Acid sulphate soils: a baseline for research and development

To Jim Brockliss, who first showed me how mangrove swamp can be reclaimed, and to Alex Macrae, who showed me that it need not be.

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David Dent

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Foreword

Acid sulphate soils suffer extreme acidity as a result of oxidation of pyrite. Often they are also unripe; sometimes also saline. Some occur naturally but most have developed as a result of drainage of previously waterlogged coastal alluvium and peat.

Acid sulphate soils pose a range of problems for communities dependent on the reclaimed land – including low crop yields, a restricted range of alternative uses, soil engineering hazards, water pollution, and other environmental risks. These difficulties are not always anticipated, or recognised when they occur, or tackled with up-to-date information. There is a fund of expertise on the causes of, and the solutions to, the problems of these severely acid soils. Drawing together this information will be of benefit to many people, especially in the developing countries of the tropics.

A range of people have to deal with acid sulphate soils:

Farmers face the difficulties at the most basic level. They see symptoms in the crops, and in drainage and floodwaters; they suffer most keenly the consequences of low yields or crop failure; and they must adopt ameliorative or preventative management practices to make a reasonable living.

Agricultural and forestry advisory staff. In most cases these are the people who must diagnose the problems in the field and instruct land users in the techniques for controlling these problems. They need practical guidelines for the identification of acid sulphate soils – guidelines that are appropriate to local conditions.

Civil engineers must cope with a unique combination of corrosion by acidity, salt, and reducing conditions, and with the difficulties of design and construction of earthworks, roads, and drainage systems in unripe materials.

Planning agencies. Economists and planners working on land development projects must be informed about the likelihood of acid sulphate soils occurring in coastal lowlands. They need to know about the agricultural and engineering hazards, and also about the damaging environmental and social impact of the reclamation and development of extensive areas of acid sulphate soils. They need to know what kind of soils information to ask for, and how to use this information in their economic modelling.

Politicians, investors, and international development agencies need to know what problems exist, where they are likely to arise, their possible magnitude, and how they may affect the success of land development. Such decision-makers need to be aware of soil variability – the likelihood of good soils in some places and difficult soils elsewhere, possibly in adjacent areas. They should also be aware of the potential role of specialists in soil survey and land evaluation and the ongoing role of these specialists in the management of the land. They need to know the different costs and likely returns on investment in areas of different soils and different soil patterns, the time scale involved in the development and amelioration of difficult soils, and the benefits of not developing land that has severe soil problems. They need guidance on the development procedure that should be adopted, the decisions that need to be taken at the highest level, and the scientific work that is required to ensure the success of land reclamation and development projects.

Soil specialists need an authoritative and up-to-date technical reference for application in land reclamation and development projects, and as a platform for further research.

It is obvious that there is a need for communication between all these people. Indeed, one of the recommendations of the Symposium on Acid Sulphate Soils held at Bangkok in 1981 was that the available knowledge on acid sulphate soils be published in a brief and easily understandable form. The International Institute for Land Reclamation and Improvement (ILRI) acted upon this recommendation and invited David Dent to write the book. He accepted the challenge and held consultations with many colleagues in ILRI, the Department of Soil Science and Geology of the University of Agriculture in Wageningen, and elsewhere. This book is the result of this joint effort.

Clearly, the need for communication between the wide range of people who have to deal with acid sulphate soils cannot be met by any one publication. To meet the needs of the widest possible range of readers, however, the book is written in discrete sections, each of interest to a particular group. Following a wide-ranging introduction, the book reviews the processes responsible for acid sulphate soils, methods of identification and mapping, agronomic, engineering, and environmental problems, and management experience. Where principles are well established and easily accessible elsewhere a condensed treatment has been possible, as in the case of soil chemistry; where information is scattered or still in embryo, more extended treatment has been needed. The further important aims of the book are to establish a useful, widely-understood terminology and to provide ground rules for management within the framework of alternative management strategies and contrasting physical environments.

