none of these procedures supplied measures of uncertainty in unobserved locations. Later, stochastic and nonstochastics interpolation procedures were developed. However, these techniques were empirical, and although they may seem reasonable for many applications, they were theoretically unsatisfactory (Burgess and Webster, 1980a). Furthermore, with most of these models discrete units were mapped (Bregt, 1992). The geostatistical models further developedthe idea of continuous spatial models already found in trend surfaces and splines analyses, and greatly improved spatial prediction techniques. Kriging, which marked the beginning of geostatistic interpolation methods, uses spatial correlations between nearby data. It is optimal among all linear procedures, as it is unbiased and has minimal variance of the prediction error (Stein, 1991). Several methods derived from kriging then were developed, with the aim to increase its efficiency and adapt to particular conditions (Isaaks and Srivastava, 1989; Stein, 1991, Cressie, 1993).

However, questions were raised about the validity and usefulness of such maps and models because variability within a single mapping unit was often greater than between delineations of the same unit (Wilding et al., 1965; Karr, 1988), and the uncertainty of the results was not considered. It became important to assess the reliability of data, of sampling and/or bulking strategies, of analytical methods (Dobermann, 1995) and of final survey results.

New approaches then were developed to reduce, estimate, rank or quantify uncertainty and to validate results. One can mention fuzzy classification (Zadeh, 1965; Burrough et al., 1992; Mac

Bratney et al., 1992), uncertainty index (Isaaks and Srivastava,1989), isolines maps with confidence limits (Burgess and Webster, 1980b; Bregt et al., 1991) and mapping of conditional probabilities that the true values exceed or are less than a specified critical threshold (Yates et al., 1986; Webster and Oliver, 1989), enabled by the spatial prediction procedure as Disjunctive Kriging or Multiple Indicator Kriging (Finke, 1992; Bouma et al., 1996). Various methods of cross validation also were developed, and are useful to check the impact of the many choices involved in the estimation methodology (Isaaks and Srivastava, 1989).

Scaling

Spatial variability in soils is a continuum from megascopic to microscopic levels of resolution (Wilding, 1985) and there is no homogeneity at all. As the factors influence soil properties in different ways, the correlation among soil properties is likely to change from one spatial scale to another. Thus, quantifying the spatial variability of a given soil property is always related to a particular spatial scale (Dobermann, 1995).

Fresco (1995) regards scale as the spatial and temporal 'observation window' through which we look at the real world. If the window is too small, factors having influence on a wider scale will not be seen. If the window is too large, only a broad view will be accessible, without explanation of details. Now, phenomenons observed at a wide range are often due to a combination and accumulation of phenomenon occurring at a small range, and phenomenon at wide range influence those observed at small range. Thus, for a complex phenomenon, involving processes at various scales, there is as many models (and even theories of the phenomenon) as scales of perception (Frontier, 1991). Fresco (1995) also pointed out that there is an optimal scale level at which each process can and must be studied. At this level, variability is minimal, but not necessarily zero.

Thus, in any work of characterisation or modelling, the choice of the spatial and/or temporal scale(s) at which the phenomenon will be studied is crucial and will greatly influence the results of the study. Depending on the scale, factors can be seen either as exogenous drivers or endogenous variables, and they are linked across different scales (Fresco, 1995).

In soil or agro-ecological surveys it is now clearly expressed that scale influences:

(1) The importance of certain variables for agro-ecological characterisation, thus the characterisation criteria for identification of units (Andriesse et al., 1994).

(2) The value or relevancy of data (Fresco, 1995).

(3) The variability of measured data.

(4) The method of approach (Job and Hachicha, 1991) and measurements (Boivin et al., 1991).

To face problems linked to scale and variability, multi-scale approaches recently were proposed (Andriesse et al., 1994; Sylla, 1994; Fresco, 1995). As explanation of observations at one scale requires an understanding at both bigger and smaller scales, only an iterative approach can efficiently lead to increasing precision and knowledge. In an iterative process, multi-scale characterisation involves the aggregation of variables in an upward direction (i.e. when going from large-scale to small-scale characterisation), and desaggregation of variables when going down the scale ladder (Andriesse et al., 1994). At each step the efficiency and precision of the overall research process are increased (at constant cost or time), or costs (or time) are decreased (for constant precision or scale of observation). Needs and available means will determine the final level of precision to be reached. This approach allows to make best possible use of available data although they may be widely different in origin, accuracy and scale, and to plan further studies of processes at optimal scales. Furthermore, not only spatial, but also temporal variations, at various scales, can be integrated in the studies. This allows the integration of relationships between spatial and temporal variations.

Variability and methods for agricultural research and production

Variability and agricultural research

Variability at different scales raises problems not only for land survey and mapping, but also affects agricultural research. Once variability has been assessed with increasing detail from macro-level (scales between 1:1 000 000 and 1: 5 000 000) to detailed level (1:5 000 to 1:10 000) as described by Andriesse et al. (1994) and that areas representative of main agro-ecological situations have been identified, the problem of field variability remains.

Spatial changes in soil related properties are often inadequately assessed in field research, and may be pooled with other effects. Even worse, effects due to spatial changes in soil properties may be left alone as replication errors (Beckett and Webster, 1971). This practice results in larger variances which can either mask significant differences due to the experimental treatments, or require more replications to statistically demonstrate significant treatments' effects (Karr, 1988).

Traditionally, experimenters have tried to cope with soil heterogeneity using blocking and randomisation. Fisher's field experimental design and analysis became a standard tool in agronomic experimentation. However the classical statistical approach is only adequate if measured soil and crop properties exhibit random variability with little or no spatial correlation. In the presence of significant spatially correlated trends, the classical assumption of independence between plots is violated (Dobermann, 1995).

Over the years, several approaches have been developed to better integrate variability in research.

Experimental layouts

Various experimental layouts were developed to handle known sources of variations. The classical randomised complete block design was designed to reduce experimental error by eliminating the contribution of a known source of variation. However, it was recognised that many experiments were poorly laid out in the field due to a blind adoption of textbook 'recipes' for randomised block rather than a careful consideration of their implementation (Preece, 1982). When single-factor experiments have a large number of treatments, incomplete block designs as lattices aim at limiting the block size to maintain homogeneity of plots within a block (Gomez and Gomez, 1984). Recently, designs such as restricted randomisation (Van Es and Van Es, 1993) or embedded field (Mac Bratney, 1985) added to these designs.

Attention was also paid to the power of experiments. The ability of field experiments to detect differences between treatments depends not only on the intrinsic differences between fertilisers but also on site responsiveness to treatments, experimental variability and degree of replication (Johnstone and Sinclair, 1991). When designing experiments, the number of replications can be assessed as a function of the expected variability in the quantities measured, the difference to be shown, and the desired power of an experiment to detect such a difference (Philippeau, 1984).

Analysis of experimental data

Various methods of analysis of data also were developed. Covariance analysis was developed for experiments in which blocking cannot adequately reduce the experimental error. On the premise that the various biophysical features of an experimental plot do not behave independently but are often functionally related to each other, the analysis of covariance simultaneously examines the variances and covariances among selected variables (Gomez and Gomez, 1984). The idea is that the treatment means are 'adjusted' to allow for the effect of the covariates, which reflect site heterogeneity. Covariates can be soil factors correlated to yield, or yield measured in a homogeneously conducted field (blank trials) the previous season. The aim is a reduction of the error variance, and a consequent increased precision for treatment comparisons (Sinclair, 1987).

Nested Analysis of variance decomposes the total variation in different variance components and the contribution and significance of each effect is tested (Sylla, 1994).

Trend analysis, as the name indicates, was developed to take into account spatial (or temporal) trends in experimental fields. One argument given for such analysis is that boundaries between contiguous blocks are artificial, in the sense that yield potential is not likely to change abruptly along straight lines corresponding to these boundaries (Brownie et al., 1993).

Papadakis analysis or more generally Nearest Neighbour Analyses also consider that yield potential varies in a smooth manner. The idea is to adjust plot values by covariance on neighbouring plots in randomised field experiments. The gain in efficiency over orthodox randomised block analysis can be appreciable when the number of treatments is fairly large, and can be increased by iteration of the analysis (Bartlett, 1978).

The most recently developed methods of analysis are based on models that account for small-scale variation in soil properties through correlations between the plots errors. Typically, these models assume that the strength of the correlation between two errors is greatest for adjacent plots and diminishes as the distance between plots increases (Brownie et al., 1993).

Use of geostatistics

Using geostatistics in the design and analysis of field experiments offers opportunities to describe quantitatively soil and crop variation and covariation and to perform block predictions and copredictions (Dobermann, 1995). In general, the use of geostatistics for field experiments may be seen in:

<u>The use of soil semivariograms to design plot and block size and shape</u>

Assuming that there are few soil properties controlling the spatial yield variation of a crop and that there is some proportional relation between these variances, then the anisotropy of the semivariogram would suggest plot and block size and shape (Mac Bratney, 1985). It is clear that variability decreases as plot size increases. Compared with the optimum plot size, the relative cost of different plot sizes is shown to be a function of the ratio of a basic area and a variogram range. Thus, taking into account costs, variability indices and variograms, Zhang et al. (1994) proposed a method to determine optimal plot shape and size. The smaller plot dimension should be in the direction of maximum variation and the larger dimension perpendicular with the ratio of the sides equal to the geometric anisotropy ratio (Mac Bratney, 1985). The geostatistical approach also showed that for auto-correlated variables, a higher number of treatments in the experiment tends to (i) increase the experimental error term due to greater average distance of comparison, and (ii) increase inequality in precision of contrasts due to greater discrepancies in distances of treatment comparison (Van Es and Van Es, 1993).

<u>Use as analytical tools</u>

Semivariograms can be used to identify spatial correlations in crop yields from field experiments and as tools for the evaluation of trend removal by nearest neighbour analysis (Bhatti et al., 1991). Preliminary geostatistical study can also help to increase the precision of trials. Maps of kriged estimates of soil properties can be used to locate treatments plots. Thus, Lopez and Arrue (1995), using incomplete block design, could reduce the average error mean square by 33%.

Multivariate geostatistics as Factorial Kriging Analysis (Wackernagel, 1994) combine interests of multivariate analysis (as Principal Component Analysis) and geostatistics. In classical PCA, i.e. without distinguishing different spatial processes, the extracted factors combine the main features of the data averaged over different scales in case the structures change with the spatial scale. In contrast, a PCA of the coregionalisation matrices yields sets of regionalised factors separately for each spatial scale, allowing the processes causing the variation over short and long distances to be determined (Dobermann, 1995). Thus, multivariate geostatistics can be of great use to distinguish spatial processes, based on the correlation structures of measured soil properties.

Farming by soil

For agricultural production, knowing the factors that cause high variability in crop yields, and if possible mapping them, would enable location-specific agricultural measures. An example would be focussing irrigation on areas where moisture deficits are most likely to occur and adding fertiliser according to local need (Finke, 1992). Indeed, uniform fertiliser applications may result in over- and underfertilised areas. Runoff and leachate from overfertilised areas may contaminate water supplies, while crop yield may be restricted in underfertilised areas (Cahn et al., 1994). The recent development in statistical and computer technology allows the development of accurate soil fertility maps and allows more flexibility in the creation of fertiliser management programs (Mulla, 1993). Thus, the concept of farming by soils, with its different alternatives, has received much attention recently.

Part II

Research on Acid Sulphate Soils: Struggling with variability

Introduction

Initially, the main accent in acid sulphate soils research was on explaining the genesis and the chemical processes, and on survey methodologies or soil classification (Van Mensvoort, 1996). In the last 10 to 15 years, more and more sophisticated statistical tools and methods have been applied in response to problems raised by the high variability of these soils. Aspects other than soil sciences progressively were added, such as soil fertility, land and water management, traditional farming systems, land evaluation, modelling and environmental problems. At the same time, higher practical applicability of research results was sought. Exchange of knowledge did not remain limited to exchanges between specialists or experts, and transfer of knowledge from researchers to farmers gained in importance (Van Mensvoort, 1996). Farmers' knowledge also became a source of information for researchers, as in the Mekong Delta where farmers used the great diversity in soil and hydrological conditions (Tuong et al., 1991a).

With this evolution, researchers extended the scope of their perception of variability of these soils. Nowadays, it includes various scales, from the regional level useful to experts and policy makers to the field level of farmers. This was a prerequisite for the development of sound techniques for agricultural use of these soils.

Van Mensvoort (1996) showed that work on identification and distribution forms the basis of acid sulphate soil research, together with genesis, and has long dominated the literature.

Identification, and distribution

Identification of acid sulphate soils

The presence of acid sulphate soils is likely in coastal wetlands, inland marsh and swamps. Vegetation and various symptoms of restricted plant development can also be indications of the problem.

The acid test is a soil pH value of less than 4 under aerobic conditions. This is usually associated with yellow mottles or coating of jarosite and deposition of ochre in the soil or in drainage waters. In flooded soils, the pH will rise above 4 because of soil reduction, but a sample of an acid sulphate soil allowed to dry will become severely acidic again (Dent, 1986). Positive identification is observation of a dramatic fall of pH following hydrogen peroxide treatment or incubation for three months, to reach pH less than respectively 2.5 and 4.

Distribution of acid sulphate soils

It was generally recognised that, worldwide, these soils cover 12 to 14 millions hectares (Beek et al., 1980; Dent, 1986; Langenhoff, 1986). However, recent estimates suggest a total of about 24 million ha where acid sulphate soils and potential acid sulphate soils are a dominant feature of the landscape (Van Mensvoort and Dent, 1996). Most acid sulphate soils are found in the tropics, especially in South, Southeast and East Asia (Langenhoff, 1986). In this region, the larger part is found in Indonesia, Thailand and Vietnam (Van Breemen and Pons, 1978), predominantly in densely populated coastal wetlands and river plains.

Genesis of acid sulphate soils

Accumulation of pyrite

Chemical processes

Pyrite (cubic FeS_2) is quantitatively the most important sulfur mineral in potential sediments. The formation of pyrite involves (Dent, 1986, Verburg, 1994):

* Reduction of sulphate ions to sulphides by sulphate-reducing bacteria, thereby decomposing organic matter (source of energy).

* Partial oxidation of sulphides to elemental sulphur or polysulphidic ions.

* Formation of iron monosulphides (FeS) by the combination of dissolved sulphides with iron. The iron originates mostly from iron III oxides and silicates in the sediment, but is reduced to iron II by bacterial action.

* Formation of pyrite by the combination of iron monosulphide and elemental sulphur.

Alternatively, pyrite may precipitate directly from dissolved iron II and polysulphide ions.

The formation of pyrite with iron III oxide as a source of iron may be represented by the following overall equation:

$$Fe_2O_{3(S)} + 4\ SO_4^{2-} + 8\ CH_2O + 1/2\ O_{2(Aq)} \text{ -----> } 2FeS_{2\,(S)} + 8\ HCO_3^{-}{}_{(Aq)} + 4\ H_2O$$

The essential conditions to make this formation of pyrite possible are the following (Dent, 1986, Verburg, 1994):

* An anaerobic environment. Sulphate reduction takes place only under severely reducing conditions, which are provided by waterlogged sediments that are rich in organic matter.
* A source of dissolved sulphate, usually sea water or brackish tidal water.
* Organic matter, the source of energy for sulphate-reducing bacteria.
* A source of iron. Most soils and sediments contain abundant iron oxides and hydroxides, reduced to Fe^{2+} in an anaerobic environment.
* Tidal flushing. Potential acidity only can develop if at least part of the alkalinity formed during sulphate reduction is removed from the system. Flushing by tidal action is likely to be particularly effective in removing HCO_3^-, renewing SO_4^{2-} and supplying the limited amount of dissolved oxygen that appears to be necessary for pyrite formation.

Variability in pyrite content

Original vegetation and accumulation of pyrite

Several authors mentioned differences in mangrove forest vegetation and attribute differences in soils, especially pyrite content, to differences in original vegetation in relation to topographic level.

Mangrove species, in particular *Rhizophora* and *Avicennia*, occupy different ecological niches.

Baltzer (1975) observed that mangrove species show frequency maxima related to topographic level, with a strict coincidence with characteristic heights of tides, and suggested two possible causes: (i) the maximal height of submersion of the soil at high tide, which controls the settlement of seedlings of *Rhizophora* and *Avicennia*, and (ii) the duration and frequency of submersion which in turn controls the salinity of the soil pore water.

In Sierra Leone, Senegal and Gambia (Tomlinson, 1957; Jordan, 1964), *Rhizophora* is the primary coloniser on freshly deposited silts and clays. It can be found in fringing creeks, in almost pure stands, but also in mixed stands of both kinds of mangrove (Hesse, 1961). In his literature review, Langenhoff (1986) mentioned that in regions where both *Rhizophora* and *Avicennia* mangrove occur, *Rhizophora* occupies the most favourable environments for pyrite accumulation: The lower topographic levels (often even below mean sea level in brackish water) with more frequent flooding, where sedimentation rates are low.

Avicennia nitida seldom occurs as a pure stand. It is particularly salt tolerant and grows well on rather sandy soils, away from the creeks, in which there is a marked accumulation of salt during the dry season (Tomlinson, 1957; Jordan, 1964). On tidal flats where mud is rapidly accumulating, *Avicennia* is the pioneer vegetation. Sow et al.(1994) in Senegal observed that silting up creates unfavourable conditions for *Rhizophora* that is replaced by *Avicennia*.

Adaption of *Avicennia* to an environment of fast sedimentation is attributed to its root system: In contrast to *Rhizophora*, *Avicennia* can generate absorbing roots very rapidly when the surface of mud rises, while *Rhizophora* possesses no such mechanism for the rapid adjustment of its feeding organs and pneumatophores to the rapid rise of the sediment (Vann, 1969).

Differences in root systems of mangrove trees (Tomlinson, 1957, Marius, 1985; Langenhoff 1986; Bertrand, 1994) also explain the development of soils with different characteristics. In particular, difference in potential acidity attributed to original vegetation has been observed by many authors (Hesse, 1961; Van der Kevie, 1973; Moorman and Pons, 1975; Allbrook, 1977, Sylla, 1994).

Rhizophora develops a very dense, deep and wide root system, with very dense root hairs, which helps the development of sulphate-reducing bacteria. In general, fibrous mangrove soils are found under a cover of *Rhizophora racemosa,* and in peat developed under this specie, fibres are very poorly decomposed.

In opposition, *Avicennia* presents a shallow root system dominated by pneumatophores, which limits sulphide accumulation and thus, potential acidity. Profiles under *Avicennia* are characterised by a clear horizon, almost ripe.

It is also thought that the organic matter produced by *Avicennia* in higher places, and thus under more oxidative conditions, might mineralises faster than organic matter produced by *Rhizophora*, which is under water most of the time.

Potential acidity, drainage and redox conditions

Differences in pyrite content are not explained only by differences in original vegetation. Potential acidity also is related to natural drainage and redox conditions, which are, as vegetation, influenced by topographic level.

Usually, former tidal creek levees show lower pyrite content than acid sulphate soils found in the lower parts of the landscape. This has been explained by better drainage and less reduced conditions during sedimentation (and therefore lower pyrite accumulation), but also stronger leaching after sedimentation (Bennema, 1953; Willet and Walker, 1982, Langenhoff, 1986).

Detailed surveys showed that elevation influences pyrite content and depth of the permanently reduced subsoil for topographic differences as low as 20 to 50 cm (Vlek, 1971; Van Breemen et al., 1973).

Finally, Dent (1986) gives a schematic sequence of soil profile development in the tidal zone which shows a clear relationship between potential acidity, elevation and natural drainage during sedimentation at a stable sea level.

Oxidation

Pyrite is stable only under reduced conditions. Drainage brings about oxidising conditions, initiating the oxidation of pyrite and the generation of acidity. Drainage may occur naturally, as a result of a fall in relative sea level or reduced frequency tidal flooding, or by some combination of deliberate exclusion of tidal action and the lowering of the water table (Dent, 1986).

Oxidation of pyrite is a complex process involving several reactions which have been extensively studied and reviewed (Bloomfield and Coulter, 1973, Van Breemen, 1973 and 1982, Dent, 1986, Langenhoff, 1986, Verburg, 1994, Van Mensvoort, 1996). The net result, with iron III hydroxide as an end product, may be expressed as (Van Breemen, 1982):

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

This releases 4 moles of acidity per mole of pyrite oxidised (Dent, 1986).

Acid sulphate soils develop where the production of acid exceeds the neutralising capacity of the parent material, so that pH falls to less than 4. The most significant source of neutralising capacity is calcium carbonate. Crudely, one part by mass of pyrite S is neutralised by three parts by mass of calcium carbonate. However, in tropical and subtropical environments, the conditions for carbonate accumulation and high pyrite accumulation appear to be mutually exclusive (Dent, 1986, Van Mensvoort, 1996).

In mineral soils, severe acidity is usually associated with yellow jarosite mottles (Dent, 1986). However, in Vietnam, Van Mensvoort and Tri (1988) observed extensive tracks of actual acid sulphate soils without jarosite. They explained the absence of jarosite by the low redox potential in the sulfuric horizon. Jarosite is formed at low pH (less than 4.0) and at Eh higher than about 400mV (Van Breemen, 1976). At lower Eh values, pyrite can still be oxidised, but only to dissolved ferrous sulphate. For actual acid sulphate soils without jarosite, Van Mensvoort and Tri (1988) measured pH in the range of 2.4-2.6, and Eh values between 300 and 400 mV. This rather low Eh was attributed to the high organic matter content.

Soil ripening

The concept of ripening embraces all the physical, chemical and biological processes by which a freshly deposited mud is transformed to a dryland soil (Pons and Zonneveld, 1965; Dent, 1986). Physical ripening essentially involves an irreversible loss of water. Evaporation and transpiration are critical to soil ripening because a large force is necessary to remove water from the small pores in the sediments. Removal of water leads to the partial collapse of the initial, very open micro-structure; to shrinkage and consequent fissuring of the soil; and to an increase in the area of close contact between individual particles and aggregates. This in turn increases the cohesive strength of the material.

Classification of acid sulphate soils

Classifications of acid sulphate soils improved with the increase in knowledge of these soils. Several classifications exist: Soil Taxonomy (Soil Survey Staff, 1975 and 1992), ORSTOM (Segalen, 1979), FAO-Unesco (1974) for instance. Proposals for modification and improvement of existing classifications are regularly made (Pons et al., 1988; Sutrisno et al., 1990; Fanning and witty, 1993). However, most classifications are based on purely technical criteria, with little attention paid to properties that are important to land use. Dent (1986) presents the ILRI classification based on five important soil properties: Acidity and potential acidity, salinity, composition and texture, ripeness and profile form, especially the depth and thickness of limiting horizons.

Simulation and modelling of processes

The development of simulation models for predicting the chemical processes in acid sulphate soils often was recommended (Dost and Van Breemen 1982; Dent, 1986; Dost, 1988) as they are a very attractive approach to assessing acid sulphate hazard over both time and space (Van Mensvoort and Dent, 1996). Various models developed to simulate physical and chemical evolution of these soils are presented by Van Mensvoort and Dent (1996), with their basis, advantages and limits. An important conclusion is that all the models deal with soil profiles, which are just points in the landscape. A simulation of the effects of management on whole landscapes demands reasonable spatial and temporal data for the key soil, the hydrological and the climatic characteristics.

Soil survey and mapping

Having established that there is an acid sulphate soil problem, the next step is to determine its extent, distribution, severity and time span in enough detail to avoid or manage the problem (Van Mensvoort and Dent, 1996). It is in this domain of soil survey and mapping that researchers directly addressed the problem of variability. Important efforts were made to assess, describe and depict the variability of acid sulphate soils. Sophisticated geostatistical tools have been rapidly applied to acid sulphate areas, as in Vietnam (Bos and Van Mensvoort, 1983; Burrough et al., 1988) or Indonesia (Bregt, 1992). However, the very high variability of these soils remains a problem for researchers.

Variability of acid sulphate soils

High spatial variability of acid sulphate soils is generally acknowledged. In the Mekong Delta, Vietnam, Bos and Van Mensvoort (1983) found a high variability of soil characteristics at short range (lower than 280 m). In Indonesia, Bregt (1992) found differences of more than 50 cm in the depth to pyritic layer within 25 m. Boivin et al (1991) in Casamance found a high spatial variability of pedo-hydric parameters at field-scale and even at soil profile scale.

Identification of relevant criteria. Sampling and observation density

Bos and Van Mensvoort (1983) studying acid sulphate soils in the Mekong Delta, Vietnam, observed that in most cases a trend was present, that the area was highly anisotropic, and that variation was short scale. Most of the properties showed different semi-variograms for all the directions, which made it difficult to identify the optimal sampling distances from the results of the study. Van Mensvoort and Dent (1996) also remark that it has proved difficult to match field characteristics with chemical data so a large number of samples is needed to make a reliable map.

Burrough et al. (1988), in the Mekong Delta applied a nested analysis of variance for several soil characteristics with the joint aims of selecting the most suitable soil properties for distinguishing between soil units and the best scales for soil survey. The short-range variance of EC (74% at 10 m distance) was so large that for all practical purposes, it was a useless attribute for distinguishing between soil units at any scale. Subsoil was more uniform in space: Hue value, texture, ripening stage, and organic matter content of the C-horizon showed large percentage short-range variance. The variance of depth to jarosite (an important characteristic in distinguishing types of acid sulphate soils according to Soil Taxonomy) had a jump between 10 m and 50 m, and between 100 m and 500 m. It was regarded as a reasonably reliable criteria for surveys at scales 1:20 000 to 1:100 000, but it was recommended to use average values from multiple observations within a small area (bulked samples) to reduce the confusion caused by short range variation. However, jarosite was not always present in profiles. For data indicating the presence or absence of jarosite, about half the variance was reached within 50 m, but between 50 and 280 m, no further rise occurred. It was concluded that in this area, the presence or absence of jarosite was a useful characteristic for surveys at mapping scale varying between 1:56.000 and 1:200.000.

In Indonesia, Bregt (1992) investigated the relationship between observation density and the accuracy of the obtained information for mapping depth to the pyritic layer, with four spatial prediction techniques. He defined the optimum observation density as the lowest possible density, where the mean square error being minimal or not statistically different from the mean square error at higher densities. A remarkable result was the fact that the optimal density of 22 observations per km^2 (map scale 1:30 000) had an accuracy equal to the accuracy obtained at an observation density of 200 observations per km^2 (map scale 1:10 000), for a cost 87% lower.

Mapping methods

Although geostatistical methods undoubtably present advantages as compared to classical methods when addressing variability, they have their limits. Bos and Van Mensvoort (1983) concluded that the biggest benefit of their survey was that the quantitative level of short range variation was known, but that not much extra-information was gained by applying semi-variance analysis to highly variable areas. With such levels of variability, all mapping methods were likely to be unsuccessful.

Bregt (1992) also attributed to the high short range variability the remarkable fact that the conceptually and operationally much more complicated kriging technique did not perform better than the simpler techniques of inverse distance and local mean. He showed that, since depth to pyrite, pyrite concentrations and total actual acidity show such high spatial variation, boundaries on maps based only on predicted values were not very reliable. However, geostatistical methods allow the mapping of conditional probability which gives a better picture of the real situation and enables planners to build in safety margins. Bregt (1992) successfully applied this approach and mapped the probability that the depth to sulphidic material exceeds 50 cm.

Van Mensvoort and Dent (1996) concluded a literature review by saying that experience with spatial statistics has been mixed. It is clear that just as much insight is needed to apply this approach than classical survey methods, and that the high sampling density and still rare skills needed to apply spatial statistics have to be justified case by case.

Land evaluation and land utilisation

With the improvement of knowledge about acid sulphate soils, land evaluation gained in accuracy and precision. Tuong et al. (1991a) used hydrological factors as land qualities to determine the suitability of the land in the Mekong Delta for rice cultivation. The study results in suitability maps of the Mekong delta for different double or triple rice cropping systems (Van Mensvoort and Dent, 1996).

Van Mensvoort et al. (1993) included soil conditions and hydrology in a land evaluation study of the Mekong delta. They identified twelve zones based on acidity, flooding depth and surface water salinity. Tri (1996) used the same methodology in two districts of the Mekong delta but in much greater detail and identified 23 to 27 land units based on soil and hydrological criteria. In these two surveys, land utilisation types were described, based on farmers' experience in the delta. The authors claim that farmers' knowledge so far has been underused. Such knowledge is built on generations of experience in using the land and it has not only generated interesting land use systems, but also has explained how they were historically developed, under what conditions or in what sequence they can be applied, and what management measures need to be taken (Van Mensvoort and Dent, 1996). Thus, an analysis of land utilisation and the integration of farmers' knowledge is another way to address to the problem of variability of acid sulphate soils which has the advantage to integrate several aspects of these soils.

Integrated approaches

Processes on acid sulphate soils are extremely complex, as they interact with each others and are highly variable. To address this high complexity and try to understand processes in a global framework, integrated approaches were recently applied to acid sulphate soils.

Multiscale approach

Sylla (1994) studied variability of soil salinity and acidity in West Africa's mangrove zone using a multiscale approach. He could distinguish different environments from climate, and coastal morphology at macro scale (west Africa region), from hydrology, physiography and vegetation complexes at meso level (watershed) and from topography, vegetation species, tidal flooding and sedimentation rate at micro level (catena).

Integrated soil, water and crop management

In Vietnam (Hanhart and Ni, 1991; Minh, 1996) and Indonesia (AARD/LAWOO, 1992), research teams incorporated agronomic aspects to soil science in an approach integrating soil, water management and crop sciences. These works yielded interesting practical results for the cultivation of rice on acid sulphate soils.

Part III

Agronomic problems raised by acid sulphate soils

Physical problems raised by acid sulphate soils

The suitability of acid sulphate soils for agricultural use is influenced by soil physical properties such as bearing capacity, permeability and storage coefficient.

In these soils, bearing capacity and permeability are a function of their ripeness. Ripening is an irreversible process of extraction of water from the soil, by evaporation, drainage and, most importantly, extraction of water by plants roots. Ripening of mud is marked by an increase in consistency, shrinking, cracking, structuration, oxidation, weathering and biotic activity (Pons, 1973). Where acid sulphate conditions develop, roots cannot penetrate the acid horizon, or any underlying layer, and ripening is arrested. Clay and organic soils remain soft, unable to bear heavy loads, are poorly-structured, and therefore poorly-drained (Dent, 1986). Furthermore, trying to increase bearing capacity of these soils by drainage would bring about strong acidification in soils with shallow sulphidic layers (Langenhoff, 1986). Field drains also may be blocked by iron oxide (ochre) deposits (Dent, 1986).

Low bearing capacity makes these soils unsuitable for large-scale mechanised rice cultivation that involves farming operations with (heavy) machinery.

Soil ripening also is associated with an increase in permeability as a result of fissuring (Dent, 1986). Thus, field permeability greatly varies with ripeness from one acid sulphate soil to another, which influences water management possibilities. On the one hand, many young acid sulphate soils in non-tidal (inland) swamps can not be reclaimed by leaching because of their slow permeability and unfavourable hydrology (Van Breemen and Pons, 1978, Langenhoff, 1986). On the other hand, high permeability on ripe soils does not allow water control at the field level. In the Plain of Reeds, Vietnam, Minh et al. (1995) measured infiltration rates with a double-ring infiltrometer at the end of the dry season. Due to a permanent crack system that remains after swelling, they found very high and variable values, with a minimum infiltration rate at saturation over 6 cm/h on average. These values are far above the threshold value given by FAO (1985) who estimates that fields are not suitable for rice cultivation when seepage through embankments and percolation exceeds 15 mm/day. For acid sulphate soils in tidal areas, permeability also may be high due to crab holes and old root channels

(Langenhoff, 1986). In Indonesia, Sevenhuijsen et al. (1992) report high hydraulic conductivity (average of 870 m/day for a brown layer) and permeability, with high micro-variability. They conclude that water levels cannot be regulated on field by means of bunds and small structures due to this high hydraulic conductivity.

Finally, in the Plain of Reeds, Vietnam, Thuan (1989) and Bil (1994) report that due to a combination of a small storage coefficient and a low lateral flow, rain and evapotranspiration have a strong impact on the ground water level. This means that the water level during the dry season, and thus the redox potential of soils, is very sensitive to dry periods and that the lowest water level depends on the length of the dry season together with occurrence of casual rainstorms. This leads to high and fast variations of redox potential, which determines the chemical status of the soil.

Chemical problems raised by acid sulphate soils

Toxicities

Dry conditions

Lowering of the water table can create adverse conditions for cultivation through acidification of soil due to oxidation of pyrite (FeS_2), and accumulation of toxic elements in top soil by upward capillary movements, especially aluminium (Minh, 1996) and salt in the case of saline soils (Tuong et al., 1991b).

Salt

Salinity levels in acid sulphate soils are inevitably variable. The highest levels occur in young acid sulphate soils in regions with a pronounced dry season. The highest values also coincide with poor drainage and an unripe subsoil (Dent, 1986). In Senegal and Gambia, Marius (1982) reports EC values over 200 mS/cm on bare tannes at the end of the dry season.

Soil salinity is detrimental to plant growth because it increases the osmotic pressure of the soil solution and thus reduces absorption of water and nutrients by roots (Ministère de la Coopération et du Développement, 1991). In addition, toxicity by specific ions, notably Na^+ and Cl^- is common (Dent, 1986). Salt may also induce toxicities, e.g. by increasing the iron and aluminium contents in solution (Langenhoff, 1986).

Yield of most crops are affected by ECe ranging from 1.5 to 7 mS/cm, and maximum tolerable levels range from 10 to 20 mS/cm (Dent, 1986).

Acidity and aluminium concentrations

In the field, pH values of acid sulphate horizons are usually in the range 3.2 to 3.8 (Dent, 1986). In the Plain of Reeds, Vietnam, Verburg (1994) measured a pH of soil solution as low as 2.75 at a depth 40 cm on Typic Sulfaquepts.

Soil acidity per se is harmful to plants and impairs the absorption of nutrients, especially of calcium and phosphorus (Sen, 1988). Rorison (1973) pointed out that plants may tolerate large concentrations of H^+ ions, as long as the concentrations of other cations are large, and the concentration of toxic polyvalent cations is small.

At pH values less than 3.5, H^+ and Fe^{3+} ions may inhibit plant growth, but soluble aluminium is likely to be the principal hazard (Dent, 1986).

The injurious effects of Al and the possible mechanisms for susceptibility to or tolerance of Al in crop plants are not yet clear. An understanding of the physiological basis of Al tolerance requires an integrated approach searching for a suite of physiological adaptations which act in a coordinated fashion to provide protection against Al stress (Taylor, 1991). Aluminium has been shown to: (i) interfere with cell division in plant roots; (ii) fix P in less available form in the soil and in or on plant roots; (iii) decrease root respiration; (iv) interfere with certain enzymes governing the deposition of polysaccharides in cell walls; (v) increase cell wall rigidity (by cross-linking pectins); and (vi) interfere with the uptake, transport, and use of several elements (Ca, Mg, P, K) and waters by plants (Foy et al., 1978).

Al^{3+} can be toxic in concentrations as low as 0.04 to 0.08 mol m^{-3} (1 to 2 ppm), although there is a great variation in tolerance from one species to another and within particular species (Dent, 1986).

Aluminium concentrations are directly related to soil pH. Nhung and Ponnamperuma (1966) gave the relation between pH and Al concentration in a soil solution as: $pAl = 2\ pH - 4.41$.

Over a wide range of conditions in Thai acid sulphate soils, Van Breemen (1993) found that activities of Al^{3+} obeyed the relationship $[Al^{3+}][SO4^{2-}][OH^-] = 17.3$. As sulphate activities vary relatively little in most acid sulphate soils, constant values of $[Al^{3+}][SO4^{2-}][OH^-]$ imply that the activity of Al^{3+} increases about tenfold with a unit decrease in pH. At pH values less than 4 to 4.5, aluminium is increasingly soluble and toxicity can be expected.

Waterlogging causes an increase of pH to a value between 6 and 7 after several weeks of flooding in most moderately acid sulphate soils (Ponnamperuma, 1972) as the reduction process consumes protons. Thus, flooding may help to avoid aluminium toxicity. However, in old acid sulphate soil (Sulfic tropaquepts), Van Breemen and Pons (1978) found a small increase of pH upon flooding, probably because of low contents of "easily reducible iron". For very acidic soils Konsten et al. (1994) in Indonesia, and Verburg (1994) in Vietnam, observed no apparent reaction of the pH to flooding and drainage. The lack of pH increase was attributed to a high buffer capacity due to relatively large amount of exchangeable and dissolved Al, basic sulphates of Al and Fe, and absorbed sulphates.

Reduced conditions

Iron

The increase of pH upon flooding is mainly due to the reduction of Fe^{3+} compounds to Fe^{2+}, a process that consumes acidity. As a result, ferrous iron toxicity often occurs in flooded acid sulphate soils (Langenhoff, 1986). Nhung and Ponnamperuma (1966) give the relationship between pH and concentration of dissolved Fe2+ as follows:

$pFe^{2+} = 2\ pH - pH_2S - 3.52$

Upon flooding, the concentration of dissolved Fe^{2+} normally increases due to a reduction of ferric oxide by organic matter. In most acid soils dissolved Fe^{2+} increases to 100-600 ppm in the first 2-10 weeks of flooding and later decreases to a level between 50 and 100 ppm. The curve is particularly steep and the peak is high at high contents of active iron and organic matter. The maximum concentrations of Fe^{2+} reached in acid sulphate soils are often maintained for prolonged periods. Especially when the pH remains below 5, sulphate reduction (to sulfides that can precipitate with Fe^{2+} in FeS) is a slow process, so Fe^{2+} decreases only after prolonged submergence (Van Breemen and Moorman, 1978). Iron concentrations also tend to increase with salinity (Van Mensvoort et al., 1984).

On acid sulphate soils, ferrous iron concentrations reported in literature are highly variable. It ranges from less than 100 ppm to 5000 ppm two weeks after submersion, with common values of 500-1000 ppm (Bloomfield and Coulter, 1973).

Hydrogen sulphide

During flooding, sulphate reduction produces H_2S (g). Even at concentrations as low as 1 to 2 10^{-6} mol/m3, H_2S can affect the plant-root system (suffocation), especially in young seedlings (Sylla, 1994). The bacteria responsible for sulphate reduction are said not to operate in acid conditions, so H_2S toxicity only develops after the soil pH as been raised to about 5 by prolonged flooding (Dent, 1986). However, Jacq et al. (1993) mention that in rice fields in mangroves they can adapt to a pH between 4 and 5.

As H_2S normally reacts with Fe^{2+}, yielding FeS and, ultimately pyrite, toxicity is associated with soils rich in organic matter and low in iron (Dent, 1986). However, Tanaka et al. (1968) argued that a high production of CO_2 may lead to the formation of $Fe(HCO_3)_2$, liberating H_2S.

The physiological disease associated with hydrogen sulphide is known in Japan as "Akiochi". The respiratory activity of the roots is impaired; affected plants are deficient in silica and bases. (Bloomfield and Coulter, 1973).

Hydrogen sulphide decreases the oxidative power of the roots and induces Fe^{2+} toxicity because the roots are no longer capable of oxidising Fe^{2+} at the root surface (Van Mensvoort et al., 1984). The roots also lose their ability to absorb nutrients and become susceptible to *Helminthosporium*, *Piricularia Oryza* and other diseases (Bloomfield and Coulter, 1973).

Carbon dioxide and organic acids

The decomposition or breakdown of organic matter produces CO_2 or organic acids. CO_2 accumulates in flooded soils, and in acid soils that are rich in organic matter and iron. The partial pressures of CO_2 in solution may rise to 80kPa within two weeks of flooding, but then decline rapidly as a result of escape and reduction to methane. Carbon dioxide concentrations greater than 15 kPa retard root development and respiration (Van Mensvoort et al., 1984), leading to wilting and reduced nutrient uptake (Dent, 1986).

Carbon dioxide and organic acids also have the capacity to dissolve various substances. When the partial pressure of carbon dioxide or the organic acid concentration in a soil is high, the concentration of various elements in the soil solution, such as iron will be high (Tanaka and Navasero, 1967).

Deficiencies

Acid sulphate soils that have undergone a long period of leaching will be depleted of bases and weatherable minerals. Their exchange complex will be saturated with aluminium (Dent, 1986). Acid sulphate soils are therefore likely to be deficient in calcium and potassium, and possibly magnesium (Bloomfield and Coulter, 1973). Deficiency of zinc, coper and molybdenum have also been reported (Dent, 1986).

However, in the absence of iron and aluminium toxicity and of harmful salinity, phosphorus deficiency is the most important nutritional disorder on (actual) acid sulphate soils (Van Breemen and Pons, 1978). At low pH, active aluminium and iron present in high quantity form very insoluble phosphates (Dent, 1986). The large amounts of exchangeable aluminium in acid sulphate soils, under dryland conditions, could cause severe phosphate deficiency. However, it is uncertain whether the deficiency can be attributed to acidity per se or to the overall shortage of phosphates (Bloomfield and Coulter, 1973).

Phosphorus plays an important role in the photosynthesis. It favours growth, roots development, and is a factor of precocity and has an essential role in fecundation (Ministère de la Coopération et du Développement, 1991).

Very good responses to added phosphate, especially rock phosphate, have been reported (Beye, 1973; Dent, 1986; Nghia, 1992). The timing of application may be important. Applied when soils are flooded, phosphorous would remain available to the rice plant, but it would crystallise as poorly soluble aluminium phosphate when applied in dry conditions (Bloomfield and Coulter, 1973).

Biological problems

Low pH strongly inhibits microorganism development. Acid sulphate soils are very poor in microorganisms, but the total microorganism content is strongly influenced by the cultivation regime and vegetation. There is an abundance of denitrifyers, as opposed to nitrifying and nitrogen-fixing bacteria (Phung and Lieu, 1993).

