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CHAPTER 21

BRUNEI: SUMMARY OF ACID SULFATE SOILS

Gerard Grealish[1], Rob Fitzpatrick[2], Anthony Ringrose-Voase[3] and Warren Hicks[3]

[1]URS Australia Pty Limited, Perth, WA, [2]CSIRO Land and Water, Adelaide, South Australia, [3]CSIRO Land and Water, Canberra, ACT

INTRODUCTION

Negara Brunei Darussalam is a small country of 5765 square kilometres located on the north of Borneo Island bordering the South China Sea and the Malaysian state of Sarawak (Figure 1). Rainforest covers about 80 percent of Brunei's land mass and its capital city, Bandar Seri Begawan is located next to the Brunei River. A recent survey and characterisation of soils in Negara Brunei Darussalam was conducted as part of the project "Soil Fertility Evaluation/Advisory Service in Negara Brunei Darussalam". The survey was carried out on twenty-nine separate development areas totalling around 4422 hectares. These development areas were either existing agricultural areas or areas under consideration for agricultural development. The distribution of the survey areas provided a reasonable baseline for the range of soils that occur throughout the country. The classification, morphology and extent of the soils are described in Grealish *et al*. (2007a, 2007b).

Acid sulfate soils were identified in nine of the twenty-nine areas studied and are widespread throughout the country. They occur adjacent to tidal rivers in mangrove and peat areas and inland they occur on terraces and down slope from where sedimentary shale containing sulfides have been exposed. Their properties, problems associated with them, suitability for agricultural development and recommendations for the sustainable management and mitigation strategies for identified hazards are described in Fitzpatrick *et al*. (2008). In the nine areas where acid sulfate soils were occurred, twenty-seven sites were inspected and a wide range of acid sulfate soil types identified. Seven of these sites were chosen for detailed analysis and thirty samples were collected and analysed for chemical, mineralogical and physical properties.

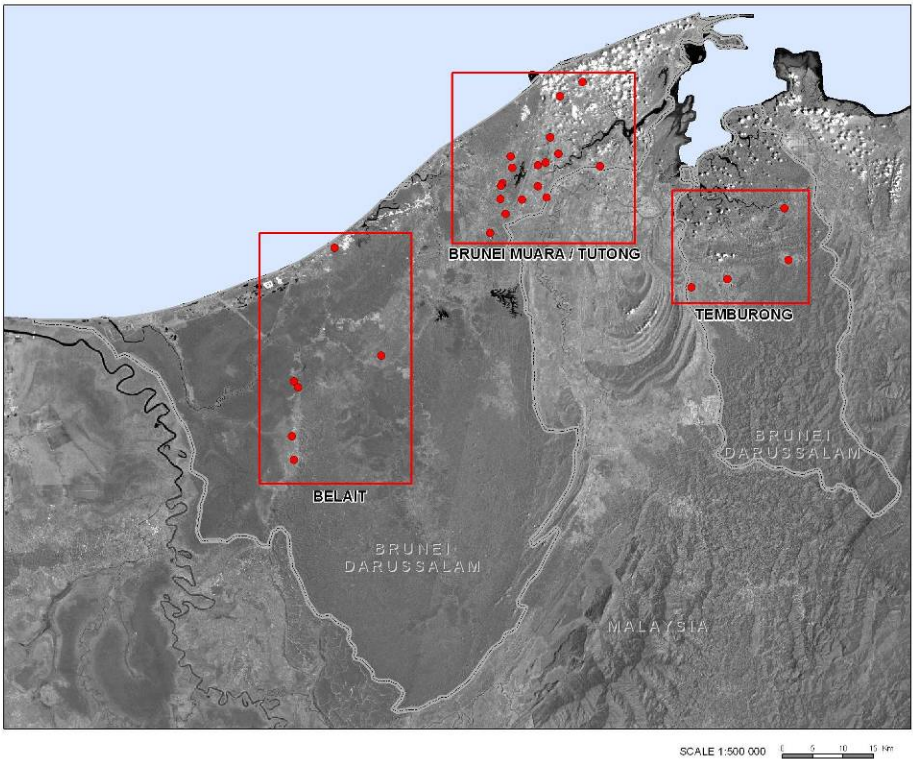

Figure 1: Location of the Surveyed Areas in Negara Brunei Darussalam (identified by the red dots).

