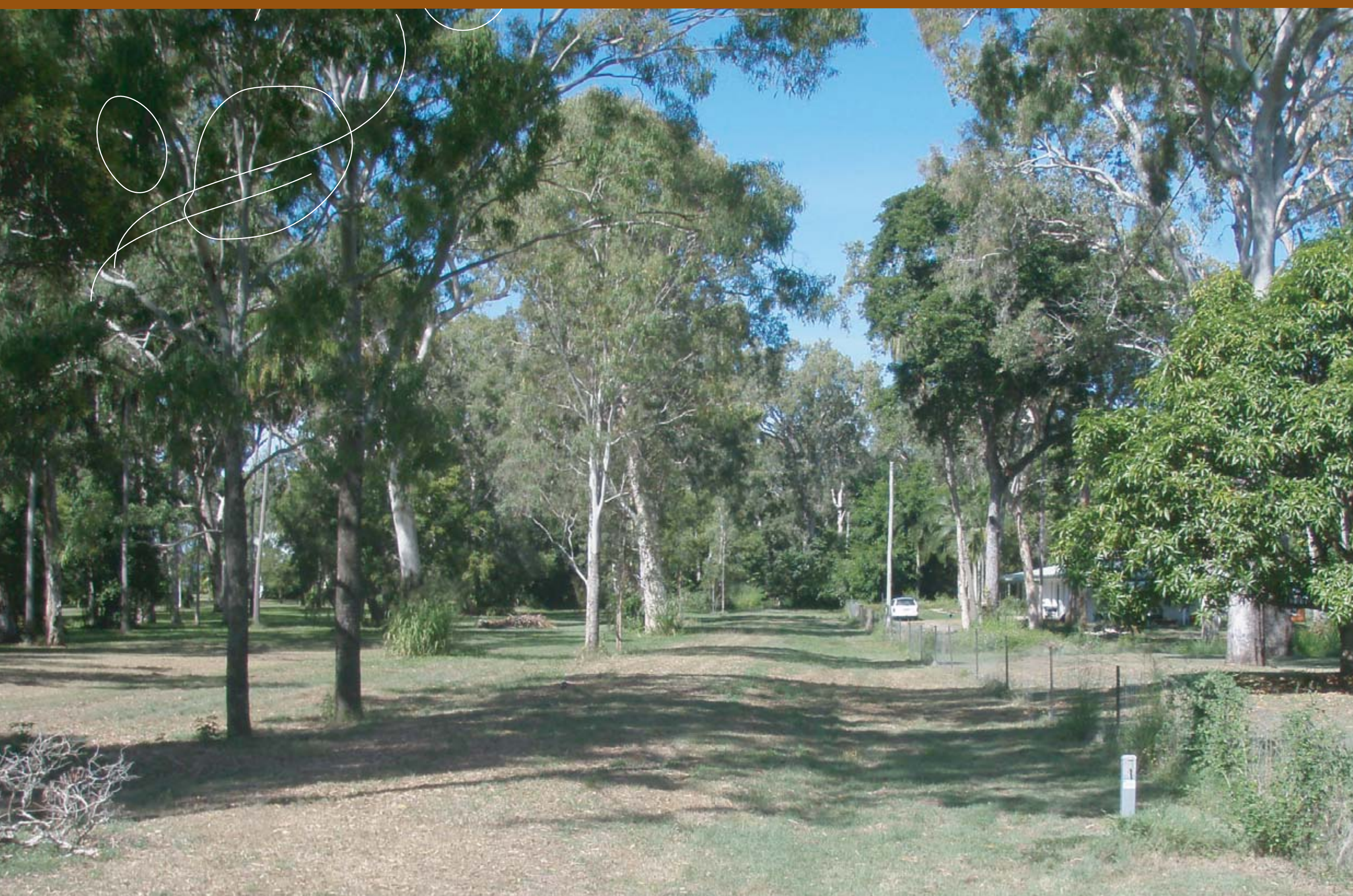
Acid Sulfate Soils of the Sarina Beaches, Hay Point to Armstrong Beach, Queensland



Queensland the Smart State

Queensland Government
Natural Resources and Water

Acid sulfate soils of the Sarina Beaches, Hay Point to Armstrong Beach, Queensland

P G Muller

Department of Natural Resources and Water
Queensland 2008

ISBN 978 1 7417 2928 3
MWQ_3

This publication was prepared by officers of the Department of Natural Resources and Water. It may be distributed to other interested individuals and organizations.

This report is intended to provide information only on the subject under review. Before acting on the information conveyed in this report, readers should ensure that they have received adequate professional information and advice specific to their enquiry.

While all care has been taken in the preparation of this report, neither the Department of Natural Resources and Water nor its officers or staff accepts any responsibility for the loss or damage that may result from any inaccuracy or omission in the information contained herein.

Department of Natural Resources and Water
Locked Bag 40
Coorparoo DC QLD 4151

Acknowledgments

The author gratefully acknowledges the assistance of the many people and organizations that made significant contributions during the course of the study, especially:

- The Natural Heritage Trust, Fitzroy Basin Association and Mackay Whitsunday Natural Resource Management Group for providing the funds that made this project possible.
- All landowners who supported the study by providing access to their properties.
- Ian Hall for operating the Geoprobe® for the deep sediment sampling and installing piezometers.
- Don Malcolm and Bernie Powell for refereeing this report.
- Janet Hooper for the database entry of field data.
- Dave Lyons and Sonya Mork for organising soil analyses and data reports.
- Michael Kooistra and Cyndi Thomson for cartographic work on the acid sulfate soil map.
- Jim McClurg for providing the photograph for the front cover.

Contents

List of figures, tables, photographs and maps

Figures

Tables

Photographs

Maps

(in back pocket of report)

Acid Sulfate Soils, Sarina Area (Scale: 1:25 000) NRW Ref No: MWQ_CWR_A0-0702801-01

Summary

This study, funded by the Natural Heritage Trust in collaboration with the Fitzroy Basin Association and the Mackay Whitsunday Natural Resource Management Group, involves an area of 2 497 ha of the Sarina beaches district, Queensland, and is part of the state-wide program to identify acid sulfate soils (ASS) risk areas. These coastal areas are commonly underlain by ASS and are experiencing significant urban growth and therefore represent a high priority for assessing the ASS risk. The soil test values obtained and risk mapping with this project constitute a current appraisal of the risks inherent in any change of land use, as well as data useful to any determination of current release of oxidation products.

The survey area extends from Hay Point in the north to Armstrong Beach in the south. ASS were mapped at 1:25 000 scale from 71 boreholes. The sites were located using free survey techniques at spacings of 200 to 400 m, depending on landform. In tidal areas where ASS occurrence and form are very consistent, boreholes were spaced further apart. Profiles were described in the field, and field peroxide oxidation tests were carried out at regular 0.25 m intervals down the profile, or from within horizons thinner than 0.25 m.

Soil samples for analysis were taken mainly at intervals of 0.5 m from each borehole. Actual acid sulfate soils (AASS) were analysed by the suspension peroxide oxidation combined acidity and sulfate method (SPOCAS), while potential acid sulfate soils (PASS) were analysed only by the chromium reducible sulfur method (S_{CR}). Three hundred and forty-five samples were analysed to determine the presence and severity of actual and potential acid sulfate soil layers.