Unfavourable conditions for microorganisms restrict the release of nutrients from the decomposition of organic matter. Under the severely-reducing conditions often met in these soils, especially in depressions, the breakdown of organic matter is incomplete (Dent, 1986). The processes of both decomposition and assimilation are much slower in a submerged soil than in a well-drained soil, and end products are different. In a normal well-drained soil the end products are mainly carbon dioxide, nitrate, sulfate and resistant residues. The products of organic matter decomposition in a submerged soil are chiefly carbon dioxide, methane, hydrogen, and organic acids derived from the carbohydrates, ammonia, amines, mercaptans and hydrogen sulphide from the proteins, and residues (Ponnamperuma, 1955).

Part IV

Rice and acid sulphate soils

Development of rice

Plant cycle

The rice cycle has been described often (Vergara, 1970, Ishizuka, 1971; Tanaka, 1976; Yoshida, 1981, Apakupakul, 1991). It can be divided in three phases:

* The vegetative phase, from seedling emergence to panicle initiation. Its length varies with variety, from 30 to 150 days according to the total length of the cycle. This phase determines the number of tillers and the number of potential panicles. Water deficits in this phase may reduce plant height, tiller number and leaf area index and may cause retarded growth (Yoshida, 1981)

* The reproductive phase, from panicle initiation to flowering, lasting 30 to 35 days, during which the number of spikelets and the number of potential grains are determined.

* The ripening phase, from flowering to physiological maturity, lasting between 25 and 35 days. During this phase, length and speed of grain filling will determine the weight of the grains and the percentage of filled grains.

During the vegetative phase, most dry matter accumulates in leaves and roots. After panicle initiation, dry matter accumulates in leaf sheaths and at the base of stems. After anthesis, most carbohydrates in vegetative organs migrate to grains. Cock and Yoshida (1972) showed that respectively 68, 20 and 12% of carbohydrates in vegetative organs migrate to grains, are used for respiration and remain in leaf sheaths and stems.

It is generally assumed that the carbon contained in the grains of rice plants is derived mainly from photosynthetic products originating from the leaves after the flowering stage (Ishizuka, 1971). However, the contribution of carbohydrates accumulated in vegetative organs before flowering to grain filling usually varies from 0 to 40%, but can reach 90%, especially when nitrogen is deficient and/or solar intensity is low during the grain filling period (Apakupakul, 1991). Ishizuka (1971) also reports that 60-80% of the total phosphorus absorbed at each stage of growth was translocated to the grain.

Rice yield build-up

In the past 20-30 years, crop simulation models have been developed to integrate the available knowledge about processes determining plant growth (Wopereis, 1993). A simple model of yield build-up, i.e. a theoretical model of biological functioning of a cultivated population of plants (Sebillotte, 1978; De Bonneval, 1993) is given for cereals by Sebillotte (1980) and Meynard and David (1992). Yield is decomposed in two terms:

$$\text{Yield} = NG \times W1G$$

Where: NG= Number of grains per square metre

and W1G = Average weight of one grain

For wheat, (and for rice in first approximation), NG is determined before anthesis (or flowering), while W1G is determined after anthesis (Meynard and David, 1992).

Observation and analysis of yield components can assist in the diagnosis and the identification of bottleneck in plant growth.

Number of filled grains per surface unit

NG can be divided in:

Number of panicles/m² x Number of spikelets per panicle x Percentage of filled grains.

Number of panicles/m²

Plant density is very variable in case of direct sowing and rice is susceptible to submergence. Tolerance to submergence varies with variety. The survival of seedlings after complete submergence in water decreases with increased duration of submergence (it sharply decreases after 6 days), with increased depth, water temperature and water turbidity, and with increased nitrogen content of the soil. Survival increases with high light intensity and plant carbohydrate content. Factors that influence the survival of submerged plants also determine the amount of N and carbohydrate in the plant (Palada and Vergara, 1972; Vergara et al., 1976; Mazaredo and Vergara, 1981). Jacq et al. (1993) also report that anaerobic sulphate reduction can lead to very high plant mortality. Singh et al.(1988), and Thangaraj and Sivasubramanian (1990), have shown that tillering is reduced by low light intensity. Competition for light explains that tillering decreases when plant density increases. Tillering is also positively correlated to the N content at the tillering stage (Ishizuka, 1971).

Finally, Matsushima (1966) showed that to be effective and produce a panicle, a tiller must start his growth before the main stem reaches the stage of panicle initiation.

Number of spikelets per panicle

Yoshida (1981) mentions that in conditions of high density (thus competition for light), the number of spikelet per panicle clearly decreases when plant density increases, but the number of spikelet per surface unit can be increased. The number of spikelets per surface unit varies with the leaf area index (Fagade and De Datta, 1971), the N content and the carbohydrates stocked in the stems (Apakupakul, 1991).

Percentage of filled grains

The percentage of filled grains is highly variable, ranging from 3 to 97% (Apakupakul, 1991). It is influenced by the variety and is decreased by:

* Early logging and diseases as *Piricularia Oryzae* (Durr, 1984).
* High temperatures (over 35°C).
* High nitrogen fertilisation before heading (Durr, 1984).
* Unbalanced equilibrium between the number of spikelets and their capacity to accept carbohydrates on the one hand, and the photosynthetic activity on the other (Apakupakul, 1991). Low solar radiation during the maturing period, for instance, reduces percentage of filled grains (Matsushima, 1966).

Weight of one grain

Weight of one grain is known to be function of (Apakupakul, 1991):

* Temperature
* Hydric deficit in the beginning of the grain filling period that provokes a decrease of filling speed and weight of grains.
* Solar intensity and photosynthetic activity: grain filling speed is linked to carbohydrates produced in leaves.
* Parasitism and toxicities.

Yield

Yield is chiefly determined by the number of grains/m², which is more variable than the weight of one grain. (Durr, 1984, Crozat et al., 1986, Apakupakul, 1991). When NG increases, W1G is usually constant at a maximal value (when there is no limiting factors), until a threshold value of NG, above which W1G decreases when NG increases (Apakupakul, 1991).

Rice physiology

Tolerance to acidity, aluminium and salt

Rice and salt

Rice is moderately tolerant of salinity. 100% yields are obtained at ECe values (soil saturation extract) of up to 3 mS/cm (Langenhoff, 1986). According to Ayers and Westcott (1976), 10%, 25%, 50% and 100% yield reductions are caused by ECe values of 3.8, 5.1, 7.2 and 11.5 respectively. Salt tolerance differs widely among varieties and varies strongly with the growth stage. It is very tolerant during germination but sensitive at the 1-2 leaf stage. The tolerance of rice progressively increases during the tillering and elongation stages of development and again decreases at the time of floret fertilisation (Richards, 1954). In those areas where salinity is only a temporary phenomenon, the duration of the saline period is as important as the concentration of the salts (Van Mensvoort et al., 1984).

Rice and acidity

Rice favours a pH between 4 to 8, with an optimum value around 6 (FAO, 1979, and Ministère de la Coopération et du Développement, 1991). However, a low pH and the associated aluminium toxicity do not always hamper the growth of rice (Langenhoff, 1986). Rice in its vegetative growth stage was found not to be affected by H^+ concentrations up to pH 3.5, although the high acidity suppressed the uptake of metallic cations (Thawornwong and Van Diest, 1974; Sen, 1988).

Rice and aluminium

The deleterious effect of aluminium on the growth of rice varies with varieties and stage of growth. It is especially noticeable in the seedling stage (Thawornwong and Van Diest, 1974). In solution cultures of low pH, Al is toxic to young seedlings at 0.05-2 mg/litre while 3 to 4-week-old plants show toxicity at 25 mg/litre. In acid sulphate soils, Al reaches 1mg/litre at pH of 4.8 and increases by a factor 10 for each unit decrease in pH. Toxicity in rice is therefore likely to occur at pH of 4.5-5.0 for seedlings and 3.4-4.0 for older plants (Van Mensvoort et al., 1984).

Critical value was also found to vary with P status of the plant, and with the Fe concentration and pH (Sen, 1988).

Symptoms of Al toxicity are white or yellow interveinal chlorosis of the older leaves. In severe cases the chlorotic parts become necrotic (Yoshida, 1981). Foliar symptoms often resemble those of phosphorus deficiency, induced calcium deficiency or iron deficiency (Foy, 1984). Aluminium is first evidenced by root injury. The roots of aluminium-affected plant are characteristically stubby in appearance, and the root tips and lateral roots may become thickened and turn brown. The whole root system has a corraloid appearance, having many thickened lateral roots but lacking in fine branching. (Bell and Edwards, 1986). However Al may cause harmful effects before it becomes visible in the leaves (Van Mensvoort et al., 1984) or even in the root system (Bell and Edwards, 1986).

Aluminium toxicity may be avoided by flooding, which raises the soil pH, but rice may still suffer from aluminium toxicity on acid sulphate soils if seeds are broadcasted prior to flooding, or if seedlings are transplanted before reduction processes have raised the pH sufficiently to immobilise aluminium (Dent, 1986). Aluminium toxicity may also persist in acid sulphate soils that show little or no pH increase. Furthermore, submersion leads to reduction which creates other toxicities.

Rice and low redox potential: Induced Fe toxicity

Under submerged conditions, iron toxicity is expected, especially on acid sulphate soils. Excess iron itself may block nutrient uptake, e.g. through coating of ferric oxide on roots (Howeler, 1973) and leads to the accumulation of free acid within the plant (Van Mensvoort et al., 1984). However, Fe toxicity is a result of multiple nutritional stresses and not simply the result of excess Fe (Ottow et al., 1983; Moore et al., 1990). The susceptibility of rice plants to iron toxicity also appears to be influenced by the physiological status of the plants (Jayawardena, 1984). Finally, Fe intoxication is frequently accompanied by a number of other soil-related, agricultural and/or phytopathogenic problems (Ottow et al., 1981).

Symptoms

First symptoms appear on the root system. Roots are scanty, coarse and often dark brown, stained brown or reddish (Van Breemen and Moorman, 1978, Van Mensvoort et al., 1984). When severely damaged they may be partially covered by black FeS and finally die (Ottow et al., 1983, Hanhart and Ni, 1993). A large number of small brown spots (= punctuate accumulation of Fe) appear on purple to dark-green leaves about three to four weeks after the rice plants have been transplanted (this phenomenon is referred to as bronzing). The symptoms first appear at the tip of the leaf, spread in a basipetal direction over the blade, and can result in the death of the oldest leaves. The development of the plant is locally very inhibited (Ottow et al., 1981). The symptoms may appear at any growth stage, but commonly at maximum tillering and heading. Low yields from iron toxicity are associated with a high percentage of unfilled grains (Van Breemen and Moorman, 1978).

Oxidising capacity of rice roots

To survive in a predominantly reduced environment, the rice plant pumps oxygen downward through the root, creating an oxidised zone around it. In this oxidised zone around the root, iron III is precipitated as a brown crust of ferric hydroxides, preventing the uptake of excess Fe^{2+} ions (Hanhart and Ni, 1993).

All factors having a negative effect on oxidising capacity of the roots or lowering the redox potential around roots will therefore favour iron uptake and thus toxicity.

Factors promoting Fe toxicity

Critical concentrations for the development of bronzing vary from as low as 30 to 500 ppm, depending mainly on the nutrient status of the plant, the concentration of naturally occurring respiration inhibitors such as H_2S and toxic organic reduction products and rice variety (Van Breemen and Moorman, 1978).

Nutritional disorders and requirements for fertilisation

Jayawardena, 1984 mentions that nutrient deficiencies cause symptoms of iron toxicity to occur under low level of soluble iron concentration.

Trolldenier, 1977 (in Van Breemen and Moorman, 1978) observed that deficiencies of potassium, calcium, magnesium, phosphorous and manganese increase the uptake of iron. He suggests that low potassium and phosphorous aggravate iron toxicity through decreased oxidising capacity of the roots. Benckiser et al., (1984) also observed that N, P, K, Ca and Mg fertilisation reduces Fe content in root tissues, and explained it by an improvement of the excluding mechanism of the plant.

For Ottow et al. (1981 and 1991), the undersupply of K, P, but also Ca results in the breakdown of the Fe(II)-excluding mechanism in the root zone and in a reduction of the tissue tolerance for Fe and Mn- accumulations. They conclude that Fe-intoxication of rice is due to multiple nutrient stress. Prade et al. (1988) also mention that insufficient supply of K, Ca and Zn probably increases root permeability, carbohydrate exudation and iron reduction, which are a prerequisite for the breakdown of the effective iron-oxidising and excluding mechanism.

P fertilisation positively affects the physiology of roots. The better the supply of P, the more effective the Fe and Al excluding mechanism of the root system seem to operate (Ottow et al., 1991).

For Moore et al. (1990), Fe stress not only involves high Fe^{2+} activities, but also a low base status and is due to the combined effects of Fe toxicity and deficiencies of other divalent cations such as Ca and Mg. They suggest that competitive inhibition for uptake sites on plant roots is based on charge alone, and proposed to include the effects of the competing ions in availability indices. Thus, Moore and Patrick (1993) correlated rice growth indices with A_{Fe} (the ratio of Fe^{2+} activity to the sum of the activities of divalent cations). They explain this correlation by competition between divalent cations. In Ca and/or Mg-deficient rice growing soil, Fe is the dominant cation in solution and Fe uptakes are high.

Finally, Okuda and Takahashi, (1964 in Van Breemen and Moorman, 1978) observed that silica has a positive effect on the oxidising capacity of intact rice roots (but not of cut root segments), probably through enlargement of increased rigidity of gas channels, and depresses the uptake of iron at high Fe^{2+} concentrations. For Tanaka and Yoshida (1970), a good supply of Si not only stabilises the formation of the aerenchymal system, but also promotes tissue tolerance towards Fe and Mn-intoxications

Acidity and salinity

High acidity may considerably increase the solubility of the iron compounds (Ottow et al., 1981), and iron concentration tend to increase with salinity (Van Mensvoort et al., 1984). Thus, low pH and high salinity due to sodium chloride or magnesium chloride increase iron uptake and may aggravate iron toxicity (Yoshida and Tadano, 1977 in Van Breemen and Moorman, 1978).

Fresh organic matter and organic acids

Organic acids produced by decomposing fresh organic matter are known to retard rice growth (Chandrasekaran and Yoshida, 1973).

Takijima (1964 a and b) showed a market root growth inhibition and root damages by organic acids, especially acetic and butyric acids, just after waterlogging. In culture with acetic acid, rice seedlings showed a remarkable reduction in plant growth and in nutrient absorption of P_2O_5, K_2O and SiO_2. However, Takajima suspected other inhibitory factors and estimated that physiologically normal roots can reduce the inhibitory effect of organic acids.

Strong anaerobia: The action of sulphate-reducing and ferric iron-reducing bacteria

Factors favouring low redox potential, such as long submersion or high organic matter content can decrease rice protections against iron. Hanhart and Ni(1993) mention that in the presence of decomposing root remnants, very strong reduction takes place. In these reduced conditions, reduction of sulphates to sulphides can take place, as a black colour and a strong H_2S smell indicate. In such situations, they observed that the brown crust around roots disappeared, which they explained by the oxidation of iron III hydroxides (which prevents excessive uptake of Fe^{2+}) to Fe^{2+} which can freely enter the root and the rice plant. Thus, they could observe plant symptoms indicating iron toxicity, when dissolved iron never exceeded 10 ppm. They described the nutrient disorder as Fe-toxicity aggravated by deep reduction.

These processes of sulphate and ferric iron reductions have been explained by sulphate- and ferric iron- reducing bacteria. In Senegal, Jacq et al. (1993) identified 14 sulphate-reducing bacteria (*Desulfovibrio* and *Desulfotomaculum*), and 46 ferric iron-reducing bacteria. They all require strong anaerobia, and the most active ones have been found in mangroves.

These bacteria progressively colonise roots. First, sulphate reducing bacteria, more anaerobic than ferric iron-reducing bacteria, colonise the spermosphere or the far rhizosphere. As soon as the mechanism of protection becomes weak, ferric iron-reducing bacteria colonise the close rhizosphere and the rhizoplan, the microbial processes being favoured by root debris and exudation of carbohydrates by rice roots used as energy (Prade et al., 1988). Production of black FeS also explains observations of black roots made by Ottow et al. (1981) and Hanhart and Ni (1993).

Jacq et al.(1993) concluded that these anaerobic bacteria, especially ferric iron -reducing ones, are opportunist. They attack plants at sensitive stages or when they already suffer, for instance from deficiencies. They lead to the accumulation of highly toxic ions, responsible for high mortality of young plants, death of old leaves, and stopping of growth and fructification on older plants, symptoms often associated with ferrous iron toxicity.

Furthermore, roots of dead plants add to the process. As fresh, easily decomposable organic matter, they are a source of energy for these bacteria and participate in the acceleration of the process.

Hydrogen sulphide

Reduction of sulphates to sulphides by *Desulfovibrio* and *Desulfotomaculum* leads to the production of H_2S. Hydrogen sulphide can be toxic to rice at a very low concentration of 1 ppm (Mitsui, 1955, Hanhart et al., 1997). Young rice plants are especially susceptible; older plants appear to be able to counteract H_2S toxicity by creating oxidising conditions around their roots or/and by proliferation of their root system. But the oxidative power of the roots may be affected by the presence of H_2S (Tanaka et al., 1968; Tadano and Yoshida, 1978, Hanhart et al., 1997). Hanhart and Ni (1993) described a nutritional disorder associated with deep reduction as H_2S-induced toxicity. Plants affected by H_2S are especially susceptible to infection. The conditions of "Akiochi" and "brusone" are associated with sulphide toxicity (Dent, 1986).

Conclusion on iron toxicity in deeply reduced conditions

Iron toxicity is a complex phenomenon, that usually does not appear alone. It can be induced by deficiencies, or by the presence of H_2S. It can be associated with activity of sulphate-reducing and ferric iron-reducing bacteria. Finally, weak plants are then susceptible to pests and diseases. The predominant diseases of rice on acid sulphate soils are caused by fungi. According to Hamdan et al.

(1990), the most important ones are brown spot (*Helminthosporium oryzae*), narrow brown spot (*Cercospora oryzae*), leaf scald (*Rhynchosporium oryzae*), blast *(Pyricularia Oryzae)* and sheat blight (*Rhizoctonia solani*). Tolerance of rice to iron toxicity and toxicities associated to low redox potential is associated mainly to the oxidative capacity of its root system. Marked varietal differences exist in the tolerance for excess iron (Ponnamperuma and Solivas, 1981). Healthy plants can support rather high concentration of ferrous iron. Plants weakened by deficiencies in P, K Ca, Mg and/or Zn or possibly by pest attacks lose their oxidative capacity. Iron uptake by the rice plant is increased. The development of anaerobic conditions even around rice roots opens the door to activity of sulphate-reducing and ferric iron-reducing bacteria producing toxic substances that will further weaken the plant. Thus, if rice roots loose a part of their oxidative capacity, rice plants enter a vicious circle of increasing external pressure and decreasing ability to sustain these conditions.

Rice cultivation on acid sulphate soils

Optimal growing period

In Sierra Leone, Sylla et al. (1993) studied acid sulphate soils spatial and temporal variability to determine a time window during which soil constraints are least. They showed that the optimal period for rice growing depends on location within the river basin as well as on toposequence position within each location.

In the Mekong Delta, Vietnam, Hanhart and Ni (1993) identified 3 main periods from the redox point of view:

* Continuous oxidation during the dry season, from January to May. During this period soil acidify and aluminium reaches its peak.

* Alternating oxidised and reduced conditions during the first part of the rainy season (May to August). At the beginning of this period, the concentration of soluble aluminium is maximum but it will gradually decrease due to leaching, surface flushing and a gradual rise in pH upon soil reduction.

* Continuous reduction during the flood (August to January). Aluminium concentration is at its minimum due to highest pH. Ferrous iron concentration is maximum 2-3 weeks after flooding but progressively decreases. Hydrogen sulphide may be produced locally in strongly reduced conditions.

Therefore, they concluded that the optimal time to start the cultivation of a crop is at the end of the flood, when pH is high and aluminium and ferrous iron concentrations are low. Irrigation could preserve these optimal conditions throughout the cultivation period.

Water management

Water management is the key to acid sulphate soils management (Dent, 1986; Sen, 1988). Tuong (1993) distinguished the effects of water table management and surface water management from those of leaching.

Watertable management

Detrimental effects of pyrite oxidation by lowering the watertable in coastal potential acid sulphate soils on crop yields led to one of the general recommendations for management of potential acid sulphate soils: controlled high watertable to keep the sulphidic subsoil waterlogged and hence prevent acid formation (Tuong, 1993). However, in areas with a long dry season, 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.

For actual acid sulphate soils, further acidification is not expected and not much gain will be gained by keeping the watertable high (Tuong 1993). In contrast, keeping the water table low is particularly important to avoid the upward transport of acid water to the rootzone (Kselik, 1990).

In recently-oxidised acid sulphate soils, pyrite may still exist in the inner cores of the soil peds of the sulphuric horizon and may be oxidised if the watertable drops for an appreciable time. Therefore Xuan (1993) recommends keeping submerged both sulphidic and sulfuric horizons.

In Indonesia, Kselik et al. (1993) proposed different water management strategies according to hydrological characteristics and soil type (actual or potential acid sulphate soils).
When possible, they recommend soil leaching for actual acid sulphate soils, and improved drainage for potential acid sulphate soils. However, this requires a rather good water control.

Tuong (1993) considers important to recognise the practical difficulties in maintaining the watertable at the desired depths on a large scale. On the one hand, the optimal watertable level is a function of depth to soil sulfuric and sulphidic horizons, which is highly variable in space. On the other hand, it is difficult to control the water table when, like in Vietnam, hydraulic conductivity is in the order of 0.1 m/day. Water control in such situations would require a very dense canal network at distances less than 20m (Tuong, 1993).

Surface water management

From the soil amelioration point of view, keeping ripe acid sulphate soils under submergence is not a necessary measure (Tuong, 1993).

For raw acid sulphate soil, it is commonly observed that rice plants in the higher spots of waterlogged fields perform better than those in continuously submerged locations. Hanhart and

Ni (1993), observed that plants growing under continuously submerged conditions were suffering from a nutritional disorder which can be described as an H_2S-induced iron toxicity. As regular oxidation of the topsoil leads to aluminium toxicity, it does not result in a significantly higher yield. Thus, Hanhart and Ni recommended limiting the dry periods to one or two periods just before flowering. This way, aluminium toxicity during the vegetative stage is prevented, as well as deep reduction during the flowering.

Leaching

Leaching can have positive effects on acid sulphate soils (Ponnamperuma et al., 1973, Van Breemen, 1976), but it is usually a slow process in natural conditions as in Indonesia (Konsten et al., 1992; Tuong, 1993). The effectiveness of leaching soluble aluminium is strongly affected by the soil's physical properties, such has the hydraulic functions, infiltration rate and porosity patterns (Minh, 1996). The arrangement and sizes of macro-pores and aggregates have a strong influence on both 'by pass' flow and the extent to which diffusion proceeds towards equilibrium and, therefore, to the leaching process (Tuong, 1993). Thus, proper land preparation and its timing to form suitable soil aggregates and to influence the initial solute distribution can enhance the leaching rate.

Land preparation

Several practices can have a positive effect for cultivation on acid sulphate soils.

Puddling is known to have important effects on soil characteristics and rice yield. It decreases tropical soils temperature and temperature amplitudes by changing bulk density, moisture content and percolation rate. It also decreases the rigidity of pores and soil resistance to penetration, thus improving root growth of rice (Sharma and De Datta, 1986). In the long-run, it creates a hardpan in the subsoil, below the puddled layer. This hardpan has a higher bulk density, lower total porosity and lower permeability than the underlying soil horizons. It increases water control and reduces capillary rises.

Surface tillage makes cracks discontinuous, and water is therefore better retained in the topsoil (Wopereis, 1993). Thus, puddled soils dry more slowly than unpuddled soils, probably because the higher unsaturated hydraulic conductivity of puddle soils can keep surface soil wet during evaporation by suppling water from lower layers, and because of increased water retention (Sharma and De Datta, 1985).

On acid sulphate soils in the Mekong Delta, Vietnam, harrowing and puddling help increase contact surface between soil and water, which enhances the effectiveness of flushing of rice fields. At the end of the flood, harrowing helps increase rice yields (Tuong, 1993; Minh, 1996).

Minh (1996) also showed that capillary rise in the dry season leads to the accumulation of aluminium in the topsoil layers. He found that mulching significantly reduces evaporation, and as the consequence, capillary rise.

Tuong et al. (1993) and Minh (1996) demonstrated the interest of ploughing which decreases the unsaturated hydraulic conductivity of the topsoil and improves the leaching rate, and thus reduces Al concentration in the soil solution

Fertilisation

The literature shows a large number of fertility-oriented experiments on irrigated rice, amending acid sulphate soils mainly with lime and various phosphorus fertiliser. Contrasting results were obtained regarding the application of lime. The main reasons for these contradictory results might well be a lack of proper characterisation in advance of the conditions under which the plants grow in the field experiments, especially water management (Van Mensvoort, 1996), and insufficient number of replications to detect differences (Johnstone and Sinclair, 1991).

Phosphorus, especially rock phosphate, and possibly lime seems to have a positive effect on rice yield, provided good water management is conducted.

Part V

Conclusions

The history of research on acid sulphate soils reflects the struggle of researchers, and farmers, with the high variability of these soils. A focus on identification, distribution and genesis formed the basis of acid sulphate soils research until the 80's (Van Mensvoort, 1996). After this period, variability of acid sulphate soils was better acknowledged and addressed, especially in the domain of land surveys and mapping. Sophisticated tools were rapidly applied to characterise soil variability, and to integrate it in the surveys. Mapping methods were proposed to assess the reliability of maps produced in highly variable environments, and to gain in reliability (Bregt, 1992). Research on soil genesis progressively integrated soil evolution, and soil classifications were adapted to integrate important sources of variability. Land use planning was improved, in particular thanks to modelling of possible developments of these soils. Actual land use and farming systems, which reflect soil variability, were also studied, and farmers' knowledge gained in consideration. Finally, integrated approaches were developed, to study variability across the scales (Sylla, 1994), or to analyse soil-water-crop interactions (AARD/LAWOO, 1992; Hanhart and Ni, 1993).

However, several gaps remain:

* Acid sulphate soils research is still mainly soil-oriented. Even in fertilisers or water management experiments, most attention has been given to soil chemistry, and the physiology of the plant has been neglected (especially true for rice, the most adapted to these soils). Only recently, plant growth under varying conditions received some attention (Hanhart and Ni, 1993; Hanhart et al., 1997).

* Farmers' knowledge is still under-used (Van Mensvoort and Dent, 1996), and the real cropping conditions they have to face are often not taken into account. Most experiments on fertilisers and water managements have been carried out in glasshouses and pots, or research stations. Idealistic "solutions", developed under highly controlled conditions are proposed, often implying sophisticated water management, when such water control is unrealistic in large areas, with farmers' means. The conduct of research under real farmers' conditions appeared only very recently, Tri (1996) being a pionner in this domain.

Furthermore, most experiments are conducted on moderately acid sulphate soils, or in fields that have been improved by cultivation. Although there is a high and urgent demand from farmers, no results are available for the reclamation of severely acid sulphate soils.

* The very high short-range variability of acid sulphate soils, although recognised, is still badly known, has not been explained, and is not integrated in experimental designs and set up. This very high variability at field scale can greatly perturb experiments. Van Mensvoort (1996) attributed the contradictory results on fertilisers to the lack of proper characterisation in advance of the conditions under which plants grow in the field experiment.

* Finally, although progress has been made with integrated approaches, interactions between soils, water and plant growth are quite complicated and relations are poorly known. Such knowledge is needed to develop cropping techniques adapted to these difficult conditions. This requires a more detailed characterisation and understanding of variability at field level.

Chapter 3

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

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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, ground water table and microtopography. On "high" locations (higher than 85 cm above mean sea level), Typic Sulfaquepts are covered with *Ischaemum spp.* Highly organic and hydromorphous Hydraquentic Sulfaquepts are found in "low" locations (lower than 75 cm above mean sea level), where *Eleocharis spp.* 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 topography 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 to microtopography.

Correlations between topographic level, soil characteristics and natural vegetation can facilitate land surveys and mapping of these highly variable soils. Integration of soil and water variability in the research programmes and use of adapted methods not only increase research efficiency but also make it possible to use variability as an important source of information.

Introduction

Worldwide, acid sulphate soils were recently estimated to cover 24 millions hectares, mostly in densely populated coastal area and river plains in South-East Asia. (Van Mensvoort and Dent, 1996). In the Plain of Reeds, a low depression located in the northern part of the Mekong delta, Vietnam, extensive tracks 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. Because of the high population pressure in Vietnam, these soils have been and are being reclaimed for agricultural use. However, 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 problems can be expected in case of deep reduction. Crop performance on recently reclaimed acid sulphate soils is highly dependent on management techniques and soil characteristics. It is therefore important to develop and transfer to farmers sound agronomic practices, adapted to the specific soil characteristics. However, technology development, technology transfer, but also land use planning and land management are made difficult by the very high spatial variability of 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.

Sylla (1994) conducted a multi-scale agro-ecological characterisation of mangrove ecosystems in West Africa, distinguishing different environments based on climate and coastal morphology at macro scale (West Africa region), on hydrology, physiography and vegetation complexes at meso level (watershed) and on topography, vegetation species, tidal flooding and sedimentation rate at micro level (catena). The short-range variability was not addressed in this survey. The lowest level of analysis was the catena level, 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). In land surveys and mapping, recent 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).

In agronomic research, little care has been given to integration of the short-range variability of acid sulphate soils. Experimental design and implementation of trials are usually made without cautious characterisation, assuming homogeneity within experimental fields or blocks. Soil and water variability can have a strong influence on crop performance at field level. Lack of recognition and characterisation of this short-range variability can lead to inappropriate design and set-up of field experiments and may induce errors in analyses. As an example, Van Mensvoort (1996) attributed the contradictory results of fertiliser experiments reported in literature to the lack of proper characterisation in advance of the conditions under which the plants grow.

Such characterisation is not easy in acid sulphate soil areas. 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 land form 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, 1996).

Studies in the Mekong delta (Agro-Ecological Map of the Mekong Delta by National Institute of Agricultural Planning and Projection, 1987 at scales 1:2 500 000 and 1:250 000, and Map of land constraints to farming in the Mekong delta; Van Mensvoort et al., 1993, scale 1: 2 500 000) and the Plain of Reeds (Atlas of the Plain of Reeds at scale 1:250 000, 1990 by National Centre for Scientific Research) identified physical zones or agro-ecological units based on soil and water constraints, the main ones being acidity, salinity, and depth and length of submersion of soils by flood water. For soils, potential and actual acid sulphate soils are distinguished, and severity of acidity is determined by the depth at which sulphuric horizon appears.

At both scales, soil types are intertwined, in patches and stripes. Zooming down inside the Plain of Reeds the same pattern is observed at larger scales (Soil Map of the Plain of Reeds from National Institute for Agricultural Planning and Projection, 1985, at scale 1:100 000 and Soil Map of Tan Thanh District from Can Tho University, 1994; scale 1:25 000). At these scales, soil variability remains very high and is not properly expressed in maps.

The objectives of this study are:

1. to characterise acid sulphate soil variability in the Plain of Reeds, at different scales, but with special attention to short-range variability (inter- and intra-field levels) 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.

Material and methods

Multi-scale approach

A multi-scale approach (Fresco, 1995) has been applied for this study. Scaling down from the Mekong delta to the Plain of Reeds was based on previous studies and made it possible to identify a village representative of major agro-ecological conditions found on acid sulphate soils in the Plain of Reeds where very detailed soil and water characterisation could be conducted. After validation in other places in the Plain of Reeds of major results obtained at this level, scaling up becomes possible. In this overall process, knowledge and precision are used for (when desegregating), and benefit from (when aggregating), analysis at the next lower level (Andriesse et al., 1994). When aggregating, some detail, including the variability in space and time, is lost, but the overall precision and knowledge achieved at small scale (i.e. on wide areas) are increased (Figure 3.1).

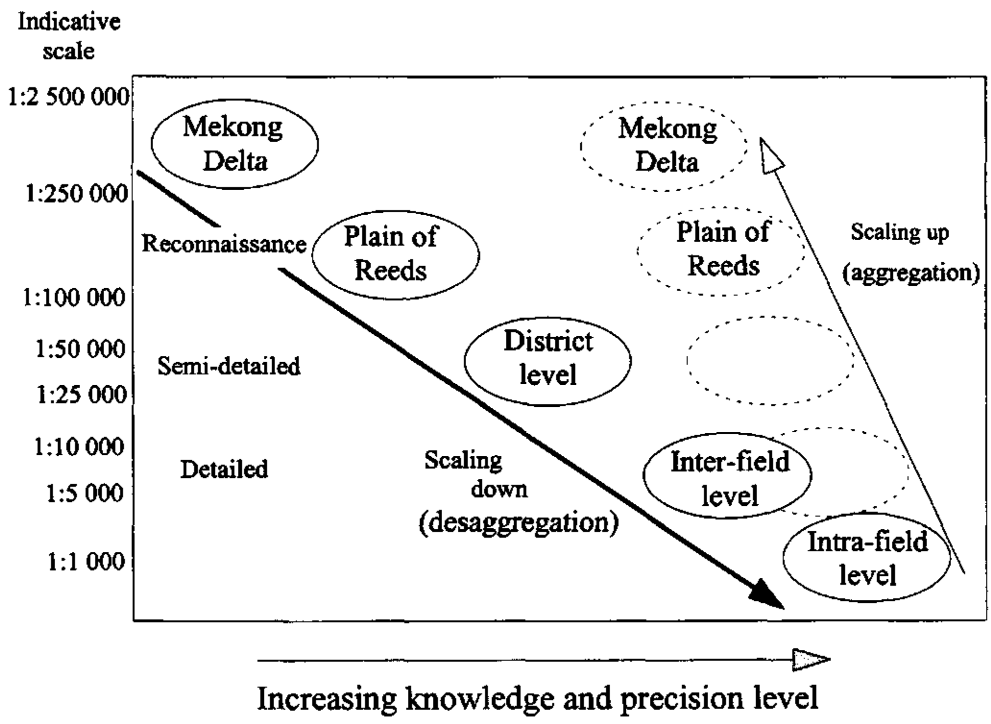

Figure 3.1. Increase of precision and knowledge on acid sulphate soils in the Plain of Reeds (Mekong delta) through a multi-scale approach.

The study area

Tan Lap Village, in Tan Thanh District is located in the central part of the Plain of Reeds, in an area of transition between 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 (Figure 3.2). Thus, major acid sulphate soil types found in the Plain of Reeds are present in this village. 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). The area was also interesting and suited for research since it was still uncultivated at the beginning of the survey, when most of the moderately and slightly acid sulphate soils were already reclaimed.

Like most of the Plain of Reeds, this area is submitted to 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 1 500 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 metre and 6 months) but may vary between years. This makes it possible to cover main cases of inundation for the entire Plain of Reeds.

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.

Data collection.

Soil descriptions presented here are the result of a survey conducted in 1994 (Verburg, 1994). Soils were classified according to Soil Taxonomy (Soil Survey Staff, 1992; Fanning and Witty, 1993). On fallow land, 140 profiles were observed in auger holes in two transects of respectively 300 and 400 metres length with approximately 5 metres between augerings. Two of these profiles have been omitted for analysis as they were located on bomb holes. Detailed soil profiles and analysis were made in three representative sites. All these measurements are in agreement with previous observations and analyses by the IAS/FOS Project on more than 500 soil augerings, and 20 detailed profiles.

Detailed soil maps of experimental fields were made before reclamation by augerings in 10 x 10 metres or 25 x 25 metres grids, with additional profiles when vegetation or topography suggested differences in soils.

Hydraulic conductivity was measured using the "falling head" method (Black et al., 1965). Given values are averages of three replications, measured with 20 cm long cylinders, 15 cm in diameter.

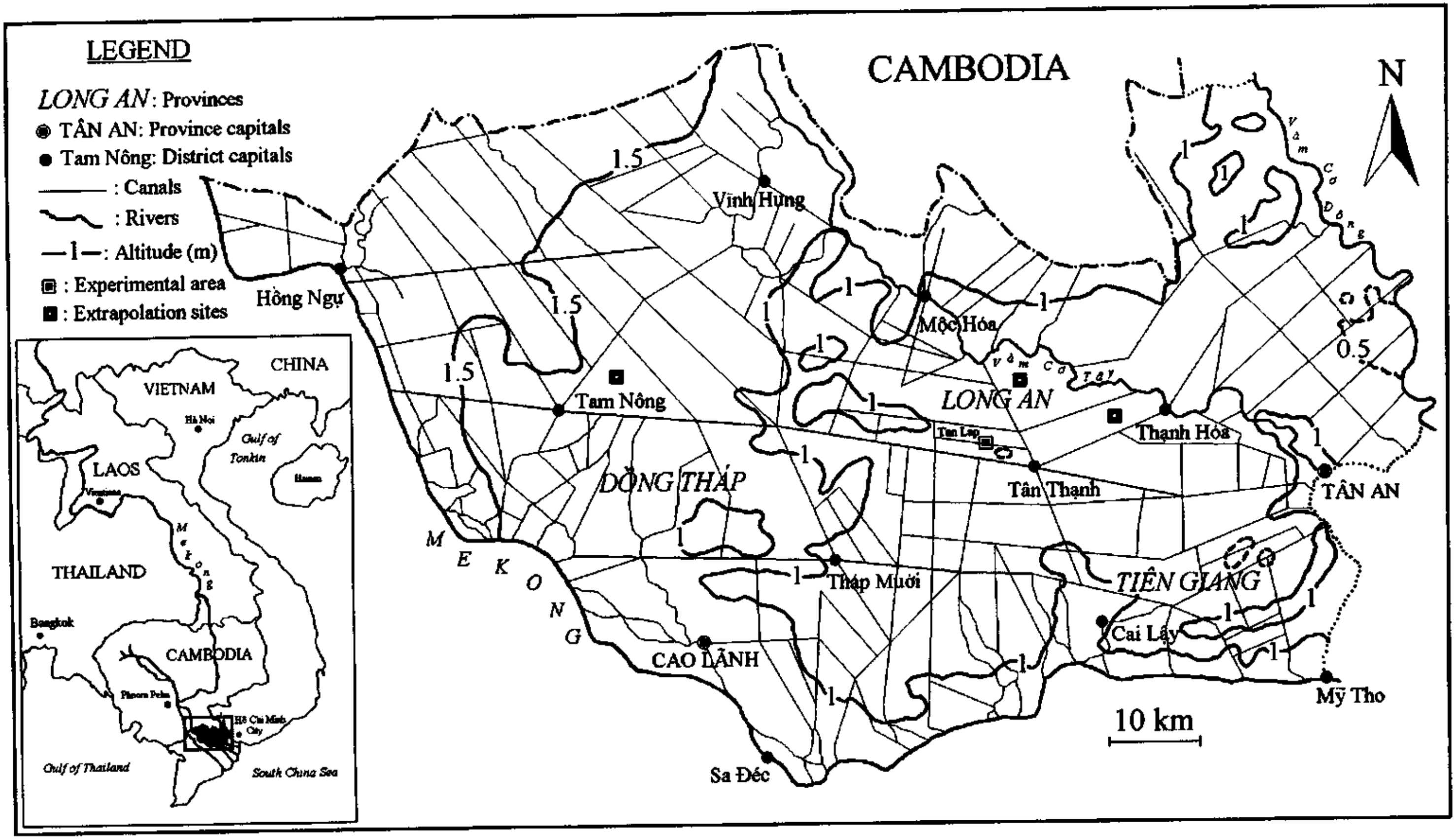

Figure 3.2. Topographic map and location of study areas in the Plain of Reeds, Mekong delta, Vietnam.

Topographic level was measured with a theodolite, and calibrated to mean sea level on a reference point given by the Long An Province Hydraulic Services.

Aluminium concentration was determined by titration with diluted 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 wave length of 420 nm. (Page et al., 1982).

One day per week, water level was measured every hour in a secondary canal in the study area.

Data analysis.

At field level data were analysed by means of scattered 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 mapping. Maps of field characteristics have been made using kriging techniques (Isaaks and Srivastava, 1989) performed on Surfer V4.1 software.

Results.

Soil types.

Two main types of soil are found in the study area, related to the microtopography. They are closely intertwined and a third type of soil with intermediate characteristics is found at the transitional areas between these two soil types.

"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 maximum at highest locations and decreases with soil microtopographic level. Around 85 cm above mean sea level, goethite and jarosites mottles are sometimes replaced by brown to dark brown (10YR4/3) mottles of organic matter fragments. Below about one metre from the surface, the soil is permanently reduced.

The organic matter content increases and wood remnants can be found. 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 3.1. At the driest period of 1994, the sulphuric horizon with jarosite mottles had a pH 2.8-3. Eh varied from 590 to 670 mV. This soil is classified as a Typic Sulfaquept.

Table 3.1. 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 (% mass)	Horizon	Organic matter content (% mass)	Horizon	Organic matter content (% mass)
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				

"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 resulting colour resembles the brown mashed-chestnut colour ("couleur purée de marron") as described by Marius (1984). In the lower part of the sulphuric horizon also 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" consistence). Many recent root channels of *Eleocharis dulcis* penetrate the sulphuric horizon. Organic matter content is very high in all horizons: from 16.2 to 22.7% by mass (table 3.1). 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 water table 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 latest modification proposed to Soil Taxonomy by Fanning and Witty (1993), this soil type is classified as Hydraquentic Sulfaquept.