Classification

Soils were described and classified according to Soil Taxonomy (Soil Survey Staff 2003). Seven soil Orders were identified leading to twenty-four Subgroups. Acid sulfate soils are represented in four of these Orders and ten Subgroups (Table 1).

Table 4. Soil Taxonomy classifications of surveyed Agricultural Development Areas in Negara Brunei Darussalam. Non acid sulfate soils are in grey font type. The soil marked *, while not acid sulfate, has pH <4.5 resulting from oxidation of sulfides.

Order	Suborder	Great Group	Subgroup
Histosols	Saprists	Sulfosaprists	Terric Sulfosaprists
			Typic Sulfosaprists
		Sulfisaprists	Terric Sulfisaprists
			Typic Sulfisaprists
Spodosols	Aquods	Epiaquods	Ultic Epiaquods
			Umbric Epiaquods
Vertisols	Aquerts	Sulfaquerts	Sulfic Sulfaquerts
		Dystraquerts	Typic Dystraquerts*
Ultisols	Humults	Kandihumults	Aquic Kandihumults
			Typic Kandihumults
		Palehumults	Aquic Palehumults
			Oxyaquic Palehumults
			Typic Palehumults
		Haplohumults	Oxyaquic Haplohumults
			Typic Haplohumults
	Udults	Paleudults	Arenic Paleudults
Alfisols	Aqualfs	Epiaqualfs	Aeric Epiaqualfs
			Typic Epiaqualfs
Inceptisols	Aquepts	Sulfaquepts	Hydraquentic Sulfaquepts
			Typic Sulfaquepts
Entisols	Aquents	Sulfaquents	Haplic Sulfaquents
			Thapto-Histic Sulfaquents
		Fluvaquents	Sulfic Fluvaquents
		Endoaquents	Humaqueptic Endoaquents

To assist users identify these soil classes a user-friendly soil identification key was developed to more readily identify the various acid sulfate soils and other soils of Brunei found in the survey (Grealish *et al.* 2007a). The soil identification key uses non-technical terms to categorise acid sulfate soils and other soils in terms of attributes that are important for charactering the soils and their fertility. The key describes practical, surrogate methods to assist extension officers and farmers to recognise and manage soils. The key is designed for people who are not experts in soil classification systems such as Soil Taxonomy. Hence it has the potential to deliver soil-specific land development and soil management packages to advisors, planners and engineers.

The key consists of a systematic arrangement of soils and a collection of plain language soil type and subtype names was developed to correspond to the major Soil Taxonomy Suborder and Subgroup classes found in the survey. These names are intended to provide some assistance in understanding the intent and general nature of the soils classified using the Soil Taxonomy classification. The four acid sulfate soil types in the Key are: (i) Organic Soils, (ii) Cracking Clay Soils, (iii) Sulfuric Soils and (iv) Sulfidic Soils. These are further sub-divided into eleven subtypes based on depth to sulfuric/sulfidic horizon; firmness; and drainage (waterlogging).

CHARACTERISATION

Morphology

Soil colour, structure, texture and consistency along with field pH are the most useful properties for soil identification and appraisal. Soil colour, structure and consistency provide practical indicators of soil redox status and existing acidity. This relates directly to soil aeration and organic matter content in the soils of Brunei. Consequently, these field indicators were used to help develop a user-friendly soil identification key to categorise the various acid sulfate soils and other soils.

Soil pH and Electrical Conductivity

The floodplain soils and sediments generally have low pH values ranging from 2.5 for the sub-surface (80–180 cm) of the Soft poorly drained sulfuric soil at Limpaki (06 0002) to 6.2 in the surface (0–5 cm) of the Mineral sulfuric organic soil from Labi Lama (23 0001), indicating that acid neutralising capacity is already exhausted. Electrical Conductivity values ranged from 0.02 dS m^{-1} at 20–70 cm in the Organic poorly drained moderately deep sulfidic soil at site 2 Melayan A (22 0002) to 8.6 dS m^{-1} for the sub-surface (80–180 cm) of the Soft poorly drained sulfuric soil at Limpaki (06 0002).