Map units were allocated an AASS code (**A**) and/or a PASS code (**S**), and a depth code number indicating the depth to these soil layers, based on the laboratory data. Colouring on the acid sulfate soil map highlights the depth to an actual or potential acid sulfate soil layer and associated level of risk. Sediments with an acid neutralising capacity (ANC) from either shells or strong alkalinity are indicated on the map units by the N subscript, e.g. $S4_N$.

The study identified 1 460 ha of confirmed PASS, and 101 ha of AASS. A further 161 ha of land was mapped as highly likely to have PASS, but this could not be confirmed by sampling due to access constraints. Mapping shows that most ASS occur in the tidal areas up to the level of the highest astronomical tide (HAT). ASS are shallowest there, occurring mainly in the upper metre of the profile and as such represent the highest level of risk. On other landforms such as the coastal dune fields and valley flats, ASS are deeper, mainly occurring at depths between three and five metres.

Analysis of AASS layers indicates that they are fully oxidised, with oxidisable sulfur (% S) contents generally less than 0.02 % S. Existing acidity concentrations (actual and retained) are also often less than the threshold level of 62 mol H^+/t with % S content varying significantly between the sandy and clayey PASS sediments. Throughout the survey area, the mean value in the sandy PASS is 0.3% S, whereas in the clay PASS sediments it is 1.2% S. This indicates that the mangrove muds pose the highest potential environmental risk. The PASS were found to have much higher levels than at Mackay or Bowen. In subsurface layers, values of 15.6 % S (0.2 - 0.3 m) and 16.6 % S (0.5 - 0.6 m) were recorded at site 986. These results are some the highest values recorded in Australia. None of the muds displayed any ANC. This can possibly be attributed to the sheltered, still water environment in which the mainly clay sediments were deposited. Fine shells in the sandy sediments provided limited to full ANC in some of the PASS layers.

The groundwater from three sites at Sarina and Armstrong Beaches is being monitored regularly to assess the shallow groundwater quality in these areas of the catchment.

1. Introduction

A mapping project to identify the extent of acid sulfate soils (ASS) at six coastal locations in Central Queensland was initiated in 2004 by the Fitzroy Basin Association, Mackay Whitsunday Natural Resource Management Group and the Department of Natural Resources and Water (NRW) with funding support from the Natural Heritage Trust. Priority areas of mapping are centered round the Mackay and Rockhampton districts. As well as providing substantial in-kind support, NRW was contracted to identify areas for mapping, undertake field surveys, install water monitoring bores and provide laboratory analyses of soil and water.

Acid sulfate soils are soils or sediments containing sulfides (primarily pyrite) or an acid-producing layer as a result of the oxidation of sulfides. They commonly occur in low-lying, very poorly drained, coastal land at elevations less than five metres AHD (Australian Height Datum). Excavating soil or sediment, extracting groundwater or filling land may cause disturbance of ASS. When exposed to air, sulfides oxidise to produce sulfuric acid. Disturbed land can release acid, aluminium, iron and heavy metals into drainage waters, thus affecting aquatic plants and animals. Concrete and steel infrastructure including pipes, foundations and bridges are susceptible to acidic corrosion leading to accelerated structural failure (Ahern, Ahern & Powell 1998; Powell & Martens 2005). Other potential impacts include deoxygenation of waterways (Bush, Fyfe & Sullivan 2004) and the excess iron stimulating blooms of cyanobacteria such as fireweed (*Lyngbya majuscula*) (). More detailed information on ASS, their formation and effects can be found in Malcolm et al. (2002).

The Sarina beaches district was selected to provide detailed ASS mapping to the Mackay Regional Council to assist with managing urban growth. These areas have been subject to significant urban growth over the last few years and as a result represent a high priority area for ASS mapping in the Mackay region. The information from this project will be used by state and local government authorities to manage ASS and to serve as a guide to developers and consultants.

The survey area is made up of the many coastal sand deposits and associated estuarine areas from Hay Point south to Armstrong Beach (Figure 1). These include the urban beach side communities of Half Tide Beach, Salonika Beach, Grasstree Beach, Campwin Beach, Sarina Beach and Armstrong Beach to Freshwater Point. The town of Sarina lies some eight kilometers west of Armstrong Beach.

The aims of the study were to map the extent of ASS at a scale of 1:25 000 and to monitor groundwater through piezometers to gain an understanding of the quality of the shallow groundwater. This would indicate if ASS had been disturbed and if off-site effects were occurring.

2. Methods

Field sampling

The Mackay 1:250 000 geological map and 1:100 000 topographic maps covering the study area were reviewed before field work began. Colour aerial photographs from 1998, at a scale of approximately 1:25 000, were used for aerial photo interpretation of the landscape, location of borehole sites, and mapping of soil boundaries.

Free soil survey techniques were employed, with boreholes located at various spacings depending on the landform (Reid 1988). Boreholes were spaced at intervals of 200 to 400 m or more on landforms outside the tidal zone. Wider intervals were used in the tidal zone because the consistency of depth to ASS within the mangrove associations meant that intensive field sampling was not warranted.

Starting on the lowest-lying land of the tidal flats, boreholes were located progressively up the catchment until ASS were no longer encountered, or a landform boundary identified that defined the inland limit of the Holocene ASS deposition. At each borehole, the soil profile was examined using various methods depending on the landform being sampled. A tapered gouge auger, 1.8 m long with an 83 mm diameter, was used to sample in mangrove areas and occasionally, on supratidal flats (saltpans) that were wet and inaccessible to a four-wheel-drive vehicle (Photograph 1).

A trailer-mounted, vacuum vibro soil coring rig was used to obtain intact 50 mm cores of saturated sediments to a maximum depth of 6 m (Photograph 2) on the coastal sand dunes and channel benches. Depending on the type of sediments present, the drier overlying soil materials were first removed with hand augers. This soil was laid out in half-metre sections on a vinyl tarpaulin. When the soil materials were moist and soft enough, the vibro-corer was inserted into the augered hole to sample the deeper, saturated Holocene sediments. The cores were extruded into 2 m x 100 mm PVC trays and cut in half for recording soil properties and for sampling. A Geoprobe® coring machine was also used for deeper sampling beyond 6 m, coring through gravelly sediments and for installing the piezometers (Photograph 3). A total of 71 boreholes were examined, described and sampled for this project.

The properties of the soil materials such as texture, colour, mottles, structure, moisture status, coarse fragments and segregations were described according to McDonald et al. (1990) and recorded in code format for each horizon on NRW field sheets. The soil was classified by the Australian Soil Classification (Isbell 2002), and other features of the land such as landform, slope and micro relief were also recorded. Mangrove and tree species were identified from Lovelock (1993), and Alcock and Champion (1989).

Field pH (pH_F) and peroxide oxidised pH (pH_{FOX}) were measured with a portable pH meter (TPS Ionode WP84) at 0.25 m intervals down the profile, or within other soil horizons if these were less than 0.25 m thick. The maximum soil sampling consisted of samples taken at 0 – 0.1 m, 0.2 – 0.3 m or 0.4 – 0.5 m, 0.5 – 0.6 m and 0.8 – 1.0 m intervals in the upper metre, and then at 0.5 m intervals, or from horizons less than 0.5 m thick, throughout the remainder of the soil profile. However if the upper part of the profile was non-pyritic, then sampling started at 0.9 – 1.0 m, with samples at 1 m intervals until the PASS were reached which was then sampled at standard 0.5 m intervals. Profiles that did not contain any ASS were sampled at 1.0 m intervals starting at either 0.9 – 1.0 or 1.9 – 2.0 m.