Transition zone.

Between the high and low parts a transitional type of soil is found. It 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 consists of fibrous organic matter (16% by mass). This soil is classified as Typic Sulfaquept.

Short-range variability of acid sulphate soils.

Soil surveys conducted before land reclamation showed that Typic and Hydraquentic Sulfaquepts, with very different characteristics, could be found at distances of 10 to 20 metres only. In the study area, geostatistical surveys on parameters such as depth to pyrite or jarosite, or percentage of jarosite showed variations at very short range (sometime less than ten metres), with a high anisotropy and a strong nugget effect (data not displayed). Data are not stationary, and the wave-length of undulations varies greatly, from a few tens to several hundred metres. Semi-variograms are often trended, or cyclic (Figure 3.3), suggesting a rippled and undulating pattern, which is reflected by the microtopography of these soils.

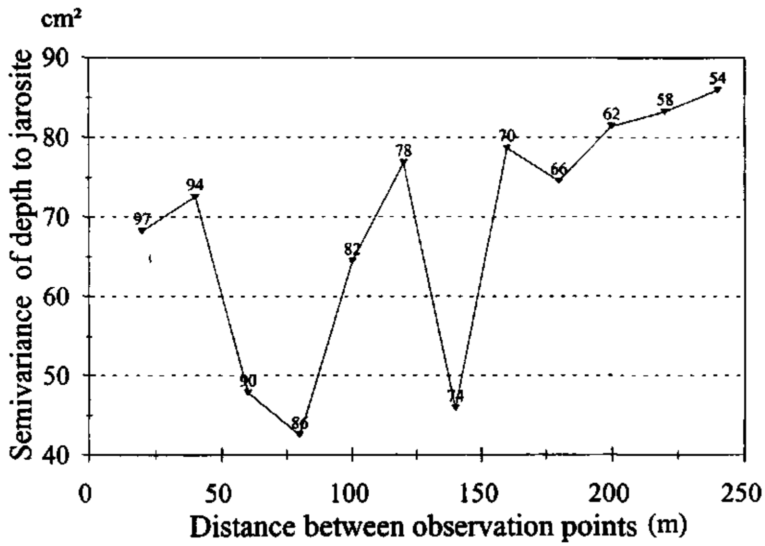

Figure 3.3. Example of unidirectional semivariogram of depth to jarosite in the study area. Values indicate number of pairs for calculation.

Microtopography and soil characteristics.

Soil profiles, water table and topography.

Soil type is correlated to microtopography. This correlation is schematically shown in a cross section (Figure 3.4) based on 138 profiles observed in two transects on fallow land and expressed by decreasing topography.

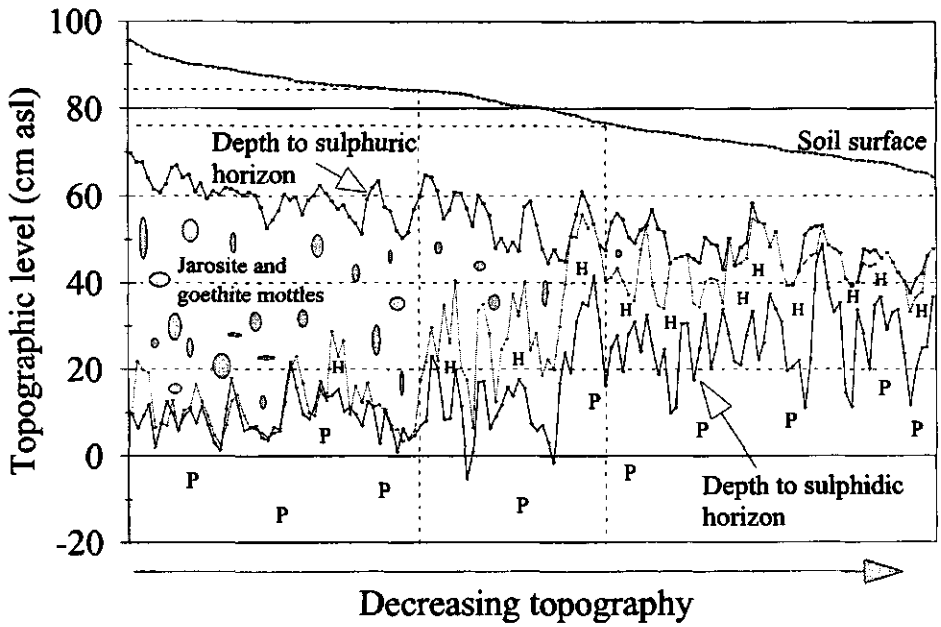

Figure 3.4. Cross section of 138 soil profiles observed in two transects and expressed by decreasing topography (in cm above mean sea level). Movering average of period 3. H indicates fragmentary organic matter. P indicates pyrite.

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 microtopography. In high locations a thicker sulphuric horizon, down to greater depth, physically riper and with a higher jarosite content is developed, reflecting deeper and longer oxidation than under the low, waterlogged parts. This deeper and longer oxidation in high locations has been confirmed by measurement of the water table 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

(Figure 3.5). As a consequence of this difference in oxidation, the depth to the sulphidic material is lower in low positions.

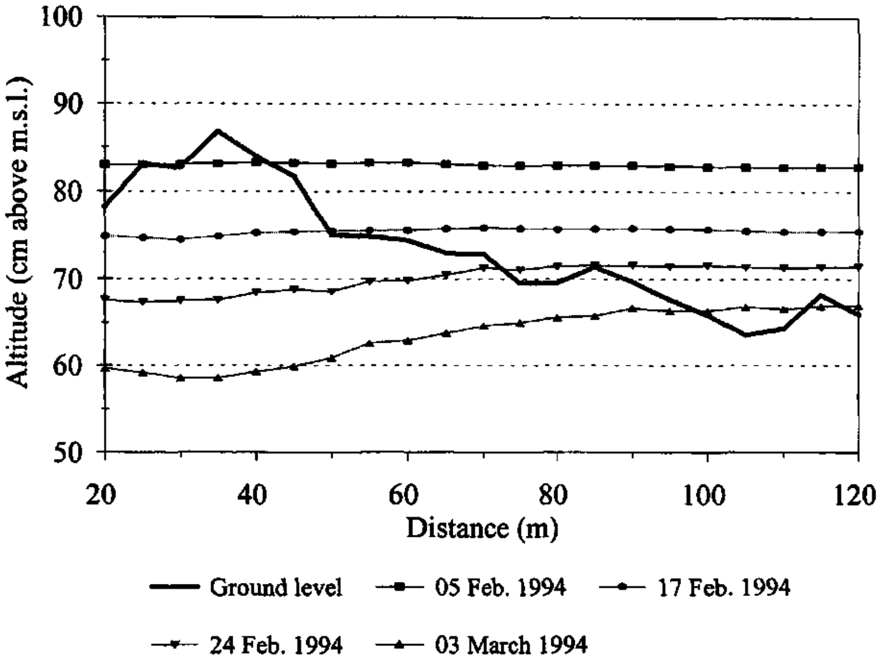

Figure 3.5. Time series of water table level in relation to microtopography (adapted from Bil, 1994).

Another consequence is that soils 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 topography. Figures 3.6 a and b show the relationship between soil and topography at field level in the study area.

Vegetation and topography.

On fallow land, natural vegetation can be used as an indicator of microtopography, and thus, of soil types in the Plain of Reeds. Two main species are present in the area: *Ischaemum rugosum* grass and *Eleocharis dulcis* reed. On low parts, where highly organic soils are found, *Eleocharis* dominates while high parts are mainly covered with *Ischaemum*. Figure 3.7 shows the correlation between the percentage of land covered with *Ischaemum* and microtopography. *Eleocharis* shows the opposite trend. Although simple visual estimation of percentage of *Ischaemum* and *Eleocharis* was done on 1 m^2 plots, R^2 is rather high: 0.58.

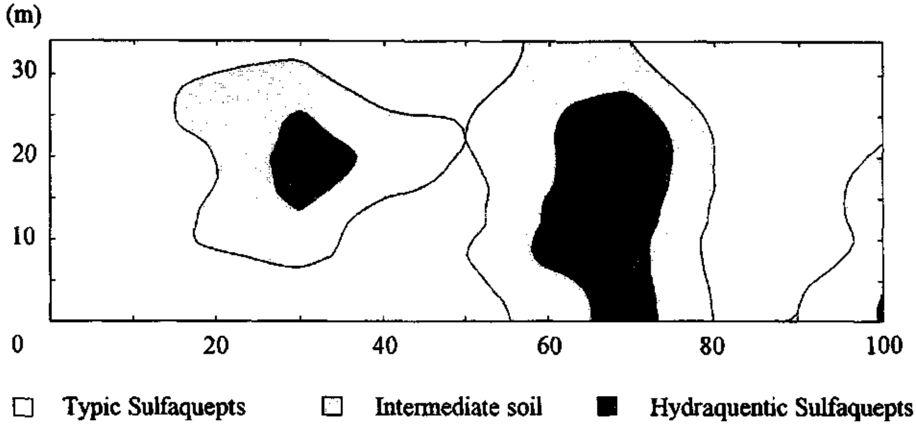

Figure 6a.

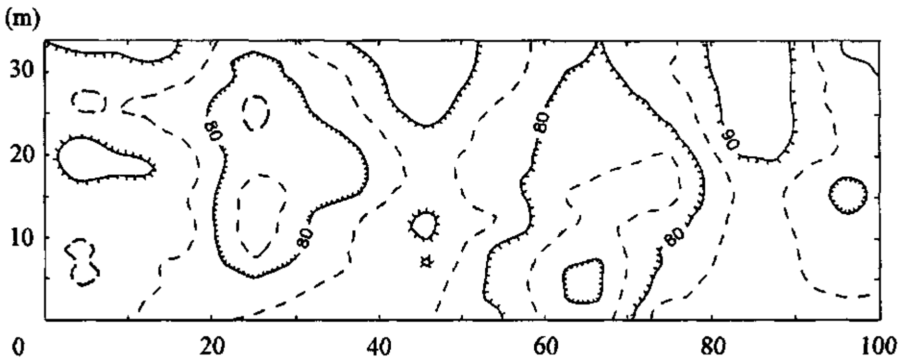

Figure 6b.

Figure 3.6. *a. Soil map of experimental field n° 35.*

b. Topographic map of experimental field n° 35.

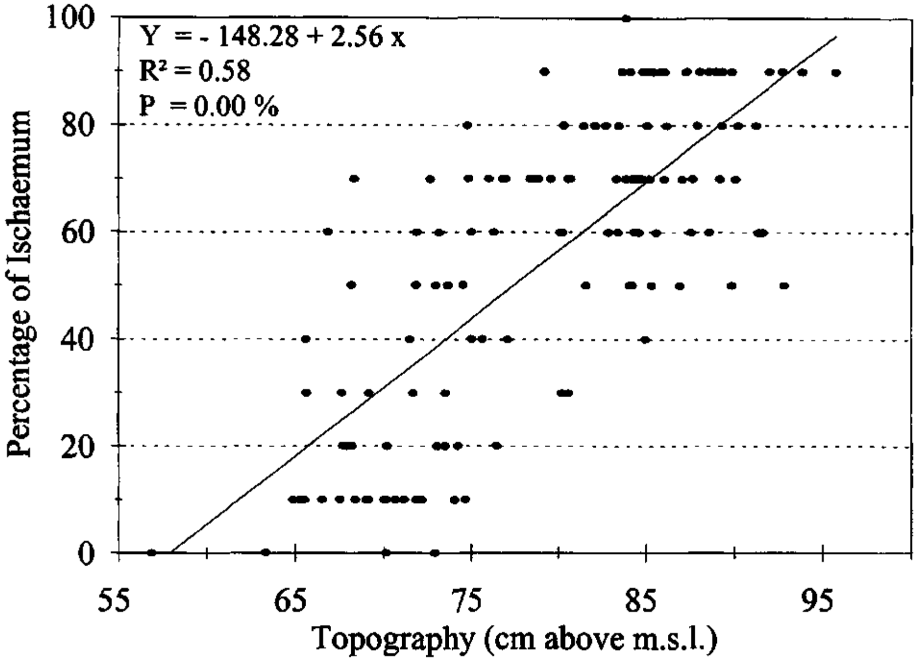

Figure 3.7. Correlation between microtopography and percentage Ischaemum rugosum in vegetation.

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 through cracks. Hydraulic conductivity varies with horizons and microtopography. 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 3.2).

Table 3.2. Vertical hydraulic conductivity (m/day) in acid sulphate soils horizons (average of 3 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

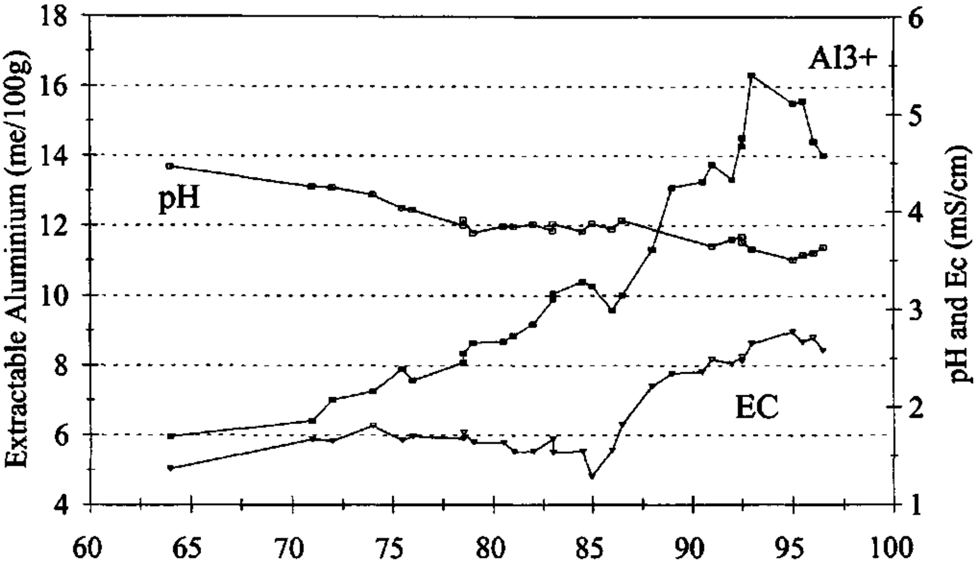

Figure 3.8.a

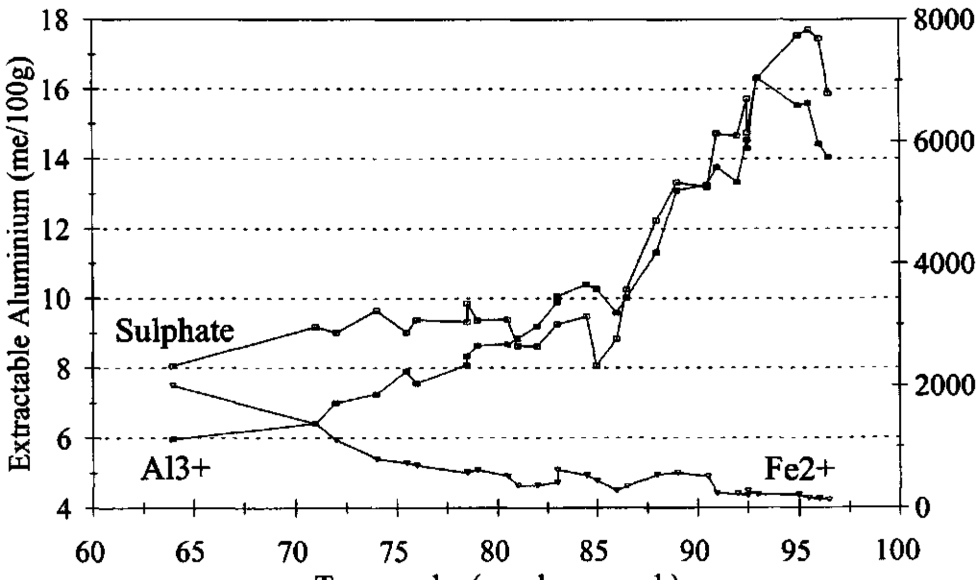

Figure 3.8.b

Figure 3.8. Chemical characteristics of topsoil as a function of microtopography. Moving averages of period 3.

a. pH, EC (mS/cm) and extractable aluminium (meq/100g).

b. Sulphates (ppm), ferrous iron (ppm) and extractable aluminium (meq/100g).

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.

Soil chemistry and topography.

Chemical characteristics of the topsoil, which influence crop growth, are correlated to topography, especially in the dry season. Figure 3.8 gives exchangeable ferrous iron, extractable aluminum, soluble sulphates, EC, and pH measured in April 1995 in a recently reclaimed field, as a function of microtopography. At that time, sulphates, aluminium and EC increase with topography, while ferrous iron and pH decrease when topography increases.

Topography 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 3.3. The Typic Sulfaquept has lost most of its potential acid 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.

Table 3.3. Total sulphidic acidity (mmol(+)/100g) 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			

Soil spatial variability and rice cultivation.

Microtopographic level 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. In relation to soil and water characteristics, rice yield is correlated to microtopography. In 83% of the 61 farmers' fields studied between 1992 and 1996, significant correlation between microtopographic level and rice yield has been observed and explained (Husson et al., 1998a). Intra-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 microtopography is usually quadratic (Figure 3.9) but can be linear in low fields sown too early (positive linear correlation between yield and topography) and in high fields sown too late or poorly irrigated (negative linear correlation).

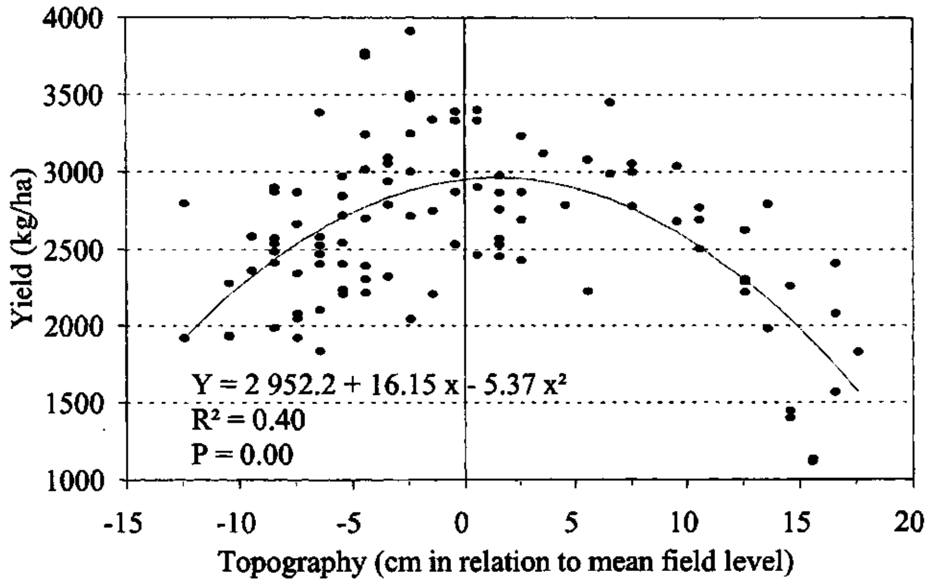

Figure 3.9. Rice yield (kg/ha) as a function of microtopography. Field representative of 61 experimental fields cultivated between 1992 and 1996 (n = 108).

At inter-fields level, correlation between average yield and mean field level is also observed. The lower Hydraquentic Sulfaquepts, without jarosite in the sulphuric horizon, are the most difficult soils to reclaim.

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 classically used to distinguish acid sulphate soils (Figure 3.10). On the other hand, considerable differences in soil characteristics and rice yield have been observed, and explained, in relation to the presence or absence of jarosite.

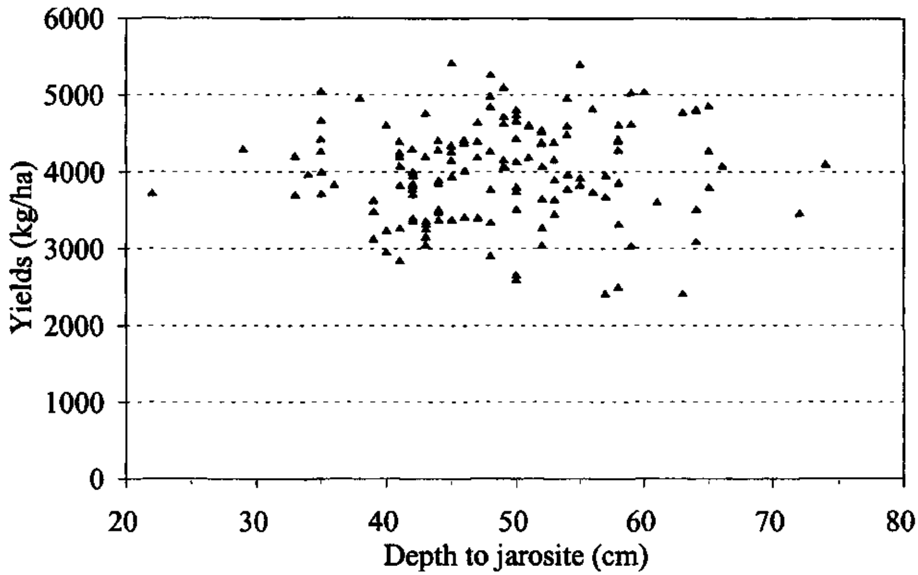

Figure 3.10. Rice yield (kg/ha) as a function of depth to jarosite (n = 142).

Discussion.

Water table level and topographic level.

Measurements of the ground water table along two transects indicate that the ground water level in the dry season remains higher in the lower parts of the area (Figure 3.5). Differences in ground water table at short distance can be maintained due to relatively low horizontal saturated hydraulic conductivity (0.5 to 1 m/day). Because of a low storage capacity and low lateral flow, 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 two ways:

* Figure 3.11. Water level at low and high tides in secondary canal of the study area. 1992-1996. when flood water recedes, 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. During this period, the low air-filled porosity of soils (10 to 20% by volume) means that water level falls 5 to 10 times faster compared with the rate of fall due to evaporation of a free water surface.

* during the dry season, low places regularly receive water through tidal movements in rivers, creeks and canals (Figure 3.11). Soils higher than 85 cm above mean sea level are too high to benefit from these water movements in the dry season, whereas below 75 cm soils never stay more than 30 days without flooding by tides.

Finally, lower water storage capacity of Typic Sulfaquepts compared to Hydraquentic Sulfaquepts, and, possibly, higher evapo-transpiration of *Ischaemum* (a grass with large leaves) than *Eleocharis* (a reed) might also contribute, although a micro-lysimeter measurement could not prove this.

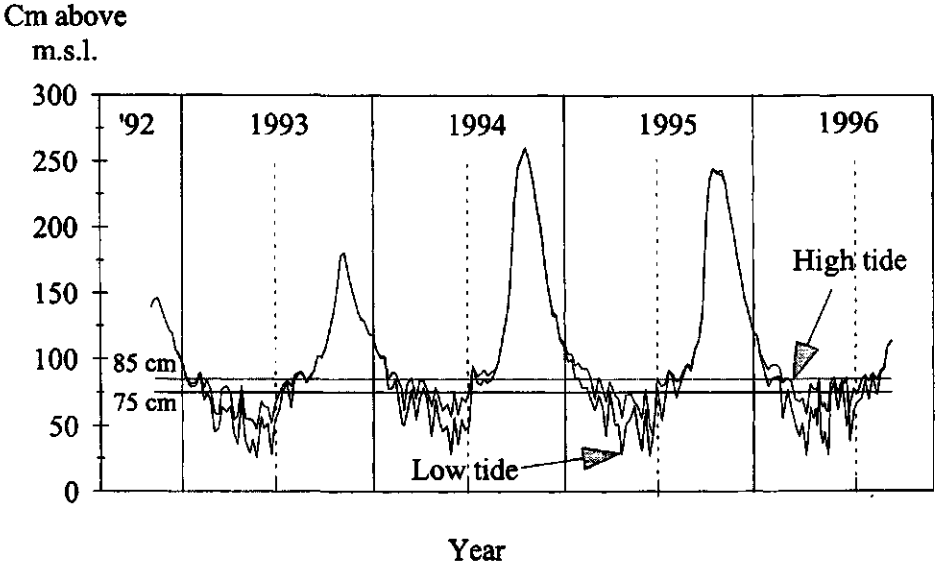

Figure 3.11. Water level at low and high tides in secondary canal of the study area. 1992-1996.

Soil genesis and soil variability.

In the Plain of Reeds, two very different kinds of parent material have been observed:

* Parent material characterised by a rather low organic matter content, with non-fibrous structure

and a greyish brown (10YR5./2) matrix.

* 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). This type is found in the low parts of the area, and underneath the first type in the high parts (Figure 3.4).

Several authors reported difference in potential acidity in relation to original vegetation (Hesse, 1961; Moorman and Pons, 1975; Sylla, 1994). These differences are mainly attributed to different "qualities" of organic matter produced by the different mangrove species, in particular organic matter produced by roots (Tomlinson, 1957; Bertrand, 1994). As mangrove species are adapted to specific environments in relation to topography (Vann, 1969; Marius, 1985 and Sow et al., 1994), differences in parent material due to original vegetation can be expected when topography varies. In such a case, the highly organic parent material observed in low positions where jarosite did not develop would have accumulated under *Rhizophora* forests, which are known to occupy the lowest topographic positions and produce considerable quantities of fibrous organic matter.

However, pollen analysis by Chiem (1994) indicates that in the Plain of Reeds, jarosite can develop on parent material accumulated under *Rhizophora*. This suggests that original vegetation is not the main cause of variability of soils in the area.

Indeed, present spatial variability can be largely explained by soil development processes following drainage, where differences in oxidation and mineralisation lead to differentiation between soil types. In particular, it can explain the differences between Hydraquentic Sulfaquepts and Typic Sulfaquepts.

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:

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

Characteristic pale yellow deposits of jarosite precipitate as pore fillings and coatings on ped faces under strongly oxidising, severely acid conditions: Eh greater than 400 mV, pH less than 3.7 (Dent, 1986).

In the Plain of Reeds, soils in low locations, which are waterlogged most of the time, have a high organic matter content in the parent material. This organic matter keeps the soil almost saturated after drainage due to its spongy structure. In these conditions, 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:

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

and jarosite cannot be formed (Van Mensvoort and Tri, 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 on 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 topography. Further drainage and oxidation will lead to further mineralisation of organic matter, and the brown matrix will turn into grey while more jarosite will precipitate, explaining the correlation between topographic level and the percentage of jarosite in the soil.

Therefore, it appears that Hydraquentic Sulfaquepts develop into Typic Sulfaquepts. The brown "beurre marron" horizon is only an intermediate stage which will develop into a sulphuric horizon with jarosite and goethite upon prolonged drainage.

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

Van Mensvoort and Tri (1988) reported occurrence of extensive tracks 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 microtopographic soil level. Small differences in topography 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 is that, in the Plain of Reeds, this threshold topographic level ruling oxidation corresponds to the mean level of soils. This threshold is often crossed, leading to the high short-range variability observed in the fields.

Soil patterns.

Bos and Van Mensvoort (1983) and Burrough et al. (1988) in the Mekong delta, Vietnam, and Ahmed and Dent (1996) in 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 topography 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 (Figure 3.3), and that soil maps at all scales (1:2 500 000 to 1: 2 000) resemble one another, with closely intertwined soil patterns evoking former river branches, creeks and depressions.

Methodological aspects.

Mapping.

In the Plain of Reeds, mapping can be made much easier by the use of observed correlations between microtopographic level, soil characteristics and natural vegetation which have been measured in Tan Lap village and three extrapolation sites (Figure 3.2), and observed in all fallow lands visited in the Plain of Reeds. Results achieved at field level can therefore be extrapolated at a higher level, after calibration of the actual level of transition between Typic Sulfaquepts and Hydraquentic Sulfaquepts that might vary slightly from one side of the Plain of Reeds to the other. As natural 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.

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. To avoid such a situation and gain in research efficiency, the variability must be integrated into the research programme. The detailed characterisation and understanding of field-scale variability experimentation has been used to integrate variability of soils and water factors into the agronomic research process and to properly design and implement experiments. Long, narrow plots (7-10 m x 100-150 m), crossing heterogeneities were preferred to square ones. Careful location of experiments made it possible to reduce CV, thus increasing research efficiency. Covariance analysis, with microtopographic level as covariate, proved to be a simple but highly efficient tool to control the high short-range variability induced by this factor (Husson et al., 1998b). Variability in soils and yields could also be used for analysis and understanding of soil-water-crops interactions, helping in the development of a model of rice yield build-up on severely acid sulphate soils (Husson et al., 1998a).

Extension of results.

In the experimental site at Tan Thanh, analysis of interactions between soil and water on the one hand, and agricultural practices on the other hand allowed us to adapt recommendations to each major agro-ecological situation. These results have been validated by extrapolation trials in various locations in the Plain of Reeds (Figure 3.2). 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) topographic level can guarantee easy adaption of technical measures to field conditions. Every farmer in the Plain of Reeds uses natural vegetation and/or water rise at the beginning of the flood to classify his field as high, medium or low and to exchange information with his neighbours.

Conclusions.

1. Two main soil types, with very different characteristics, are observed close to each other in the study area. Their occurrence is related to microtopography. In the Plain of Reeds, an area of recently drained acid sulphate soils, strong correlations exist, at different scales, between microtopography, water table level, soil profiles, soil physical and chemical characteristics and natural vegetation. These correlations are explained by the influence of the microtopography during soil genesis, especially upon drainage as it influences soil aeration, thus mineralisation and oxidation processes.

The two main soil types found in the area correspond to various stage of development of acid sulphate soils. Hydraquentic Sulfaquepts are expected to develop into Typic Sulfaquepts upon further drainage.

The high soil variability is explained by the fact that slight differences in topography induce important differences in intensity and length of soil oxidation and mineralisation, and consequently, important differences in soil types and characteristics. On each side of a threshold topographic level, soils rapidly dry out or remain waterlogged. In the Plain of Reeds this threshold level corresponds to the mean soil level, which leads to the high short-range variability observed.

Land surveys and mapping at large scales can be eased by correlations observed between soil characteristics, microtopography and natural vegetation. The presence or absence of jarosite proved to be an interesting criterion for soil classification as it is correlated to soil characteristics and plant growth, contrary to the depth-to-jarosite criterion which has no agronomic meaning.

Integrating soil variability in experimental research programmes not only reduces experimental errors, but also makes it possible to use variability as an important source of information.

Chapter 4

Temporal variability of soil and water as indicator for optimal growing period, water management and agricultural practices in acid sulphate soils of the Plain of Reeds, Vietnam

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Abstract.

In the Plain of Reeds (Mekong delta, Vietnam), water and soil characteristics show a high temporal variability which can be explained by changes in relative soil/water levels. Acid, aluminium and iron concentrations in canal water increase when the annual river flood water recedes and the drainage/flushing of the acid sulphate soils begins. The high intra-annual variability of soil chemical characteristics is explained by sensitivity to changes in redox potential.

Due to the high concentrations of toxic ions, cropping conditions are favourable for an extremely short period which starts at the end of the annual flood. Optimal time window for cultivation, and optimal cropping techniques are related to the microtopography of the fields and to their permeability, which is very high in the first years following reclamation. Maintaining favourable conditions by irrigation is therefore not possible before a less permeable plough-pan has been created by cultivation. To reclaim these soils, the only solution is then to start cultivation as early as possible. Determination of the sowing date is a key issue. Flood characteristics, in particular the speed of recession and water turbidity, the topography and the age of the field as they determine permeability and water control should be taken into account.

Introduction.

Acid sulphate soils variability.

The Plain of Reeds, a broad backswamp located in the northern part of the Mekong delta, is covered with 400 000 ha of acid sulphate soils. These soils develop upon drainage of pyritic parent material which produces sulphuric acid when oxidised. They are known to be highly variable in space and time. Henry (1948) mentions a cyclic occurence of "alun" (at that time acid sulphate soils were known as "sols alunés" in French) in the Plain of Reeds. "Alun" appears during the dry season, is flushed from high parts and concentrates in low areas. Old farmers recalled to Henry that in the past, when there were no canals, no "alun" appeared and attributed the phenomenon to increased drought by drainage. Thus, fifty years ago, these soils were already known to have very fast chemical changes. Later, Van Breemen (1975) showed processes of acidification and deacidification of coastal plain soils in relation to periodic flooding, and the strong impact they have on soil chemical characteristics. Upon oxidation, acidification induces dissolution of aluminium which is toxic to plants. Submersion and deep reduction favour development of ferrous iron and hydrogen sulphide toxicities. Husson et al. (1998c) explained soils genesis in the Plain of Reeds, Vietnam, where two types of acid sulphate soils occur closely intertwined.

Optimal cropping period.

In acid sulphate soils with a high short-range variability in soil and water characteristics and in levels of toxicities, the determination of the period of minimal stress is a key issue for cultivation. In the Mekong delta, Vietnam, Tuong et al. (1991) observed that crops in the dry season suffer from lack of water and salinity intrusion, whereas floods and the flow of acid-contaminated water are limitations in the rainy season. Submersion of soils is known to raise soil pH, essentially through the reduction of ferric to ferrous iron, a process that consumes protons (Ponnamperuma, 1955 and 1972, Tadano and Yoshida, 1977; and Hanif et al., 1986). However, the rise in pH in acid sulphate soils is slower than in moderately acid wetland rice soils (Konsten et al., 1994).

Hanhart and Ni (1993), also in the Mekong delta, studied seasonal variations of the soil solution in acid sulphate topsoils and identified three periods in a year, related to redox potentials: 1) Continuous oxidation during the dry season, starting at the recession of the flood; 2) Alternate oxidition and reduction during the first part of the rainy season; and 3) Continuous reduction during the flood.

They measured the highest concentrations of soluble aluminium and ferrous iron at the start of the rainy season and identified the end of the flood as the best time to start cultivation, when soluble aluminium concentration is low, pH is near neutral and ferrous iron level is moderate. They could preserve optimal conditions throughout the cultivation of this "winter-spring" crop through continuous submergence of the topsoil by irrigation. Thus, the annual acidification of the topsoil by drying was prevented and a second crop could be grown directly after the first one.

The study area.

The Plain of Reeds has a monsoon climate, with a marked dry season from December to April (Northeastern monsoon), a rainy season from May to November (Southwestern monsoon) and is flooded annually with Mekong river water.

The study area is located in the central part of the Plain of Reeds, where intermediate characteristics are met regarding tidal movements, water quality and salt intrusion. Because of interannual variations, most of the conditions found in the Plain of Reeds can be found there.

The study area has two very different kinds of soils which are seen at very short distance, and related to microtopography:

* Typic Sulfaquepts (Soil Survey Staff, 1992) are found at high positions (higher than 85 cm above mean sea level). They have a parent material characterised by a rather low organic matter content, a greyish brown (10YR5/2) matrix and jarosite and goethite mottles in the oxidised horizon.

* Hydraquentic Sulfaquepts (Fanning and Witty, 1993), with parent material characterised by a high fibrous organic matter content, a brown to dark brown matrix (10YR5/3 or 10YR4/3) but no goethite or jarosite. These soils are found below 75 cm above mean sea level.

In between is a transitional soil type with intermediate characteristics.

Differences in soils have been explained by differences in duration and intensity of drainage in relation to microtopography. Typic Sulfaquepts are drained naturally and dry out deeply for a long period in the dry season, while the low Hydraquentic Sulfaquepts are waterlogged most of the time (Husson et al., 1998c).

Objectives of the study.

The strong and highly variable toxicities make crop performance extremely sensitive to the starting date of cultivation. Early or late sowing can have disastrous consequences on water management opportunities and consequently rice yield (Husson et al., 1998d). The sowing date should be carefully determined by field conditions. It is anticipated that cropping techniques can enlarge the time window during which cultivation is possible, but this requires precise characterisation of temporal variability in cropping conditions, taking spatial variations into account.

The improvement of physical characteristics by cultivation can facilitate water control, while the reduction of toxic ion concentrations by flushing and leaching reduces toxicities on plants (Tuong et al., 1993). However, these ions are released into the surface water. Monitoring, explanation and prediction of temporal variations of soils and water characteristics are also important to assess and try to prevent environmental degradation (Minh, 1996).

The objectives of the study are:

(i) to characterise and explain temporal variability of soils and water characteristics in the Plain of Reeds, at various time scales. The study is focused on an area of recent land reclamation, important in the context of the present fast development in the Plain of Reeds.

(ii) to identify optimal time windows for cultivation of rice after land reclamation, in actual conditions of production, and

(iii) to identify cropping practices prolonging short time windows.

Material and methods.

Water pH and EC were measured weekly in canals around the experimental area from 1992 to 1996 with field pH and EC meters. One day per week water level, pH and EC were also measured every hour at the experimental area in a secondary canal.

Topographic level was measured with a theodolite and calibrated to mean sea level on a reference point given by the Long An Province Hydraulic Services.

Hydraulic conductivity was measured with three replications, using the "falling head" method (Black et al., 1965), with 20 cm long cylinders, 15 cm in diameter.

Aluminium concentration was determined in a simple field laboratory by titration with diluted 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 oxidation. Sulphates were determined by spectrophotometry at wave length of 420 nm (Page et al., 1982).

Identification of optimal time window for cultivation was done by analysis of plant growth. Influence of cropping conditions on rice growth at various stages of cultivation was assessed by analysis of yield components, including plant, tiller and panicle densities, number of filled grains/panicle, number of empty grains/panicle, plant height, weight of one grain (measured on 1 000 grains counted with a Numigral), dry matter and grain yield. These yield components were measured for every experimental field in a minimum of 40 observation plots of one square metre, selected by systematic grid-sampling.

Results and discussion.

Temporal variability of canal water.

Water level.

Drainage of the Plain of Reeds is attributed to opening of canals in the 1920's and 30's, during the French colonisation. This drainage is therefore recent, but also partial. Figure 4.1 presents water levels in a secondary canal in the central part of the Plain, from 1992 to 1996. Soils in the lowest positions (lower than 75 cm above mean sea level) remain submerged most of the year, and (shallow) drainage at these places occurs only for very short periods at the end of the dry season. Fields only 10 to 20 cm higher are drained and dry out for more than six months per year.

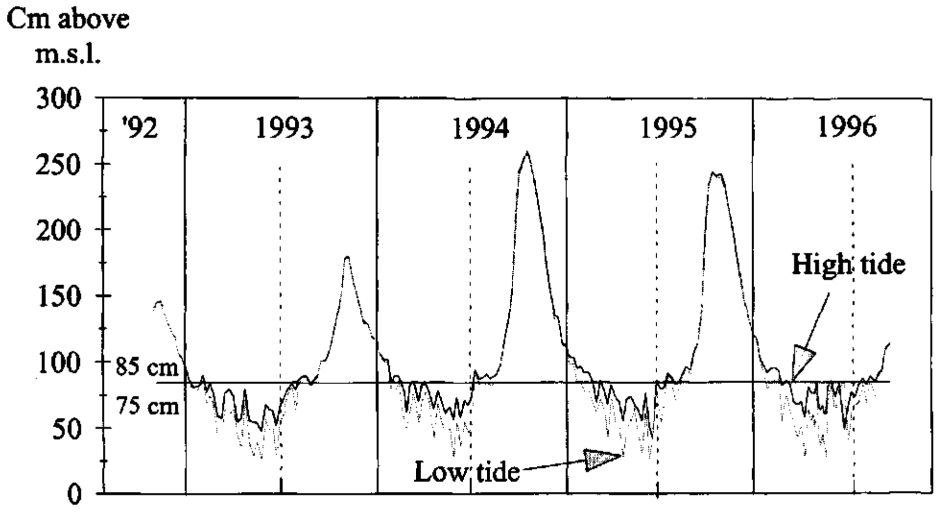

Figure 4.1. Water level at low and high tides in the secondary canal of the study area. 1992-1996.

Variations in water level indicate two seasons: the flood period, which starts a few months after the beginning of the rainy season, and ends 1 to 3 months after the last rains, and the dry season. Duration of the flooded period is spatially variable, and depends on microtopography and location in the Plain of Reeds. It can vary from three to seven months. The difference of water level between these two seasons is considerable, sometimes surpassing 2 metres.

Tidal movement occurs in the Plain of Reeds when river discharge and water level are low. Tidal difference depends on distance from sea and rivers or primary canals. In the study area, tidal movements are observed when the water level is below about 90 cm above mean sea level. Maximum amplitude observed in this canal during the period 1992-1996 was 33.5 cm.

Water quality.

Figure 4.2 shows variations in water level, pH and EC in a secondary canal of the study area, in 1994-1995. pH is low during the dry season, with an average value around 3 in 1994 and 1995. The minimum value can be below 2.5, with a minimum pH of 2.3 measured in 1993 after the very shallow flood of 1992. pH suddenly increases and is usually above 6 during the flood. Variations in water level and relative soil/water levels are key factors explaining the very rapid transitions between these two periods and the strong variations in water quality.