Sulfur

Total sulfur values in samples, range from 0.04% below 30 cm at Tungku (09 0015) to 4.4% in the sub-surface (80–180 cm) at Limpaki (06 0002). Chromium reducible sulfur values range from below the detection limit (0.005%) throughout the soil profile at Tungku (09 0015) to 3.4% in the sub-surface (150–200 cm) at Betumpu (01 0015). Generally, chromium reducible sulfur concentrations are lower to around 50 cm (<0.05%) and higher below 100 cm (>1%). In the limited number of analysed profiles the exception is Limpaki (ADA 06) where the top 40 cm contains chromium reducible sulfur concentrations >0.2%. The soft poorly drained sulfuric soil at Tungku is also an exception, but here the acid originates in adjacent outcrops of weathering pyritic shale and not in the soil profile.

Carbon

Carbonate minerals in a soil are a component of its acid neutralising capacity (ANC). However, in the low pH, highly leached Brunei environment carbonate levels are expected to be low. The exceptions would be soils in proximity to carbonate rich sedimentary rocks or in soil profiles containing shell. In Brunei acid sulfate soils, pH values were too low for measurable carbonate, shells were absent from the profiles and none of the acid sulfate soil profiles occurred near carbonate rich sedimentary rocks. While shell may be present in soils closer to the coast, it should be noted that carbonate from shell material is usually not a good source of neutralising capacity, as it can become unreactive when acidic waters result in the shell fragments becoming coated with iron and/or gypsum. Repeated wetting and drying cycles in wetlands may similarly armour carbonates with unreactive coatings. Detailed discussion of the precautions and factors recommended when using carbonate values as a measure of ANC can be found in manuals and technical documents published for coastal acid sulfate soils (e.g. Dear *et al.* 2002). None of the soils examined had measurable acid neutralising capacity (i.e. carbonate minerals in the soil).

In the Organic soils, organic carbon concentrations are (by definition) at least 12% in at least half of the top 80 cm. In the organic soil class, the maximum concentration was 59% organic carbon at 60–80 cm in a Sulfuric organic soil at Meranking (21 0007) and 0.35% at 70–150 cm in a Mineral sulfidic organic soil at Labi Lama (23 0004). Sulfuric soils have a range in carbon concentrations from 0.18% in the Soft poorly drained sulfuric soil from site 15 at Tungku (09 0015) to 17% in a poorly drained sulfuric soil at site 11 in Betumpu (01 0011). The range in organic carbon found in Sulfidic soils was from 0.14% at 20–70 cm to 24% at 130–200 cm, both in the Organic poorly drained moderately deep sulfidic soil at Melayan A (22 0002). Cracking clay soils contain between 0.94% organic carbon between 20–70 cm at Si Tukak, Limau Manis B (03 0001) and 6.5% between 0–10 cm of the same soil (see Fitzpatrick *et al.* 2008) for the complete set of results.

ACID-BASE BUDGET

Total Actual Acidity

Actual acidity is a measure of the existing acidity in acid sulfate soils that have already oxidised. The method measures acidity stored in a number of forms in the soil such as iron and aluminium oxyhydroxides and oxyhydroxysulfate precipitates (e.g. jarosite, schwertmannite and alunite) which dissolve to produce acidity. Because some samples thawed in transit and potentially oxidised before analysis for total actual acidity, this measure as a stand alone variable to assess the current level of acidity in Brunei acid sulfate soils is not reliable. However, it can be applied to the acid–base budget, which uses the total of actual and potential acidity to assess the acid generation potential of a soil. All sites had existing acidity, which ranged from 49 moles H^+ t^{-1} in the sub-surface (30–50 cm) of the Soft poorly drained sulfuric soil at Tungku (09 0015) to 760 moles H^+ t^{-1} in the sub-surface (80–150 cm) of the Sulfidic organic soil at Betumpu (01 0015).