Soil samples were placed in sealable plastic bags and refrigerated in the field before being transferred to a freezer for longer-term storage. Samples were then sent frozen to the NRW soil laboratory at Indooroopilly for analysis. Three hundred and forty-five soil samples were analysed by the methods described below.

Photograph 1. Gouge auger, 1.8 m long, used for hand sampling in mangrove forests

Photograph 2. Trailer mounted vibro-coring soil rig used for sampling wet sediments

Photograph 3. Geoprobe® used for deep sediment sampling

Laboratory soil analysis

The method of analysis selected depended on whether the ASS layers were assessed as being AASS or PASS. AASS samples containing jarosite or with a pH of 4 or less, were analysed by the suspension peroxide oxidation combined acidity and sulfate method (SPOCAS) or by the chromium suite of analyses (Ahern, McElnea & Sullivan 2004).
Analytes from the SPOCAS methods include:

- titratable actual acidity (TAA)
- titratable potential acidity (TPA)
- peroxide oxidisable sulfur (S_{POS})
- 1M potassium chloride (KCl) extractable sulfur (S_{KCl})
- 4M HCl extractable sulfur
- 1M KCl and peroxide oxidised extracted calcium and magnesium.

Titratable sulfidic acidity (TSA) is calculated from the acid trail (TSA = TPA – TAA), while the peroxide oxidisable sulfur (S_{POS}) is determined by the sulfur trail ($S_{POS} = S_p - S_{KCl}$). An additional analyte of the SPOCAS method is the 4M HCl extractable sulfur (S_{HCl}), which enables net acid soluble sulfur (S_{NAS}), otherwise known as retained acidity ($S_{NAS} = [S_{HCl} - S_{KCl}] \times 0.75$), to be calculated (Ahern, McElnea & Sullivan 2004). The chromium suite is essentially similar except that the oxidisable sulfur is determined by the chromium reducible sulfur method, and the other analyses include TAA, S_{KCl}, S_{HCl} and 1M KCl extracted calcium and magnesium as outlined above.

The potential acid sulfate soil (PASS) samples were analysed by the chromium reducible sulfate (S_{CR}) method only (Sullivan et al. 2000). The acid neutralising capacity (ANC) of the PASS samples was determined by the back titration method (Ahern, McElnea & Sullivan 2004).

All field and laboratory data were entered into the NRW Soil and Land Information (SALI) database and are available from NRW upon request.

Interpretation of field and laboratory data

The determination of which horizons constitute AASS or PASS is based on an assessment of field morphological properties (e.g. soil colour, mottles and coarse fragments such as shell), field pH tests and laboratory results. The texture-based action criteria (Ahern, Ahern & Powell 1998) are used to identify ASS based on laboratory results. The action criteria are based on the sum of existing acidity plus potential acidity (i.e. net acidity), soil texture and the amount of soil being disturbed. For disturbances of 1 to 1 000 tonnes of soil, the action criteria are 0.03 % S for sands, 0.06 % S for loams to light clays, and 0.1 % S for medium to heavy clays. If more than 1 000 tonnes of soil are being disturbed, the action criterion is 0.03 % S regardless of texture. If these values are met or exceeded, the soil is an acid sulfate soil and requires treatment. For the purposes of this report, the identification of ASS is based on the action criteria where the volume of disturbance is 1 to 1 000 tonnes.

PASS were assessed using the S_{CR} and in a few cases using the S_{POS} method. If these values met or exceeded the texture-based ASS action criteria, the soil was identified as PASS. Existing acidity (i.e. AASS) was assessed using TAA and S_{NAS} results, the presence of jarosite and a field pH (pH_F) and/or laboratory value (pH_{KCl}) of 4 or less. Neutralising capacity was determined by either the sum of reacted calcium and magnesium cations for the AASS, or the acid neutralising capacity back titration method (ANC_{BT}) for the PASS samples.

The results of selected laboratory analyses and field pH test results are reported in the Appendix.

Mapping unit categories

The presence and depth to ASS layers form the primary basis for defining the mapping units. The upper depth of the first horizon in which the action criteria have been exceeded has been assigned a 'depth to sulfide' code, as follows:

- **S0** indicates that the action criteria were exceeded between 0 and 0.5 m.
- **S1** indicates that the action criteria were exceeded in the 0.5 to 1 m interval.
- **S2** indicates that the action criteria were exceeded in the 1 to 2 m interval.
- **S3** indicates that the action criteria were exceeded in the 2 to 3 m interval.
- **S4** indicates that the action criteria were exceeded in the 3 to 4 m interval.
- **S5** indicates that the action criteria were exceeded in the 4 to 5 m interval.
- **S5**+ indicates that the action criteria were exceeded at depths greater than 5 m.

If AASS layers were present, the horizon was assigned an A code, as well as the depth code as shown above. For example, '**A0**' denotes a horizon with a pH of 4 or less, occurring between depths of 0.0 and 0.5 m. As it is not uncommon to find AASS overlying PASS, the 'A' code and the 'S' code are combined in these cases. For example '**A0S2**' denotes a soil layer with a pH of 4 or less, between depths of 0.0 and 0.5 m, overlying PASS at 1 to 2 m.

Some of the PASS layers were found to have either significant quantities of fine shell, or were strongly alkaline, thus providing effective acid neutralizing capacity for these layers. The 'N' subscript at the end of a map unit code indicates the presence of neutralising agents in the ASS sediments, e.g. '$\mathbf{S2_N}$'.

Other map units used in the study are:

$\mathbf{S_{LA}}$ — (limited assessment) indicates land that was inaccessible to field survey because of its topography, wetness or thick vegetation, but was in a landscape position that indicated it had a high probability of being underlain by ASS.

$\mathbf{S_{DL}}$ — (disturbed lands) indicates various types of disturbed land that were likely to contain or be underlain by ASS.

LP — (low probability) indicates land at or below an elevation of 5 m AHD (Australian Height Datum), which field survey showed had little if any probability of being underlain by ASS.

LP5 — indicates land above an elevation above 5 m AHD that had little if any probability of being underlain by ASS.

NA — (not assessed) indicates land not assessed by field survey, and therefore excluded from the defined ASS map units.

Soil mapping

The distribution of ASS was mapped onto the 1998 colour aerial photographs, based on interpretation of the field data and landforms on the photographs. Quite often, a distinct landform change was used to identify the limit of ASS. When this was not available, the boundary was determined using additional boreholes. Once analytical data were available, ASS areas were subdivided into units of the previously mentioned categories showing the AASS and/or PASS codings. PASS depth categories were coloured in shades of red, pink, orange and brown, with red denoting the shallowest depth. Where AASS were present, a yellow dot overlay was also used to indicate this. Those map units that were found to have significant neutralising capacity, at least 1.5 times the level of oxidisable sulfur, are indicated on the map with green dots.

The location of each site is also shown on the map. Cartographers at NRW Rockhampton transferred the line-work from the aerial photographs to a base map to produce the 1:25 000 ASS map.