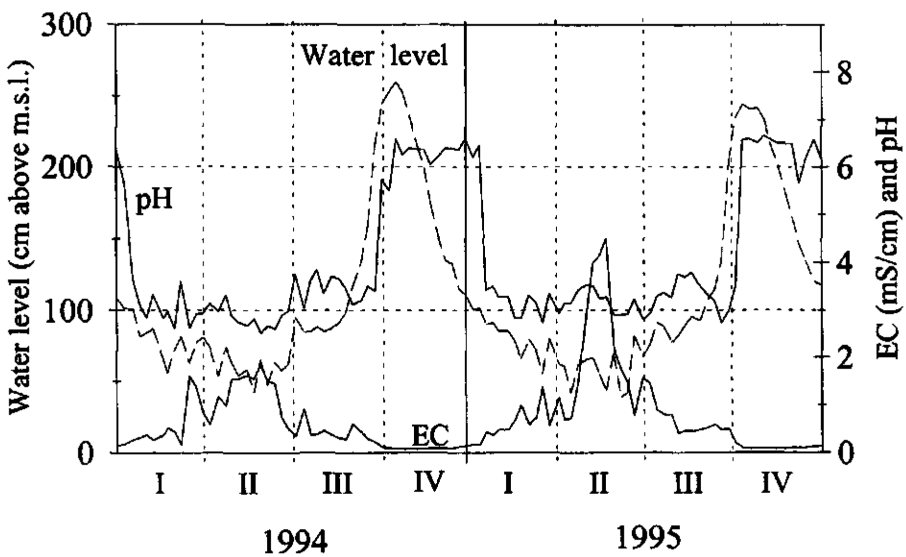

Figure 4.2. Water level, pH and EC in the secondary canal of the study area.1994-1995.

When flood water comes in and reaches 90-100 cm above mean sea level, i.e. the altitude of the highest fields, water pH first decreases, then increases very rapidly. This decrease can be attributed to acidification of water by soils which dried out and have accumulated soluble acid salts on the surface during the dry season. The subsequent increase of pH cannot be attributed to increase of soil pH usually observed upon flooding of moderately acid soils (Ponnamperuma, 1972), as acid sulphate soils in the Plain of Reeds hardly show this rise and remains at pH value by far lower than the surface water. In these conditions, the increase of water pH can be attributed mainly to the dilution of acidity by neutral water brought by the flood and drainage to the sea of the initially acid water.

At the end of the flood, pH in the secondary canal suddenly drops when water reaches the altitude of 90-100 cm above mean sea level. At that point, acid and aluminium are drained from fields into canals (Figure 4.3a). Iron is also flushed in high quantities, especially when the water level falls below the level of 75 cm above mean sea level, which corresponds to the level of low lying, iron-rich fields (Figure 4.3b). Farmer practices (land preparation and drainage) also probably have a negative impact on pH and ion concentrations in canals.

Acid and aluminium accumulate in surface soils or dikes during the dry season, but particularly so during the early rainy season, when alternate dry and wet periods favour generation of acid and capillary rise to the soil surface. They are then flushed by rains and wind up in the canal water, which explains the very low pH observed between April and June.

Extensive land reclamation in the Plain of Reeds which leads to excavation of new canals and deeper drainage yielded an important release of acid, aluminium and iron in a canal network not yet capable of rapidly flushing all these toxic ions. Pollution of water is harmful to human and animal life, and can last for many years. Verburg (1994) showed that dikes still produce high quantities of acid 5 years after excavation. However, contamination of water is expected to (slowly) decrease once the entire Plain of Reeds is reclaimed. Because of land hunger, farmers and authorities in the Plain of Reeds are willing to endure this pollution.

Although EC is correlated to acidity and aluminium, the strong rise of EC observed in April and May (Figure 4.2) can also be due to salt intrusion. EC, which is around 0.1 mS/cm during the flood period, shows a peak in May. This period of maximal salt intrusion corresponds to the end of the dry season, when water level is low: all measurements of EC higher than 1.5 mS/cm were made when average water level in the canal was below 70 cm above mean sea level.

Inter-annual variations of salinity also can be explained by water table level. Salt intrusion is stronger in years with a long dry season, when surface water levels are very low.

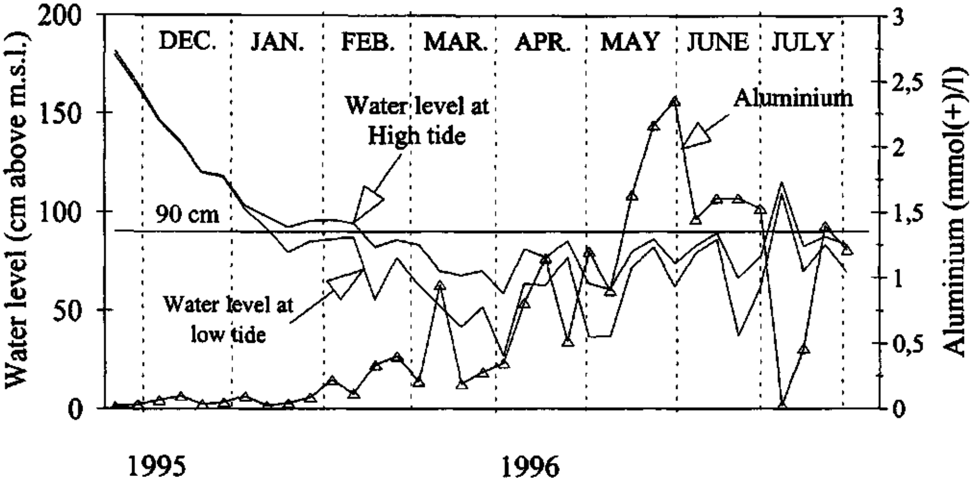

Figure 4.3.a

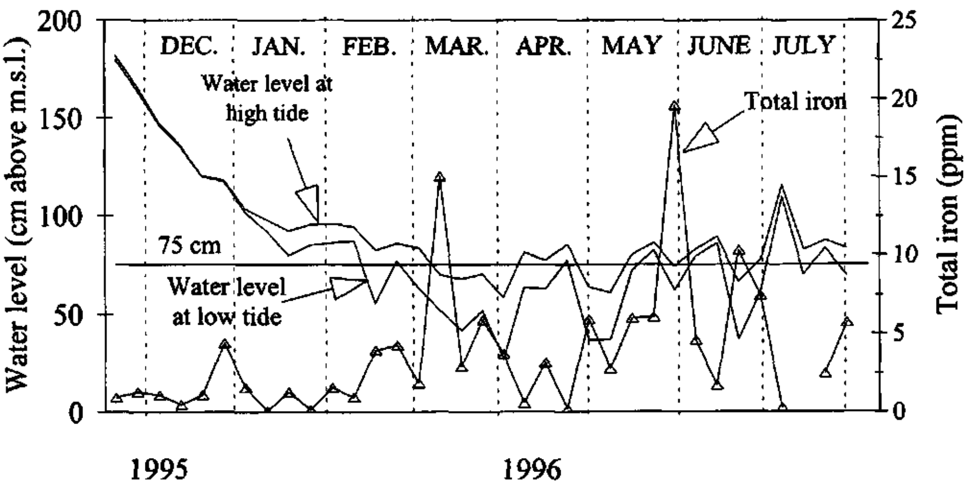

Figure 4.3.b

Figure 4.3. Water level and changes in chemical characteristics in the secondary canal of the study area. 1995/1996.

Figure 4.3a. Soluble aluminium.

Figure 4.3b. Total iron.

High short-range temporal variability of water quality and water management practices.

A striking feature in the Plain of Reeds is the speed with which water quality changes at certain key periods. pH suddenly rises from 3.5 to 6 a few days after flooding, and decreases as fast, from 6 to 3.5, when flood water recedes. At these periods, water quality can considerably vary within one day: On 12 January 1996 for instance, when flood water was receding and reached the level of 95 cm above mean sea level, pH dropped from 6 to 4.4 in one day.

This short-range variability of water quality in canals during the cropping season makes the timing of cropping practices, especially irrigation, extremely important. Anticipating changes in water quality can allow adjustments in the timing for pumping, leading to significant differences in the quality of water used for irrigation. In the secondary canal of the experimental area for instance, irrigation conducted on March 3, 1994 when water level in the canal was rising, brought water of a pH 3.6 and EC of 0.16 mS/cm on the fields. Eight days later, in a period of water recession, irrigation would have been harmful to rice plants as water pH was only 2.6 and EC was 1.6 mS/cm, reflecting presence of aluminium, iron and possibly salt.

Temporal variability of soil chemical characteristics.

Short-range variability of soil chemical characteristics in relation to redox potential.

Figure 4.4 shows variations in soil pH, EC, extractable aluminium and ferrous iron concentrations in relation to water table level, from December 1995 to July 1996 in an uncultivated soil at medium topographic level (82 cm above mean sea level). pH of the topsoil rapidly decreases when soils get dry. In relation to this decrease in pH, aluminium concentration increases. Ferrous iron shows the opposite trend, decreasing when the water table decreases, and increasing after the beginning of the rainy season (April 1996). The same trends are observed in cultivated fields. Within a cropping season, pH, extractable aluminium, ferrous iron and soluble sulphate are extremely variable, and are correlated to microtopography. Ferrous iron concentrations decrease with time as soil dries. In April, when soil is dry, the lowest concentrations are found in the highest parts of the field which are drier (Figure 4.5a). Contrary to ferrous iron, aluminium (Figure 4.5b) and soluble sulphate (Figure 4.5c) concentrations increase with time. Concentrations are higher on high locations, which can be attributed to differences in redox potential, but also to stronger capillary rise on the high locations which fall dry earlier and get drier. These figures show the very high sensitivity of these soils to the oxidation status and the importance of capillary rise, and explain the very high short-range temporal variability of acid sulphate soils chemical characteristics.

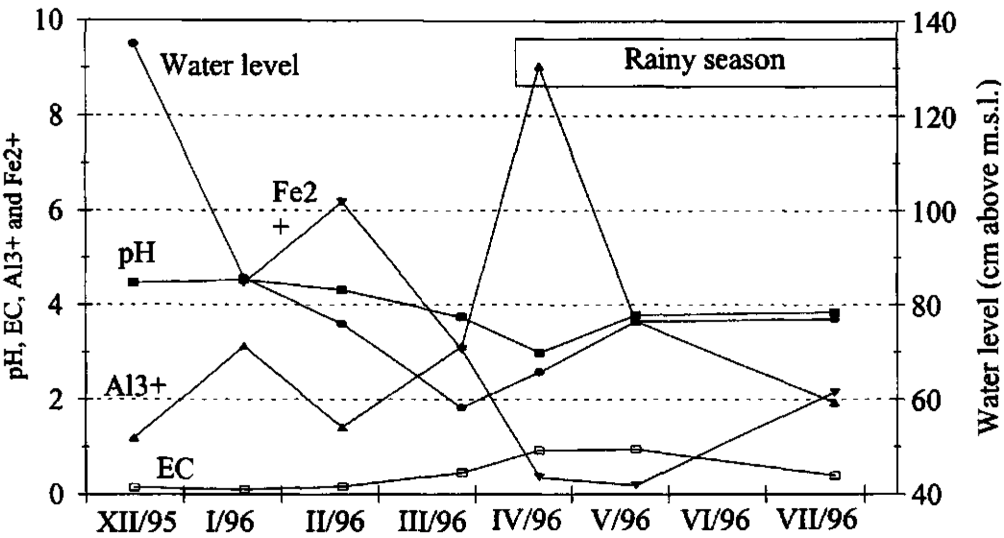

Figure 4.4. Water table level and changes in soil chemical characteristics. 1995/96. EC in mS/cm, extractable aluminium in meq/100g and ferrous iron in ppm/1000. Bulking of ten samples before analysis.

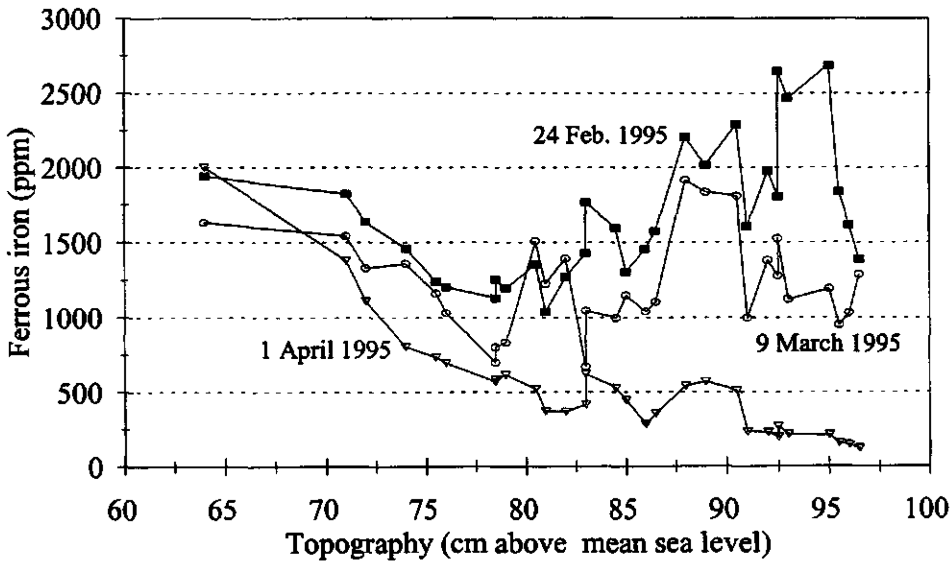

Figure 4.5.a

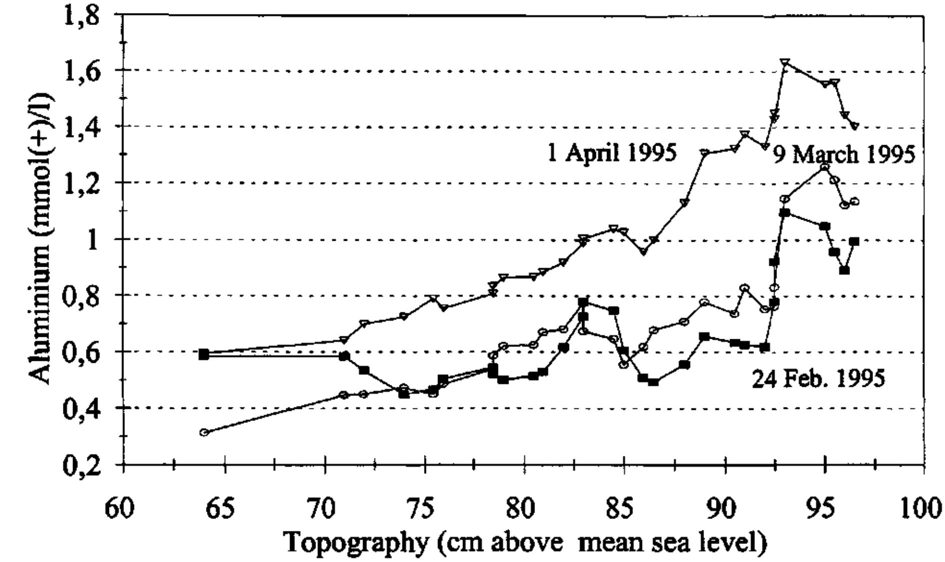

Figure 4.5.b

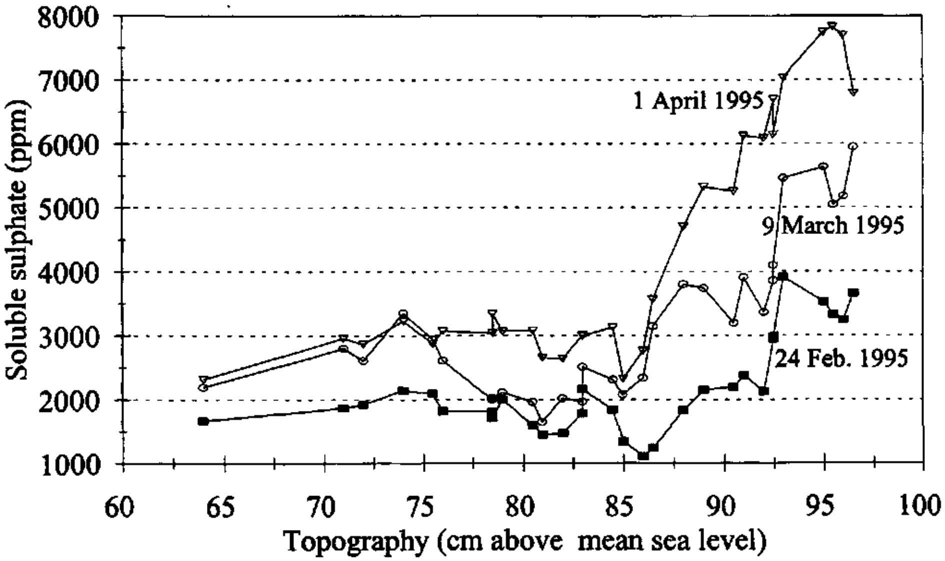

Figure 4.5.c

Figure 4.5. Changes in ferrous iron (Figure 5a), extractable aluminium (Figure 5b) and soluble sulphate (Figure 5c) in topsoil as a function of time and microtopography. Moving averages of period 3. First cultivation after reclamation.

Intra-annual variability of redox potential in relation to microtopography.

Redox potential is governed by the relative soil/water table level. The low air-filled porosity of these soils (10 to 20% by volume), makes ground water levels fall 5 to 10 times faster compared to a free water surface. As soils at low topography emerge later than the high ones, and are regularly submerged by tidal movements, water table level under soils at high topography decreases for longer periods and faster than under low positions (Husson et al., 1998c). Measurements of water table level decrease at the end of the flood confirms this tendency and shows that ground water table is not horizontal and is lower under high positions than under low ones (Figure 4.6). This has two consequences: (i) Relative soil/water table level, and therefore redox potential, are extremely sensitive to microtopography. Soils at high topography can strongly and deeply oxidise when soils only 10 to 20 cm lower are maintained in reduced conditions; and (ii) Redox potential is highly variable in space and time.

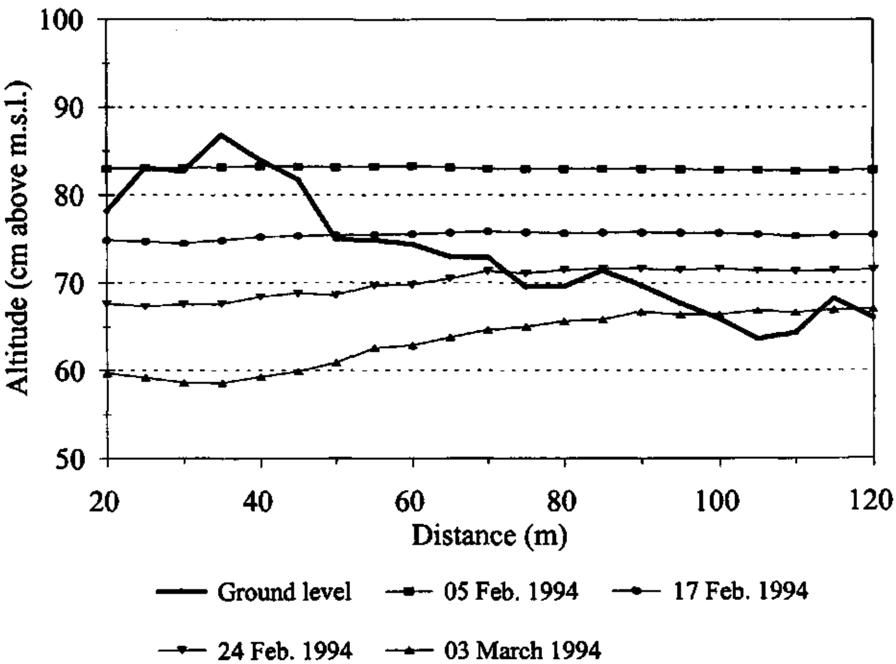

Figure 4.6. Time series of water table level in relation to microtopography (adapted from Bil, 1994).

This high spatial variability of redox potential should be considered when identifying periods of optimal conditions for cultivation. Figure 4.7, based on 1995 data, shows that in the Plain of Reeds 3 main situations can be distinguished:

* On high topographic positions, higher than 85 cm above mean sea level, a period of complete submersion and, as a consequence, of reduction, lasts from mid-August to Mid-January. This period is followed by a short period (Mid-January to Mid-February) during which tidal movements lead to alternating reduction and oxidation. Then comes a long period of deep oxidation until the beginning of the rainy season in April-May. From that time, alternating periods of oxidation and reduction will last until complete submersion by flood water in August.

* At intermediate topographic level (75-85 cm above mean sea level), the same four periods can be identified. However, the timing is different. The period of complete submersion starts earlier (mid-July), and ends later (end of January) than on higher positions. The following period of alternating reduction and oxidation due to tidal movements is longer and lasts until March. Consequently, the period of oxidation is shorter (end of March to the first rains in April or May) and oxidation is not as severe as on higher positions.

* At low topographic positions, complete submersion by flood water is long, starting at the end of June, and ending in the beginning of February. It is followed by two months of alternating oxidation and reduction due to tidal movements. The period of oxidation is extremely short, starting only in the beginning of April. Oxidation is very limited as from the end of April or the beginning of May rains lead to alternating oxidation and reduction.

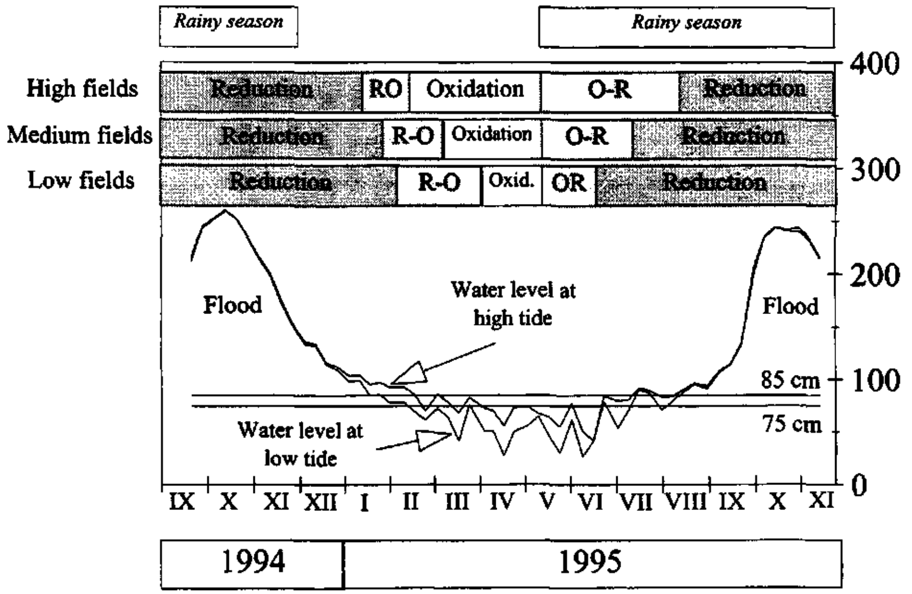

Figure 4.7. Changes in redox potential in relation to water table level and microtopography. 1994/95.

Optimal time window for cultivation and cropping practices.

Optimal cropping period.

The optimal period to start cultivation in the Plain of Reeds is at the end of the annual flood, before acidification and salt intrusion. However, several factors make optimal growing periods in the Plain of Reeds shorter, and possible crops fewer than elsewhere:

(i) The deep flood (over 1 metre) prevents cultivation of dryland crops with a long growth cycle or trees.

(ii) In the eastern part of the Plain, salt water in rivers and canals makes it necessary to end cultivation of the "winter-spring" cropping season before the end of April and poses serious problems for cultivation of a second crop at the end of the dry season.

(iii) Very poor water control due to high field permeability in the years following reclamation makes extention of the period of favourable conditions through irrigation difficult. Water level in fields is dictated by surface water levels in the area, implying that optimal conditions for cultivation during the "winter-spring" season only are met for a very short period. Transplanting of rice seedlings can enlarge the time window for cultivation but requires a lot of manpower, not available in this area of new colonisation. To use this time window as best as possible, farmers in the Plain of Reeds use short -cycle (90-100 days), high -yielding varieties, tolerant to aluminium, and sow pregerminated rice seeds in flood water, before its complete recession.

Sowing under deep water.

Pregermination is done by immersion of rice seeds for 24 hours followed by 12 to 18 hours of incubation to obtain a small radicle. These seeds are then directly broadcasted at densities of 200 to 300 kilograms per hectare, in fields still covered with 20 to 40 cm of water. Seeds sink when broadcasted directly in water but seeds with radicles longer than 1 to 2 mm stay afloat. In addition, 20-30 kg/ha urea is broadcast with the aim of making water clear (floculation of particles due to acidification, possibly on NH_4^+ ions). Young rice plants are expected to grow under water and stand above the water surface after about 2 weeks. Water depth at sowing should be carefully determined as excessive submersion of young rice plants leads to high plant mortality and bad tillering (Husson et al., 1998a).

Spatial variability of optimal time window for cultivation and cropping practices.

On fields higher than 85 cm above mean sea level where Typic Sulfaquepts are found, flood water recedes relatively fast. Water decrease is 1 to 1.5 cm/day between 140 and 100 cm above mean sea level. Once soils have emerged, they dry rapidly. Because of the high permeability, water control is poor: after irrigation has stopped, water level in the field adjusts to water table level in the area within 24-48 hours. Maintaining soils wet after the end of March or the beginning of April would require permanent pumping and is not practical nor economically feasible. Thus, less than two months after soils have emerged, oxidation of the top soil can hardly be avoided. One month later, oxidation can occur to a depth of 50 or 60 cm, which leads to strong acidification and rise of aluminium. This makes the time window during which favourable conditions for cultivation can be maintained after water has receded extremely short. Farmers reclaiming these soils have to face a dilemma: to avoid oxidation at the end of the cycle, the only solution is to start cultivation very early, which means sowing pregerminated rice seeds in deep water (over 30 cm) at the risk of obtaining low densities.

Fields between 75 and 85 cm above mean sea level, only 10 cm lower than the previous ones, also face risks of oxidation at the end of the plant cycle, but present a different situation. On the one hand, when flood water level is between 115-120 and 85-90 cm above mean sea level, recession is only 0.5 to 1 cm/day. Sowing in more than 30 cm of water would result in plant submersion longer than two weeks, which should be avoided. On the other hand, these fields are naturally submerged until the middle of February, and then benefit regularly from tidal flooding until the end of March. Thus, favourable time window for cultivation on these soils starts later but is longer than on high fields.

Low fields on Hydraquentic Sulfaquepts (lower than 75 cm above mean sea level) present very different cropping conditions. They remain permanently submerged until February, and tidal movement maintains waterlogged conditions after the end of March. Drainage is hardly possible because of their low position and their high permeability. To avoid the period of salinity and strong acidity of water after April, cultivation should start before the end of January. At that time, water level in these fields is still rather high (20-30 cm), water recession is very slow and tidal movements ensure that fields are regularly flooded with more than 15 cm of water for several weeks. Besides long submersion, seeds and young rice plants have to face adverse chemical conditions related to deep reduction. The high organic matter content keeps the redox potential low, resulting in high ferrous iron, organic acids, and H_2S contents, and sulphate-reducing bacteria contribute to development of strong toxicities (Husson et al., 1998d). In contrast to higher fields in which water management strategy aims at avoiding oxidation, in these low fields it should aim at creating (slight) oxidation to prevent problems linked to deep reduction.

Inter-annual variability of optimal time window for cultivation.

As optimal starting date for cultivation depends on water level, inter-annual variability of flood characteristics also leads to inter-annual variability of the optimal time window for cultivation. The level of the flood peak, the date at which flood peak is reached, and the speed of flood recession influence the date at which optimal water level for sowing is reached. These parameters can vary strongly. Since 1960 flood peak in the north of the Plain of Reeds varied between 1.1 and 3.0 metres above mean sea level, with a standard deviation of more than 50 cm. In the past 15 years, this peak was reached between 22nd September and 20th October, a period of 29 days (Source: Moc Hoa meteorological office). In the lunar calendar used by farmers of the Plain of Reeds, variations are smaller: they correspond respectively to the 18th day of the eleventh month, and the 4th day of the twelfth month, a period of 16 days.

These variations can have a strong influence on optimal sowing date. After the low flood peak of 1992 (peak at 146 cm above mean sea level reached at the end of September), a flood level of 130 cm above mean sea level, at which highest fields could be sown, was already reached on 20 November 1992. After the high flood of 1994 (peak at 280 cm above mean sea level on 13 October 1994), 130 cm above mean sea level was reached on 12 December.

Water turbidity is also important. As plant mortality and tillering are related to light (Husson et al., 1998a), submersion has fewer consequences when water is clear, because light will reach the seedlings. In such cases, sowing can be advanced as in the 1992/93 cropping season.

Evolution of time window for cultivation upon reclamation.

Upon reclamation and cultivation acid sulphate soils rapidly develop an impermeable plough-pan. However, development of this plough-pan is a function of soil physical characteristics which are correlated to topography. Figure 4.8 shows the decrease in vertical hydraulic conductivity for high Typic Sulfaquepts, low Hydraquentic Sulfaquepts and transitional soils over a 3 years period, for the depth 10-30 cm. On the clayey Typic Sulfaquepts, which have the highest vertical hydraulic conductivity before reclamation, creation of the plough-pan is extremely fast. In three years, hydraulic conductivity of this layer is reduced to one fifth. This results in a fast decrease of field permeability, and consequently improvement of water control. Oxidation can be prevented for a longer period, and at a lower cost. In fields at medium and high topographic level, delay in sowing to reduce plant mortality and increase in plant density can be achieved, while maintaining wet conditions throughout the cycle remains possible. Progressively, optimal time window for cultivation is enlarged, and starts later.

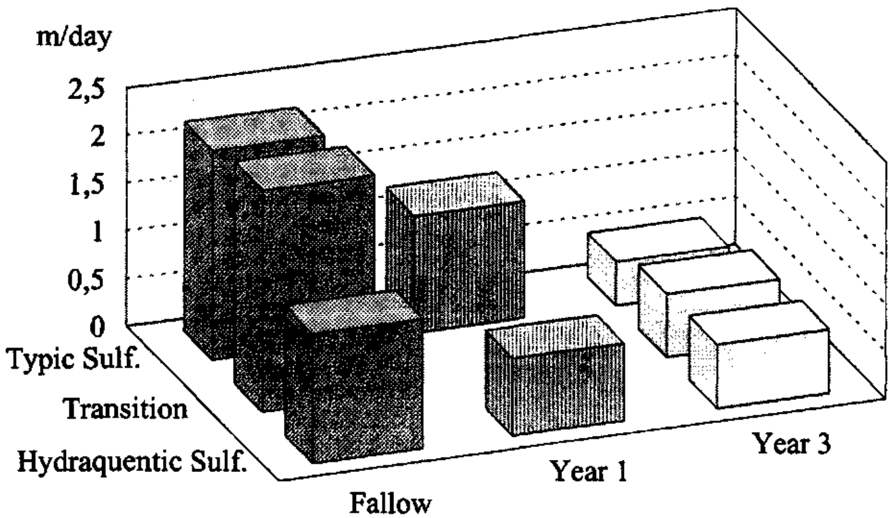

Figure 4.8. Evolution with cultivation of vertical hydraulic condutivity at depth 10-30 cm for three main soil types. Average of three replications.

In high or medium fields, where problems are linked to excessive oxidation at the end of the cycle, agricultural practices should aim at improving water control. Land preparation such as ploughing and harrowing, which leads to rapid development of a plough-pan, and careful maintenance of dikes are to be encouraged.

The low Hydraquentic Sulfaqueptshave a high organic matter content which retards creation of a plough-pan and improvement of water control. Drainage of these soils is hardly possible, because of their very low position. In such conditions, problems linked to deep reduction remain a major limiting factor for cultivation for many years. Priority for land preparation should be given to removal of organic matter because it lowers redox potential and induces toxicities.

Conclusion.

Inter and intra-annual variability of soil and water characteristics can be explained by soil and surface water levels. Flushing and leaching of acids, soluble aluminium and iron at the transition between submersion and drainage of soils can lead to high concentration of these substances in canals. The short-range temporal variability of soil chemical characteristics is mainly due to their sensitivity to changes in redox potential.

Optimal conditions for cultivation are met at medium redox potential. As it is determined by relative soil/water level, it is strongly variable in space and time and sensitive to microtopography. The transition from reductive to oxidative conditions is very fast, which means that optimal conditions for cultivation are met only during short periods. As water control is limited by the high permeability of these soils in the years following reclamation, extending the time window for cultivation through water management is hardly possible. Consequently, optimal conditions for cultivation can be maintained for short periods only. Farmers sow pregerminated rice seeds under water which allows enlargement of this time window. Precise determination of the sowing date is a key issue and should consider the age of the field (which influences its permeability), its average topography (which influences redox potential), and the flood characteristics, especially speed of recession and water turbidity.

Figure 4.9 shows constraints and optimal time windows for the three major situations met in the Plain of Reeds upon reclamation of severely acid sulphate soils, based on water characteristics measured during 1994/95 cropping season. Slight differences in topography induce important differences in starting date and duration of the optimal period for cultivation.

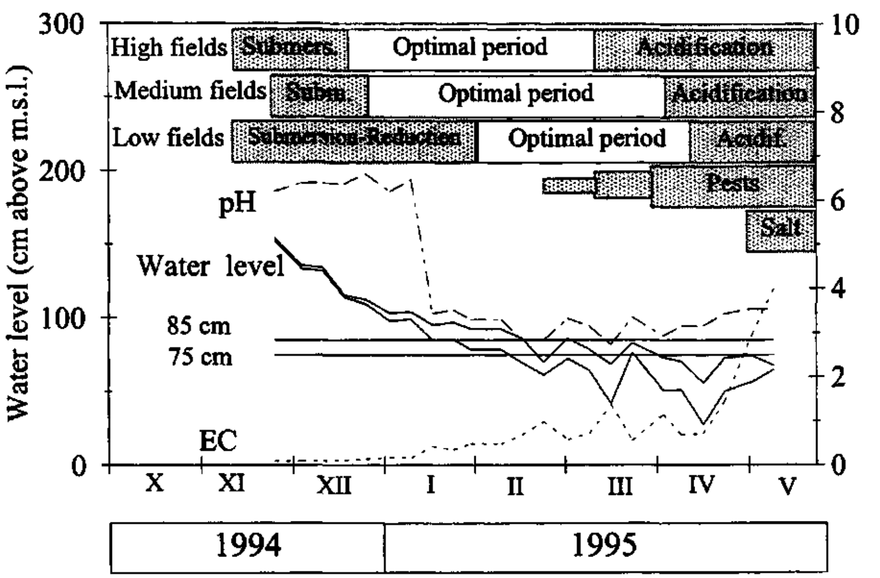

Figure 4.9. Major constraints for cultivation and identification of optimal cropping period for three major topographic positions. 1994/95.

In high fields (higher than 85 cm above mean sea level), fast water recession makes transition from submersion to deep oxidation very fast. Time window for cultivation is extremely short and sowing in deep water is needed. However, with cultivation a plough-pan is created in these soils. After three years, water control is sufficiently improved to make it possible to delay sowing while maintaining favourable conditions until the end of the plant cycle.

Fields at medium topography (75-85 cm above mean sea level) also face risks of oxidation at the end of the plant cycle, but as water recession is slower, time window for cultivation is longer than on high fields in the years following reclamation. However, improvement of these soils is slower than on higher fields.

Low fields (lower than 75 cm above mean sea level), although only 10 to 20 cm lower than the others, present very different problems as they are submerged most of the time. In these fields, rice plants suffer from toxicities linked to deep reduction. They can hardly be drained and develop very slowly with cultivation, which makes them the most difficult ones to reclaim.

Chapter 5

Field-scale variability of acid sulphate soils in the Plain of Reeds, Vietnam: An analysis of the effects of microtopography, soil and water on rice growth and yield

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Field-scale variability of acid sulphate soils in the Plain of Reeds, Vietnam: An analysis of the effects of microtopography, soil and water on rice growth and yield.

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Abstract.

In the Plain of Reeds, Vietnam, acid sulphate soils characteristics, water levels, and water quality are highly variable in space and time, in relation to microtopography. The sensitivity of soil chemical characteristics to redox potential, the rapid transition from submersion to strong oxidation and poor water control due to high soil permeability render favourable conditions for cultivation possible during a very short period. To extend this period, pregerminated rice seeds are broadcasted in deep water before flood water has receded completely.

Yield components were analysed in recently reclaimed farmers' fields. A semi-quantitative model was developed, explaining rice growth and yield as a function of different biophysical conditions on severely acid sulphate soils.

Intra-field variability of rice growth and yield is explained by the high short-range variability of soil and water, which is explained by microtopography. Long submersion and deep reduction raise important agronomic problems in the beginning of the plant cycle and lead to low plant, tiller and panicle densities. Strong oxidation leading to acidification and solubilisation of aluminium is frequent at the end of the cropping season and is responsible for poor plant growth and grain filling.

Inter-field variability of plant growth and yield is explained by differences in soil and water in relation to mean field level and number of years after reclamation. A typology of fields based on rice development is proposed as a guideline to extension in the Plain of Reeds.

Introduction.

The Plain of Reeds is a wide depression located in the north of the Vietnamese Mekong Delta where acid sulphate soils are found on 400 000 ha. In 1990, the most severely acid soils (150 000 ha) were still uncultivated and it became a national priority to reclaim them for agricultural purposes. However, they pose tremendous problems for cultivation. Oxidation of pyritic materials in these soils leads to acidification, and consequently to solubilisation of aluminium which rapidly reaches toxic levels. In reduced conditions, plants suffer from hydrogen sulphide and induced ferrous iron toxicity, among others. Water management is key to cultivation, but the very high permeability of the soils limits water control before a plough-pan has been created. To overcome these problems, farmers in the Plain of Reeds try to use the most favourable period for cultivation, at the end of the annual flood, when acidity and toxicities have been reduced by several months of flooding (Husson et al., 1998e). But these favourable conditions are very limited in time. When flood water recedes (January-February), soils rapidly change from deep reduction to strong oxidation. The only solution to avoid this oxidation and the poor water quality at the end of the crop cycle is to start cultivation as soon as possible. In this respect, farmers developed an original method which consists in sowing pregerminated rice seeds in deep water (20-40 cm), before flood water has completely receded (Husson et al., 1998e).

The time window during which favourable conditions for cultivation are met is not only very short but also spatially variable and a function of microtopography of the fields and of the relative soil/water level. By microtopography it is understood topographic level whose variations are measured in centimetres (the difference between the lowest and the highest points measured during this study is less than 50 cm), even at considerable distances (in the range of a few kilometres).

In the study area, low positions (lower than 75 cm above mean sea level) are kept submerged much longer than high locations (higher than 85 cm above mean sea level) and hardly dry out (Husson et al., 1998e). In the dry season they regularly benefit from tidal movements in canals, in contrast to soils at high topography. As a consequence, after flood recession the water table is higher in low topographic positions than in high ones which can strongly and deeply oxidise. These differences in drainage lead to differences in soil development. Below 75 cm above mean sea level, soils consist of very organic Hydraquentic Sulfaquepts, when above 85 cm above mean sea level clayey Typic Sulfaquepts are found. In between, a transitional soil type is found, with intermediate characteristics (Husson et al., 1998c).

The high sensitivity of soil forming processes to microtopography explains that soil types and characteristics can vary greatly within a few metres. Short-range spatial variability of soil and water is very high and, as a consequence, rice growth and yields are extremelly variable and relate to microtopography.

In this context, simple modelling of rice growth and yield is needed to develop adapted cropping systems. Sylla (1994) studying mangroves in West Africa concluded that crop simulation models can be of great importance to define iso-yield lines for mapping potential and actual rice yields, but he observed that the complexity and the high variability of soil constraints were real challenges to cope with. Van Mensvoort (1996) stated that at this moment, the application of crop simulation models for acid sulphate soil conditions is not very useful since the soil-plant relationships, i.e. the reaction of plants to the dynamics of acid sulphate soils, are not yet well understood. Such knowledge of the influence of soil and water on rice growth is all the more needed in the Plain of Reeds because farmers urgently need research results and recommendations for reclamation of these severely acid sulphate soils, cropping techniques are unusual, chemical and physical processes occurring in acid sulphate soils are more complex than in any other soil, and their management is complicated by the very high variability.

A simple model of yield build-up ("*modèle d'élaboration du rendement*"), i.e. a theoretical model of biological functioning of a cultivated population of plants (Sebillotte, 1978; De Bonneval, 1993) is given by Sebillotte (1980) for cereals and by Yoshida (1981) for rice. Yield is explained by number of grains /m^2, which can be divided in number of panicles/m^2 multiplied by the number of filled grains per panicles, and weight of one grain.

In the Plain of Reeds, the high variability of rice growth and yields in relation to topography makes it necessary to take into account microtopography for agronomic studies, distinguishing two levels:

(i) Within fields, as at this level topography determines soil types and characteristics, influences redox potential, and therefore greatly affects cropping conditions, and

(ii) between fields, as water table levels and water control opportunities are a function of the average field topography.

Studying intra-field variability helps to understand processes of rice yield build up and the participation of the various yield components in the grain production. Analysis of inter-field variability over a period of time allows the evaluation of potential yield and the assessment of evolution of these fields upon reclamation.

Experimental and observational work on soil characteristics and agronomy of rice was therefore conducted with a view to:

(i) develop a model of rice yield build-up, in the actual conditions of reclamation of severely acid sulphate soils as found in the Plain of Reeds. This model should take into account the very dynamic characteristics of acid sulphate soils and their high spatial variability.

(ii) identify and rank major factors limiting rice growth in the Plain of Reeds.

(iii) determine the conditions and the causes of development of these factors.

(iv) assess potential yield in relation to field characteristics.

Materials and methods.

Experimental setting.

Experiments were conducted by farmers in actual conditions of production, in 61 field with the following experimental factors: fertilisers (types, doses, periods of application), varieties, and sowing densities. In most cases, 4 treatments were applied in large fields, without replications. Based on a previous detailled site characterisation, long (100-150 metres) and narrow (7-15 metres) plots, crossing different field conditions were preferred, to cover various situations and to "homogenise heterogeneity" between plots (Figure 5.1). Eight fields were conducted homogeneously to assess the impact of tertiary canals on rice growth and yield.

The 61 fields were located at various topographic levels, which influences soil characteristics and water management requirements, and were different regarding the number of years since reclamation (1 to 4 years) which influences permeability and consequently water management possibilities.