Acid Neutralising Capacity (ANC)

By definition any soil with a pH <6.5 has a zero ANC. All acid sulfate soils examined had pH values of <6.5 throughout the profile.

Acid Generation Potential (AGP)

This parameter is calculated from the concentration of reduced sulfur in the sample. Methods for analysing soil samples to assess AGP are given in Ahern *et al.* (2004), which includes the chromium reducible sulfur (CRS or SCr) (Method Code 22B) and its conversion to AGP.

Net Acid Generation Potential (NAGP)

NAGP is calculated by subtracting the ANC from the AGP and is a measure of the overall acidification risk of a soil. A positive value indicates an excess of acid and the likelihood of sulfuric materials (or an actual acid sulfate soil material) forming in the soil when it is disturbed and oxidised:
NAGP = AGP – ANC.

Net Acidity

The net acidity of a soil where there is existing acidity includes both NAGP and the existing or titratable actual acidity (TAA) so that:
Net Acidity = TAA + AGP – ANC

or

Net Acidity = TAA +NAGP.

All soils sampled had positive net acidities. Net acidities ranged from 49 moles H+ t^{-1} in the sub-surface (30–50 cm) of the Soft poorly drained sulfuric soil at Tungku (09 0015) to 2,900 moles H^+ t^{-1} in the sub-surface (150–200 cm) of the Organic sulfidic soil at Betumpu (01 0015). The soil at Limpaki (ADA 06) had a high acid generating potential, being >500 moles H^+ t^{-1} throughout the profile and >2000 moles H^+ t^{-1} below 80 cm.

Arsenic and Cadmium

Arsenic concentrations in the acid sulfate soils analysed ranged from 0.1 to 20 mg kg^{-1}. Cadmium concentrations in these soils ranged from less than the detection limit of 0.2 mg kg^{-1} to 1.8 mg kg^{-1}. Both arsenic and cadmium were below the serious risk concentrations in soil for human and ecotoxicological protection set in soil standards for the Netherlands (576 and 85 mg kg^{-1} respectively for As and 28 and 13 mg kg^{-1} respectively for Cd; Lijzen *et al*. 2001) and below the soil investigation levels set in Australia (100 mg kg^{-1} for As and 20 mg kg^{-1} for Cd; Imray and Langley 1999). The highest levels of cadmium were found at Labi Lama (23 0001) and may reflect fertilisation of the orchard. There is evidence of over-fertilisation in some intensively used areas, which carries with it the risk of elevated concentrations of cadmium in soil and produce. Such areas may need further investigation. Another difficulty in assessing levels of arsenic and cadmium in the soil of Brunei is the low pH, compared with the soil pH values assumed in developing the standards (pH 7.0 and 6.0 respectively for the Netherlands and Australia). The low pH values (3.9–4.2) of the Brunei soils may increase metal availability and uptake by crops.

DISTRIBUTION

Brunei contains a wide range of different types of acid sulfate soils in various physical settings, which occur because of changing hydrological and biogeochemical conditions. There are two broad situations in which various organic matter fractions (mostly sapric) and minerals (e.g. pyrite, jarosite and schwertmannite) form acid sulfate soils via various micro-scale weathering pathways:

i) Drained conditions, which develop during the excavation and construction of drains; buildings and other infrastructure; or when erosion of sulfide-rich sediments or weathered pyritic sedimentary rocks occurs

ii) Undrained/partly drained conditions, which develop in natural tidal, intertidal and supratidal zones; and fluvial floodplains

In general terms, these acid sulfate soils occur in association with lowland peat domes where specific characteristics such as clay and organic carbon contents depend upon their topographic setting within the peat dome (Figure 2). Exceptions are acid sulfate soils in which the sulfuric horizon has been formed as a result of acid leachate from the weathering of pyritic shale (Figure 3).