3. Results: Description of landforms, ASS map units and analytical data

Coastal landforms

The coastal landscape from Hay Point to Armstrong Beach consists of undulating rises to low hills formed on intermediate volcanic rocks, which separate small, confined embayments that are drained by coastal creeks and streams (Figure 1). Most estuaries are fronted by a series of three to four low coastal sand dunes that have been deposited behind the beach front resulting in a series of wave-dominated or barrier type estuaries (Dalrymple, Zaitlin & Boyd 1992). The exception is the Plane Creek estuary which is typical of a funnel-shaped tide-dominated estuary (Dalrymple, Zaitlin & Boyd 1992). This coastal morphology is very similar to that north of the Pioneer River (Muller & Coutts 2005)

The embayments or central basins are confined by the undulating coastal hills and their size is dependant upon the size of the streams and creeks that drain into them. For example, the Half Tide and Salonika Beach estuaries are only small basins, about one kilometre wide, as they are surrounded by the hills and rises with only very short (less than 2 km long) ephemeral creeks at the basin head. As a result, there has only been limited down cutting by these low-energy creeks to produce only small, shallow basins that also lack bay-head development of alluvial floodplains.

By contrast Plane Creek is a major coastal stream some 20 km in length that extends inland to the coastal ranges. This increased size of catchment has given it sufficient energy to cut a deep, long basin into the surrounding bedrock, with an extensive central basin some six kilometres long and bay-head development along the Plane Creek with significant channel benches being laid down in the valley floor. These extend inland as far as Sarina.

Following the end of the ice age, the sea level rose to its current levels and these basins in filled with clay and sand sediments in which the ASS of today formed. As these estuaries matured, sand dunes were deposited at the beach fronts as the wave energy exceeded that of the creeks energy and alluvial deposition occurred at the bay or estuary heads.

This study found ASS present under the coastal sand dunes, at depths of 3 to 5 m, only at Sarina and Armstrong Beaches. The central basins represented by the tidal lands are dominated by ASS that occur in the upper metre of the sediments, while the alluvial landscapes are underlain by ASS at depths of 2 to 3 m.

Acid sulfate soil map units and analytical data

The ASS mapping of the study area found 101.4 ha of AASS and 1 460 ha of PASS. AASS occur mainly on the saltpans and marine couch (*Sporobolus virginicus*) flats of the central basins with one area of AASS also underlying the northern end of the coastal sand dunes at Armstrong Beach. Similarly, PASS also mainly occur in the tidal zones with extensive uniform shallow areas of PASS in the mangrove forests. ASS were found to underlie the coastal sand dunes at only Sarina and Armstrong Beaches, while the only other landforms in the survey area to be underlain by ASS are the channel benches of Plane Creek and a valley flat of a short coastal creek in the northern part of the Plane Creek estuary.

All of the AASS are underlain by PASS with the exception of one small area where the AASS directly overlies the basement clay. These data show that the AASS are mainly fully oxidised with potential % S levels less than 0.03% in most soils. Retained acidity levels are also generally below this level as well with only a few profiles having % S contents for potential and retained acidity > 0.1%. Actual acidity levels are mainly between 10 to 70 mol H^+/t, with only a few greater than this, up to the maximum of 140 mol H^+/t.

Therefore the AASS present a lower level of risk compared to the PASS which consistently has % S contents > 1%. The PASS are predominantly clay sediments and were found to have, on average, twice the % S levels of the Mackay (Muller & Coutts 2005) and Bowen areas (Muller 2006). Very few sandy PASS lenses occur in these soils.

Figure 1. Contour map showing the topography of the survey area.

The PASS are shallowest in the mangrove areas of the tidal zone, and are usually present on the soil surface. Many of the salt pans also had PASS occurring at depths of 0.2 to 0.4 m and these are also S0 map units. Otherwise the salt pans and marine couch flats either had PASS occur just below half a metre (S1 map units) or were not underlain by ASS at all. The S1 map unit consists of a mangrove forest of milky mangroves on a drier more inland part of the intertidal zone furthest up the Cabbage Tree Creek of the Castrades Inlet, with the PASS occurring at 0.6 m. The S2 to S5 map units occur either on the channel benches of Plane Creek, on valley flats of small creeks or on the coastal sand dunes of Sarina and Armstrong Beach.

The limited assessment lands where ASS are likely to occur (S_{LA}) included the former tidal flat at Half Tide Beach. This flat was dammed in the 1970s and was flooded during the field work component of the project, making conventional sampling impossible. Two areas of disturbed lands with ASS (S_{DL}) were found in the survey area at Hay Point and Sarina Beach, while the LP map units consist of low-lying lands located on either the foot slopes of the surrounding rises and hills underlain by bedrock or the frontal sand dunes that directly overlie the Pleistocene basement clays.

These areas are described in more detail in the following sections. Table 1 below outlines the total areas of the map units of the Sarina Beaches survey area.

Table 1. Areas and proportions of the Sarina ASS survey map units

Map unit	Map unit area (ha)	Percentage of area assessed (%)
Actual acid sulfate soils		
A0	4.2	0.2
A0S2	57.2	2.3
A1S2	40.0	1.6
Total	**101.4**	**4.1**
Potential acid sulfate soils		
S0	1 159.4	46.4
S1	74.7	3.0
S2	19.6	0.8
S3, $S3_N$	23.0	0.9
$S4_N$	151.1	6.0
S5, $S5_N$	32.4	1.3
Total	**1 460.2**	**58.4**
Acid sulfate soil on undisturbed land		
S_{LA}	161.4	6.5
Acid sulfate soil on disturbed land		
S_{DL}	2.7	0.1
Low probability land		
LP	541.9	21.7
LP5	229.0	9.2
Total	**770.9**	**30.9**
Total area	**2 496.6**	**100.0**

3.1 Actual acid sulfate soils on relatively undisturbed land

A0 (AASS layer 0 to 0.5 m depth)
The A0 map unit is a small area of 4.2 ha on the more elevated lands of the tidal zone behind the northern part of the Armstrong Beach frontal dunes. This area appears to be slightly more elevated than the surrounding salt pans and has an open woodland of blue gum (*Eucalyptus tereticornis*) and long-leaved paperbark (*Melaleuca viridiflora*). The soil consists of 1.35 m of clayey ASS that directly overlies the Pleistocene basement heavy clay. The dark light clay surface soil is 0.25 m deep and overlies a dark grey, light clay with many < 5 to 15 mm, red and brown mottles. Yellow jarosite mottles occur in a 0.2 m thick AASS layer at 1.15 m. This layer had a pH of 3.8 to 4.0 and a net acidity of 0.12 % S. Actual (TAA of 0.04 % S equivalent) and retained acidity (S_{NAS} 0.08 % S) accounted for all of this with no PASS measured as evidenced by the S_{POS} value of < 0.02 % S. The AASS abruptly changes to a Pleistocene clay basement at 1.35 m and the pH_F increases sharply to 6.2 in this layer.

A0S2 (AASS layer 0 to 0.5 m depth and PASS layer 1 to 2 m depth)
There are two A0S2 map units, with an area of 57.2 ha, on the broad salt pans and marine couch flats on the southern side of the Plane Creek inlet, just to the north-west of the Armstrong Beach frontal sand dunes. As these areas of the tidal lands adjoin the foot slopes of the surrounding hills, the central basin at these locations is shallow with only 1.2 to 2.1 m of estuarine sediments overlying the basement heavy clays. The salt pans are mostly bare of vegetation with only small patches of bead weed (Sarcocornia quinqueflora). The marine couch flats have grasslands of marine couch with rushes and sedges in wetter depressions, and low open woodlands of paperbark and milky mangrove in less inundated areas at the back of the flats.