To allow comparisons between fields, one treatment was applied in all experiments (and in the homogeneously conducted fields). Fertilisation level F2 consist of 100 N, 100 P_2O_5 and 0 K, which is a medium fertilisation for farmers in the Plain of Reeds. All experiments were cultivated either with IR 9729-67-3 or IR 59606-119-3-3, two varieties with fairly similar characteristics.

In experimental fields, observation plots of one square metre were used for measurement of yield and yield components, soil characteristics, topography, and soil analysis. Yield components were divided in plants/m², tillers/m², panicles/m², number of filled grains/panicle, number of empty grains/panicle, plant height, weight of one grain (measured on 1 000 grains counted with a Numigral), dry matter and grain yield. Topography was measured with a theodolite and calibrated to mean sea level through a reference point given by the Long An Province Hydraulic Services.

For every treatment, 15 to 21 observation plots (according to the subject of the experiment and field size) were selected by systematic grid sampling (Figure 5.1). Thus, yield components were measured in a minimum of 60 plots per field. In homogeneously conducted fields, measurements were made in 100 to 200 observation plots with a rectangular grid (2.5 x 10 metres).

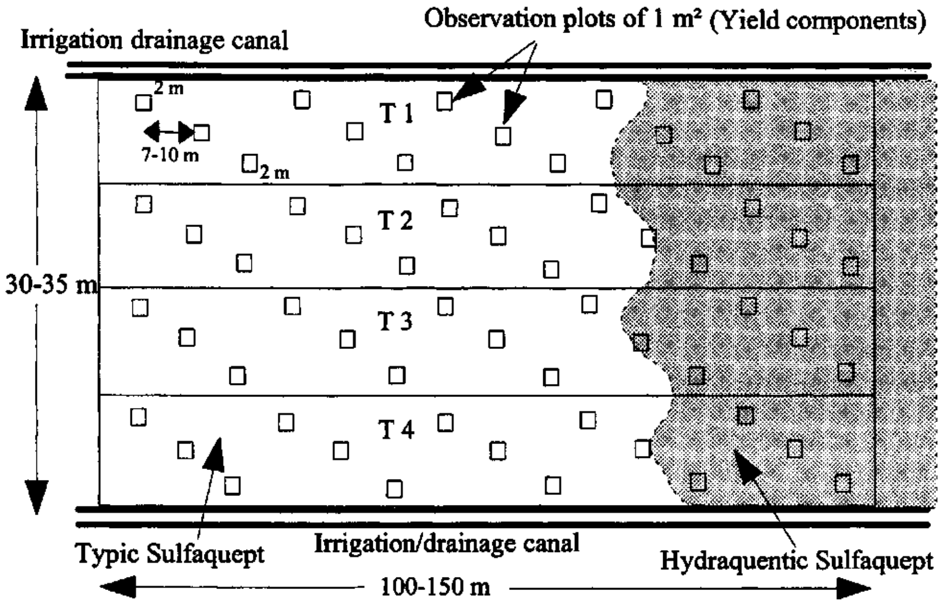

Figure 5.1. Set up of experiments according to field characteristics.

Analysis.

Special care was given to the identification of the main factors influencing rice growth and yield, and to the study of interactions between these factors. At both intra- and inter- field levels, the analysis of yield components and the study of the contribution of each yield component to grain yield allows: (i) to identify bottlenecks and rank factors limiting rice growth and yield; (ii) to determine when rice plants face stresses during their development; and (iii) to identify possible causes for the stress.

Within fields, measurements of yield components conducted on observation plots were used as replications to perform covariance analysis (Gomez and Gomez, 1984). Data were also analysed by means of scattered plots and multiple linear regressions. In order to have a sufficient amount of data for these analyses, measurements made in the whole field were used with no distinction of treatments. A synthesis of correlations observed in the 61 fields is presented and one field representative of most experimental fields is given as an example. This field is located at 76.6 cm above mean sea level on

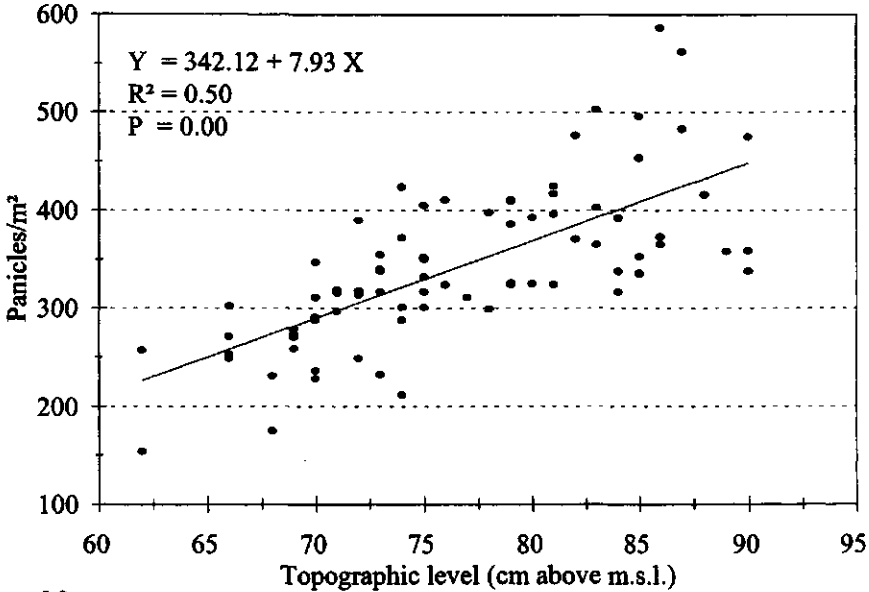

Figure 5.2.a.

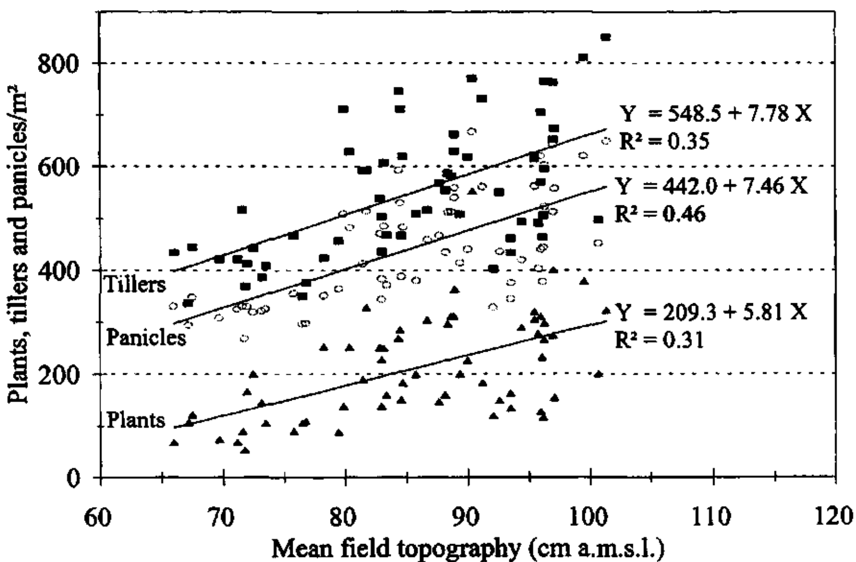

Figure 5.2.b.

Figure 5.2. Densities as a function of microtopography. X indicates centred values.

Figure 5.2a: Panicle density. Field A. n = 84.

Figure 5.2b: Plant, tiller and panicle densities. Synthesis of 61 fields.

most experimental fields is given as an example. This field is located at 76.6 cm above mean sea level on average and was cultivated for the second season after reclamation during the 1993/94 cropping season.

Between fields, scatter-plots analyses and multiple linear regressions have been performed, using averages of data measured in each field for fertilisation level F2.

Results and discussion.

Plant, tiller and panicle densities.

Results.

At intra-field level, positive linear regressions are observed between plant, tiller and panicle densities on the one hand, and microtopography on the other. Figure 5.2a presents the correlation between panicle density and topography in field A, given as example. Table 5.1 gives a synthesis of regressions found in the 61 fields analysed and shows that field A is representative of most fields.

Table 5.1: Synthesis of regressions between plant, tiller and panicle densities, and topography.

	Plant density	Tiller density	Panicle density
Percentage of significant correlations (α=5%)	61%	85%	90%
Percentage of highly significant correlations (α=1%)	43%	79%	85%
Average R^2	0.27	0.34	0.34
R^2 "low" fields (lower than 75 cm amsl)	0.20	0.33	0.35
R^2 "medium" fields (75-85 cm amsl)	0.36	0.42	0.39
R^2 "high" fields (higher than 85 cm amsl)	0.16	0.28	0.29
Maximum R^2	0.64	0.72	0.71

Plant, tiller and panicle densities show a significant positive linear regression with topography in respectively 61%, 85% and 90% of fields. In all cases, R^2 are higher for fields at medium topography (between 75 and 85 cm above mean sea level on average) than for higher or lower fields. In the lowest fields, correlations between plant density and topography are weak. Only 44% of fields lower than 75 cm above mean sea level show significant correlations, with a low average R^2 of 0.20. In these fields, and especially in the lowest locations, emergence is extremely uneven and a black ferrous sulphur coat can be observed around germinating seeds.

Tillering is correlated to plant density and microtopography as in field A in which correlation with a multiple R^2 of 0.78 is obtained, using centred values:

Nb Tillers/plant = 1.9457 + 0.0485 Topography (cm) - 0.0097 Plants/m² + 0.00003 (Plants/m²)².

In this field, multiple regression explaining tillering shows that, at constant topography, differences in plant density are offset by differences in tillering due to plant density. At medium topography, with a medium plant density of 215 plants/m², tiller density is 419 tillers/m². With only 115 plants/m², tiller density is still 366 tillers/m². From a difference of 47% on plant density, a difference of only 13% remains on tiller density. This particularly holds when density is below 250 plants/m². There is also a strong effect of topography on tillering. At medium plant density and medium topography, tiller density is 419 tillers/m², whereas 10 cm lower, tiller density is 314 tillers/m².

Multiple regressions also indicate that the proportion of fertile tillers is a function of the number of tillers/m² but also of microtopography, as in field A:

Number of panicles per tiller = 1.04- 0.0005 tillers/m² + 0.0037 Topography, R^2= 0.28, P= 0.00.

Significant regression between number of panicles per tiller and topography alone or topography and tiller density is found in 55% of fields, but with low R^2 (0.1-0.3). This means that topography has an effect, although small, on the production of panicles, independently of its effect on tiller density.

With respect to inter-fields variability, using average values of treatment F2 for each field, regressions are observed between plant, tiller and panicle densities, and microtopography. Again, positive linear correlations are observed between densities and topography (Figure 5.2b).

Between fields, tillering is poorly correlated to topography but it is significantly correlated (multiple R^2 = 0.75, P = 0.00) to:

* Plant density (-0.01 tiller/plant per plant/m²), as at intra-field level.
* Number of cropping seasons after reclamation (+0.27tiller/plant/year).
* Water level at sowing (-0.03 tiller/plant/cm of water).
* Variety. IR 9729 produces 0.44 tiller/panicle more than IR 59606.

Between fields, panicle density is correlated to topography but also to the water level at sowing (WLS, shown on figure 5.3) and to the number of years after land reclamation (NYAR). Multiple regression combining effects of topography, water level at sowing (WLS) and number of years after reclamation (NYAR) explains 63% of the total variation in panicle density, all factors having highly significant effect:

Panicles/m² = 452 + 5.8 Topo + 26.3 NYAR - 2.25 WLS

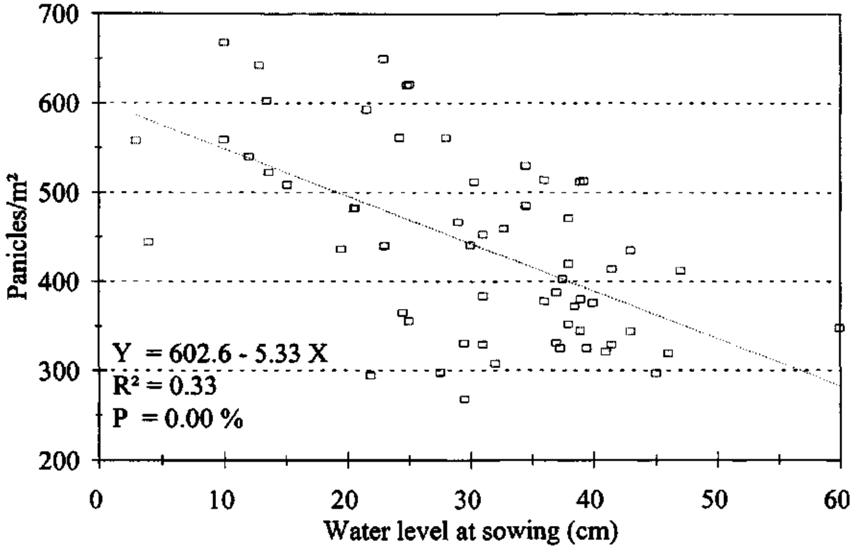

Figure 5.3. Panicle density as a function of water level at sowing. Synthesis of 61 fields.

Discussion.

The intra- and inter-fields effect of microtopography on plant density can largely be explained by differences in submersion. Within a field, seedlings at low locations are submerged longer and deeper than those at high locations. Between fields, faster water recession on high fields sown first leads to shorter submersion than on low fields. A consequence of longer and deeper submersion is higher plant mortality. Palada and Vergara (1972) showed that the survival percentage of submerged rice seedlings sharply decreases after 6 days of submersion and is greatly reduced by water turbidity, probably because it reduces light intensity. Visual field observations in Vietnam confirm this effect of water turbidity on plant mortality.

The great unevenness of emergence and the black ferrous sulphur coat observed around seeds in the very low locations are clear symptoms of development of sulphate-reducing and ferric-iron reducing bacteria. These anaerobic bacteria colonise rhizosphere and produce toxic sulphur and ferrous iron extremely harmful to young seedlings and can induce 100% mortality (Jacq et al., 1993). In such low places, organic acids produced by decomposing fresh organic matter may also slow rice growth (Chandrasekaran and Yoshida, 1973) and increase plant mortality.

Singh et al. (1988), and Thangaraj and Sivasubramanian (1990) have shown that tillering is reduced by low light intensity. As for plant density, the effect of topography on tillering can be attributed mainly to differences in light intensity induced by differences in duration and depth of submersion.

Offsetting low plant density by high tillering and the influence of submersion on tillering explain why correlations between microtopography and densities are higher for tiller (and panicle) densities than for plant density, which is often uneven in directly broadcasted farmers fields.

Matsushima (1966) showed that to be fertile, a tiller must start its growth before the main stem reaches the stage of panicle initiation. Visual field observations showed that for long submersion, elongation of leaves is important, and many of the first leaves finally die, as well as first tillers produced on plants. Thus, only tillers of second or higher order survive long submersion. Tillers of high order (5 or higher) appear too late to be fertile. After long submersion, i.e. at low topography, most of the primary and secondary tillers die, and the ratio panicle/tiller is lower than on high places where most of the primary and secondary tillers survive and produce panicles.

Again, the strong impact that water level at sowing has on panicle density (Figure 5.3) can be attributed to differences in depth and duration of submersion.

The strong increase in panicle density over the years after reclamation may be explained by:

(i) improvement of physical characteristics by cultivation. In particular, land preparation leads to the rapid creation of an impermeable plough-pan. Water control, almost nil in the first year, improves quickly, which allows the delay of sowing and the broadcasting of rice seeds in shallow water. In such conditions, plant density is increased.

(ii) improvement of chemical characteristics by flushing and leaching of toxic elements such as iron, aluminium and salts.

These hypotheses are reinforced by the fact that improvement is faster at high or medium topographic level, where these phenomenons are more important and occur faster than on low positions.

The fact that panicle density increases with time after reclamation suggests that water depth and duration of submersion are not the only factors influencing densities. Physical and chemical characteristics, which vary with topography and evolve with time, probably also affect densities, especially in the lowest locations.

Number of grains per surface unit.

Results.

In 77% of fields, numbers of filled grains (NFG) and empty grains per panicle significantly decrease when topography increases. The number of spikelets per panicle is known to be correlated with carbohydrates stocked in stems and to decrease when panicle density increases (Apakupakul, 1991). In field A given as example, plant height, an indicator of plant growth, is correlated to microtopography in a quadratic trend (Height in cm = 78.4 -0.53 Topo - 0.04 $Topo^2$, $R^2 = 0.42$), which is the case in most fields. In low positions, plant growth slightly decreases when topography decreases. At high topography, plant growth strongly decreases when topography increases. In this field, an increase in plant height of 2.5 cm adds 1 grain/panicle whereas an increase of 100 panicles/m^2 leads to a decrease of 2.5 filled grains/panicle. However, the number of filled grains/m^2 increases when panicle density increases.

This results, in most fields, in a number of filled grains/m^2 correlated to topography in a quadratic trend, with a maximum at medium topography as presented for field A (Figure 5.4).

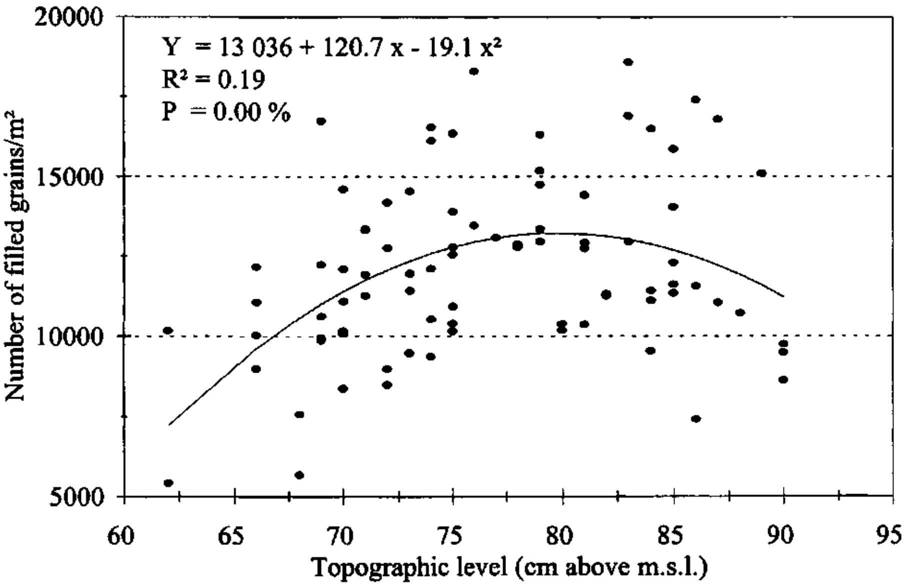

Figure 5.4. Number of filled grains per m^2 as a function of microtopography. Field A. n= 84. X indicates centred values.

Comparing between fields, number of filled grains/m^2 is explained at 67% by topography and number of years after reclamation (Figure 5.5). The effect of time is clear, with a gain of

2350 grains/m² per year due to both increase in panicle density (+ 26.3 panicles/m² per year) and number of filled grains per panicle (+ 3.2 filled grains/panicle per year). Varietal differences also exist: IR 9729 produces fewer grains per panicle than IR 59 606 (-4.26 grains/panicle) for similar panicle density, what leads to a production of 1 812 grains/m² lower.

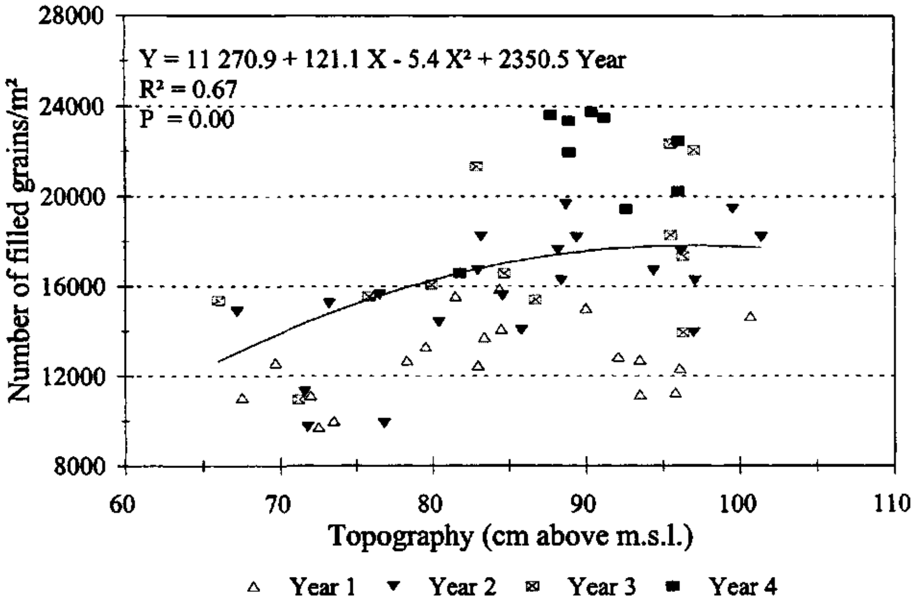

Figure 5.5. *Number of filled grains per m² as a function of microtopography and number of years after reclamation. Synthesis of 61 fields.*

Discussion.

Although no experiment has been conducted, it can be thought that poor plant growth on high parts of fields is due to adverse chemical characteristics in dry conditions. Field observations showed that rice plants in high topographic position have fragile, stunted roots, attributed by Hanhart and Ni (1993) to aluminium toxicity. Hydric deficit 0-2 weeks before heading is also known to cause grain sterility and as a consequence to lead to low number of filled grains per panicle (Yoshida, 1981). Stronger hydric deficit on higher places probably leads to lower number of filled grains/panicle.

In low locations, long and deep submersion leads to thin and weak plants, sensitive to diseases and showing clear symptoms of bronzing on leaves. In the lowest places blacks roots are observed. Bronzing has been attributed to iron toxicity (Ponnamperuma et al., 1955) following a multinutritional stress (Ottow et al.; 1983; and Ottow et al.; 1991). Stresses linked to deep reduction are increased by the development of ferric iron-reducing and sulphate-reducing bacteria which progressively colonise rice rhizosphere and favours production of H_2S and the reduction of iron (Jacq et al., 1993). In these conditions of deep reduction, iron toxicity is probably induced by H_2S as described by Tanaka et al. (1968) and Hanhart and Ni (1993): In moderately reduced conditions, oxygen is pumped by rice plants into the root zone, precipitating excess ferrous iron at the root surface and preventing rice plants from excessive ferrous iron uptakes. When H_2S and FeS are present, they are oxidised first as they are lower in the oxidation/reduction range than ferrous iron. Rice roots are then not able to maintain on their surface the brown crust of ferric hydroxides which prevent excessive ferrous iron uptakes, and iron toxicity can develop (Hanhart and Ni, 1993).

Weight of one grain.

Weight of one grain is known to be a function of (Apakupakul, 1991): (i) Temperature, (ii) Hydric deficit in the beginning of the grain filling period that provokes a decrease of filling speed and weight of grains, (iii) Solar intensity and photosynthetic activity: grain filling speed is linked to carbohydrates produced in leaves, and (iv) Parasitism and toxicities.

In field A, the weight of one grain (in mg) is correlated to plant height (-7.55 + 0.781 Height - 0.0045 Height^2; $R^2 = 0.57$; $P = 0.00$) and dry matter production ($R^2 = 0.21$; $P = 0.01$), which are both indicators of plant growth. Visual field observations showed that tall plants had higher leaf areas than short plants which had thin leaves. The correlation of weight of one grain to plant height and dry matter indicates that in this field also, grain filling was limited by carbohydrates produced in leaves.

As plant growth is usually correlated to topography, a significant effect of topography on the weight of one grain is observed in 69% of fields. Average R^2 is 0.33, with a maximum of 0.72. Regression between the weight of one grain and microtopography shows a quadratic trend, with maximum values at medium topographic level (Figure 5.6 presents the example of field A). A slight decrease towards low topographic positions can be attributed to iron toxicity and parasitism, especially in low fields where very long submersion occurred. Field observations indicate strong symptoms of bronzing and high attacks by *Helminthosporium oryzae* and *Pyricularia oryzae* in these lowest places, where plants are weak.

A strong decrease in the weight of one grain when going upward can be attributed to low carbohydrate production by thin leaves of short plants which suffered from acidity and high aluminium concentration, and to hydric deficit that can be severe on the highest positions, especially in high, poorly irrigated fields.

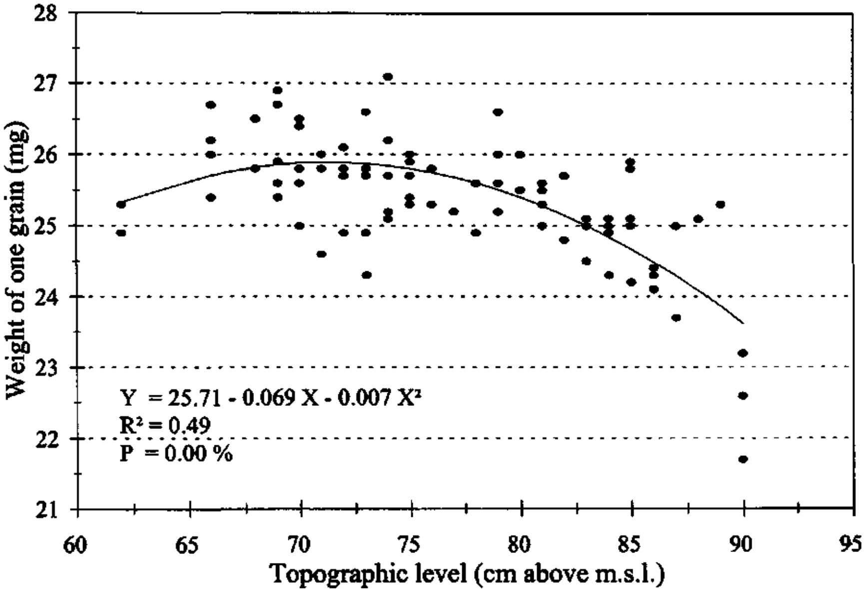

Figure 5.6. *Weight of one grain as a function of microtopography. Field A. n = 84. X indicates centred values.*

The weight of one grain increases when the number of filled grains per panicle increases (Figure 5.7), which seems unusual. This can be easily explained when looking into details of the conditions of growth. A low weight of one grain and a low number of grains/panicle are observed on high topographic levels where panicle density is high, and as a consequence the number of grains per panicle is low. In these high positions, dry conditions also lead to poor plant growth and bad grain filling, explaining the low values observed for the weight of one grain. High values for the weight of one grain and the number of filled grains per panicle are observed for lower topographic positions. In these places, a low panicle density leads to a high number of grains per panicle. Favourable hydric conditions allowed better growth and grain filling, leading to the higher weight of one grain.

In comparing between fields, the weight of one grain is significantly correlated to topography and the number of years after reclamation : Weight of 1 grain = 24.012 + 0.054 Topo + 0.476 NYAR. Correlation is rather low (0.34) but this is explained by the fact that in the first year after reclamation, weight of one grain shows a quadratic trend with topography, as seen at field level, with a maximum at medium topographic level, whereas in the following years weight of one grain increases more on high fields than on low fields. In the third and fourth year, linear correlation is observed between weight of one grain and topography.

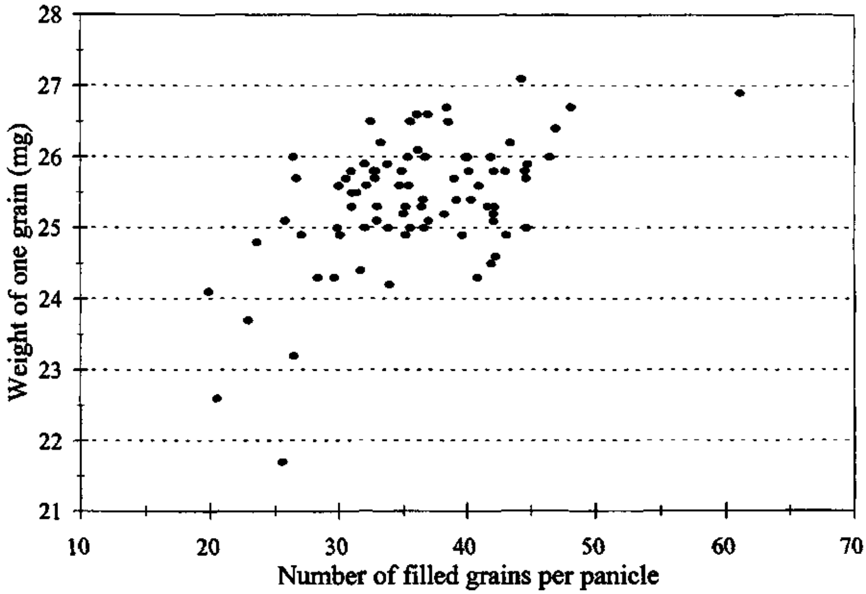

Figure 5.7. Weight of one grain (mg) as a function of number of filled grains per panicle. Field A. n = 84.

Low grain filling in the lower fields can be attributed to poor carbohydrates production linked to iron toxicity, and parasitism (in particular *Helminthosporium oryzae*).

Yield.

Yield is the combination of number of grains per square metre and weight of one grain. Both are correlated to microtopography and, logically, yield is significantly correlated to topography in 73% of fields. R^2 can reach 0.65, with an average value of 0.32. A quadratic trend with maximum yields at medium topography is observed for most fields (Figure 5.8 shows the example of field A), but linear regression can be observed:

* In low fields that have been sown early. Panicle density is then very low and is the main component explaining yield. Thus, a positive linear regression is observed between yield and topography. In these cases, coefficient of the regression is usually high, and can reach 150 kg/ha per cm.

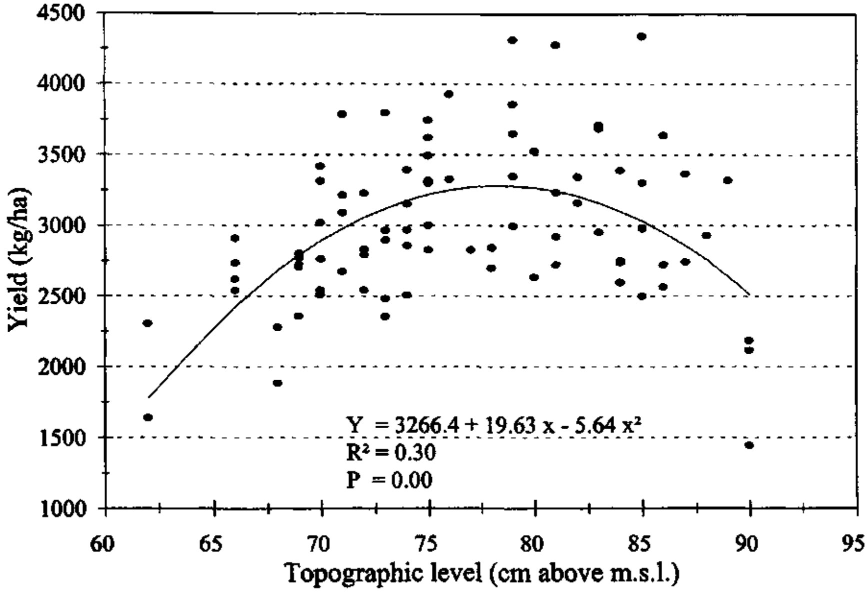

Figure 5.8. Yield as a function of microtopography. Field A. n = 84. X indicates centred values.

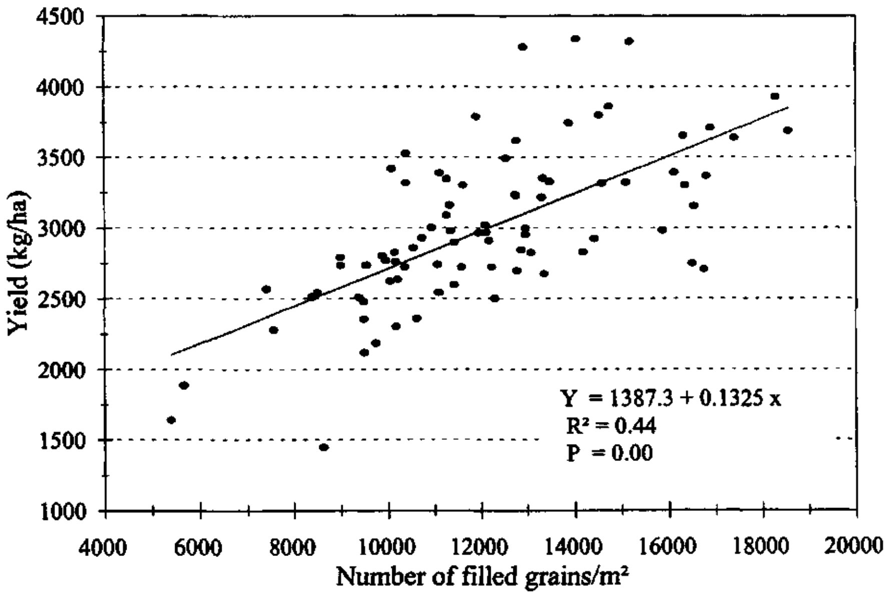

Figure 5.9. Yield as a function of number of filled grains / m^2. Field A. n = 84.

* In high fields, sown early and poorly irrigated. Panicle density is usually high and yield is mainly determined by weight of one grain. A negative linear regression is observed between yield and topography, with a regression coefficient of up to - 100 kg/ha per cm.

Yield is mostly correlated to the number of filled grains per square metre (Figure 5.9), but rarely to the weight of one grain. This is in accordance with Durr (1984) and Crozat et al. (1986) who found that yield mainly is determined by the number of grains per surface unit, and that there is generally no relationship between yield and weight of one grain which is usually less variable. However, in fields with poor irrigation, weight of one grain is very low and variable and has a strong impact on yield (Figure 5.10a).

At inter-fields level, correlations between weight of one grain and yield (Figure 5.10b) on the one hand, and number of filled grains/m² and yield on the other hand (Yield = 169.9 + 0.225 number of filled grains/m², $R^2 = 0.87$) indicates that yield is indeed limited by grain density and grain filling.

Improvement of rice growth and yield upon reclamation.

Figure 5.10b also shows that grain filling is strongly influenced by the number of years after reclamation, as is the number of filled grains/m². As a consequence, yield increases with the number of years since reclamation (Figure 5.11). This increase can be explained by progressive flushing of toxic ions and, primarily, by improvement of water control which allows better water management and enlargement of the time window during which favourable cropping conditions are met.

However, topography, which is correlated to hydric conditions and soil types, influences the evolution of fields upon reclamation.

In low fields, drainage is hardly possible. They are covered by water most of the time and flushing of toxic elements is very limited. On the contrary, toxic elements leached from higher positions are concentrated in low places. Thus, physical and chemical characteristics evolve very slowly. For several years, when sown under water, rice plants suffer from deep reduction and submersion, leading to low densities and poor plant growth. Lowest yields are always found at low topography (Figure 5.11). This result is in accordance with Bos and Van Mensvoort (1983) who suggested that in the Vietnamese Mekong delta yields were lower when rice was cultivated on soils with peaty parent material than on soils with clayey parent material.

Figure 5.12, gives the average yield as a function of the number of years after reclamation for three different classes of fields based on topography. Low fields have an average topographic level below 75 cm, with a minimum at 66 cm above mean sea level. Medium fields are between 75 and

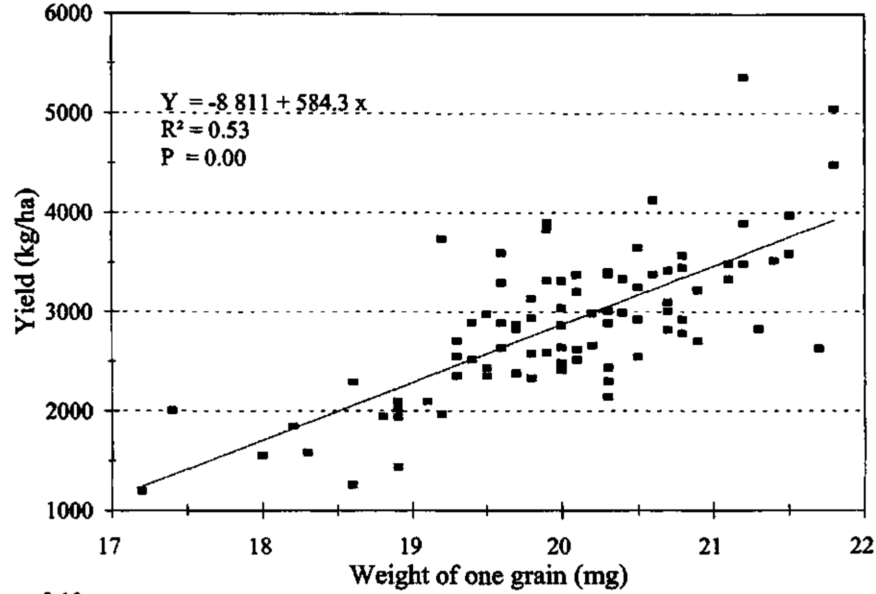

Figure 5.10.a.

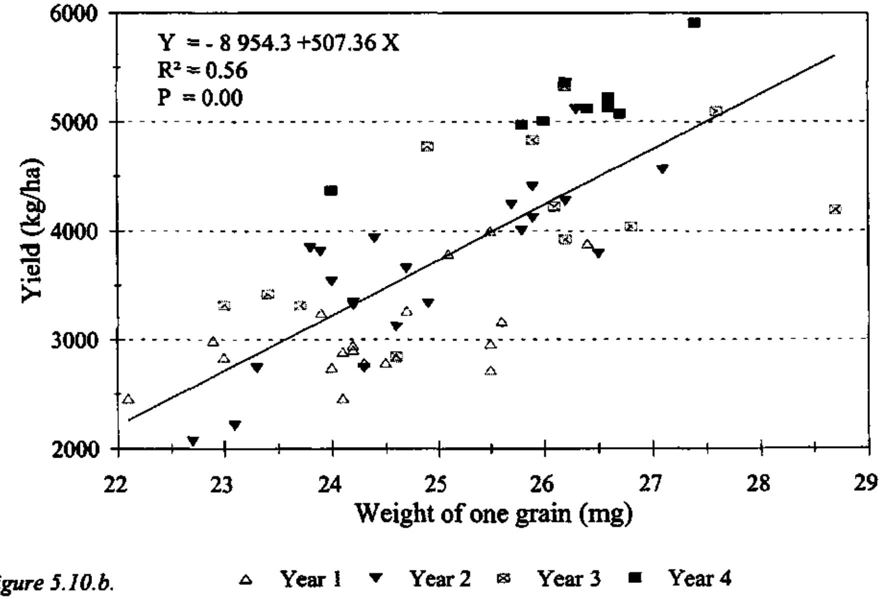

Figure 5.10.b.

Figure 5.10. Yield as a function of weight of one grain.
Figure 5.10a. Field B. n = 90.
Figure 5.10b. Synthesis of 61 fields.

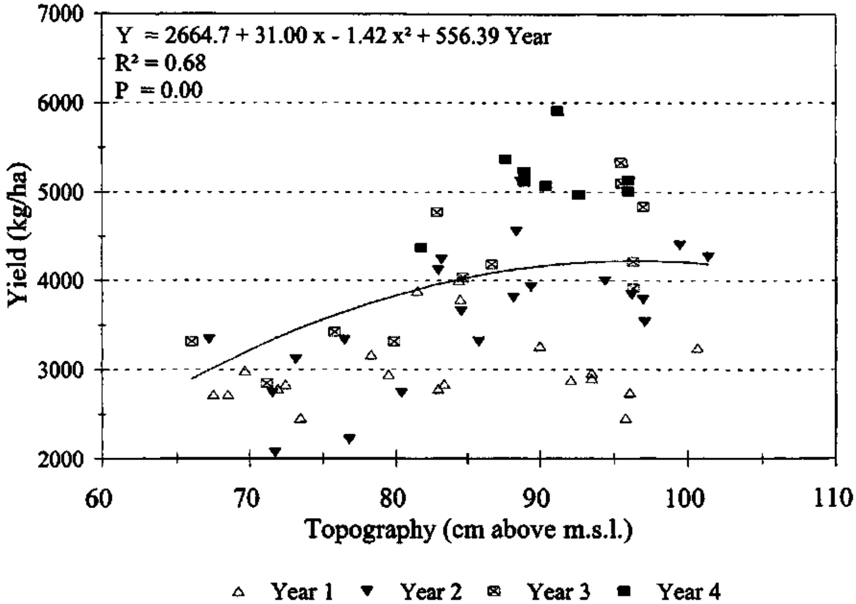

Figure 5.11. Yield as a function of microtopography and number of years after reclamation. Synthesis of 61 fields.

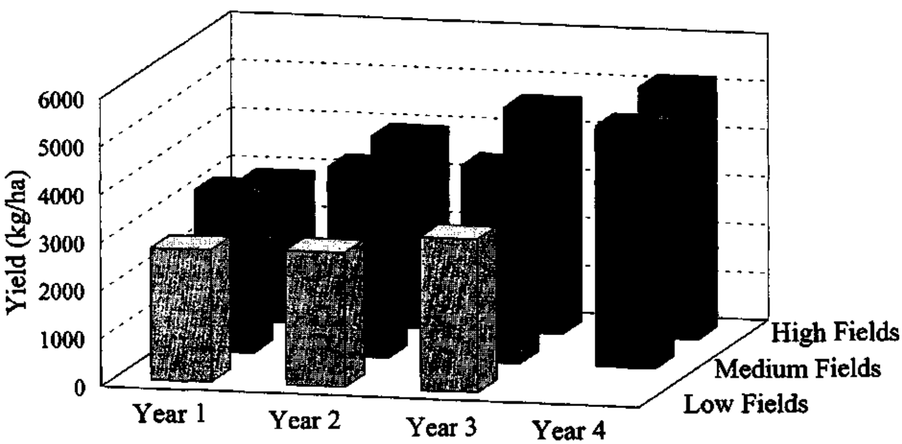

Figure 5.12. Evolution of rice yield with number of years of cultivation upon reclamation, for three main topographic positions. Synthesis of 61 fields.