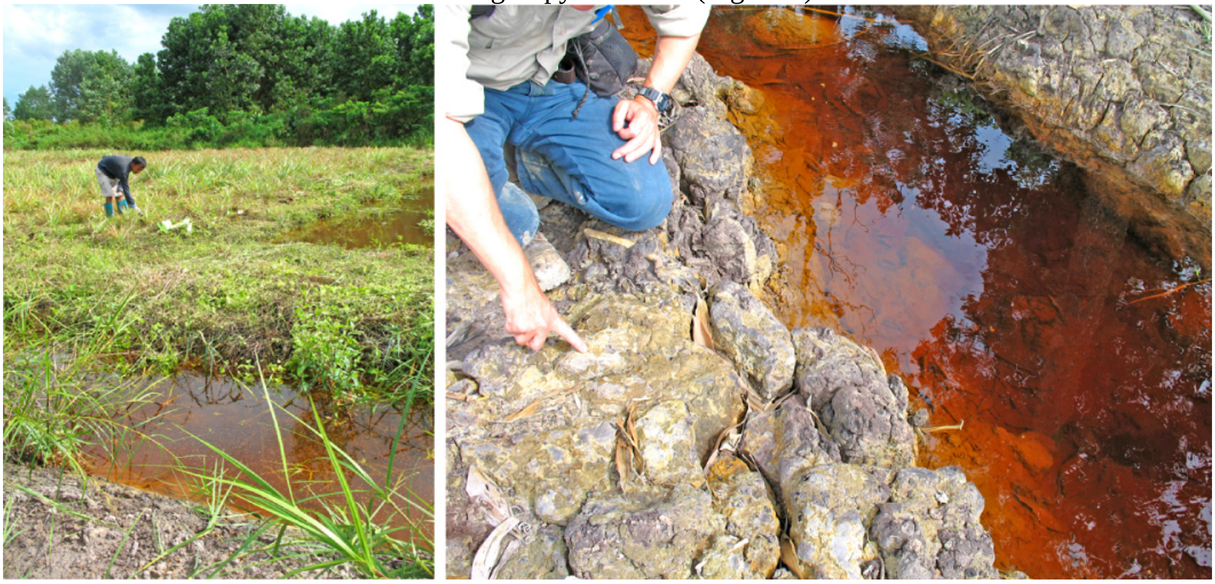

Figure 2. Recently cleared land and excavated drains in the Betumpu Agricultural Development Area showing: (a) good pineapple growth on the higher mounded areas and stunted growth on the lower areas adjacent to the drains with precipitates of iron oxyhydroxysulfate minerals (schwertmannite) on the edges of the drain / wetland margin (pH 3.5–4.2), and (b) close-up view of a sulfuric horizon in spoil bank of a drain showing bright yellow jarosite mottles (pH 3.5) and clear reddish coloured water in the drain (pH 3) with patches of oil-like bacterial surface films.

Figure 3. Damage to road infrastructures by erosion and corrosion of concrete and road material (pH 3.5 - 4.2) from the exposure (oxidation) of pyrite contained in the pyrite-rich shale at Tungku.

Acid Sulfate Soils Hazard Maps

Acid sulfate soils of the flat terrace areas are already acidic, and appear to have been so for a long period of time. Much of this condition may be attributable to a lowering of the shallow water table by drainage. The key to management and sustainable production on these lowland soils both for soil fertility and environmental protection is an understanding of their complex hydrology so that the water table can be managed appropriately (Melling *et al.* 2002). Unless properly managed the economic usefulness of these soils will be short lived.

Management of acid sulfate soils is but one facet of this management. Poor management of the water table will result in increased acidification, poor production, environmental degradation and ultimately the loss of the soil resource itself. Acidification or occurrence of sulfuric materials is considered to be a risk because all the sulfide containing wetland soils we examined have little acid neutralising capacity. In soils, acid neutralising capacity is provided by carbonate minerals and clays. In Brunei, as in all high rainfall, highly leached acid tropical soils, carbonate contents are low; however many locations in Brunei have high (>30%) clay contents which provide some buffering.