These soils have 0.15 to 0.25 m of a dark, light clay surface soil with a pH_F of 4.4 – 6.0 that overlies extremely acidic AASS. These layers are light to dark grey, light clays with 20 – 50%, brown and red mottles. The jarosite layers have between 10 to 50% of jarosite mottles, are present below 0.5 m and vary in thickness from 0.5 to 1.5 m. All of these horizons have pH_F of 3.2 to 4.3. The dark grey light clay PASS occurs between 1.05 and 1.6 m and usually overlies a gleyed, medium clay basement layer by 1.2 to 2.1 m depth.

The AASS layers are generally fully oxidised with little PASS remaining (S_{POS} of up to 0.03%). Like the A0 unit actual (0.1 %S) and retained (0.21 %S) acidity account for most of the net acidity (0.34 %S). The higher proportion of residual acidity (0.21 %S) reflects the significant quantities of jarosite present.

A1S2 (AASS layer 0.5 to 1 m depth and PASS layer 1 to 2 m depth)
The are two A1S2 map units, with an area of 40 ha, one a saltpan on the southern end of the tidal flats to the west of Armstrong Beach and the other on the northern end of the frontal dunes also at Armstrong Beach. The saltpan was inundated at time of investigation while the low-lying land at the end of the sand dunes has a tall, closed forest of blue paperbark (*Melaleuca dealbata*), Moreton Bay ash (*Corymbia tessellaris*) and palms. The upper metre of the soil profile was very strongly acidic with a pH_F of 4.1 to 5.3, with a pH_F of 3.9 at 0.8 m for both soils. There was no visible jarosite in either of the two soils and laboratory analysis showed minimal amounts of actual or retained acidity.

The acidic topsoil overlies PASS layers which extend from 1.0 to 3.0 m. The PASS layers with up to 1.6 % S are generally comprised of dark grey light clays with some fine sand lenses. At the northern sand dune site, the clay PASS had a small quantity of fine shell. This layer changed to a fine sandy PASS at 2.6 m and this sediment contained up to 20 % of fine to medium sized (2 – 20 mm) shells which provided an effective ANC.

3.2 Potential acid sulfate soils on relatively undisturbed land

S0 (PASS layer 0 to 0.5 m depth)
The S0 map units are the most extensive of all the map units with a total area of 1 159.4 ha. They consist of nearly all of the mangrove forests and some of the wetter salt pans adjacent to the mangroves. The mangrove forests consist mainly of the dense stands of red (*Rhizophera stylosa*) and grey (*Avicenia marina*) mangroves (Photograph 4) adjacent to tidal creeks. These forests are sometimes surrounded by forests of grey and yellow (*Ceriops tegal*) mangroves as the tidal influence decreases with distance inland. These two species are also found within red mangrove forests on its outer fringes. Due to the restricted access of mechanized sampling equipment, these sites were hand sampled with a gouge auger which limited sampling depth to 1.8 m.

The soils generally consist of black, very dark grey, dark grey or very dark grey brown, mangrove muds that display no profile development except for some organic matter enriched darkening in the surface. The profiles are generally pyritic throughout with up to 3.5 % S in surface layers (0 - 0.1m site 972). In subsurface layers, values of 15.6 % S (0.2 - 03 m) and 16.6 % S (0.5 - 0.6 m) were recorded at site 986). These results are some the highest values recorded in Australia. None of the muds displayed any ANC.

Where the S0 units occur on saltpans, the PASS occur at depths of 0.2 to 0.35 m. The surface soil is a thin (0.05 to 0.15 m), dark brown to grey-brown, light clay that overlies a dark to light grey, light clay, upper subsoil that has 10 – 50%, brown mottles. This layer overlies the black to very dark grey, light clay PASS.

S1 (PASS layer 0.5 to 1 m depth)
The S1 map units occur either on the more elevated and less inundated mangrove forests (Photograph 5) or on salt pans (Photograph 6) throughout the survey area and have a total area of 74.7 ha. The dense mangrove forests consist of either milky mangrove (*Exoecaria agallocha*) and large-leafed orange mangrove (*Bruguiera gymnorrhiza*) with an under storey of river mangrove and mangrove fern, or a low closed forest of grey mangrove with a mid-stratum of yellow and red mangrove. The saltpans are either bare or have isolated patches of bead weed (not identified). Manual sampling with gouge augers to 1.6 m depth was undertaken due to wetness limitations which prevented machine access and therefore deep sampling.

Like the S0 map units, these soils have thin, 0.1 to 0.2 m, dark, light clay topsoils over, dark to light grey, light clay with many, brown mottles. Very dark grey, silty light clay PASS with up to 3.2 % S occur at depths of 0.55 to 0.7 m. On the edge of the salt pans where the central basin is shallow, the PASS in places were found to overlie a non sulfidic gleyed, heavy clay basement at 0.8 to 1.1 m. The surface soil and subsoil do not contain any sulfides and were all found to have a % S of < 0.02%.
No ANC was identified in any PASS samples analysed.

S2 (PASS layer 1 to 2 m depth)
Only one S2 map unit of 19.6 ha was found in the upper part of the Plane Creek estuary. It consists of the drier more elevated and inland tidal flats and adjoining marine couch flats on the edges of the Plane Creek channel benches (Photograph 7). These lands have either low closed forests of milky mangrove and large-leafed orange mangrove, or grasslands of marine couch.

The soils have 0.15 to 0.2 m thick, dark brown, light clay surface soil with many fine orange mottles. This overlies thick dark grey, light clay subsoils with many fine brown mottles that extend to depths of 1.5 to1.8 m. Fine sandy lenses are sometimes present in these layers as well. The PASS underlie the mottled subsoil and are generally a black, light clay with up to 1.3 % S. At each of the two sites sampled, the PASS are only 0.5 m thick and overlie sandy gravel deposits of the former Plane Creek streambed.

S3 and $S3_N$ (PASS layer 2 to 3 m depth)
Three small S3 map units with a total area of 23 ha occur on three distinct landforms. They are the frontal sand dunes at Armstrong Beach, the Plane Creek channel bench (Photograph 8) and a valley flat of a short coastal creek. The first two have been cleared for housing or sugar cane while the valley flat is still vegetated with a tall closed forest of cabbage palm (*Livistona decipiens*) and long-leaved paperbark. The soils also varied between landforms. The sand dune soil consisted of 2.9 m of pale fine sands that overlie the sandy PASS, while the alluvial landforms have dark to brown, mottled clay soils with thick, sandy lenses in the upper metre of the profile.

The PASS occur between depths of 2.4 to 2.9 m in these three soils. At Armstrong Beach, the sandy PASS layer is only 0.5 m thick and overlies the gley, heavy clay basement at 3.4 m. It has up to 1.1 % S and also contains many small fine shell fragments which provide and effective ANC equivalent to 1.6 % S (including 1.5 safety factor).

The very dark grey, clay PASS (1.7 % S) in the valley flat soil are also only one metre thick and overlie the gleyed, heavy clay basement at 3.5 m, whereas the channel bench soil has 0.6 m thick, very dark grey, clay PASS with up to 2.1 % S and overlies a dark grey sandy PASS at 3.2 m with up to 1.2 % S. This sandy layer is only 0.4 m thick and overlies gravelly, streambed deposits at 3.6 m.