David Dent presents a series of recommendations to those who are in a position to influence the course of land development and research. These provide a strategy for land reclamation and conservation that has been developed through consultation and detailed study. These recommendations are placed at the beginning of the book so that readers cannot miss them. Their substance is further developed in the subsequent sections.

I would like to express the satisfaction I feel with the issue of this book. I want to thank everyone involved, and I include not only the author, David Dent, who has done a splendid job, but also the staff of the Department of Soil Science and Geology of the University of Agriculture in Wageningen, who contributed much to this undertaking. It is my fervent hope that this book will truly help towards a better understanding of the problems we are facing when reclaiming coastal lands with potential acid sulphate soils or combatting the problems of acid sulphate soils that have already developed.

Dr. Ir. J.A.H. Hendriks
Director, ILRI

Contents

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David Dent

List of plates

List of figures

List of tables

Recommendations for action and targets for research

Continued pressure on land resources will demand further development of marginal and difficult soils including acid sulphate soils. Uniquely, extensive areas of acid sulphate soils have been created directly as a result of attempts at land reclamation – by making polders and draining wetlands – so these problems are of our own making. But all coastal and estuarine alluvial soils are not potential acid sulphate soils, nor are all acid sulphate soils equally bad. Some are indeed very difficult to manage, but as a group they offer a wide range of opportunities for development.

There is a body of scientific knowledge and experience of these soils; further research will surely add to this. There remains a gap between research and its application to management. Recommendations to bridge this gap have been drawn up in consultation with many specialists in this field. Together, these recommendations provide a strategy for land reclamation and improvement.

Recommendations

Policy-makers should seriously consider the benefits of conserving and utilising existing potentially acid wetlands, especially in tidal areas. The mangrove belt serves many functions (including support of offshore fisheries) that are not always appreciated by short-term developers. Freshwater acid sulphate areas are biologically less diverse and less productive. An active policy of developing freshwater acid sulphate areas can include the options of forestry, wetland rice in a monsoon environment, and oil palm or rubber in a permanently wet tropical climate.

If the development option is chosen, there will be local, temporary failures. Delay in achieving acceptable levels of production must also be anticipated. In land settlement schemes, space should be set aside, either to accommodate farmers who have to abandon difficult areas or to be taken up at a later stage when management problems have been solved.

Pilot schemes will be needed to learn essential technical and social lessons on the ground.

No land development should take place without a soil survey and an evaluation of the range of alternative uses. Soil survey can assist land-use planning by identifying and mapping areas that have different requirements or different responses to management. The survey must address the special characteristics of acid sulphate soils that determine performance in both agricultural and non-agricultural uses. These include severe acidity or potential acidity, salinity, drainage, engineering hazards, the severity of these hazards, and the depths at which they occur.

Interpretative maps can be compiled to show land suitability for a range of alternative uses or the severity of specified hazards, and predictions can be made of the effects of alternative systems of management.

Water management is the key to soil management. Development planning must pay particular attention to the nature of wet and dry seasons, and to the availability of water for leaching, irrigation, and the maintenance of groundwater levels. On the basis of present experience, Section 2 outlines ground rules for management within the framework of alternative management strategies. Detailed prescriptions can be made only within specific social contexts and for specific physical environments.

The introduction of new management practices should always be based on the experience gained in local trials, in cooperation with the farmers who work the land. These field experiments must be supported by systematic site characterisation, so that experience and technology can be transferred to comparable areas. Clearly, it would help if a common code of site description, soil classification, and methods of analysis was applied. Proposals for soil classification are made in Section 5 and for survey and analytical methods in Section 7.

Applied research

The emphasis of applied research should be directed to *improvements in low-cost management*, where constraints include the availability of water and fertilizers. Research requirements for rice-based cropping systems include:

- Minimising the oxidation of pyrite and maximising the removal of acidic products by leaching;
- Safely discarding acid surface and drainage water;
- Liming in relatively low doses (a few tonnes per hectare) has sometimes yielded promising responses, but is not always effective. The reasons for these differences should be investigated. Allied to this, studies should be made of the effects of very small applications of lime (0.2 to 0.4 tonnes per hectare) in promoting rapid, healthy soil reduction following flooding.