85 cm above mean sea level, while high fields are higher than 85 cm above mean sea level, with a maximum at 102 cm above mean sea level on average.

In low fields average gain is only 165 kg/ha per cropping season. In fields at medium topography, where the highest yields are measured in the first cropping season, gain is uneven but averages 560 kg/ha per cropping season. High fields have medium yield in the first cropping season but improve very fast and gain on average 765 kg/ha per cropping season. In these high fields, during the first year after reclamation poor water control makes early sowing necessary, leading to low densities. Furthermore, aluminium toxicity in dry conditions and poor grain filling because of hydric stress can hardly be prevented, which also leads to low grain filling. Due to the rapid improvement of the physical and chemical characteristics of the soil with cultivation, and consequently the improvement of the water control (Husson et al., 1998e), both densities and grain filling progressively increase, leading to high yields. This gain is very important between the first and the second cultivation (over 1100 kg/ha), then logically decreases to about 600 kg/ha between the third and the fourth year as yields become high. It is expected that after 5 to 6 years of cultivation, yearly gains will be small. These high fields will then be regarded as fully reclaimed. It will take longer to completely reclaim fields at medium topographic level, in which flushing is less important and permeability decreases more slowly. Low fields, on Hydraquentic Sulfaquepts improve very slowly and are the most difficult to reclaim.

Significance of statistical relations.

Coefficients of correlations presented here may appear rather weak as compared to R^2 measured in "classical" studies conducted in controlled conditions, where factors are isolated and studied separately.

However, one should consider that in this study, all experiments are conducted in actual conditions of production, in farmer-managed fields and on severely acid sulphate soils. Factors are not controlled nor isolated but are studied in interaction. A direct consequence of not separating factors is a lowering of the coefficients of correlations. Another drawback of this approach is that the high variability of these soils and the limits in precision of measurements (especially for measurement of microtopography in poorly levelled fields) also lower the coefficients of correlation. However, this approach has the advantage of giving a different perspective as compared to other research, integrating variability of, and interactions between, the different factors explaining rice growth.

Furthermore, the relatively low values of R^2 are compensated by the high significance of the correlations and the large number of fields in which these correlations are measured. Within fields, significant correlations between yield components and microtopography have been measured in 61 to 90% of the 61 fields analysed which excludes any risk of erroneously correlating two factors.

Furthermore, in this study, the relationships between rice growth at various stages and a single factor are only pieces in the model and the combined weight of the correlations should be considered. When bilateral relationships are measured, one should also pay attention to the agronomic significance of the correlated variables and to the practical conclusions which can be drawn from the correlations. Microtopography was not considered in previous agronomic studies on acid sulphate soils. This study shows that, within and between fields, microtopography is correlated to the various yield components with average coefficients of correlation of 0.3-0.4 and maximum values over 0.7. In some fields, microtopography alone could explain 65% of rice yield.

Finally, it should be mentioned that: (i) at intra-field level, regressions were calculated from data measured in the entire fields, without considering the effects of the various treatments. This probably leads to an underestimation of R^2, and (ii) between fields, multiple regressions show R^2 values of 0.67-0.75, which can be regarded as high as differences in variety, land preparation and water management, a key issue to cultivation on acid sulphate soils, were not considered.

Conclusions and recommendations.

1. Role of the microtopography.

Both within and between fields, the microtopography plays a crucial role and largely explains differences in rice growth at all stages of the plant cycle, and consequently differences in yield. For research purposes, experimental designs should include this effect of topography. Covariance analysis with microtopography as the covariate proved to be a very efficient tool to control the high heterogeneity of these soils (Husson et al., 1998b).

2. Rice yield build-up in the cropping conditions of the Plain of Reeds.

The main yield component is the number of filled grains per surface unit, which is itself determined by panicle density. This density is correlated primarily to microtopography and water level at sowing which determine: (i) depth and duration of submersion, and (ii) soil chemical, physical and biological characteristics. Weight of one grain is usually more stable than the number of filled grains per m^2, but can strongly influence yield, especially in dry conditions.

3. Management of acid sulphate soils.

When reclaiming the highest fields (higher than 85 cm above mean sea level), dry conditions at the end of the cycle lead to poor grain filling, especially in the highest locations. To avoid excessive physiological drought at the end of the cycle, early sowing of pregerminated rice seeds in deep water is needed, but it is done at the cost of reducing plant density.

At medium topographic level (75-85 cm above mean sea level), a compromise can be found avoiding excessive submersion at the beginning of the cycle, but maintaining sufficient irrigation to achieve good plant growth. Thus, rather high densities and good plant growth, and consequently rather high yields, can be obtained from the first year after reclamation with sowing under water.

In low fields (lower than 75 cm above mean sea level) grain density is the main limiting factor: in the beginning of the cycle, very long submersion, reduced conditions and sulphate and ferric iron reducing bacteria lead to adverse chemical characteristics.

4. Evolution upon reclamation.

With time and cultivation, chemical characteristics are improved by the progressive leaching and flushing of toxic elements. Water control is also improved as permeability decreases. As a consequence, yields increase in the years following reclamation. Improvement of soil characteristics and increase of yield are faster on high fields in which yield can reach more than 5 000 kg/ha after four years of cultivation. In medium fields, because of different soil characteristics and poorer opportunities of flushing, improvement is slower. In low fields, the absence of drainage, poor flushing and a slow decrease of permeability because of the high organic matter content lead to much slower improvements of yield upon reclamation than on fields at high or medium topography. Because of long submersion and unfavourable chemical conditions, especially the very low redox potential, densities and consequently yields are always low when seeds are sown under water.

5. Typology of fields and model of rice yield build-up as decision making tools for farmers.

From the two main yield components explaining yield (the number of grains per square metre and the weight of one grain), a typology of fields could be developed. Figure 5.13, based on the 61 fields observed between 1992 and 1996, shows seven main types of field. Table 5.2 presents the main characteristics of each types and sub-types. They sometimes overlap but all fields within one type or sub-type present the same characteristics, and they all face the same kinds of problem.

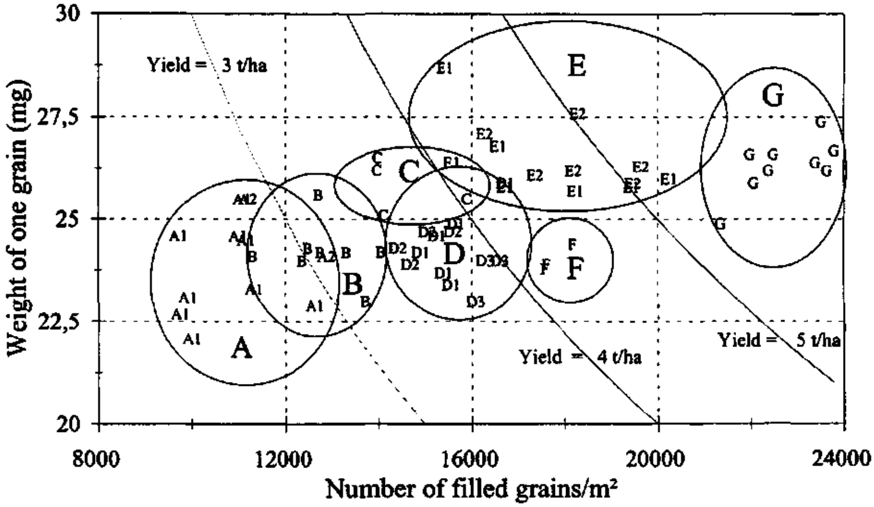

Figure 5.13. Typology of fields based on filled grain density and weight of one grain. 61 fields.

This typology completes the model explaining rice growth and yield. It reflects the various cropping conditions and agronomic problems met in the Plain of Reeds and the effect of water management on crop performance. Together with the model of rice yield build-up, it can be used as a decision making tool at farm level. Field topography can be simply assessed by soil characteristics and natural vegetation (Husson et al., 1998c). Knowing the topography and the history of the field, these tools make it possible to evaluate the potential yield and to determine the optimal cropping practices, especially regarding water management.

Table 5.2. Synthesis of field characteristics and rice yield components for 7 types and 11 sub-types of fields identified in the Plain of Reeds.

Type / Sub-Type	Number of fields in sub-type	Average topography (cm a.m.s.l.)	Number of years after reclamation	Average water level at sowing (cm)	Average number of panicles/m²	Average number of filled grains per m²	Average weight of one grain (mg)	Average yield (kg/ha)
A1	9	71.8	1-2	36.9	317	10 730	23.7	2 629
A2	2	92.8	1	40.3	337	12 037	24.8	2 925
B	8	86.9	1	35.6	376	12 836	24.2	2 896
C	4	90.6	1-3	25.0	540	14 483	25.8	3 876
D1	6	73.6	2-3	35.5	324	15 577	24.5	3 441
D2	4	88.9	1-2	29.6	441	14 931	24.4	3 228
D3	3	86.3	3-4	18.0	527	16 327	23.7	3 741
E1	7	88.4	2-4	30.8	448	17 457	26.5	4 333
E2	6	95.0	2-3	27.2	577	18 209	26.5	4 610
F	3	91.3	2	29.5	431	17 792	24	3 862
G	9	90.9	3-4	21.0	566	22 723	26.3	5 195

Chapter 6

Water management for rice cultivation on Acid Sulphate Soils in the Plain of Reeds, Vietnam

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Submitted to Agricultural Water Management.

Water management for rice cultivation on Acid Sulphate Soils in the Plain of Reeds, Vietnam.

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Abstract.

In the Plain of Reeds, Vietnam, severely acid sulphate soils are highly permeable which greatly limits water control in the years following reclamation. Using a semi-quantitative model of rice growth and yield in these conditions, water management practices are compared for fields at different topographic levels. In "high" fields (higher than 85 cm above mean sea level) on Typic Sulfaquepts, dry conditions and consequent acidification at the end of the plant cycle are to be feared. Water management should therefore aim at maintaining wet conditions in the topsoil as long as possible. However, keeping the soil permanently wet is not feasible nor recommended. Dry conditions at the end of the plant cycle also can be prevented by sowing earlier while the land still is flooded. Sowing too early also is not recommended since it reduces plant density, and thus yield. Problems in fields at "medium" topography (75-85 cm above mean sea level) with intermediate soil type are similar to those in "high" fields but to a lesser extent, as the drop of water level is slower, allowing better water control. In "low" fields (lower than 75 cm above mean sea level) on Hydraquentic Sulfaquepts, waterlogging and deep reduction are the problems. Slight oxidation of the topsoil is favourable and greatly increases plant growth and yield. Sowing rice seeds on wet soil after pumping water out of the field greatly reduces plant mortality and gives highest yield.

Year by year, with repeated cycles of land preparation and cultivation, water control and soil conditions in fields at high and medium topographic level gradually improve. In these fields it becomes possible to delay sowing, while maintaining wet conditions and a favourable redox potential until the end of the plant cycle, with a some irrigation. Cropping conditions in low fields improve very slowly as soils have a high organic matter content and can hardly be drained.

Introduction.

Water management on acid sulphate soils.

On acid sulphate soils, the redox potential determines the occurrence of various toxicities. In case of oxidation, acidification and consequent solubilisation of aluminium is possible, whereas deep reduction leads to ferrous iron problems. In these conditions, water management is acknowledged to be the key to soil management (Dent, 1986). In recently-oxidised acid sulphate soils in the Plain of Reeds, Xuan (1987) recommended keeping submerged both the sulphidic horizon (which contains oxidisable S compounds but has not yet oxidised) and the sulphuric horizon (in which sulphide-rich materials, mainly pyrite, have already oxidised, producing sulphuric acid), as pyrite may still occur inside cores of the soil peds of the sulphuric horizon. To avoid strong reduction in fields with a distinct plough layer, Hanhart et al. (1997) proposed improving the general drainage condition of the field or removing surface water before flowering. This requires water control, which has proved to be quite difficult. Kselik et al. (1993) in Indonesia faced high hydraulic conductivity of soils and could not satisfactorily control water levels. In the Plain of Reeds, Minh et al. (1995) and Husson et al. (1998e) measured high and variable infiltration rates. Tuong (1993) recognises the practical difficulties in maintaining the water table at the desired depths on a large scale, because of the high spatial variability of acid sulphate soils which complicates management of the system.

Spatial variability of acid sulphate soils.

Detailed studies of spatial and temporal variability of acid sulphate soils in the Plain of Reeds (Husson et al. 1998c and e) showed the microtopographic level to be a key factor influencing: (i) soil type, soil characteristics, and their evolution upon reclamation; (ii) the optimal time window for cultivation (starting date and duration); and (iii) agronomic problems and opportunities.

At "high" topography (higher than 85 cm above mean sea level), clayey, ripe Typic Sulfaquepts are found, characterised by a greyish-brown sulphuric horizon with yellowish-brown and pale yellow mottles of goethite and jarosite respectively. Below 75 cm above mean sea level, highly organic, unripe Hydraquentic Sulfaquepts are found. The sulphuric horizon has a brown matrix colour, with brown to dark brown mottles, but without goethite or jarosite. Between 75 and 85 cm above mean sea level, a transitional soil type is found, with intermediate characteristics. For these three main soil types, pH is below 4 in all horizons during the dry season. When left uncultivated, they all show high permeability which greatly reduces technical possibilities for water control. In the first years after reclamation, before field permeability has been reduced by the creation of a plough-pan, water control is extremely difficult and the water level in the fields is mainly determined by the natural water table levels in surrounding canals.

Optimal time window for cultivation.

The Plain of Reeds has a warm monsoonal climate, with a marked dry season (December to April) and a rainy season (May to November) with a total amount of rains of about 1 500 mm/year. High amounts of rainfall in combination with high discharges of the Mekong river cause inundation of the land from July/September until December/February.

Hanhart and Ni (1993), working in the central part of the Mekong delta and Husson et al. (1998e) working in the Plain of Reeds, identified the end of the flooding season to be the optimal period to start cultivation. Toxicities are then minimal and irrigation can help to preserve favourable cropping conditions in the dry season. However, because of poor water control in the Plain of Reeds, the time window during which favourable conditions for cultivation can be maintained is very narrow and is not always sufficient to allow a full plant cycle. Furthermore, agronomic problems and the starting date and duration of the favourable period for cultivation vary with the mean field topography. Figure 6.1 (from Husson et al., 1998e) shows that on high positions, the decrease of the water table is very fast.

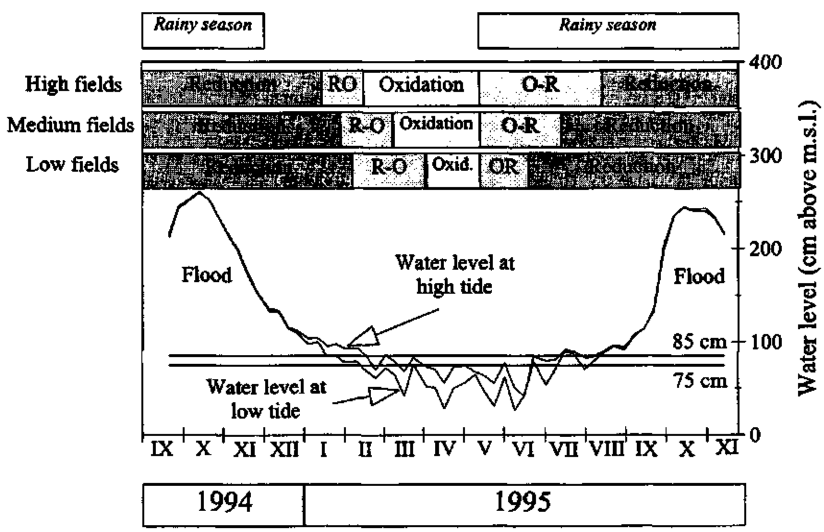

Figure 6.1. *Changes in redox potential in relation to water table level and microtopography. 1994/95. RO indicates transition from reducive to oxidative conditions. OR indicates transition from oxidative to reducive conditions, with alternate periods of oxidation and reduction.*

The optimal period for cultivation is very short as strong oxidation rapidly follows the long period of submersion. At medium topographic level, water decrease is slower and the topsoil is drained more slowly. Favourable conditions are met during a longer period, but oxidation can be a problem at the end of the cycle. To extend the period during which cultivation is possible, farmers in the Plain of Reeds sow rice very early, before flood water has completely receded. They broadcast pregerminated rice seeds in 20 to 40 cm of water, at the end of December or the beginning of January (Husson et al., 1998e). The short -cycle varieties (90-100 days) are then harvested at the end of March, or the beginning of April. However, with this technique low densities are usually achieved, seriously limiting yields.

Low fields, although only 10 to 20 cm lower, face very different problems. They remain submerged most of the time and maintain deeply reduced conditions until April, inducing ferrous iron toxicity. During the whole dry season, they regularly receive water through tidal movements (Figure 6.1). Oxidation is not feared, but sowing should be early enough to avoid the period of May through June during which water is salty and highly acidic, with pH sometimes below 2.5 (Husson et al., 1998e). Therefore, rice must be sown in January, when water table levels are still above the soil surface.

Objectives of the study.

The objectives of this study are to compare various water management practices for the main cropping conditions met in the years following reclamation of strongly developed acid sulphate soils in the Plain of Reeds. This should allow development of water management strategies adapted to field conditions.

As microtopography and cultivation greatly influence soil and water characteristics, water management strategies should be compared in relation to mean topography and history of fields. High Typic Sulfaquepts, low Hydraquentic Sulfaquepts and transitional types of soil at intermediate topographic levels are considered, together with the number of years of cultivation after reclamation.

Materials and methods.

Between the 1992/93 and the 1995/96 cropping seasons, water management was monitored in a total of 74 farmer managed fields where experiments were conducted. Water levels were measured every other day and before and after irrigation in each field, during the entire cropping season.

Yield components (divided in plants/m², tillers/m², panicles/m², number of filled grains/panicle, number of empty grains/panicle, plant height, weight of one grain -measured on 1 000 grains counted with a Numigral- , dry matter and grain yield) were measured on a minimum of 40 locations of 1 m² per field, selected by systematic grid sampling. The microtopography of each location was measured with a theodolite and calibrated to mean sea level thanks to a reference point given by the provincial hydraulic service.

Three different varieties were used for the 74 fields, but they presented similar characteristics. For comparison between fields, a fertiliser treatment (F2 = 100 N-100 P_2O_5) was common to all fields. In most fields, yields components were measured for this treatment F2 in 15 to 21 locations, but according to experimental set up, the number of samples could be higher (up to 200).

The 74 fields were representative of the major agro-ecological conditions met on acid sulphate soils in the Plain of Reeds, covering the major soil types along the toposequence (from "high" Typic Sulfaquepts, 105 cm above mean sea level, to "low" Hydraquentic Sulfaquepts 66 cm above mean sea level). The number of cultivations since reclamation also was considered, as it influences field permeability and consequently water control, with fields cultivated for the first to the sixth time. In these fields, different water management strategies were applied, varying in sowing date and number of irrigations.

For each field, yield components were analysed by means of scatterplots and simple or multiple regressions. An analysis of yield components and the study of the contribution of each yield component to grain yield allows: (i) to identify bottlenecks and rank factors limiting rice growth and yield; (ii) to determine when rice plants face stress during their development; and (iii) to identify possible causes for the stress.

Associated with the careful monitoring of water level in the fields, yield components analysis makes it possible to assess and compare water management strategies by comparison of the various yield components, each of them reflecting growing conditions at a specific period of growth. Results are presented as representative examples for the major cropping conditions met in the plain of Reeds.

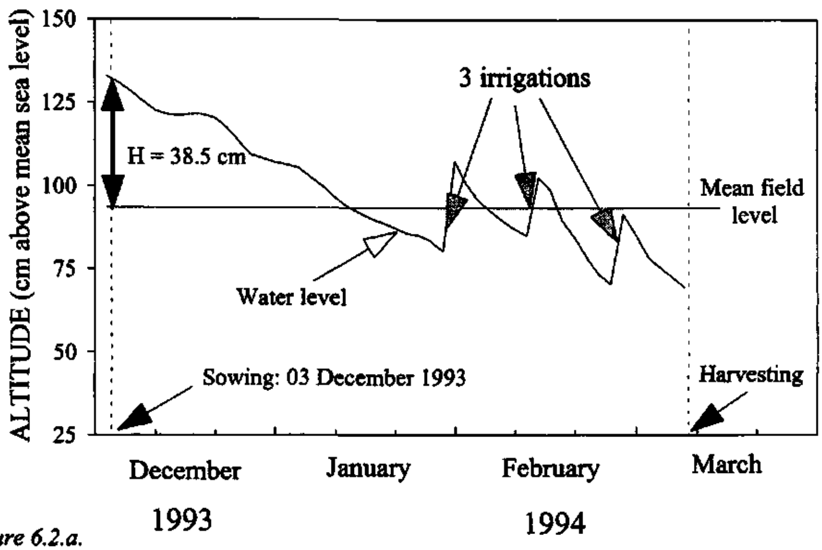

Figure 6.2.a.

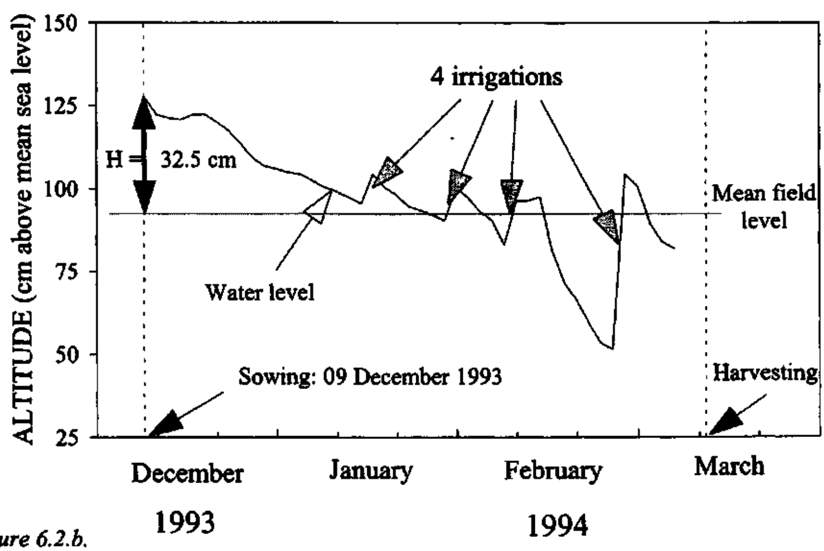

Figure 6.2.b.

Figure 6.2. Water management in high fields cultivated for the first time.
Figure 6.2a. Field H1a, very early sowing.
Figure 6.2b. Field H1b.

Results and discussion.

Water management in high fields (Typic Sulfaquepts).

Table 6.1 gives a synthesis of water management and rice growth on Typic Sulfaquepts in 5 high fields (higher than 85 cm above mean sea level on average) with contrasting conditions and water management strategies.

Table 6.1. Synthesis of water management and rice growth in 5 fields at high topographic level.

Field	Topography (cm above m.s.l.)	Irrigations	Water level at sowing	Years after reclamation and variety	Panicles per m²	Filled grains / panicle	Weight of 1 grain (mg)	Yield (kg/ha)
H1a	93.5	3	38.5 cm	1 / IR 9729	292	34.0	23.0	2 180
H1b	92.5	4	32.5 cm	1 / IR 9729	458	37.0	20.8	3 250
H3a	91.5	3	22cm	3/ IR 50404	665	29.7	22.9	4340
H3b	93	6	21 cm	3 / IR 9729	605	32.3	24.5	5 030
H4	87	4	0 cm	4/ IR 50404	699	35.1	25.9	5 555

Influence of water level at sowing.

Water management is compared for two high fields with similar characteristics. Field H1a, on average at 93 cm above mean sea level was sown early (3 December 1993) in 38 cm of water on average, and irrigated only 3 times. Soil was oxidised at four periods and oxidation may have been considerable at the end of the cropping period (Figure 6.2a). Field H1b (92 cm above mean sea level) was sown six days later in 32 cm of water. A strong and deep oxidation occurred at the end of February although it was irrigated four times (Figure 6.2b).

In both fields, plant, tiller and panicle densities show a positive linear regression with topography. Figure 6.3 shows for example the regression between panicle density and topography in field H1a where an increase of more than 5 panicles/m² is observed for each cm increase in topography. The positive correlation is observed in most fields in the Plain of Reeds. It can be explained by the higher plant mortality and poorer tillering in the lowest positions, attributed to deeper and longer submersion, which reduces light reaching the submerged rice seedlings. In the lowest positions, deep reduction and the presence of reduced sulphur-species, inducing iron toxicity, also may cause mortality.

The negative effect of submersion on plant, tiller and panicle density observed within fields also explains differences between fields. In field H1b, sown in less water, densities are higher than in field H1a. Field H1b had very low densities of 139, 399 and 292 (respectively plants/m², tillers/m², and panicles/m²), whereas densities of 240, 566 and 458, on average, were measured in field H1b.

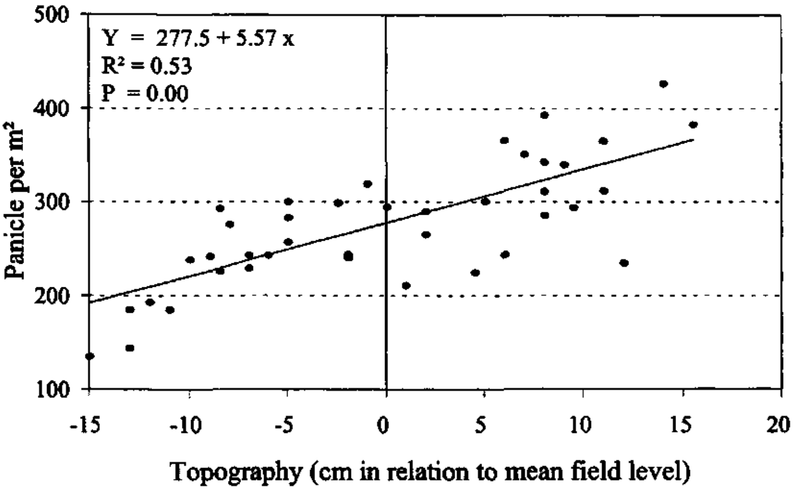

Figure 6.3. Panicle density as a function of microtopography. Field H1a.

Differences induced by hydric conditions and water management practices do not only affect densities, they also affect plant growth and grain filling. At intra-field level, the weight of one grain is also correlated to microtopography, but in a quadratic trend. The example of field H1a given on figure 6.4 shows that the weight per grain decreases in low positions and is maximum at intermediate levels. In high positions, it strongly decreases when topography increases. Poor plant growth and grain filling in the lowest parts of the field can be explained by reductive conditions. Deep oxidation, and associated acidification and solubilisation of aluminium, together with water stress, are presumably the main causes of the very poor plant growth and grain filling observed in the highest positions.

The negative effects on plant growth and grain filling of both high and low water levels also are felt when comparing between fields. In field H1b, plant growth was good (plant height of 74.5 cm and 5 825 kg/ha of dry matter) and the number of filled grains/panicle was high (37 grains/panicle) but pronounced water deficits and consequent acidification during the grain filling period resulted in very poor transfer of carbohydrates to grains, leading to very light grains (20.8 mg/grain). In field H1a, long submersion led to weak plants. Later on, rice also may have suffered from oxidation, leading to acidification and consequent solubilisation of aluminium. As a result, plants were short (66.9 cm on average), dry matter produced was low (2 900 kg/ha) and the number of filled grains per panicle was lower than in field H1b (34 filled grains/panicle). However, relatively good hydric conditions at the end of the cycle made that grain filling was much better than in field H1b. Weight of one grain is higher on average, although it was limited by poor grain filling in the highest parts of the field (Figure 6.4).

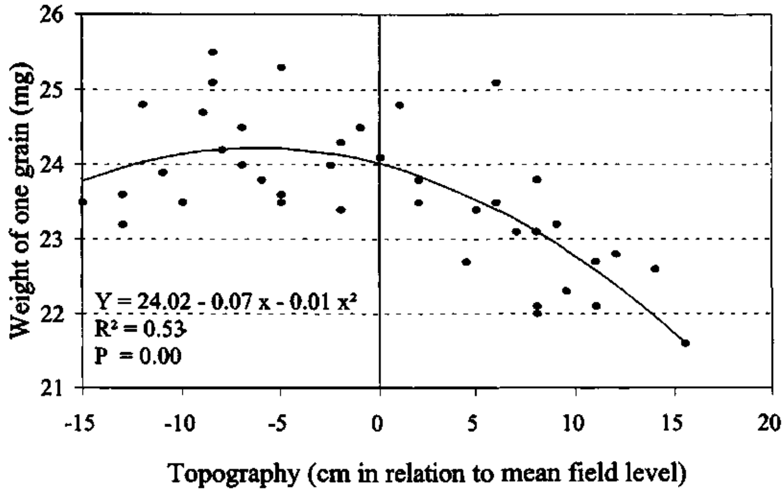

Figure 6.4. Weight of one grain as a function of microtopography. Field H1a.

As a consequence, yields in both fields are correlated to microtopography, but in very different ways. In field H1a, yield was mainly limited by panicle density in the low parts and by poor grain filling in the high parts of the field. It is correlated to topography in a quadratic trend (Figure 6.5a). Because of the low panicle density due to long and deep submersion and poor growth, average yield is low: 2 180 kg/ha on average.

In field H1b, density was higher which explains the higher yield (3 250 kg/ha on average). The main limiting factor was the poor grain filling due to the dry conditions at the end of the cycle. Logically, the negative effects of oxidation are stronger in the high parts of the field. This results in a negative correlation between yield and topography, with a strong decrease of more than 125 kg/ha for an increase of 1 cm of topography (Figure 6.5b).

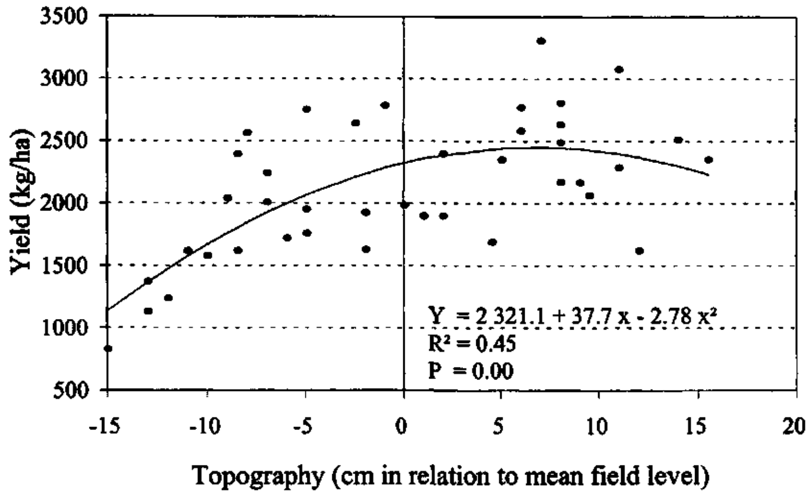

Figure 6.5.a.

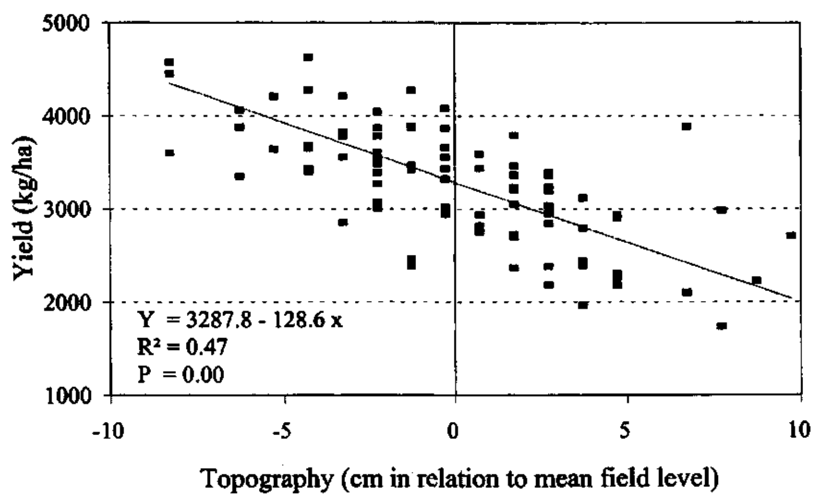

Figure 6.5.b.

Figure 6.5. Rice yield as a function of microtopography.
Figure 6.5a. Field H1a, very early sowing.
Figure 6.5b. Field H1b.

These examples illustrate the very high sensitivity of rice growth and yield to water management and the difficulty to maintain correct hydric conditions during the whole plant cycle for these high fields. Only 6 days between seeding and 6 cm of water height differentiate these two fields, but they suffered from different problems. A compromise between correct plant density and good growth is difficult to obtain, and requires frequent irrigation and extremely precise water management. Farmers have to face a dilemma: sowing early to avoid strong oxidation at the end of the cycle, which leads to poor density, or delaying sowing, thereby increasing the risk of poor plant growth and bad grain filling. However, the case of field H1a clearly shows that very early sowing which farmers often like to do, hoping to reduce irrigation needs, reduces yield potential significantly.

Number of irrigations and rice growth.

The impact of irrigation on rice growth is compared in two high fields (Typic Sulfaquepts) cultivated for the third time in the 1994/95 cropping season. Field H3a and field H3b were sown in 22 and 21 cm of water respectively but the first one was irrigated only 3 times whereas the second one received six irrigations. This resulted in two strong and deep oxidations of the soil at the end of the cropping period in field H3a (Figure 6.6a), whereas only slight oxidation occured in field H3b, also at the end of the plant cycle (Figure 6.6b).

Again, densities are correlated to topography, but this time high densities were obtained in both fields. Important differences between the two water management strategies are observed in terms of plant growth and grain filling which are significantly lower in the field irrigated only three times (plant height of 68.2 cm and 76.8 cm for respectively field H3a and H3b, and weight of one grain of 22.9 mg in field H3a compared to 24.5 mg in field H3b). This can be attributed to the negative effect of aluminium which is solubilised when dry conditions allow oxidation and consequent acidification of soils, as it was the case in field H3a. This is confirmed by the fact that lowest plant growth was observed in the highest parts of the fields.

As a consequence of better growth and grain filling in the carefully irrigated field H3b, yield is 690 kg/ha (i.e. 15.8%) higher than in field H3a. However, thanks to high density and relatively good plant growth, the yield in field H3a is still rather good (4340 kg/ha), much higher than in fields cultivated for the first time.

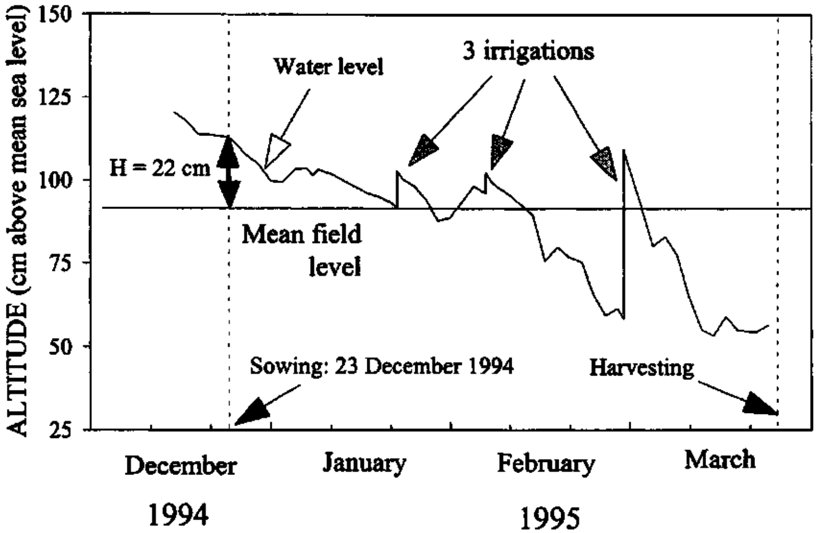

Figure 6.6.a.

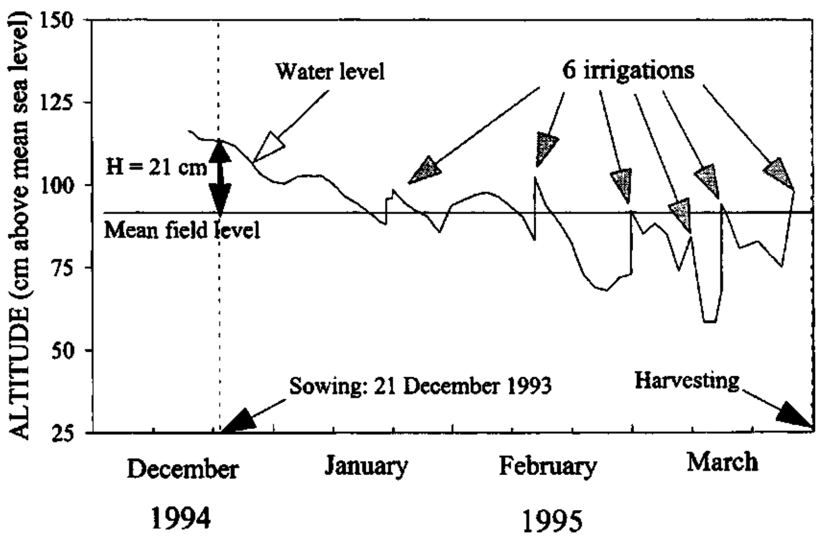

Figure 6.6.b.

Figure 6.6. Water management in high fields cultivated for the third time.
Figure 6.6a. Field H3a. Three irrigations.
Figure 6.6b. Field H3b. Six irrigations.

Evolution of water management requirements and opportunities.

Comparing fields according to the number of years (i.e. cropping seasons) after reclamation shows the evolution of water management requirements and opportunities.

In the third year of cultivation, field H3a sown in only 22 cm of water could yield 4 340 kg/ha with only 3 irrigations, thanks to high panicle density. This was not possible in field H1a or H1b. In the first one, 3 irrigations resulted in a yield of only 2 180 kg/ha because it required early sowing (and as a consequence low panicle density) to achieve correct plant growth. In field H1b, although it was sown in deeper water, and irrigated one time more than field H3a, correct hydric conditions could not be maintained until the end of the plant cycle. Poor plant growth and bad grain filling caused yields of only 3 250 kg/ha, despite the high plant density.

With cultivation, the creation of an impermeable plough-pan over the years progressively increases water control. This allows the reduction of the water level at sowing, which, in turn, increases densities, while maintaining correct hydric conditions until the end of the plant cycle. Besides improving water control, cultivation probably favours flushing of iron and aluminium and consequently reduces toxicities. However, although water control improves and toxicities decrease, water management remains a key issue for cultivation of severely acid sulphate soils, as shown by the significant yield difference between fields H3a and H3b.

After 4 to 5 years of cultivation, sowing under water, which is done at the prejudice of panicle density, can be avoided. Field H4 is a rather high field (87.1 cm above mean sea level) and was cultivated for the fourth time in 1995/96. It was sown on wet soil, after pumping water out of the field. With 4 irrigations only, good cropping conditions could be maintained until the end of March (Figure 6.7). Thanks to a high density (700 panicles/m^2) and good plant growth and grain filling (25.9 mg/grain), the yield reached 5 555 kg/ha.

Water management in fields at intermediate topographic level.

Fields at medium topographic level (75-85 cm above mean sea level) present basically the same kind of agronomic problems as higher fields. These fields also suffer from dry conditions at the end of the cycle when not properly irrigated. However, because of their lower position, hydric stresses are less marked and water management can be slightly different.

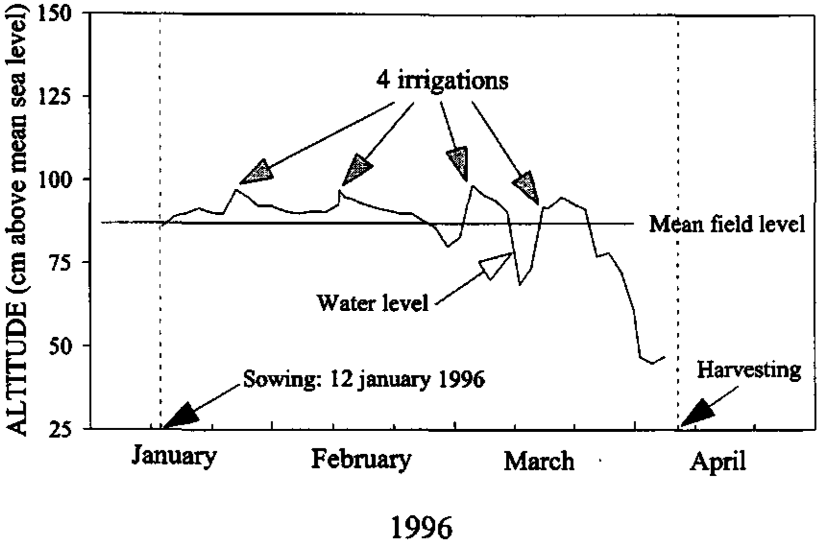

Figure 6.7. Water management in high field cultivated for the fourth time. Field H4, sowing in mud after pumping water out of the field.

Table 6.2 gives a synthesis of water management and rice growth in 4 fields at medium topographic level.

Table 6.2. Synthesis of water management and rice growth in 4 fields at medium topographic level.