$S4_N$ (PASS layer 3 to 4 m depth)
Two $S4_N$ units covering 139 ha and 12 ha were mapped in the Armstrong Beach area. The largest unit is comprised of frontal sand dunes adjacent to Armstrong Beach. (Photograph 9). This sand dunes system is about 500 m wide and extends along the beachfront for three kilometres. Apart from the beach ridge, the four or five parallel dunes of this landform are quite subdued and are only about 0.5 to 1m high. The southern half of the dune field has been developed for housing, while the northern half is still largely undeveloped and has a tall forest of Moreton Bay ash, blue-leaved paperbark and cabbage palm, with an under storey of wattle and other small trees. Lantana (*Lantana camara*) has also invaded much of this area and is a problem weed.

The soils on the frontal dune system show strong profile development for a relatively young soil. The very dark brown, non-sulfidic fine sandy topsoil is up to 0.35 m thick and overlies a well-developed, dark brown or dark yellow-brown, fine sand subsoil. This subsoil becomes paler with depth and overlies a brown, fine sand estuarine sediment that contains 10 – 50 %, fine, broken shell fragments between depths of 1.8 to 2.6 m. This layer is usually about one metre thick and overlies a shelly, dark grey, sandy PASS layer with up to 2.1 % S (at 3.1 to 3.7 m). The PASS contain 20 – 50 %, of fine shells < 2 to 20 mm in size which provide an effective self-neutralising capacity that is equivalent to 2.5 % S (including 1.5 safety factor). The sandy PASS occasionally overlie a loamy or clay PASS with up to 2.7 % S. No shell was evident in this layer. The basin underlying the sand dunes is also shallow at times, with the gleyed, heavy clay basement occurring at depths of 4.15 to 5 m.

S5 and $S5_N$ (PASS layer 4 to 5 m depth)
Two S5 map units occur on the frontal sand dunes at Sarina Beach and on the southern area of Armstrong Beach. They have an area of 32.4 ha and have been cleared for housing. The soils vary between these two areas. The recently deposited aeolian soil at Sarina Beach occurs just behind the beachfront, lacks profile development, and is a pale brown sand to a depth of 3 m. Below this are thin, interbedded layers of fine sands, loams and clay sediments which overlie the very dark grey, light clay PASS at 4.2 to 4.8 m. The PASS layer is also only 0.5 to 0.7 m thick and overlies the gley, heavy clay basement between 4.9 and 5.5 m. This layer is also sulfidic.

The soil at Armstrong Beach occurs further inland and therefore is older than the Sarina Beach map unit. It is similar to the soils of the S4 map units and has a well-developed colour B horizon. The colour B horizon is dark yellow-brown or dark brown and extends to 3.3 m where it overlies a pale brown estuarine shelly sand. This layer overlies the very dark grey, fine sandy PASS at 4.15 m, which continue to a depth of 6.0 m. The PASS are shelly with 10 – 20 % of broken, fine shells, < 2 – 20 mm in size.

The clayey PASS at Sarina Beach have higher % S levels of 0.8 to 1.9 % S, whereas the sandy PASS at Armstrong Beach are lower at 0.4 % S. The fine shells provide an effective acid neutralising capacity equivalent to 1.9 % S.

Photograph 4. Red and grey mangrove forest fringing the tidal creeks with PASS in the surface 0.5 m, S0 map unit

Photograph 5. Yellow mangrove forest of the S1 map unit

Photograph 6. Typical salt pan with bead weed, and PASS at 0.5 m, S1 map unit

Photograph 7. Marine couch flats and milky mangroves in drainage lines adjacent to Plane Creek, S2 map unit

Photograph 8. Plane Creek channel bench (foreground), S3 map unit, with elevated alluvial plain in the background

Photograph 9. Frontal dunes at Armstrong Beach, $S4_N$ map unit

3.3 Acid sulfate soils on undisturbed limited assessment land

S_{LA} (Limited field assessment on lands underlain by ASS)
There is one S_{LA} map unit at Salonika Beach. It consists of a large, former tidal inlet that has been dammed for many years (Photograph 10). As the dam prevents the tide from entering, the area becomes a lake in the wet season and gradually dries out over the dry season. At the time of field work, after more than 750 mm of rain in January and February 2007, the lake was full which prevented soil sampling. As it was originally similar to the tidal lands just to the south, which is mapped as S0, it is expected that this former tidal area would also have PASS in the upper metre of the soil profile over most of it. There is a vegetated "island" in the southern part of this map unit which may not be underlain be PASS. However it is included as it was not possible to sample during the period of field work.

The other S_{LA} map units are at Armstrong Beach and these are sand dunes that have been stranded within the mangrove forests as the tidal zone continued to progress seawards. These are still fully vegetated, which prevented access with the vibro-corer. The tidal land around them was found the contain ASS, so it expected that these sand dunes will also be underlain by ASS. These map units have an area of 161.4 ha.

3.4 Land with a low probability of acid sulfate soil occurrence

LP (Land predominantly below an elevation of 5 m AHD)
The LP lands were found to be some of the frontal dunes (Photograph 11), salt pans and coastal rises. The frontal dunes were checked quite intensively as in places they are underlain by ASS. However as the rises and hills adjacent to the tidal lands rise rapidly from the edge of the tidal flats, the extent of the Holocene deposition was usually able to be confirmed by a soil observation site on these surrounding foot slopes or on some of the saltpans. In this survey area, not all saltpans were found to be underlain by ASS, which is the first time this has been found in the Mackay area. In Cabbage Tree creek, sites continued up the valley flat until ASS no longer occurred. The LP map units have a total area of 541.9 ha.

LP5 (Land predominantly above an elevation of 5 m AHD)

The LP5 lands are made up of the high frontal dunes and foot slopes of the rises and hills with elevations greater than 5 m AHD. They are essentially similar to the LP lands, but occur at a higher elevation and have an area of 229 ha.

NA (Land not assessed for ASS)
The NA lands are mainly the hills and rises above the 5 m contour. However they also include some of the channel benches of Plane Creek that are underlain by ASS but were not included in this survey area, and the saltpans of the large tidal zone to the south of Armstrong Beach that was too extensive and wet at the time of sampling to be have sufficient soil observation sites to be mapped accurately.

Photograph 10. Flooded salt pan, S_{LA} map unit

Photograph 11. Frontal dune at Salonika Beach, LP and LP5 map units

Photograph 12. Coastal Rises, LP and LP5 map units

4. Discussion

This study maps ASS risk in coastal lands from Hay Point to the southern end of Armstrong Beach. It was designed to include all of the coastal potential urban areas in the Sarina district of the Mackay Regional Council, where developments could occur that have the potential to disturb ASS. There are more extensive low-lying lands on the Rocky Dam Creek floodplain to the south of Armstrong Beach which appear most likely to be also underlain by ASS. However as there are no land use pressures on these grazing lands, they were not included in this study.

The accompanying ASS map displays a colour scheme that reflects depth to AASS and or PASS layers. The darker the red colour, the shallower the ASS and hence the greater risk of disturbance by excavation or lowering the water table through deep drainage or dewatering. Thus the A0 and S0 map units pose the highest risk and require the greatest levels of management as the ASS are very shallow.

The study identified 101.4 ha of AASS of which 57 % occurred within 0.5 m of the soil surface. Analytical results of the AASS layers were similar to those mapped in the Mackay (Muller & Coutts 2005) and Bowen (Muller 2006) areas where it was found that whilst the AASS layers had actual acidity (from the oxidation of sulfides) and retained acidity (from jarosite) there was limited, if any, potential remaining (< 0.03 % S).