Studies needed for both rice and dryland crops include:

- The effects on leaching of dryland versus wetland tillage, and cropping systems combining rice with short-duration dryland crops;
- Varietal screening for short-duration, acid-tolerant, salt-tolerant, iron-tolerant cultivars. Fast growth enables the crop to short-cut the period of greatest stress. Comparisons should be made between promising indigenous varieties from different countries;
- Studies on fertilizer application should aim at optimising the use of phosphate. While nitrogen is usually deficient in acid sulphate soils, its application rarely presents specific problems.

Research should be conducted within a framework of baseline survey, followed by the monitoring of crop performance, soil and water composition, and hydrology over at least three consecutive years.

Basic research

Targets for basic research include:

- The physiological mechanisms of tolerance to high aluminium and iron levels in soil solution;
- The main factors determining the rate of reduction following flooding and the rate

of pH-rise to levels beyond those at which toxicity occurs;

- Development of quantitative models to predict the progress and environmental impact of land reclamation. A model of pyrite oxidation is described in Section 3. More comprehensive systems can be built up by fitting together a number of models. These could include models of soil porosity and its development following drainage, the relationships between flooding, or water movement through the soil, and the removal of salts and acidity;
- The effects of changing watertables, or of irrigation or other management techniques, which can now be predicted both spatially and over time by computer simulation. This technique can provide decision-makers with quantitative forecasts of the consequences of alternative policies, but it also places greater demands both on the conceptual and mathematical models available and on the basic survey data;
- The key role of soil survey in development planning, which has already been emphasised. Soil survey must also be supported by an active research programme. Surveyors can adopt one of two strategies: intensive systematic grid survey with massive laboratory support, which is nearly fail-safe but is prohibitively expensive, or rapid free survey, which relies on the surveyor's conceptual model of the relationships between surface features and the soil profile characteristics that determine performance. These field relationships can only be established by local and regional studies of earth surface processes, ecology, environmental chemistry, and soil morphology;
- Modern statistical sampling techniques, which are being developed for rapid estimates of the scales at which acid sulphate soils can be mapped efficiently;
- The severity and reserves of acidity. These cannot be quantitatively determined from morphology and field relationships, but rapid and simple methods are being developed to estimate the amount of acid present and the amount that will be generated upon drainage. These techniques do not require sophisticated laboratory facilities.

1 Fundamental properties of acid sulphate soils

1.1 Significance of the problem

Acid sulphate soils develop as a result of the drainage of parent materials that are rich in pyrite, FeS_2. Pyrite accumulates in waterlogged soils that are both rich in organic matter and flushed by dissolved sulphate, usually from sea water (Plate 1.1). When drainage brings oxygen into these previously waterlogged soils, the pyrite is oxidised to sulphuric acid. Acid sulphate soils develop where the production of acid exceeds the neutralising capacity of the parent material, so that the pH falls to less than 4.

Under these conditions, the range of crops that can be grown is severely restricted and yields are low. Physiological stress on crops in drained acid sulphate soils is attributed principally to aluminium toxicity and associated nutrient deficiencies, especially of phosphate. Acidity can be corrected by liming, but soils that still have reserves of pyrite may require more than 100 tonnes of limestone per ha and this must be incorporated throughout the normal rooting depth of the crop. Unless limestone is available locally, it is impracticable to apply even one tenth of this amount. Flooding,

Plate 1.1 *Rhizophora mangle*, Wageningen Creek, Surinam (Leen Pons). Mangrove swamp is the most extensive potential acid sulphate environment, but mangroves also stabilise the coastline and create a diverse and productive ecosystem that supports a great variety of wildlife, including valuable fisheries. Mangrove forest can be managed to yield timber and wood products on a sustained basis.