The main risks to the development of acid sulfate soils for agricultural production are:

- Lowering the water table and exposing the remaining sulfidic material to further oxidation and acidification
- Subsidence due to oxidation of the organic soils (peats) and loss of the soil resource

Unless well managed and controlled, the development of acid sulfate soils will result in decreased production due to the toxicity and plant nutrition effects of the low pH. The discharge of acid drainage water will cause offsite environmental degradation from acidic discharges into waterways affecting aquatic life and fisheries. There will also be cumulative global effects due to greenhouse gas emissions from the release of fossil carbon currently stored in the soils.

Grealish *et al.* (2007b) prepared maps of the acid sulfate soils hazard for each area. These maps are derived from the soil maps shown in the same report. The acid sulfate soils hazard class of each soil map unit is based on the estimated proportion of the map unit area occupied by soil types with sulfidic material or a sulfuric layer. These soil types are those with the ‘c’ attribute in the Fertility Capability Classification (Sanchez *et al.* 2003) that indicates the presence of sulfidic/sulfuric material as discussed in Wong *et al.* (2007) and Grealish *et al.* (2008). The acid sulfate soils hazard classes are defined in Table 5.

Table 5: Acid Sulfate Soil Hazard Classes

	Class	Proportion of area with sulfidic material or a sulfuric layer
1	Negligible	≤5%
2	Low	>5% and ≤25%
3	Moderate	>25% and ≤50%
4	High	>50% and ≤75%
5	Very high	>75%

These acid sulfate soils hazard classes indicate the likelihood of a site being an actual or potential acid sulfate soils. They do not indicate the severity of problem when encountered, which is given by the ‘Treatment class’ of Fitzpatrick *et al.* (2008).

Hazard subclasses are defined by the most common depth to the sulfidic material or sulfuric layer sometimes with the minimum depth in brackets. For example, “3 / 40cm [15cm]” means there is a moderate likelihood (i.e. Class 3 in Table 2) of sulfidic material or a sulfuric layer, which is most commonly at 40 cm depth but can be as shallow as 15 cm.

The maps show that the greatest problem with actual or potential acid sulfate soils are in surveyed areas in the low-lying areas of Brunei-Muara and, to a lesser extent, Belait. Their occurrence in Tutong and Temburong is negligible. Several patterns of acid sulfate soils occurrence can be identified. In Brunei-Muara, six areas (Betumpu, Si Tukak Limau Manis, Si Bongkok Parit Masin, Lumapas, Limpaki and Pengkalan Batu) are almost entirely covered by actual or potential acid sulfate soils (very high hazard). Only in the elevated part of Si Tukak Limau Manis A are the acid sulfate soils negligible. In addition, the areas are dominated by Organic soils that mostly require very high levels of treatment with smaller areas of Sulfuric soils requiring high levels of treatment, and Sulfidic soils requiring moderate levels.

Wasan also has extensive areas of acid sulfate soils (if the Acid poorly drained cracking clay soils are included), but because they are Cracking clay soils they require only low to moderate treatment. The pattern of acid sulfate soils in Tungku is rather different, with acid sulfate soils being only moderately extensive in most of the area. Soft poorly drained sulfuric soils occur in the lower parts of the landscape and require moderate levels of treatment.

In Belait, four survey areas (Tungulian, Melayan A, Labi Lama and Km26 Jalan Bukit Puan Labi) have parts of very high acid sulfate soils hazard in the lowland parts of their areas associated with the AN (be) map unit. This map unit is dominated by Organic soils requiring very high levels of treatment. In Km26 Jalan Bukit Puan Labi there are also pockets of Organic poorly drained moderately deep sulfidic soils that require a high treatment level. Within these four areas, much of the area with very high acid sulfate soils hazard is currently undeveloped for agriculture. Given that very high levels of treatment are necessary to successfully develop these areas, consideration should be given to leaving them undeveloped.

Merangking Bukit Sawat has isolated pockets of acid sulfate soils, accounting for only a small part of its total area. If this survey area s developed for agriculture, these areas of organic soil would best be left undeveloped, since they require a very high treatment level.

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