Of the 1 460 ha of PASS mapped, over 79 % or 1 160 ha occurred at depths less than 0.5m. The PASS however were found to have much higher levels of oxidisable sulfur (up to 16.6 % S) than at Mackay or Bowen. This can possibly be attributed to the sheltered, still water estuarine environment in which the mainly clay sediments were deposited. When sandy PASS were found they were mainly present in thin layers between the clay sediments.

The protected conditions may also be responsible for the presence of some salt pans where no ASS are present. There may not have been sufficient energy to erode out the marine margin to a depth whereby estuarine deposits could be laid down and allow formation of ASS. This observation is not uncommon further south, e.g. at Bajool (Ross 2007) and The Narrows (Ross 2005) between Rockhampton and Gladstone, but such phenomena have not been noted in earlier ASS risk surveys in the Mackay region (Muller and Coutts 2005; Muller 2006).

Approximately 195 ha of PASS ($S3_N$, $S4_N$, $S5_N$) were found to have some natural acid neutralizing capacity in the form of finely crushed shell. Analytical results showed that in some cases the ANC may be capable of buffering any acid produced by the oxidation of sulfides in the sediment. This may reduce the risk of acid production should disturbance of these areas occur.

5.

References

Ahern, CR, Ahern, MR & Powell, B 1998, *Guidelines for sampling and analysis of lowland acid sulfate soils (ASS) in Queensland*, Queensland Acid Sulfate Soil Investigation Team (QASSIT), Department of Natural Resources, Indooroopilly, Queensland, Australia, DNRQ980124.

Ahern, CR, McElnea, AE & Sullivan, LA 2004, *Acid Sulfate Soils Laboratory Methods Guidelines*, Queensland Department of Natural Resources, Mines and Energy, Indooroopilly, Queensland, Australia.

Alcock, H & Champion, I 1989, *One hundred and one trees of Mackay,* rev. 1999, Mackay Branch of the Society for Growing Australian Plants, Mackay, Australia.

Bush, RT, Fyfe, D & Sullivan, LA 2004, 'Occurrence and abundance of monosulfidic black ooze in coastal acid sulfate soil landscapes', *Australian Journal of Soil Science,* 42, pp. 609–616.

Dalrymple, RW, Zaitlin, BA and Boyd, R 1992 'Estuarine facies models: conceptual basis and stratigraphic implications', *Journal of Sedimentary Petrology* 62(6): 1130-1146.

Isbell, RF 2002, *The Australian soil classification*, CSIRO Publishing, Collingwood, Australia.

Lovelock, C 1993, *Field guide to the mangroves of Queensland*, Australian Institute of Marine Science, Townsville.

Malcolm, DT, Hall, IR, Barry, EV & Ahern, CR 2002, *Maroochy–Caloundra acid sulfate soil sustainable land management project*, vol. 1, *Report on acid sulfate soil mapping*, Department of Natural Resources and Mines, Indooroopilly, Queensland, Australia.

McDonald, RC, Isbell, RF, Speight, JG, Walker, J & Hopkins, MS 1990, *Australian soil and land survey field handbook*, 2nd edn, Inkata Press, Melbourne, Australia.

Muller, PG & Coutts, AJ 2005, *Acid sulfate soils and water quality of the Mackay district, Vol. 1,* Department of Natural Resources and Mines, Central Region, Queensland, Australia.

Muller, PG 2006, *Acid sulfate soils of Bowen, North Queensland*, Department of Natural Resources, Mines and Water, Central Region, Queensland, Australia.

Powell, B & Martens, M 2005, 'A review of acid sulfate soil impacts, actions and policies that impact upon water quality in Great Barrier Reef catchments, including a case study on remediation at East Trinity inlet, Cairns', *Marine Pollution Bulletin*, 51, pp. 149–164.

Reid, RE 1988, 'Soil survey specifications', in RH Gunn, JA Beattie, RE Reid & RHM van de Graaf (eds), *Australian soil and land survey handbook guidelines for conducting surveys*, Inkata Press, Melbourne, Australia.

Ross, DJ 2005, *Acid sulfate soils of The Narrows, Central Queensland Coast.* Department of Natural Resources, Mines and Water, Central Region, Queensland, Australia. QNRM05524

Ross, DJ 2007, *Acid sulfate soils, Bajool – Port Alma Area, Central Queensland Coast.* Department of Natural Resources, Mines and Water, Central Region, Queensland, Australia.

Sullivan, LA, Bush, RT, McConchie, D, Lancaster, G, Clark, MW, Lin, C & Saenger, P 2000, *Chromium reducible sulfur: Method 22B*, in CR Ahern, KM Hey, KM Watling & VJ Eldershaw (eds), *Acid sulfate soils: environmental issues, assessment and management*, forum and technical papers, Brisbane, 20–2 June, 2000, Department of Natural Resources, Indooroopilly, Queensland, Australia.

6. Glossary

Acid sulfate soils (ASS): Soils or soil horizons which contain sulfides or acid soil horizons affected by oxidation of sulfides. 'Acid sulfate soils' is the common name given to naturally occurring sediments and soils containing iron sulfides (principally iron disulfide or their precursors). The exposure of the sulfide in these soils to oxygen by drainage or excavation leads to the generation of sulfuric acid. The term 'acid sulfate soils' includes both actual and potential acid sulfate soils. (See below.)

Action criteria: The oxidisable sulfur (% S) values of soil samples which exceed the Queensland acid sulfate soils guidelines (Ahern, Ahern & Powell 1998). Soils that exceed these criteria are classed as ASS, and may require remedial treatment such as application of neutralising agents if disturbed or drained. The action criteria used as the determinant of PASS are:

- 0.03 % S or 18 mol H^+/t for sands
- 0.06 % S or 36 mol H^+/t for loams to light clays
- 0.1 % S or 62 mol H^+/t for light medium to heavy clays.

Note that when excavations exceed 1 000 tonnes (or m^3), the action criterion of 0.03 % S or 18 mol H^+/t applies regardless of texture.

Actual acid sulfate soils (AASS): Soils containing highly acidic soil horizons or layers resulting from the aeration of soil materials that are rich in iron sulfides, primarily pyrite. This oxidation produces hydrogen ions in excess of the capacity of the sediment to neutralise the acidity, resulting in soils of pH of 4 or less, and often the formation of the iron mineral jarosite. These soils can usually be identified by the presence of yellow mottles and coatings of jarosite.

Anaerobic: Conditions where oxygen is excluded, usually by waterlogging.

Australian Height Datum (AHD): The datum used for determining elevations in Australia. Using a national network of benchmarks and tide gauges, a mean sea level has been set as zero elevation.

Borehole: The hole created when an auger or push tube is inserted into the soil body. The portion removed (the core) demonstrates the soil profile and is used for profile description and soil sampling.

Holocene: The period of time about 10 000 years before present. It is an epoch of the Quaternary period (the last 1.8 million years).

Jarosite: An acidic, pale yellow iron sulfate mineral, $KFe_3(OH)_6(SO_4)_2$. The most conclusive indicator of AASS, jarosite is a byproduct of the acid sulfate soil oxidation process, and forms at a pH less than 3.7. It is commonly found along root channels and other soil surfaces exposed to air.

Pleistocene: An epoch of the Quaternary period—the period of time from 1.8 million years ago to about 10 000 years ago (the start of the Holocene epoch).

Potential acid sulfate soils (PASS): Soils containing iron sulfides of sulfidic material, which have not been exposed to air or have oxidised. The field pH of these soils in the undisturbed state can be 4.1 or more, and may be neutral or slightly alkaline. However, they pose a considerable environmental risk when disturbed, as they will become very acidic from oxidation of the iron sulfides to sulfuric acid when exposed to air.