Plate 1.2 Tidal land bordering the Gulf of Thailand. Most of the useful timber has been cut out. Coastal wetlands offer apparently attractive, easily-reclaimed land, but the acid sulphate hazard cannot be assessed without a soil survey.

for rice cultivation, usually eliminates acidity, but iron toxicity and possibly sulphide or other toxicities, may then occur. In contrast, in old acid sulphate soils where oxidation of pyrite is complete, there may be a significant crop response to quite small applications of lime and fertilizer.

In addition to chemical limitations, there are physical limitations. Root development is restricted, so water reserves in the subsoil are not available to the crop. Soil ripening is arrested, so the soil remains soft and sometimes very slowly permeable, even saline, at shallow depth.

Acid sulphate soils are an almost unique case where the soil 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 fertilizer requirements), to economic and social planning at regional and local level, to the environmental impact of reclamation.

In recent coastal plains and inter-tidal swamps, there are an estimated 12 million ha, mostly in the tropics, in which the topsoil will become severely acid or has already done so as a result of land reclamation. There is probably a much greater area of potentially acid material covered by a shallow layer of non-acid peat or alluvium. Inland, acid sulphate soils have developed naturally as a result of changes in hydrology or relative sea level. The best known example is the Bangkok Plain in Thailand, where acid sulphate soils occupy an estimated 600000 ha. On a world scale, acid sulphate soils are not extensive. But they are important in many regions of critical population pressure, notably in South East Asia and West Africa, where alternative land for subsistence food production and cash crops is not available. The tidal swamps offer apparently attractive and easily reclaimed land, but the distribution and severity of the acid sulphate hazard cannot be assessed without detailed soil survey (Plate 1.2).

The soil problem is deceptively simple – excess acid production leading to toxicity; and the slow rate or, alternatively, high cost of amelioration. However, acid sulphate soils are not uniformly and equally bad; often they occur in intricate patterns in association with non-acid soils. Always there are local variations in the nature and severity of problems, and in their response to alternative management practices.

Better management requires:

- Soil survey to identify and so avoid, or at least anticipate, acid sulphate problems;
- A code of practice for field experimentation and site characterisation, so that experience and experimental data can be transferred to similar areas;
- Quantitative data as a basis for decisions about land development. These may be provided by quantitative models to predict the rate of acid generation and leaching following drainage, the rate of pH rise following flooding, the extent of iron and other toxicity problems, and the rate of amelioration of acid sulphate soils under alternative management;
- Practical guidelines for the reclamation and management of acid sulphate soils, in particular for the identification of the problem in the field, and simple cheap measures to minimise the oxidation of pyrite and combat its consequences;
- Long-term monitoring of alternative management practices and local trials in cooperation with the farmers working the land. These will provide a basis for introducing new practices.

1.2. Identification of acid sulphate soils in the field

The acid test is a soil pH value of less than 4 under aerobic conditions. This is usually associated with yellow mottles or coatings of jarosite and deposition of ochre in the soil or in drainage waters (Plate 1.3, p. 99). In flooded soils, for example in paddy fields, the pH will rise above 4 because of soil reduction, but a sample of an acid sulphate soil allowed to dry will become severely acid again. Sometimes, usually in poorly-drained soils, jarosite cannot be seen even under severely acid conditions.

Acid sulphate conditions occur in sand, peat, and clay, although acid sulphate clays are most extensive. Clay and peat soils that have become acid as a result of recent land drainage typically remain unripe, or under-consolidated. Unripe soils have a very high water content, so they are soft and can be squeezed between the fingers. Drainage eventually brings about soil ripening, which entails an irreversible loss of water, but the process is inhibited by severe acidity because roots are unable to enter the acid layer to extract the excess water. As a result, acid sulphate soils remain poorly-drained and often saline.

Old acid sulphate clays that have ripened naturally typically have a very dark-coloured topsoil, a prominently-mottled subsoil with reddish-brown mottles and nodules of iron oxide, and yellow jarosite mottles at greater depth (Plate 1.4, p. 99).

Although crops may suffer severe physiological stress on acid sulphate soils, specific symptoms are usually absent. In dryland crops, the principal symptom is exaggerated