Field	Topography (cm above m.s.l.)	Irriga-tions	Water level at sowing	Years after reclamation and variety	Panicles per m²	Filled grains / panicle	Weight of 1 grain (mg)	Yield (kg/ha)
M1a	83	4	39 cm	1 / IR 9729	341	37.6	22.7	2 585
M1b	80	2 + Tidal	34 cm	1 / IR 9729	420	35.2	26.1	3 670
M3	82.5	2 + Tidal	22.5 cm	3 / IR 9729	465	35.9	26.7	4 050
M6	78.5	1+ Tidal	0 cm	6 / IR 50404	853	26.6	25.0	4 935

Land reclamation in fields at medium topography.

Field M1a, was treated like field H1a but is lower: 83 cm above mean sea level on average. It was sown early (12 December 1993), in 39 cm of water on average, and irrigated only 4 small times, which resulted in dry conditions in March (Figure 6.8).

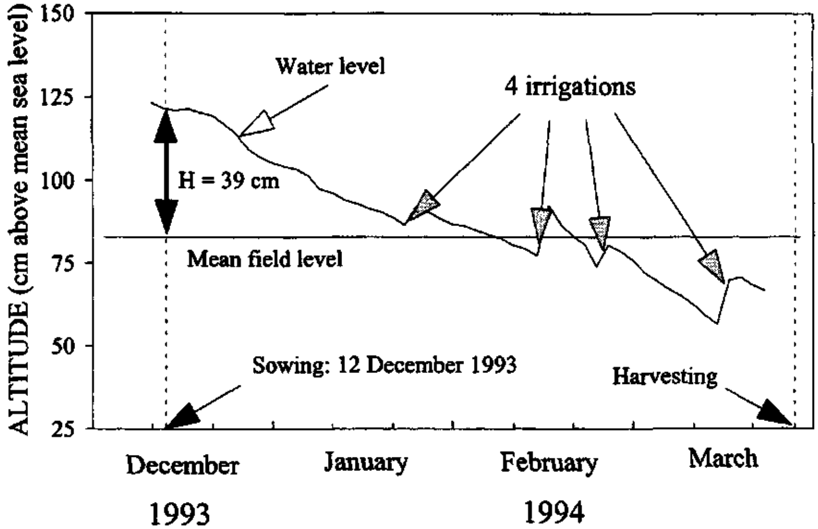

Figure 6.8. Water management of field at medium topographic level cultivated for the first time. Field M1a. Early sowing.

This practice led to low densities, with 146 plants/m², 441 tillers/m² and 341 panicles/m². These densities are higher than densities observed in field H1a, which may be explained by differences in water turbidity, length of submersion and/or toxic ions concentrations (lower EC values have been measured at medium topography as compared to high positions).

Plant height was similar to plant height in field H1a (67.6 cm on average), but production of dry matter (3985 kg/ha) and number of filled grains per panicle (37.6 filled grains/panicle) were higher. However, very poor grain filling in the high parts of the field, probably due to hydric stress and soil toxicities, made that on average, weight of one grain is only 22.7 mg/grain.

Yield shows a quadratic correlation with topography. It strongly increases with topography at low position and decreases at high position (Yield = 2924.4 - 5.53 Topography ^{2}, $R^2 = 0.51$, $P = 0.00$). This pattern (already observed in field H1a) reflects poor water management of the field, where the crop was sown too early and not sufficiently irrigated. The patterns can be explained by the poor plant density and the poor growth of plants submerged too long in low positions, and by poor grain filling on high locations.

Comparison with field M1b, shows that higher densities and better plant growth and grain filling could have been obtained had the seeds been sown in shallower water and had irrigation been managed more carefully. As for high fields, sowing in deep water reduces panicle density and greatly affects yield: For a difference in water level at sowing of only 5 centimetres, field M1b yielded 42 % more than field M1a.

A comparison of field M1b with fields H1a and H1b also is interesting. It shows that in medium fields, water management opportunities are higher than in high fields in the first year of cultivation. As the water table decreases more slowly, maintaining correct hydric conditions is feasible at reasonable cost, even when sowing has been delayed. Sown rather early, in 34 cm of water, field M1b was maintained in good conditions with only two mechanical pumpings and the use of tidal movement in canals. This is hardly possible in high fields which suffer either from deep and long submersion in the beginning, or from strongly oxidised conditions at the end, of the plant cycle.

Evolution of water management strategies upon reclamation.

As in high fields, toxicities and field permeability decrease and water control is increased with time and cultivation. Water level at sowing can be progressively reduced. Comparison of field M1b and field M3 (cultivated for the third time after reclamation) shows significant differences in rice growth. In field M3, sown in 22.5 cm of water and irrigated only twice, higher density (465 panicles/m^2) and very good plant growth (83.6 cm) and grain filling (26.7 mg per grain) could be achieved. This resulted in a yield of 4 050 kg/ha, 10% higher than in field M1b, and 57% higher than in field M1a.

After 5 to 6 years of cultivation, sowing on wet, non-flooded soil is possible. Field M6 (78 cm above mean sea level), cultivated for the sixth time, was sown on wet soil after pumping water out of the field. With only one mechanical irrigation in addition to 4 tidal irrigations, dry conditions occurred only at the end of March. Their impact on plant growth seems limited, possibly because of lower toxicities after the flushing of soil for several years. Very high densities could be obtained, with 421 plants/m^2; 1026 tillers/m^2 and 853 panicles/m^2. Plant growth and grain filling was rather good, with an average plant height of 80.3 cm and 25 mg per grain. Here again, yield is correlated to microtopography in a quadratic trend (Yield = 5173.1 + 27.9 Topo - 24.7 $Topo^2$, $R^2 = 0.41$). The combination of very high panicle density and good plant growth and grain filling made it possible to reach a yield close to 5 000 kg/ha.

Water management in low fields.

In fields below 75 cm above mean sea level, the situation is very different. These fields on highly organic Hydraquentic Sulfaquepts can be easily maintained in wet conditions during the entire cropping periods using tidal movements in canals. The main difficulty on these soils is to obtain correct densities since the fields are kept submerged for a long period after the beginning of cultivation. Submersion, low redox potentials, the development of ferric iron-reducing and sulphate-reducing bacteria, high concentrations of toxic ions that accumulated in these low places, and fungal diseases are important factors limiting densities and plant growth (Hanhart et al., 1997; Husson et al., 1998a).

For these low fields, table 6.3 gives a synthesis of water management and rice growth in 3 fields used for the comparison of the main water management strategies. The traditional practice consists, as in higher fields, of sowing rice seeds under water. In a new technique, developed in 1996, it is preferred to sow rice on wet, slightly oxidised soil after pumping water out of the field.

Table 6.3. Synthesis of water management and rice growth in 3 fields at low topographic level.

Field	Topography (cm above m.s.l.)	Irriga-tions	Water level at sowing	Years after reclamation and variety	Panicles per m²	Filled grains / panicle	Weight of 1 grain (mg)	Yield (kg/ha)
L1a	71.5	1 + Tidal	29.5 cm	1 / IR 9729	312	34.3	22.5	2 240
L1b	70	Tidal	30.5 cm	1 / IR 9729	308	41.0	22.9	2 990
L1c	66	Tidal	0 cm	1 / IR 50404	690	22.9	23.3	3570

Sowing under water.

Ten fields below 75 cm above mean sea level and sown under water were monitored between 1992 and 1995. The water level at sowing varied from 20 to 41 cm, but although plant density varied greatly (from 69 to 145 plants/m²), panicle density remained in all cases between 300 and 360 panicles/m².

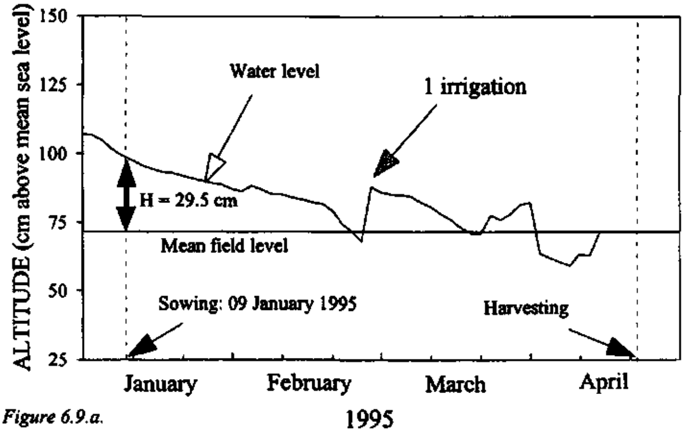

Figure 6.9.a.

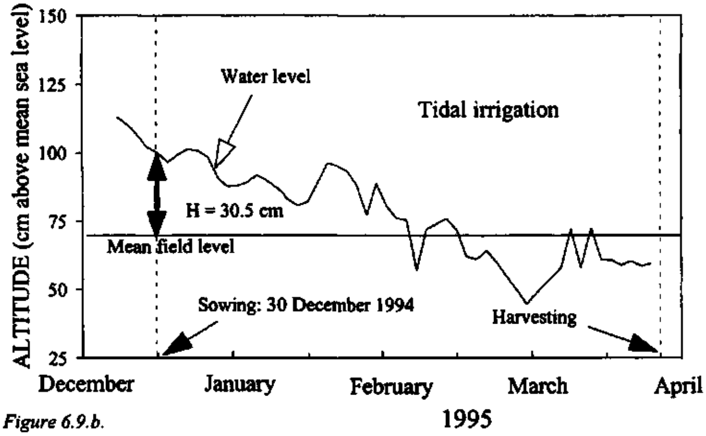

Figure 6.9.b.

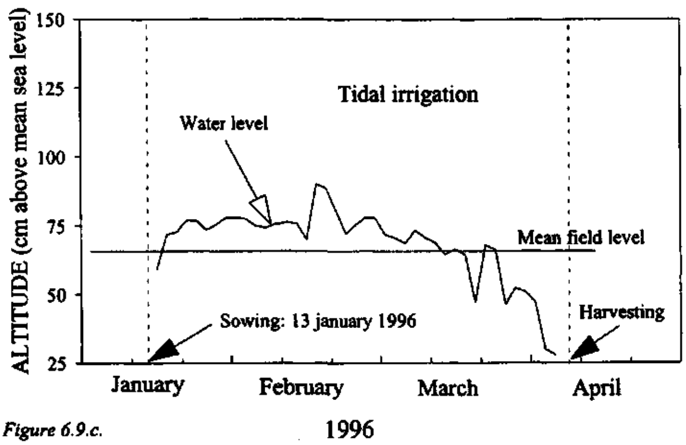

Figure 6.9.c.

Figure 6.9. Water management in low fields cultivated for the first time.
Figure 6.9a. Field L1a. Continuous submersion.
Figure 6.9b. Field L1b. Slight oxidation before flowering.
Figure 6.9c. Field L1c. Sowing in mud after pumping water out of the field.

In all low fields, transplanting in very low places was needed to reach these densities. Low densities can be explained by the high mortality due to long submersion and multiple ions stresses and toxicities linked to deep reduction (Husson et al., 1998a). It seems that higher tillering in places of low density leads to a rather homogeneous panicle density, with a maximum around 350 panicles/m². Due to these low densities, maximum yield is below 3 000 kg/ha. Yield differences can be explained by differences in water management more than by water level at sowing.

Two different water management practices can be compared after sowing under water. Field L1a was sown under 29.5 cm of water on average, and kept submerged for 80 days after sowing (Figure 6.9a). Field L1b sown in 30.5 cm of water received only tidal irrigation. Slight oxidation of soil occurred 50 days after sowing, and the field was not submerged after flowering (Figure 6.9b). Similar densities were observed with 312 and 308 panicles/m² for respectively field L1a and L1b, but in field L1a panicles produced fewer grains (34.3 and 41grains/panicle in respectively field L1a and L1b). Weight of one grain was also higher in field L1b (22.5 and 22.9 mg/grain for respectively field L1a and L1b). These differences can be attributed to healthier plants in field L1b. In the permanently submerged field, weak plants suffered from parasitism and diseases, especially from attacks by *Helminthosporium oryzae* and *Pyricularia oryzae*. Symptoms of bronzing, attributed to ferrous iron toxicity were also more important in field L1a than in field L1b. As a consequence, yield in field L1a is low: 2240 kg/ha. In field L1b, which was not permanently submerged, yield is 33% higher: 2 990 kg/ha. Slight oxidation of these soils seems to be favourable to plant growth.

Sowing on wet soil after pumping water out of the field.

To prevent deep reduction at sowing, a technique has been developed with farmers in the experimental area. It consists in pumping water out of the field before sowing. Within a few days, water comes into the field again, but this technique greatly improves cropping conditions. An example is given for field L1c, a very low field cultivated for the first time during the 1995/96 Winter-Spring cropping season. Figure 6.9c shows that within two days, the water level increased by 12.5 cm in this field, and that after one week, the soil was covered with more than 10 cm of water on average. This level could be maintained for one month, allowing good tillering. This resulted in double densities as compared to fields sown under water: 283 plants/m², 844 tillers/m² and 690 panicles/m². Opposite to other low fields sown under water in which plant density was poorly or not correlated to microtopography, plant density in this field is highly significantly correlated to topography:

Plants/m² = 283.2 + 14.2 Topography (cm/mean field level) $R^2 = 0.43$ P= 0.00

In low fields, high mortality of young plants, the death of leaves and the end of growth on older plants were explained mainly by deep reduction and development of sulphate-reducing and ferric iron-reducing bacteria, gradually colonising seeds and rice rhizosphere, and producing toxic H_2S and FeS (Jacq et al., 1993; Husson et al., 1998a). These substances are oxidised before ferrous iron by the oxygen pumped by rice plants into the root zone. In their presence, rice roots are not able to maintain at their surface the brown crust of ferric hydroxides which prevent excessive ferrous iron uptakes, and iron toxicity can develop (Hanhart and Ni, 1993).

The slight oxidation of topsoil created by pumping water out of the field seems sufficient to prevent development of these anaerobic bacteria and to greatly reduce iron toxicity. In low fields sown under water, black seeds and roots and high mortality indicated strong development of these bacteria. In fields sown after pumping water out of the field, these symptoms were not observed, except for the lowest positions which had not been oxidised. This explains the correlation between plant density and topography within the field: in the lowest parts of the field, oxidation was not sufficient to prevent development of these bacteria.

Probably because of this high density, but possibly also because of a period in March during which the soil became dry, the number of filled grains per panicle is rather low (22.9 on average). Although plant growth and grain filling were higher than in fields sown under water, weight of one grain is rather low: 23.3 mg/grain. Despite this rather poor growth, the high density made it possible to achieve a yield of 3 570 kg/ha. This is a very interesting result for a very low field, which is by far the most difficult to reclaim. Important costs linked to transplanting in low places, needed in most cases when sowing under water, are avoided, and final yield is higher.

Evolution upon reclamation.

Because of very high organic matter content, the permeability of these fields remains high for several years after reclamation, which limits water control. At this very low level, prolonged drainage is rarely possible and when possible would lead to subsidence of the very organic soil. Therefore, these fields improve very slowly. When sown under water the maximum yield remains below 3 500 kg/ha even after 4 years of cultivation and risks of low yield (below 2 000 kg/ha), bringing negative economic return, are significant. The technique of pumping water out of the field may help to flush toxic ions and improve field chemical characteristics, but the main improvement seems to be due to a temporary raise of the redox potential. As it is a very recent technique, no data on long term development are available yet, and it would be interesting to assess such long term effects in further research.

3. Conclusions.

1. The originality of this integrated study is that it:

(i) was conducted in actual conditions of production on severely acid sulphate soils as met in the Plain of Reeds, integrating farmers' knowledge and practices;
(ii) performed a dynamic, integrated analysis of water-soil-plants interactions; and
(iii) took into account and used the very high short-range variability of acid sulphate soils

This work resulted in the proposal of practical water management strategies for cultivation of rice upon reclamation of these problem soils.

2. On acid sulphate soils in the Plain of Reeds, very small topographic differences have a strong influence on soil physical and chemical characteristics and on water management requirements. Water management should be precisely adjusted, taking into account field characteristics, especially microtopography, permeability which increases after reclamation, and flood characteristics such as speed of recession and water turbidity.

3. In high fields (higher than 85 cm above mean sea level on average) on Typic Sulfaquepts, soil oxidation, acidification and water stress at the end of the cultivation cycle are the main limitations in the years following reclamation, when water control is poor. Farmers therefore try to evade problems at the end of the cycle by sowing pregerminated seeds in fields still flooded with 20-30 cm of water. However, sowing in too deep water results in low densities caused by long submersion (reducing light reaching the seedlings) and toxicities induced by deep reduction. Water management in these fields should therefore aim to:

(i) sow pregerminated rice seeds in sufficiently shallow water to achieve sufficient densities, and
(ii) prevent lowering of the field water level towards the end of the crop cycle by applying a sufficient number of irrigations to avoid strong oxidation, acidification and water-stresses.

The fields on Typic Sulfaquepts have a high yield potential. The gradual development of a less permeable plough layer enables the farmers to abandon the practice of sowing under water without running the risk of soil oxidation and water stress at the end of the cycle. Yields over 5 000 kg/ha can be obtained 3 years after reclamation.

4. Fields at medium topographic level (75-85 cm above mean sea level) basically face the same problems as high fields. However, thanks to slower water recession, oxidation at the end of the plant cycle is not as deep nor strong as in high fields. Potential yield is higher than on high fields in the first cropping season, but improvement is slower. After three years of cultivation they give lower yields than the high fields.

5. In low fields (lower than 75 cm above mean sea level) on Hydraquentic Sulfaquepts, rice suffers from opposite problems: waterlogging, submersion and deep reduction inducing iron toxicity and fungal diseases. Because of their low elevation, deep drainage is hardly possible and is not recommended as it would lead to acidification and subsidence of these highly organic soils. However, slight oxidation of topsoil is needed to reduce the population of anaerobic sulphate-reducing and ferric iron-reducing bacteria, which produce toxic H_2S and FeS, and to prevent the development of induced ferrous iron toxicity. Water management should therefore aim at creating slight oxidation of topsoil as soon as possible. The best solution consists in sowing pregerminated rice seeds on wet soil, after pumping water out from the field.

Chapter 7

Variability of results in fertiliser experiments on acid sulphate soils in the Plain of Reeds, Vietnam

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Variability of results in fertiliser experiments on acid sulphate soils in the Plain of Reeds, Vietnam.

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Abstract.

Contradictory results are observed in literature on fertilisation of acid sulphate soils. In the conditions of the Plain of Reeds, Vietnam, where pregerminated seeds are directly broadcast in 20-40 cm of water in recently reclaimed acid sulphate soils, three major sources of yield variability have been identified: microtopography, distance from tertiary canals, and water management.

The proper design and setup of experiments based on a careful characterisation of experimental fields helps to control variability due to distance from canals and microtopography. However, the use of covariance analysis with microtopographic level as a covariate is needed most of the time. The use of covariance analysis reduces the coefficient of variation from 26.3% (with simple variance analysis) to 20.3% on average, and mean square error by 33.3%, consequently increasing precision and efficiency of experiments.

An analysis of 15 fertiliser experiments showed that fertilisation only leads to economically interesting yield increments under proper water management. A good indicator is panicle density which reflects duration and depth of submersion of young rice plants. Significant differences between fertiliser treatments have been observed only in fields with densities higher than 350 panicles/m². In such cases, thermophosphate fertiliser associated to Di-Ammonium Phosphate (DAP) gave yields that were 27% higher than those obtained with DAP alone. At densities higher than 350 panicles/m², optimal fertilisation rate (on agronomic and economic point of view) increases with density, and rates between 100 N - 44 P and 100 N - 53 P can be recommended. At lower densities, increasing fertilisation is not economical and a rate of 60 N - 35 P is sufficient.

Introduction.

The large number of fertility-related experiments on irrigated rice on acid sulphate soils shows very contrasting results. Beye (1973) remarked that results of experiments on sources of phosphorus are not in agreement: For some authors, superphosphate gives equivalent or higher yields than rock phosphates on acid soils, while for other authors, rock phosphates are a better source of phosphorus for these soils. An illustration of the differences between fertiliser experiments is given in the proceedings of the Bangkok Symposium on acid sulphate soils held in January 1981 (Dost and Van Breemen editors, 1982). Khouma and Touré (1982) reported no effect of lime on rice yield, whereas Charoenchamratcheep et al. (1982) and Maneewon et al. (1982) found only effects of lime when combined with P-fertilisers. In the same symposium, Arulandoo and Pheng (1982) reported that lime application at a rate of 2.5 tons/ha increased yields substantially through a general improvement in crop growth and plant nutrient status. These differences cannot be attributed only to differences in soils or in research methods. Within the same area, with the same research method, results of experiments can vary. On Sulfic Tropaquepts in the Mekong delta, Vietnam, Ren et al. (1993) found significant differences between applying 13 or 26 kg P/ha in only half of the twelve experiments they conducted.

The main reasons for these contradictory results might be:

i) the differences in experimental conditions, pot trials omitting the potentially detrimental effects from the subsoil (Van Mensvoort, 1996);

ii) a lack of proper characterisation in advance of the conditions under which the plants grow in the field experiments, especially conditions related to water management (Van Mensvoort, 1996); and

iii) insufficient number of replicates to detect differences (Johnstone and Sinclair, 1991).

Because of the variability in soil, water regime, and management, it is difficult to draw general conclusions about fertiliser response (Dent, 1992). Attempts have been made to better characterise cropping conditions, as Ren et al. (1993) who distinguished Typic Sulfaquepts from Sulfic Tropaquepts. Unfortunately, in this study experiments were conducted with only three replications of 18 m^2. The authors also recognised that good water management conditions undoubtedly played an important role in the relatively high yields obtained and that their results cannot be extrapolated to fields with poorer water management. Kselik et al. (1993) also observed differences in results of fertiliser experiments conducted on actual acid sulphate soils which could be irrigated only during spring tides or on potential acid sulphate soils under daily tidal influence. They developed water management strategies and fertility options for five classes, based on 4 hydrological types and two kinds of soils.

These two recent studies show that research on fertility is moving from classical pot trials and field trials to more integrated fertility approaches recognising the importance of other management aspects of the land on the fertility status of the soil. Proper water management is now recognised as a precondition for sound effects of fertiliser applications (Van Mensvoort, 1996). However, precise monitoring of water management in fertiliser experiments rarely is done.

Water management is not the only cause of variability in results of fertiliser experiments. All sources of yield variability which are not taken into account in the experimental design can also interfere with research. In the Plain of Reeds, Vietnam, Husson et al. (1998a) showed that on recently reclaimed Typic Sulfaquepts and Hydraquentic Sulfaquepts, the high soil variability, in relation to microtopography, induces a great variability in yield. As flushing and leaching of toxic iron, aluminium and acid are limited to a fringe of 10-15 metres along the drainage canals (Tuong, 1993; Hanhart et al., 1993) distance from tertiary canals may also affect yields and consequently perturb experiments.

The objectives of this study are to:

i) identify sources of variability in fertiliser experiments conducted in the Plain of Reeds, Vietnam, and explain heterogeneity of results,

ii) adapt research methods to control the high variability, and

iii) develop recommendations for fertilisation of severely acid sulphate soils upon land reclamation in the Plain of Reeds.

Materials and methods.

Cropping conditions.

All experimental fields were farmers' fields, cultivated in actual conditions of production, at real scale, by farmers themselves (under supervision of researchers).

In the years following reclamation of severely acid sulphate soils in the Plain of Reeds, field permeability is very high and water control is limited. The time window during which favourable conditions for cultivation are met is very short and, to extend it, farmers developed a technique of directly broadcasting pregerminated rice seeds under deep water, at the end of the annual flood (Husson et al., 1998e).

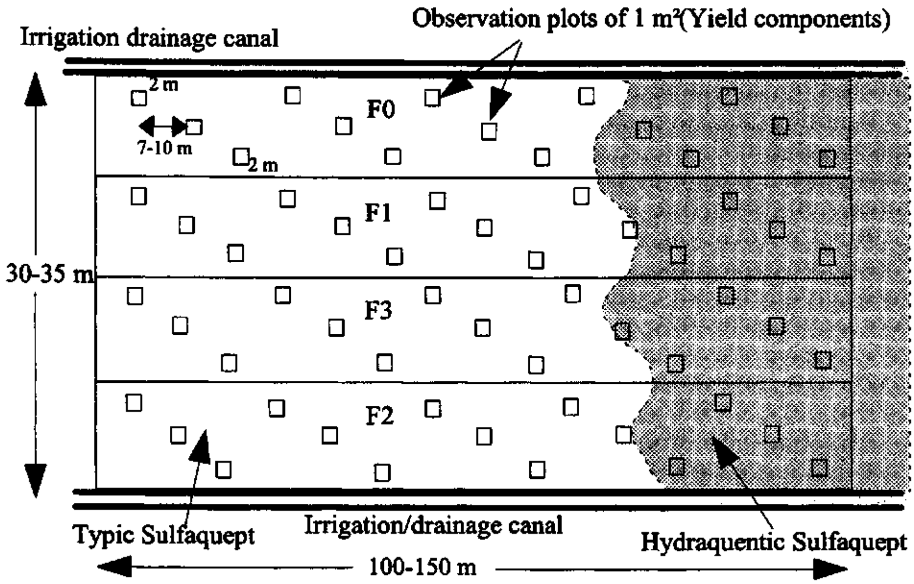

Figure 7.1. Set-up of fertiliser experiments according to field characteristics.

Table 7.1. Kinds and application periods of fertilisers in experimental fields.

	F0			F1, F2, F3		
	N (% total N)	P (%total P)		N (% total N)	P (% total P)	
Days after sowing	DAP + Urea	DAP	Thermo-phosphate	DAP + Urea	DAP	Thermo-phosphate
0	0	0	0	0	0	60
1-3	10	0	0	10	0	0
10-15	30	0	0	30	0	0
25-30	40	80	0	40	30	0
40-45	20	20	0	20	10	0

Table 7.2. Rates of fertilisers in experimental fields.

	1992/93 and 1993/94 cropping seasons		1994/95 and 1995/96 cropping seasons	
	N (kg/ha)	P (kg/ha)	N (kg/ha)	P (kg/ha)
F0	100	61	100	44
F1	64	38	60	35
F2	96	58	100	44
F3	128	73	100	53

Experimental design and setup.

Before design and implementation of experiments, detailed soil maps were made (scale 1:1 000), also indicating canal systems. All experiments were designed according to these maps.

Two series of experiments were implemented between 1992 and 1996:

(i) To test the hypothesis of the influence of distance from tertiary canal on rice yield, seven fields were treated homogeneously. In these fields, yield components were measured at different distances from canals, along 6 to 10 transects, in observation plots of $1 m^2$. In the Plain of Reeds, long (500 to 1000 metres) and narrow (30 to 35 metres) fields are granted to farmers. Usual spacing between tertiary canals is therefore 30 to 35 metres. However, farmers receiving two adjacent plots often gather them in a single field, with 60-70 metres between tertiary canals. Four experiments were conducted in these wide fields, and three were conducted in fields with 30-35 metres between canals.

(ii) To test the hypothesis of the influence of microtopography and water management practices on the results of experiments, four fertiliser treatments were compared in 19 experimental fields. These fields were located at different topography and received different water management.

Each treatment was applied to a plot of 700 to1400 m^2, without replication. Long (100 to 150 metres) and narrow (7 to 12 metres) bands, cutting across soil heterogeneity, were preferred to square plots (Figure 7.1). For each treatment, measurements were done in 10 to 35 replications of one square metre.

Tables 7.1 and 7.2 give the kinds of fertiliser, the application periods and the rates applied for the various treatments. In the experiments, F0 corresponds to farmers' mean fertilisation, with Di-Ammonium Phosphate (DAP: 18-46-0) as the unique source of phosphorus. As application of DAP in flood water leads to the development of algae which suffocates rice plants still under water, it cannot be applied before flood water has receded, four weeks after sowing. F2 represents sensibly the same N and P contents as F0, but as a combination of thermophosphate (TP, 60%), applied at sowing (i.e. under water), and DAP (40%). Van Dien thermophosphate produced in the North of Vietnam has a rather low P content (15% P_2O_5), a very fine texture, and is poorly soluble in water. It also contains SiO_2 (24%), MgO (17-20%), CaO (28-32%) and micro-nutrients such as boron (500-800 ppm).

F1 and F3 also used thermophosphate as a source of phosphorus for 60% of the total amount, and correspond to respectively a lower and a higher N-P rate than F2. No potassium was applied as previous experiments in the area did not show significant effect on rice yield.

Data measurements.

The observation plots selected by systematic grid-sampling (Figure 7.1) were used for measurement of yield components (divided in plants/m², tillers/m², panicles/m², number of filled grains/panicle, number of empty grains/panicle, plant height, weight of one grain -measured on 1 000 grains counted with a Numigral- , dry matter and grain yield), soil characteristics, and topographic level.

Topography was measured with a theodolite and calibrated to mean sea level through a reference point given by the Long An Province Hydraulic Services.

In each field, water level was measured every other day and before and after irrigation, during the whole cropping season.

Data analyses.

Husson et al. (1998a) developed a model of rice growth and yield under these cropping conditions. Yield is mainly determined by panicle density and plant growth, reflected in the weight of one grain. Within fields, plant, tiller and panicle densities are linearly correlated to microtopography, which has been explained by higher plant mortality in low positions due to deeper and longer submersion, deep reduction and the development of ferric iron-reducing and sulphate-reducing bacteria in the lowest positions. Plant growth can be affected by deep reduction, inducing iron toxicity in the lowest locations. It is strongly limited on the high locations, as aluminium toxicity develops in dry conditions at the end of the plant cycle. Consequently, yield is correlated to microtopography in a quadratic trend, with maximum values at medium topographic levels. It strongly increases with topography in low positions, and sharply decreases when topography increases at high topography.

Using this knowledge of rice growth and yield in the conditions of the Plain of Reeds, analysis of yield components made it possible to identify the factors which limited rice growth and yield, and when these factors occurred.

For comparison between treatments, data were analysed at the field level by means of scatterplots and variance analysis. When analysed variables showed significant correlation to microtopography, covariance analysis with topographic level as a covariate (Gomez and Gomez, 1984) was preferred to analysis of variance.

A comparison between fields was done by means of scatterplots, integrating water management practices, significance of differences between treatments, agronomic parameters and microtopography.

Results and discussion.

Effect of the distance from tertiary canals on rice growth and yield.

In six of the seven experiments conducted to assess the impact of tertiary canals on rice growth, yield was correlated to microtopography and covariance analysis therefore was used. Figure 7.2 gives an example of rice yield (after correction to consider the effect of microtopography and compare yields at the mean field topography) as a function of the distance from a tertiary canal in a 58 metres-wide field.

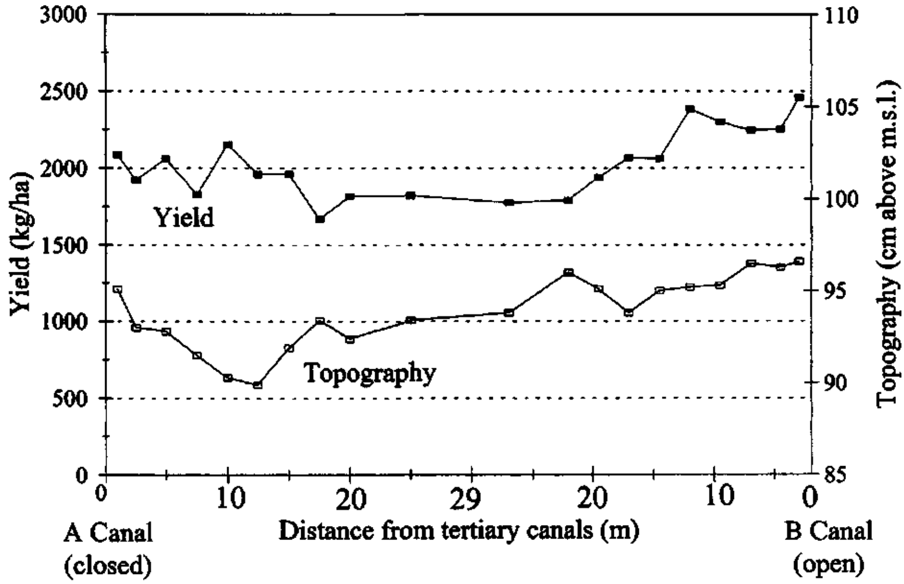

Figure 7.2. Rice yield (kg/ha) as a function of distance from tertiary irrigation/drainage canals. Average yields corrected to mean field level in covariance analysis performed with 10 replications.

The four experiments conducted in fields with 60-70 metres between canals all showed a significantly higher yield in the first 10 to 20 metres from irrigation/drainage canals. The positive effect of tertiary canals on yield can be attributed to the improvement of soil chemical characteristics by flushing and leaching of toxic ions from soils. Although it was significant, this effect was limited when tertiary canals were not directly connected to secondary canals (canal A on figure 7.2). It was stronger when tertiary canals were opened to secondary canals (canal B on figure 7.2), which can be explained by stronger flushing and leaching of toxic ions from the soil as water movements in the canal were more important.

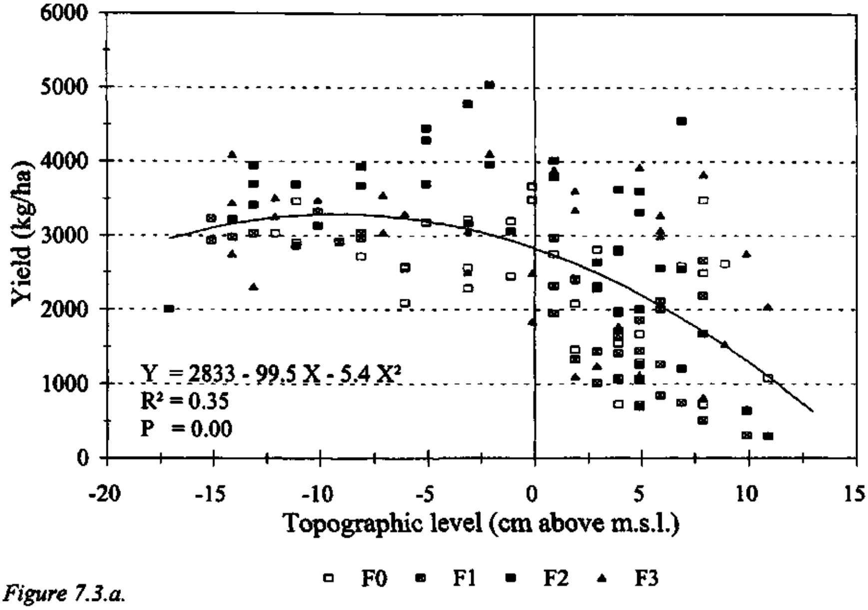

Figure 7.3.a.

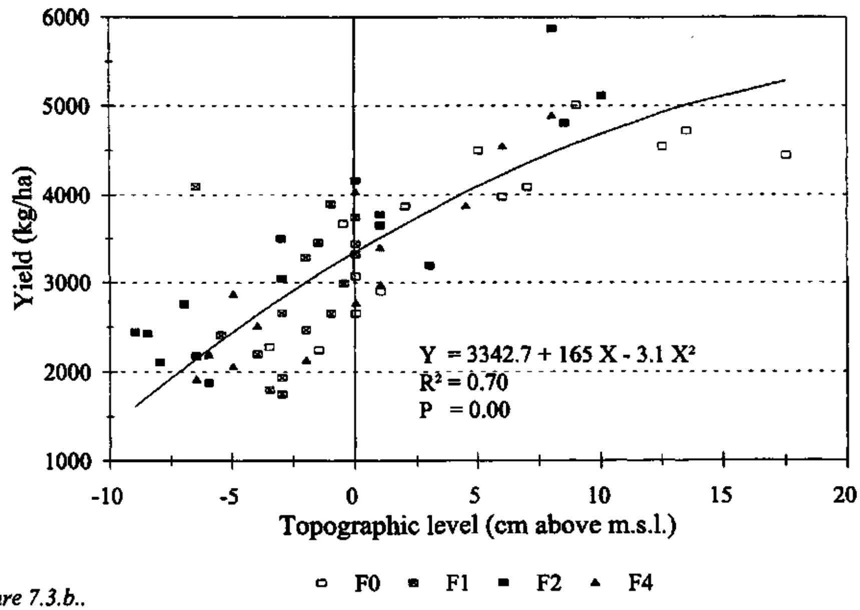

Figure 7.3.b..

Figure 7.3. *Rice yield (kg/ha) as a function of microtopography.*
Figure 7.3a: Field M.
Figure 7.3b. Field H.

In the three fields with canal distances of only 30 to 35 metres, and in which the maximum distance to a tertiary canal was thus 17.5 metres, no significant difference was observed.

Thus, in fields with wide spacing between tertiary canals, the distance from irrigation/drainage canals can interfere with the experimentation. In the field given as an example, yield difference between a plot located between 20 and 30 metres from both canals and a plot located between 5 and 15 metres from a canal was 300 kg/ha, i.e. 13.5%. The poor positioning of experimental plots can reduce the power of experimentation, induce a violation of the assumption of independence between plots and lead to erroneous conclusions.

Fertiliser experiments.

From the 19 experiments on fertilisers, four were implemented in 60-70 metres-wide fields in which the distance to tertiary canals interfered with the treatments. These fields were removed from analysis. Table 7.3 presents a synthesis of the results of 15 experiments conducted in 30-35 metres-wide fields.

Need for covariance analysis to take into account the effect of microtopography on yield.

In the 15 experiments, coefficients of variation were very high, with an average of 25.1% and a maximum value of 38.6%. This can be explained by the considerable effects of microtopography on rice yield. In 80% of the experiments, yield was significantly correlated to microtopography, either through a quadratic or a linear function. This sensitivity to microtopography actually reflects sensitivity of rice growth to hydric conditions and demonstrates the importance of water management on severely acid sulphate soils. Figures 7.3a and 7.3b present rice yields as a function of microtopography in a high field on Typic Sulfaquepts (field M at 89.5 cm above mean sea level on average) and a low field on Hydraquentic Sulfaquepts (field H at 73.5 cm above mean sea level). Although the difference in altitude between these two fields is small, it induces considerable differences in soil characteristics and influences water management requirements and possibilities (Husson et al., 1998a and d). At the field level, this difference in topography can be assessed simply by observation of the natural vegetation (Husson et al., 1998c).

The figures show that the influence of topography on yield can be dramatic, over 100 kg/ha/cm.

This high variability in yield increases CV and greatly reduces the power of experimentation. This means that a large number of replications are needed to show significant differences, or that only considerable differences between treatments will appear as significant in classical variance analysis. The high sensitivity of plant growth and yield to microtopography also means that the classical

Table 7.3. Synthesis of fields characteristics, cropping conditions and results of fertiliser experiments in 15 fields.

	Fields	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
	Topography (cm a.m.s.l.)	92.5	87	73.5	72	76.5	93.5	82	73.5	91	90	90	88	89.5	91.5	89
	Number of replications	10	14	35	15	21	15	20	20	20	20	15	20	35	20	20
	Panicles/m²	283	322	325	337	342	342	350	354	398	432	449	480	496	592	658
A	F0	2094ns	2770ns	2496ns	2488ns	2719ns	2563ns	2297 b	3697ns	3929 c	3677 b	2335 c	4852ab	2326bc	4649 b	4648 a
N	F1	1965ns	2850ns	2375ns	2567ns	3111ns	2643ns	2263 b	2847ns	4222bc	4579 a	2740bc	4327 b	1936 c	4136 c	3892 b
O	F2	2216ns	3059ns	2459ns	2785ns	3169ns	2965ns	2786 a	3396ns	4709ab	4972 a	3268 a	5364 a	3116a	5028 b	4488 a
V	F3	-	-	2106ns	2593ns	-	3087ns	2867 a	3060ns	4986 a	4852 a	3022ab	5577 a	2605ab	5871 a	4769 a
A	CV (%)	26.2	25	33.7	32.6	18.2	20.3	38.2	29.5	16.4	20.6	26	17.6	38.6	17.7	16.6
C	F0	2382ns	3133ns	2359ns	2814ns	3010ns	-	2663bc	3129 b	3710 c	3620 c	-	4800 c	2676 b	4803 c	-
O	F1	2187ns	3187ns	2386ns	2889ns	3317ns	-	2573 c	3242 b	4403 b	5120 b	-	4679 c	2288 c	4239 d	-
V	F2	2341ns	3232ns	2623ns	2963ns	3286ns	-	3156a	3720 a	4917 a	5513 a	-	5353 b	3328 a	5272 b	-
A	F3	-	-	2436ns	2913ns	-	-	3129ab	3278 b	5325 a	4882 b	-	5893 a	2959ab	6028 a	-
R	(F2-F0)/F0	-1.7 %	3.2 %	11.2 %	5.3 %	9.2 %	15.7 %	18.5 %	18.9 %	32.5 %	52.3%	40.6 %	11.5%	24.4 %	9.8 %	-2.5 %
.	CV (%)	20.1	19.5	30.8	29.1	15.5	20.3	31.7	17.4	11.9	12.8	26.0	11.5	31.1	11.7	16.6

ns indicates that the four treatments are not significantly different. Means followed by a same letter are not significantly different at the 5 per cent level.

assumption of independence between plots made for variance analysis is most of the time violated on these highly variable acid sulphate soils. The average standard deviation for topography in 15 fertiliser experiments, measured on 40 to 140 samples, was 6.5 cm. Although experiments carefully were located according to microtopography, the average maximum difference between two treatments within one experiment was 4.6 cm. In the cropping conditions of field M, common in the Plain of Reeds, a difference of 5 cm between two treatments induces a difference in yield of 500 kg/ha (i.e. 17.6%) which is not due to the treatments but only to the setup of the experiment. For the same topographic difference, yield difference is even greater in field H: it reaches 825 kg/ha or 24.7%.

In these conditions of high variability, the failure to both consider microtopography and verify the assumption of independence between treatments before performing variance analysis can obviously lead to erroneous conclusions.

Using covariance analysis with topography as a covariate instead of variance analysis for the 12 fields in which yield was correlated to microtopography (no significant correlation was observed in fields F, K and O) reduced the CV from 25.1 to 20.4% on average. Mean Square Error (MSE) also was reduced by 33.3% on average, considerably increasing the precision and the power of the experiments. As a consequence, covariance analysis showed more significant differences between treatments than simple variance analysis in 7 (fields G, H, I, J, L, M and N) of the 12 experiments in which it could be used (Table 7.3).

Sources of variability in experimental results.

Although covariance analysis could control the effect of microtopography, the variability of results between experiments remained high. For instance, comparisons between treatments with thermophosphate (F2) or with Di-Ammonium Phosphate only (F0) showed highly significant (α = 1%) or significant (α= 5%) differences in 8 of the 15 experiments (Fields G to N in Table 7.3).

At a given risk α, the power of an experiment, i.e. the chance to show a significant difference, is a function of the coefficient of variation (CV), the difference measured between treatments and the number of replications (Philippeau, 1984). For fertiliser experiments conducted in the Plain of Reeds, CV and the number of replications had little influence. Significant differences were observed at CV varying from 11.7 to 31.7%, and both significant and non significant differences were observed with 15 or 35 replications. The main parameter influencing significance of results seemed to be the difference measured between treatments: All differences lower than 9.8% were not significant, while all differences higher than 15.7% were significant. This difference between treatments can be largely explained by average panicle density of experiments (Figure 7.4). Below 400-450 panicles/m², difference between treatments F2 and F0 increased with panicle density. At higher panicle densities, difference between treatments decreased. As a consequence, the probability to observe an F value higher than the F value of the experiment if treatments were actually identical was correlated to difference between treatments ($R^2 = 0.74$), but also to panicle density (R^2=0.63), following a quadratic function.

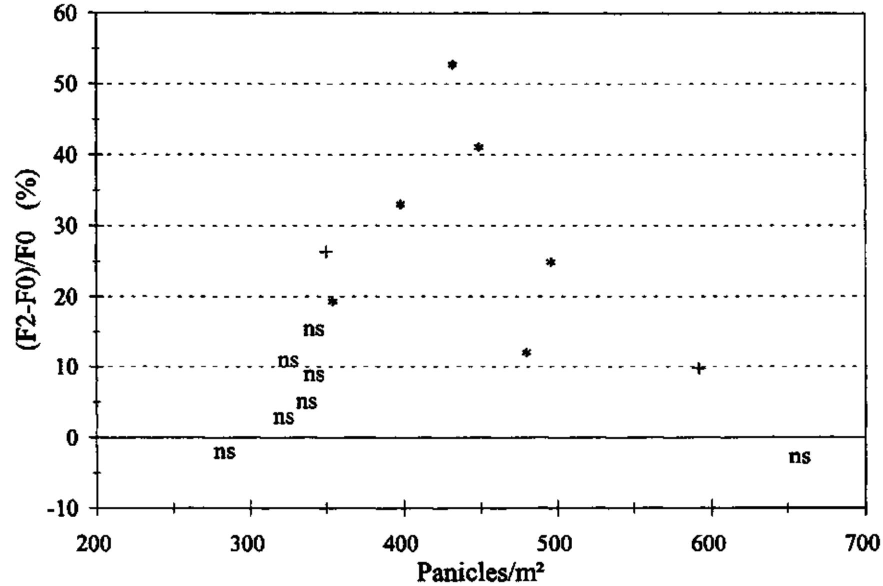

*Figure 7.4. Percentage difference in yield between F2 (Thermophosphate and Di-Ammonium Phosphate) and F0 (Di-Ammonium Phosphate only) as a function of panicle density. Synthesis of 15 experiments. ns indicates non significant difference, + indicates significant differences ($\alpha = 5\%$) and * indicates highly significant difference ($\alpha = 1\%$).*

Panicle density is therefore a key factor explaining why significant differences are or are not observed in experiments. Six of the seven experiments in which no significant differences could be observed had less than 350 panicles/m² on average (fields A to F). The last one (field O) showed a very high density, over 650 panicles/m² (Figure 7.4 and Table 7.3). All experiments showing significant differences between F0 and F2 (fields G to N) had between 350 and 600 panicles/m².

However, differences in yield between treatments were not due to differences in panicle density: Significant differences in density were found in only two out of 15 experiments.

In the cropping conditions of the Plain of Reeds, panicle density is largely determined by water level at sowing and average topographic level of the field, which determine depth and duration of submersion. Early sowing in deep water on high fields (higher than 85 cm above mean sea level), or sowing under water on low fields (lower than 75 cm above mean sea level), leads to low densities because of long submersion and deep reduction (Husson et al., 1998d). These very adverse conditions in the first part of the plant cycle lead to weak plants and reduced plant growth even after hydric and chemical conditions have been improved. An analysis of yield components for the 15 experimental fields showed that differences in yield between treatments were indeed the result of differences in plant growth and grain filling. F2 gave taller plants, higher number of filled grains per panicle and a higher weight of one grain than F0 in respectively 87, 62 and 75% of the fields in which significant yield differences were observed (fields G to N).

A low panicle density reflects a long submersion and a high plant mortality. In fields with less than 350 panicles/m², the limiting factor to rice growth was not fertilisation but long and deep submersion. As a consequence, the effects of fertiliser were masked and no differences between treatments were observed.

Differences between treatments faded at very high density (above 500-550 panicles/m²), probably because of insufficient fertiliser rates which led, at these densities, to insufficient nutrient supply. This hypothesis is supported by the fact that fields with more than 500 panicles/m² were the only ones in which the low rate F1 (with thermophosphate) yielded significantly less than F0, and that at these densities, increasing fertiliser rate significantly increased yields.

The greatest differences between treatments (over 30%) were observed in fields with medium density (fields I, J and K with 400 to 450 panicles/m²). In these fields, plants did not remain submerged too long, and irrigation made it possible to avoid dry conditions at the end of the plant cycle. Fertilisation was indeed the main factor limiting yield and differences between fertiliser treatments could be observed.

Advantages of Van Dien thermophosphate (TP) as compared to Di-Ammonium Phosphate (DAP).

In 9 fields (G to O in table 7.3) density was higher than 350 panicles/m² and fertilisation could be regarded as the main factor limiting rice growth. In 8 of these fields (G to N), covariance analysis showed significant differences between treatment F2 (associating TP and DAP) and F0 (with DAP only). On average, yield was 27% higher for F2 than for F0. This difference was even higher (42%) in the 3 fields with density of 400- 450 panicles/m² (fields I, J and K). At these densities, even with F1 (using TP but at lower rates of nitrogen and phosphorus than F0) yields were significantly higher

(22.5% on average) than with F0 in two fields (I and J) out of three.

These differences in yield were measured both on Typic Sulfaquepts and Hydraquentic Sulfaquepts and are explained by differences in plant growth. With TP, rice plants were taller (+8.2 cm, i.e. 11.1%, on average for F2 compared to F0 in the eight fields in which significant yield differences were measured), with a higher number of filled grains per panicle (+7.7 filled grains/panicle, i.e. 20.9%) and showed better grain filling (+ 1.1 mg/grain, i.e. + 4.5%).

Better rice growth and higher yields obtained with TP may be explained by:

(i) the low solubility of phosphorus in TP which causes slow release and makes it available for rice plants during a longer period.

(ii) the possibility to apply it when rice seedlings are still submerged; this is not possible in the case of DAP as it would result in a rapid development of algae suffocating rice plants that are still under water. As a consequence, with TP phosphorus can be applied to rice plants when their needs are highest, i.e. in the first weeks after sowing. With DAP, which can be applied only when flood water has receded, i.e. about three weeks after sowing, phosphorus is brought to plants too late.

(iii) apart from P_2O_5, TP includes silicon, an important component of rice plants, CaO which can increase pH locally, and MgO. Absorption of magnesium by rice roots is competitive to Fe^{2+} and Al^{3+} ions (Loué, 1986). It can therefore help to reduce the toxic effects of these elements. In addition, thermophosphate contains micro-nutrients as boron which seems to have a positive effect on rice growth on high and dry Typic Sulfaquepts of the Plain of Reeds.

(iv) thanks to its very fine texture, TP can very easily be mixed with pregerminated seeds. Fertiliser is then located around seeds and can be directly used, which may increase its efficiency.

(v) the fine texture also causes high surfaces of contact between soil and fertiliser. It might create considerable surfaces of favourable micro-environment where micro-biological life can develop. Brinkman (1982) has suggested that bacterial action can result in reduction and consequent decrease of acidity and aluminium toxicity.

In properly managed fields, locally-produced Van Dien thermophosphate proved to bring a highly significant increase of rice yield compared to imported DAP, at similar costs. It therefore can be recommended for fertilisation of severely acid sulphate soils in the Plain of Reeds. However, TP has the inconvenience of a rather low P content, raising problems of transportation, manipulation and storage. Although precise conclusions could not be made, experiments to assess the optimal ratio between TP and DAP suggest that TP should represent about 50-60% of the applied P.

Rates.

Optimal rates of fertiliser are a function of water management strategies.

When early sowing in deep water leads to low panicle density (below 350 panicles/m^2) and weak plants, high or very high fertilisation levels will not bring significant improvement as compared to lower fertilisation. No significant differences between F1 and F2 or F3 were observed in fields A to F (Table 7.3). In fields with poor land preparation and very early sowing, fertilisations up to 128-74-120 (N-P-K in kg/ha) and 120-132-0 have been tested, without bringing any yield improvement.

When panicle density exceeds 350 panicles/m^2, increasing fertiliser rates significantly increases yields. Between 350 and 450 panicles/m^2, yields were on average 500kg/ha higher with F2 (100 N - 44 P in kg/ha) as compared to F1 (60-35), and were also higher or not significantly different as compared to F3. F2 had a cost 290 000 VND (equivalent to 26 US$ or about 210 kg of paddy in 1995) higher than F1, and therefore brought the most interesting economic return. When density was higher than 450 panicles/m^2, increasing fertiliser rates to F3 (100-53) also increased yields in two fields out of four.

Conclusions.

Results of fertiliser experiments on acid sulphate soils are highly variable and should not be extrapolated without precise characterisation of soil and cropping conditions. In the conditions of the Plain of Reeds, three major sources of yield variability usually not considered in experiments were identified: microtopography, distance from tertiary irrigation/drainage canals, and crop husbandry, especially water management. They can greatly interfere with fertiliser experiments, leading to low research efficiency and non-conclusive or even contradictory results. The high yield variability also makes it difficult to statistically show significant differences between treatments below 10%.

As much as possible, treatments should be located at similar topography. This requires detailed characterisation of experimental fields and can be eased by implementation of long and narrow plots, with the longer side parallel to the topography gradient. Covariance analysis with microtopography as a covariate is needed most of the time. It proved to properly control the effects of soil and water variability on rice growth and yield, and consequently to greatly improve the efficiency and precision of experiments. It only requires the measurement of topography, which can be achieved easily with a simple theodolite.

In fields with canal spacing exceeding 35 metres, the influence of the distance from the canal can be controlled by locating the long side of the plots perpendicular to canals. In case the topography gradient is parallel to tertiary canals, fisher blocks design is needed.

Poor water management, and especially very early sowing in deep water, limits plant density and growth and, consequently, differences between fertiliser treatments.

When proper water management allows panicle density to exceed 350 panicles/m^2 and the development of vigorous plants, the use of Van Dien thermophosphate in association with Di-Ammonium Phosphate improves rice growth and significantly increases yield by 27% on average compared to Di-Ammonium Phosphate alone. Optimal rates also vary with water management, which can be assessed by the panicle density, a useful indicator to derive fertiliser response. Below 350 panicles/m^2, increasing fertiliser rates is not economical, and fertilisation of 60-35 is sufficient. Above this density, increasing fertiliser rates to 100-44, or 100-53 at density over 450 panicles/m^2, significantly increases yields both on Typic Sulfaquepts and Hydraquentic Sulfaquepts.

Chapter 8

Epilogue

Conclusions.

This study is original in that it :

(i) was conducted in actual conditions of production on severely acid sulphate soils as met in the Plain of Reeds,

(ii) integrated farmers' knowledge and practices,

(iii) performed a dynamic, integrated analysis of water-soil-plants interactions, and

(iv) took into account and used the very high short-range variability of acid sulphate soils.

The detailed soil surveys provided an important documentation of variation of acid sulphate soils at short distances. Soil variability was explained by variability in the relative soil-water level, which is spatially correlated to soil elevation and temporally correlated to water movements. In such conditions, soil temporal variability should be studied in relation to elevation. An integrated spatio-temporal analysis makes it possible to use variations in microtopography, which can occur at very short distance, to assess soil evolution upon drainage.

The detailed agronomic surveys showed strong variations in rice growth and yield, within and between fields, which were explained and put in relation to soil and water variations.

The intensive work conducted for four years with farmers, in actual cropping conditions, at real scale and in a large number of fields not only yielded an inventarisation of farmers' practices but also made it possible to compare the agronomic efficiency of these practices. Based on the understanding of rice growth under various conditions, modifications in crop management could be proposed and tested. This work resulted in the proposal of practical water management and fertiliser strategies for the cultivation of rice following land reclamation on severely acid sulphate soils, adapted to the main cropping conditions met in the Plain of Reeds. In a pragmatic approach, it was preferred to make best possible use of actual cropping conditions instead of trying to control them, which is usually costly and difficult to manage on a large scale. For instance, instead of developing 'optimal' water management for these soils assuming that precise water management is (or will be) possible, recommendations are based on the recognition that water control is very poor in the first years after reclamation.

The understanding of major processes in acid sulphate soil development and in rice growth obtained through this very detailed study can be extrapolated to the whole Plain of Reeds. Recommendations to adapt cropping practices to the actual field conditions, identified through simple criteria (as microtopography which can be assessed by observation of natural vegetation), allow the extension of results on a large scale even in such a highly variable environment.

The results of this study are meaningful to:

(i) farmers, as shown by the rapid reclamation of severely acid sulphate soils in the Plain of Reeds. Hopefully, extension of the knowledge developed on acid sulphate soils and their management will reduce the risk of failure when reclaiming these soils and help to slow down the extremely rapid social differentiation in the Plain of Reeds,

(ii) extension agents, who now have simple means to adjust recommendation according to field conditions,

(iii) policy makers, who can make use of the technical references developed on land reclamation of severely acid sulphate soils, and

(iv) researchers, for technical and methodological aspects. Knowledge on acid sulphate soil genesis and variability, has been increased. A model of rice growth and yield in the cropping conditions of the Plain of Reeds has been developed, and management practices have been proposed. The interests of these results are not limited to the Plain of Reeds. In particular, correlations between microtopography and soils characteristics and rice growth and yield can be expected in other acid sulphate soils areas of the world.

On methodological aspects, some recommendation can be proposed for future research in the Plain of Reeds. Detailed analysis of yield components proved to be a useful tool for these research conditions. The study also shows that for experiments on acid sulphate soils, differences between fields are often more important than differences between treatments. Comparison between fields can therefore bring important information. When planned in the research programme, a common treatment ("bridge") applied to all experimental fields makes such comparison possible. For the comparison between treatments on severely acid sulphate soils, the study shows the interest of performing covariance analysis with topography as covariate, instead of simple variance analysis. Finally, this study shows that when integrated in the research programme and treated as an object of research, variability can become an important source of information. In this respect, the Plain of Reeds, with its extreme cropping conditions and its high short-range spatial variability, reflecting differences in long-term soil development, is a perfect location for an analysis of water-soil-plant interactions and a study of the genesis of acid sulphate soils.

Summary.

Acid sulphate soils in the Mekong delta cover 1.6 million hectares, of which 400 000 ha are located in the Plain of Reeds. Due to the presence of pyrite that yields acid when oxidised, all acid sulphate soils are (potentially) strongly acidic. Reclamation of the 150 000 ha of severely acid sulphate soils still uncultivated in 1990 became a national priority and now attracts local farmers and migrants. However, these soils present important agronomic problems and farmers urgently need advice to reclaim them. However, the development of recommendations and the cultivation of acid sulphate soils on a large scale are made difficult by their very high variability.

The objectives of this thesis are to:

(i) characterise and explain spatio-temporal variability, at various scales, of acid sulphate soils and water in the Plain of Reeds, Vietnam.

(ii) assess the impact of soil and water variability on rice cultivation.

(iii) develop a simple model of rice yield build-up under conditions following land reclamation of severely acid sulphate soils in the Plain of Reeds.

(iv) apply this model to identify and rank limiting factors, to precisely identify the optimal time window for cultivation and develop optimal agricultural practices (in particular water management and fertilisation) for the main cropping conditions found in the Plain of Reeds.

Spatio-temporal variability in soil and water is very high, at all scales, as explained by the relative soil/water level which influences oxidation, and consequently the soil chemical status in the short term, and soil development in the long term. Soil microtopography is a key factor as slight differences in altitude induce important differences in intensity and length of soil oxidation and mineralisation. This resulted in the differentiation of two very different but closely intertwined soil types, separated by soils with intermediate characteristics. In the study area, located in the central part of the Plain of Reeds, organic Hydraquentic Sulfaquepts occupy locations below 75 cm above mean sea level where soil development is slow because of waterlogged conditions. Upon drainage, these soils are expected to develop into clayey Typic Sulfaquepts with jarosite and goethite mottles as found above 85 cm above mean sea level.

Because of the high sensitivity of plants to soil chemical characteristics, water management which determines redox conditions and Fe and Al concentrations, is a key to the cultivation on acid sulphate soils. Unfortunately, the very high soil permeability makes water control very difficult, especially in the years immediately following reclamation. This makes it difficult to maintain good

cropping conditions through irrigation or drainage. Consequently, the time window during which optimal cropping conditions are met is very short. Its starting date and duration are also spatially variable, in relation to microtopography. To extend this time window, farmers in the Plain of Reeds start cultivation as soon as possible, broadcasting pregerminated rice seeds in flood water, before it has completely receded. In these cropping conditions, farmer-managed trials were conducted for four years, after precise site characterisation (using geostatistical methods). Detailed studies of crop phenology and yield led to the development of a semi-quantitative model of rice yield build-up. Yield is mainly determined by panicle density and plant growth, reflected in the weight of one grain.

Within fields, plant, tiller and panicle densities are linearly correlated to microtopography. This has been explained by higher plant mortality and poorer tillering in low positions due to deeper and longer submersion which reduces light intensity, but also to action of sulphate-reducing bacteria in the deeply reduced conditions of the lowest positions. Plant growth can be affected by the deep reduction inducing iron toxicity in the lowest locations. It is, however, mainly limited by aluminium toxicity linked to acidification of the high positions in oxidised conditions at the end of the growing season. This results in plant growth and yield correlated to microtopography in a quadratic trend, with maximum growth at medium topographic level, and with a strong decrease at high topographic levels.

Between fields, similar correlations are observed in the first year after reclamation. With cultivation, improvement of water control results in yield increase every year. This increase is faster on high fields, in which better plant growth can be obtained together with high densities. Thus, after 3 years, average yields of the fields become linearly correlated with the average topographic level, with maximum values at high topographic levels.

Application of this model allows the improvement of water management strategies, based on field characteristics: it determines the proper timing for sowing pregerminated seeds and optimal water management practices, as a function of field topography and age, and flood characteristics.

High fields (higher than 85 cm above mean sea level), and to a certain extend fields at medium topographic level, mainly suffer from acidification at the end of the growth cycle. Water management on these soils should aim at maintaining wet soil to avoid oxidation. In this respect, early sowing, in deep water (30 to 35 cm) is required in the first year after reclamation. Although this leads to lower densities, it is the only way to maintain wet conditions until the end of the cycle and to allow acceptable plant growth. With improvement of water control, sowing can be progressively delayed, until sowing on wet soil becomes possible. In contrast to this situation, low fields (lower than 75 cm above mean sea level) suffer from submersion and deep reduction. Water management should aim at creating a slight oxidation of the top soil as soon as possible. The best practice consists of sowing on wet soil after pumping water out of the field, which is not always possible in the first year after reclamation because of the high permeability.

The model also allows identification of sources of variability in fertiliser experiments conducted on these soils. The advantages of thermophosphate fertiliser over Di-Ammonium phosphate are shown and explained.

Tools and methods to control variability and to use it as information are also presented, such as the use of correlations between microtopography, soil types and natural vegetation for mapping, the proper design and set up of experiments upon precise characterisation of fields and the use of co-variance analysis with microtopography as a covariate.

The results of the study are meaningful to farmers as well as policy makers, and provide a semi-quantitative picture of the dynamics, risks and opportunities for reclamation and agricultural use of acid sulphate soils in the Plain of Reeds and beyond.

Key words: Acid sulphate soils, variability, microtopography, Plain of Reeds, Vietnam, rice, land reclamation, yield components, covariance analysis, water management, fertilisation, on-farm research, integrated study.

Résumé.

Les sols sulfatés acides couvrent 1,6 millions d'hectares dans le delta du Mékong, dont 400 000 hectares dans la Plaine des Joncs. A cause de la présence de pyrite qui produit de l'acide en cas d'oxidation, ces sols sont (potentiellement) très acides. La mise en valeur des 150 000 ha de sols fortement sulfatés acides toujours en friches dans la Plaine des Joncs en 1990 est devenue une priorité nationale et attire les paysans locaux comme de nombreux migrants. Cependant, ces sols présentent de fortes contraintes agronomiques et les paysans ont un besoin urgent de conseils pour leur mise en valeur. Mais le développement de recommendations et la culture à grande échelle sur ces sols est rendue difficile par leur très forte variabilité.

Les objectifs de cette thèse sont:

(i) de caractèriser et d'expliquer la variabilité spatiale et temporelle, à différentes échelles, des sols sulfatés acides dans la Plaine des Joncs.

(ii) d'évaluer l'impact sur la culture du riz de la variabilité des sols et des conditions hydriques.

(iii) de développer un modèle simple d'élaboration du rendement du riz dans ces conditions de culture, après défriche de sols fortement sulfatés acides dans la Plaine des Joncs.

(iv) d'utiliser ce modèle pour identifier les facteurs limitant la culture, d'identifier précisement la période de culture optimale et de développer des techniques de culture (en particulier de gestion de l'eau et de fertilisation) adaptées aux principales conditions de culture observées dans la Plaine des Joncs.

La variabilité spatio-temporelle des sols et des conditions hydriques est très forte, à toutes les échelles, et s'explique par les variations du niveau relatif de l'eau par rapport au sol, ce qui influence l'oxidation et en conséquence, le statut chimique du sol dans le court terme et le développement des sols dans le long terme. Comme des différences d'altitude minimes induisent de fortes différences d'intensité et de durée d'oxidation et de minéralisation, le niveau microtopographique du sol est un facteur clef. Ceci a conduit à la différenciation de deux types de sols très différents mais étroitement imbriqués, séparés par des sols aux caractèristiques intermédiaires. Dans la région d'étude, située au centre de la Plaine des Joncs, les 'Typic Sulfaquepts', sols argileux dans lesquels ont peu observer des mottes de goethite et de jarosite sont présents au dessus de 85 cm au dessus du niveau moyen de la mer, alors que les zones en dessous de 75 cm au dessus du niveau moyen de la mer sont occupées par les 'Hydraquentic Sulfaquepts', sols fortement organiques.

A cause de la forte sensibilité des plantes aux charactèristiques chimiques des sols, la gestion

de l'eau, qui détermine les conditions d'oxidation et les concentrations en fer et en aluminium, est un facteur clef pour la mise en valeur de ces sols. Malheureusement, leur très forte perméabilité rend le contrôle de l'eau très difficile, en particulier dans les années suivant la défriche. Dans ces conditions, il est difficile de maintenir de bonnes conditions de cultures par irrigation ou drainage. En conséquence, la période durant laquelle des conditions de culture favorables sont réunies est très courte. La durée et la date à laquelle débute cette période sont également variable dans l'espace, en fonction du niveau topographique. Afin d'allonger cette période, les paysans de la Plaine des Joncs débutent la culture dès que possible, semant des semances de riz prégermées dans l'eau de la crue, avant qu'elle ne se soit complètement retirée. Dans ces conditions de culture, des essais en milieu paysan ont été conduits pendant 4 années, après une caractèrisation fine du milieu (utilisant des méthodes géostatistiques). L'étude détaillée du développement des plantes et du rendement ont conduit au développement d'un modèle semi-quantitatif d'élaboration du rendement du riz. Il existe une relation quadratique entre la croissance et le rendement d'une part, et la microtopographie. Une longue submersion réduit l'intensité lumineuse et en conséquence augmente la mortalité des plants et réduit le tallage. Les plants souffrent de la forte réduction et de toxicité ferreuse induite dans les parties basses (en dessous de 75 cm au dessus du niveau moyen de la mer), de toxicité aluminique dans les parties hautes (au dessus de 85 cm au dessus du niveau moyen de la mer) et les rendements maximum sont obtenus à altitude moyenne (75-85 cm au dessus du niveau moyen de la mer). L'utilisation de ce modèle a permi d'améliorer les stratégies de gestion de l'eau, en fonction des caractèristiques des champs: il détermine le meilleur moment pour le semis des semences prégermées et la gestion de l'eau optimale en fonction de l'altitude et de l'histoire du champs et des caractèristiques de la crue. Le modèle a aussi permis d'identifier les sources de variabilité dans les essais de fertilisation sur ces sols. Les avantages du Thermophosphate par rapport au Di-Ammonium Phosphate (DAP) sont montrés et expliqués. Des outils et des méthodes pour contrôler la variabilité et pour l'utiliser comme source d'information sont également présentés comme l'élaboration des plans d'expérimentation et le placement des essais en fonction des caractèristiques précises des champs et l'utilisation de l'analyse de covariance avec la topographie comme covariable.

Les résultats de cette étude peuvent servir aux paysans comme aux responsables politiques, et fourni une image semi-quantitative des dynamiques, risques et opportunités de la mise en valeur agricole des sols sulfatés acides dans la Plaine des Joncs et ailleurs.

Samenvatting

In de Mekong delta bestaat 1,6 miljoen hectare grond uit zogenaamde kattekleien: zure, sulfaathoudende grond. Vierhonderd duizend ha van die kattekleien ligt in de zgn. *Plain of Reeds* (Rietvlakte). Als gevolg van de aanwezigheid van pyriet dat zwavelzuur produceert bij het oxideren, zijn die gronden - potentieel- uiterst zuur. De exploitatie van 150 000 ha van de gronden in de Rietvlakte - die nog altijd braak lagen in 1990 – is een nationale prioriteit geworden en trekt zowel lokale boeren als vele migranten aan. De gronden leveren echter zware landbouwkundige moeilijkheden op en de boeren hebben daarom dringend behoefte aan advies voor hun exploitatie. De ontwikkeling van aanbevelingen en de exploitatie van die gronden op grote schaal, wordt echter bemoeilijkt door hun zeer grote variabiliteit.

De doelstellingen van deze thesis zijn:

- het kenschetsen en interpreteren van de ruimtelijke en temporele variabiliteit van de kattekleien in de Rietvlakte, op verschillende niveaus;
- het evalueren van de impact van de variabiliteit van die gronden en van de hydrologische voorwaarden op de rijstteelt;
- het ontwikkelen van een eenvoudig model voor de samenstelling van het rendement van rijst, na het ontginnen van de zeer zure, sulfaathoudende bodems in de Rietvlakte
- het gebruiken van dit model om: (a) de beperkende factoren voor rijst te identificeren, (b)de optimale teeltperiode van rijst op een nauwkeurige manier te bepalen en (c) cultuurtechnieken te ontwikkelen (in het bijzonder wat betreft de waterhuishouding en de bodemverbetering) die aangepast zijn aan de belangrijkste teeltomstandigheden die voorkomen in de Rietvlakte.

De ruimtelijke en temporele variabiliteit van de bodems en van de hydrologische situatie is op alle niveaus bijzonder groot en wordt nader verklaard door de variaties van het relatieve niveauverschil van het water ten opzichte van de grond. Dit relatieve niveauverschil beïnvloedt dan weer de oxidatie die op haar beurt de scheikundige samenstelling van de grond op korte termijn en de bodemontwikkeling op lange termijn beïnvloedt. Aangezien minieme hoogteverschillen al sterke verschillen in intensiteit en duur van de oxidatie en de mineralisatie tot gevolg hebben, speelt de micro-topografische situatie van de grond een sleutelrol. Dit heeft geleid tot de differentiëring van twee types van gronden die heel verschillend zijn maar toch nauw met elkaar in verband staan, en die gescheiden zijn door gronden met overgangskenmerken.

In het studiegebied, gelegen in het centrum van de Rietvlakte, vinden we de 'Typic Sulfaquepts' (die kleigronden waar hier en daar goethiet en jarosiet in voorkomen) op 85 cm boven het gemiddelde zeeniveau. Zones die lager dan 75 cm boven het gemiddelde zeeniveau gesitueerd zijn, bestaan uit sterk organische 'Hydraquentic Sulfaquepts'.

Als gevolg van de grote gevoeligheid van planten voor de chemische kenmerken van gronden, is het waterbeheer - dat de voorwaarden tot oxidatie alsook de concentraties aan ijzer en aluminium bepaalt - een sleutelelement om deze gronden goed uit te baten. Jammer genoeg wordt door de zeer grote permeabiliteit van die gronden het waterbeheer zeer moeilijk gemaakt, in het bijzonder gedurende de eerste jaren na het ontginnen van de braakliggende gronden. In die omstandigheden is het moeilijk om goede teeltvoorwaarden te handhaven door middel van irrigatie of drainage. Bijgevolg is de periode waarin de gunstige teeltvoorwaarden tegelijkertijd voorhanden zijn erg kort. De duur en de begindatum van die periode zijn ook afhankelijk van het topografisch niveau. Om die periode te verlengen, beginnen de boeren van de Rietvlakte zo vroeg mogelijk met de teelt: ze zaaien rijst die gekiemd is in het gerezen water van de Mekong, voor die zich helemaal terugtrekt.

Na een diepgaande studie van de kenmerken van het milieu, met behulp van geostatistische methodes, werden gedurende 4 jaar testen gedaan op de boerderijen onder plaatselijke landbouwkundige omstandigheden. De gedetailleerde studie van de fenologie van de rijstplant en van de rijstopbrengst heeft geleid tot de ontwikkeling van een semi-kwantitatief model voor de samenstelling van het rendement van rijst. Er bestaat een kwadratisch verband tussen de groei en het rendement enerzijds en de microtopografie anderzijds. Een langdurige overstroming verkort de intensiteit van het licht en verhoogt bijgevolg de sterfte van de kiemplanten en vermindert de beworteling. De kiemplanten hebben te lijden onder de sterke reductie en ijzertoxiciteit geïnduceerd in de lagergelegen gedeeltes (lager dan 75 cm boven het gemiddelde zeeniveau) en de aluminiumtoxiciteit in de hoger gelegen gedeeltes (hoger dan 85 cm boven het gemiddelde zeeniveau). De hoogste rendementen worden bereikt bij een gemiddelde hoogte (75-85 cm boven het gemiddelde zeeniveau).

De toepassing van het model heeft het mogelijk gemaakt de strategieën voor waterbeheer te verbeteren, als functie van de veldkarakteristieken: het model bepaalt het meest geschikte ogenblik voor het zaaien van de voorgekiemde zaden en het optimale waterbeheer in functie van de hoogte en de geschiedenis van het veld, en van de karakteristieken van het waterpeil.

Het model laat ook toe de bronnen van variabiliteit te identificeren bij bemestingsproeven. De voordelen van Thermofosfaat in vergelijking met Di-Ammonium Fosfaat (DAP) worden aangetoond en geïnterpreteerd. Ook worden middelen en methodes om de variabiliteit te controleren en te gebruiken als informatiebron voorgesteld. Deze zijn bijvoorbeeld: (a) het vaststellen van correlaties tussen micro-topografie, bodemtype en natuurlijke vegetatie; (b) het ontwerpen en opzetten van proeven en (c) het bepalen op welke plaatsen ze uitgevoerd zullen worden als functie van de veldkenmerken en (d) het gebruik van covariantie-analyse met de topografie als covariabele.

De resultaten van deze studie kunnen van nut zijn voor de boeren zowel als voor de politiek verantwoordelijken, en geven een semi-kwantitatief beeld van de dynamieken, risico's en geschiktheid voor het exploiteren van de kattekleien in de Rietvlakte en elders.

TÓM TẮT

Đất phèn ở Đồng bằng sông Cửu Long chiếm 1,6 triệu ha trong đó Đồng Tháp Mười có 400.000 ha. Chất pyrite hiện diện trong đất phèn khi bị oxyt hóa sẽ sản sinh axit làm cho đất trở nên rất chua. Từ năm 1990, với chính sách ưu đãi của nhà nước Việt nam đã thu hút nông dân địa phương và những người dân di cư đến khai phá 150.000 ha đất phèn nặng còn hoang hóa ở vùng đất này. Đây là vùng đất có nhiều khó khăn vì vậy nông dân rất cần những hướng dẫn về kỹ thuật khẩn hoang; tuy nhiên việc đưa các khuyến cáo canh tác trên đất phèn cho toàn vùng rất khó thực hiện vì đất phèn có sự biến động rất cao.

Mục tiêu của đề tài này là :

(i) Mô tả và giải thích các sự biến đổi của đất và nước phèn theo không gian và thời gian ở các tỉ lệ khác nhau tại Đồng Tháp Mười.

(ii) Đánh giá sự tác động qua lại giữa đất và nước trong việc canh tác lúa.

(iii) Trình bày một mô hình canh tác lúa trong điều kiện khai hoang trồng lúa trên đất phèn nặng ở Đồng Tháp Mười.

(iv) Áp dụng mô hình này để nhận dạng và xếp hạng các yếu tố hạn chế, để xác định lịch thời vụ tối ưu và đề xuất các biện pháp canh tác hợp lí (đặc biệt trong việc quản lí nước và bón phân) đối với điều kiện trồng trọt ở Đồng Tháp Mười.

Có sự biến động rất lớn theo không gian và thời gian trong đất và nước, với mọi tỉ lệ như đã giải thích về sự liên quan đất/nước đến quá trình oxy hóa, đặc biệt trạng thái hóa học của đất trong thời gian ngắn và sự phát triển của đất trong thời gian dài. Sự khác biệt về tiểu địa hình đất là yếu tố chính dẫn đến những khác biệt về cường độ và độ lớn quá trình oxy hóa và khoáng hóa đất. Chính điều này đã hình thành hai loại đất khác nhau nhưng liên quan với nhau, được tách biệt do các đặc tính của chúng. Trong vùng nghiên cứu, nằm ở giữa Đồng Tháp Mười, loại đất Hydraquentic Sulfaquepts chứa nhiều chất hữu cơ thường thấy ở những nơi có địa hình thấp, có cao độ dưới 75 cm so với mực nước biển. Loại đất này phát triển chậm do luôn bị ngập nước. Ở những nơi có địa hình cao hơn, với cao độ trên 85 cm so với mực nước biển, tiêu nước dễ hơn thì hình thành loại đất Typic sulfaquepts chứa nhiều sét với các đốm jarosite (tầng phèn màu vàng rơm) và goethite (oxyt sắt).

Cây trồng cảm ứng mạnh với các đặc tính hóa học của đất, sự quản lí nước quyết định trạng thái oxy hóa khử của đất và nồng độ của sắt và nhôm. Tuy nhiên, do khả năng thấm nước của đất cao nên việc quản lí nước gặp nhiều khó khăn, đặc biệt trên đất mới khai hoang. Điều này dẫn đến việc khó mà duy trì tốt các biện pháp canh tác qua việc tưới tiêu không chủ động. Hậu quả là thời vụ bố trí cho cây trồng phát triển trong điều kiện tối ưu rất ngắn. Thời vụ gieo sạ cũng biến động theo không gian, liên quan đến các tiểu địa hình khác nhau. Để lợi dụng nước tốt sau lũ, nông dân vùng Đồng Tháp Mười đã tiến hành gieo sạ càng sớm càng tốt trong vụ Đông Xuân bằng cách áp dụng phương pháp sạ ngầm trước khi lũ rút. Trong những điều kiện này, các thử nghiệm làm trên ruộng nông dân do dân quản lí dưới sự chỉ đạo của cán bộ kỹ thuật đã được tiền hành trong suốt bốn năm, sau khi đã chọn điểm thí nghiệm một cách chính xác (sử dụng phương pháp lập bản đồ đất chi tiết). Các kết quả nghiên cứu đã được rút ra để xây dựng thành một qui trình canh tác lúa trên đất phèn nặng mới khai hoang. Năng suất lúa được xác định chủ yếu bởi số bông trên đơn vị diện tích và sự sinh trưởng của lúa, được phản ánh bằng trọng lượng hạt.

Trong ruộng lúa, mật độ cây, số nhánh đẻ và số bông có quan hệ tuyến tính đến địa hình ruộng. Điều này được giải thích bằng số cây bị chết cao và quá trình đẻ nhánh yếu ở những nơi có địa hình thấp liên quan đến quá trình ngập nước sâu hơn và lâu hơn, làm giảm cường độ ánh sáng, đồng thời cũng ảnh hưởng đến hoạt động của các vi khuẩn khử sulphát trong điều kiện bị khử mạnh ở những chỗ trũng. Quá trình khử ở những chỗ trũng đã sản sinh ra độc chất sắt đã ảnh hưởng đến sự sinh trưởng của cây trồng. Trong khi đó ở những chỗ cao, trong điều kiện bị ôxyt hóa mạnh vào cuối vụ thì độc chất nhôm gây hại chính cho cây. Các kết quả nghiên cứu đã cho thấy sự sinh trưởng và năng suất của cây có tương quan với tiểu địa hình theo phương trình bậc hai, với sự sinh trưởng tối ưu đạt được ở địa hình trung bình và giảm mạnh ở địa hình thấp và địa hình cao.

Quan sát nhiều ruộng lúa mới khai hoang năm đầu tiên trên toàn cánh đồng đã cho thấy có sự tương quan tương tự. Theo thời gian canh tác, chế độ nước được cải thiện đã làm cho năng suất tăng dần hàng năm. Năng suất tăng với tốc độ nhanh ở ruộng cao thông qua sự sinh trưởng của cây lúa tốt hơn với mật độ cây cao. Như vậy sau ba năm, năng suất trung bình của ruộng lúa sẽ có quan hệ tuyến tính với địa hình, với các giá trị cực đại ở các địa hình cao.

Việc áp dụng mô hình này cho phép cải tiến các chiến lược quản lí nước dựa vào đặc điểm từng ruộng. Việc xác định thời vụ gieo sạ thích hợp và biện pháp quản lí nước tối ưu tùy thuộc vào : (i) địa hình ruộng : lô cao, lô trung bình, lô thấp; (ii) đặc tính lũ và thời gian lũ : lũ lớn, lũ nhỏ.

Ruộng cao (cao hơn 85 cm so với mức nước biển) và ruộng có địa hình trung bình chủ yếu bị ảnh hưởng do xì phèn vào cuối vụ. Quản lí nước trên các ruộng này nhằm mục đích duy trì độ ẩm đất để tránh bị oxy hóa. Muốn đạt mục tiêu trên, cần phải sạ sớm bằng phương pháp sạ ngầm khi mực nước trên ruộng còn cao 30 - 35 cm, điều này là bắt buộc đối với những ruộng mới khai hoang năm đầu. Mặc dù việc này đưa đến mật độ cây thấp, nhưng là một phương cách duy nhất giữ độ ẩm đất cho đến cuối chu kì và cho phép cây có thể tăng trưởng ở mức có thể chấp nhận được. Với việc cải thiện về quản lí nước, thời vụ gieo sạ (sạ ngầm) có thể trễ dần cho đến khi sạ gác có thể thực hiện được. Ngược lại, các ruộng trũng (thấp hơn 75 cm so với mực nước biển) phải chịu ngập nước quá lâu và khử mạnh. Việc quản lí nước phải nhằm tạo chế độ oxyt hóa nhẹ ở lớp đất mặt càng sớm càng tốt. Biện pháp tốt nhất bao gồm sạ gác sau khi bơm nước ra, điều này không phải lúc nào cũng có thể thực hiện được trong năm đầu khai hoang vì độ thấm nước cao của đất.

Mô hình này còn cho phép nhận dạng các nguồn biến thiên trong các thử nghiệm phân bón trên loại đất này. Các lợi điểm của phân lân nung chảy (thermophotphat) so với diammonium phosphate (DAP) được chỉ ra và giải thích.

Các công cụ và phương pháp để điều chỉnh sự khác biệt và sử dụng chúng như là các thông tin cũng như được trình bày, như sử dụng mối tương quan giữa các tiểu địa hình, các loại đất và thảm thực vật tự nhiên để lập bản đồ, việc thiết kế và bố trí các thí nghiệm thích hợp trong đặc tính chính xác lô ruộng và sử dụng phương pháp phân tích đồng phương sai trong đó coi tiểu địa hình như là một biến.

Các kết quả nghiên cứu này rất có ý nghĩa đối với nông dân cũng như các nhà chính sách và đưa ra một bức tranh về động lực, rủi ro và các cơ hội cho việc khai hoang và sử dụng đất phèn tại Đồng Tháp Mười.

***Từ khóa*:** Đất phèn, sự biến thiên, tiểu địa hình., Đồng Tháp Mười, Việt Nam, lúa, khai hoang, các yếu tố cấu thành năng suất, phân tích đồng phương sai, quản lí nước, bón phân, nghiên cứu trên ruộng nông dân, nghiên cứu tổng hợp.

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