Pyrite: Pale bronze or brass yellow, isometric mineral (FeS_2). It is the most widespread and abundant of the sulfide minerals.

Quaternary: A geological period of time extending from 1.8 million years ago to the present. It incorporates both the Pleistocene and Holocene epochs.

Water table: The portion of the ground saturated with water; often used specifically to refer to the upper limit of the saturated ground.

Chemical acronyms used for acid sulfate soil analytical procedures

SPOCAS: Suspension peroxide oxidation, combined acidity and sulfate method

pH_F: Field pH

pH_{FOX}: Field oxidised pH of the soil sample by 30 % hydrogen peroxide

pH_{KCl}: pH of a 1:5 solution of soil and 1 molar (M) potassium chloride (KCl)

S_{CR}: Chromium reducible sulfur method

S_{POS}: Oxidisable sulfur measured by the SPOCAS method

TAA: Titratable actual acidity

TPA: Titratable peroxide acidity

TSA: Titratable sulfidic acidity

ANC_{BT}: Acid neutralising capacity estimated by the back titration method

Notes for the appendix

Texture codes: The texture codes, such as ‘FS’ for fine sand, used in the Appendix are from McDonald et al. (1990)

s-ANC_{BT}: The ANC converted to % S units, i.e. % $CaCO_3$ x 3.121 = equivalent % S

s-ANC: Acid neutralising capacity estimated by the sum of the reacted calcium and magnesium cations from the SPOCAS method, expressed in equivalent % S units

To convert mol H^+/t to the equivalent % S, divide by 623.7

The dotted line between some samples indicates a change in soil horizon, due mainly to texture, but also because of changes in colour, mottles, gravels and shells, calcareous and/or manganese concretions and sediment type.

Not all the SPOCAS and field pH data are presented in the Appendix. Full data sets are available from NRW upon request. The data shown are only for those horizons that were sampled and analysed.

Appendix

Selected profile pH and analytical data

Site	Depth (m)	Texture	pH_F	pH_{FOX}	S_{CR} % S	s-ANC_{BT} % S	TAA	TPA	TSA	S_{POS} % S	S_{NAS} % S	s-ANC % S
							mol H^+/t					
594	0.9-1.0	FS	7.9	8.1	<0.02							
	1.9-2.0	FS	8.0	8.4	<0.02							
	2.9-3.0	FS	7.9	6.9	<0.02							
	3.4-3.5	FSL	7.1	6.3	<0.02							
	3.9-4.0	FSLC	7.7	6.2	<0.02							
	4.4-4.5	LC	6.4	0.8	1.7							
	4.9-5.0	FSLC	6.8	1.1	0.92							
	5.4-5.5	MHC	6.7	1.4	1.9							
596	0.9-1.0	MC	6.9	5.9	<0.02							
	1.9-2.0	MHC	7.5	6.0	<0.02							
	2.9-3.0	MHC	7.8	6.2	<0.02							
597	0-0.1	ZLC	6.3	3.3	0.25							
	0.4-0.5	ZLC	6.2	0.8	0.71							
	0.9-1.0	ZLC	6.0	0.9	1.5							
598	0.9-1.0	MC	6.3	6.2	<0.02							
	1.9-2.0	MC	6.3	6.0	<0.02							
	2.9-3.0	LMC	6.6	6.0	<0.02							
599	0-0.1	KSLC	7.0	5.4	<0.02							
	0.5-0.6	LC	6.5	1.7	0.6							
	0.9-1.0	ZLC	6.8	1.5	1.6							
	1.4-1.5	ZLC	6.9	1.4	3.2							
934	0.9-1.0	FS	7.7	6.2	<0.02							
	1.9-2.0	FS	8.1	6.1	<0.02							
	2.9-3.0	FS	8.3	6.0	<0.02							
	3.9-4.0	FS	8.3	6.2	<0.02							
	4.9-5.0	FS	7.9	6.1	<0.02							
	5.6-5.7	FS	7.6	6.2	<0.02							
935	0.9-1.0	FS	7.9	7.1	<0.02							
	1.9-2.0	FS	8.1	7.7	<0.02							
	2.9-3.0	FS	7.7	7.2	<0.02							
	3.9-4.0	FS	7.8	8.2	<0.02							
	4.9-5.0	FS	7.9	7.4	<0.02							
936	0.9-1.0	FS	7.0	5.7	<0.02							
	1.9-2.0	FS	6.9	6.0	<0.02							
	2.9-3.0	S	7.1	7.7	<0.02							
	3.9-4.0	S	8.0	8.1	<0.02							
	4.9-5.0	S	8.0	7.5	<0.02							
937	0-0.1	FSCL	7.2	6.8	<0.02							
	0.25-0.3	LC	6.1	0.7	0.19							
	0.5-0.6	LC	6.1	0.7	0.94							
	0.9-1.0	LC	6.4	1.1	0.91							
938	0.9-1.0	FS	7.8	6.1	<0.02							
	1.9-2.0	FS	7.9	6.2	<0.02							
	2.9-3.0	FS	7.8	6.2	<0.02							
	3.9-4.0	FSCL	7.9	6.0	<0.02							
	4.7-4.8	MHC	6.1	5.1	<0.02							
939	0.9-1.0	CFS	6.1	6.0	<0.02							
	1.9-2.0	CFS	6.1	5.8	<0.02							
	2.9-3.0	S	7.0	5.9	<0.02							
940	0.9-1.0	FS	6.6	6.4	<0.02							
	1.9-2.0	CFS	6.7	5.8	<0.02							
	2.9-3.0	CFS	6.3	5.5	<0.02							
	4.4-4.5	LC	6.7	5.8	<0.02							

Site	Depth (m)	Texture	pH_F	pH_{FOX}	S_{CR} % S	s-ANC_{BT} % S	TAA mol H^+/t	TPA	TSA	S_{POS} % S	S_{NAS} % S	s-ANC % S
941	0-0.1	FSLC	6.5	5.4	0.16							
	0.4-0.5	FSLC	6.2	2.6	0.39							
	0.9-1.0	FSLC	6.2	0.4	1.1							
	1.4-1.5	FSLC	6.6	0.4	0.94							
942	0-0.1	LC	7.3	5.7	<0.02							
	0.4-0.5	LC	5.8	4.7	<0.02							
	0.6-0.7	LC	5.1	1.1	0.98							
	0.9-1.0	LC	5.3	0.9	1.2							
943	0-0.1	ZLC	6.2	0.7	1.1							
	0.2-0.3	ZLC	6.3	0.3	1.1							
	0.5-0.6	ZLC	6.3	0.4	1.0							
	0.9-1.0	LC	6.3	0.5	1.8							
	1.4-1.5	LC	6.3	0.4	1.8							
944	0.9-1.0	FS	5.7	5.6	<0.02							
	1.9-2.0	FS	6.0	5.7	<0.02							
	2.9-3.0	FS	6.2	6.4	<0.02							
	3.9-4.0	FS	6.1	6.4	<0.02							
	4.9-5.0	FS	7.1	7.4	<0.02							
	6.9-6.0	FS	7.6	8.4	<0.02							
945	0.9-1.0	FS	6.3	6.0	<0.02							
	1.9-2.0	FS	6.4	6.2	<0.02							
	2.9-3.0	FS	6.7	6.8	<0.02							
	3.9-4.0	FS	8.0	7.8	<0.02							
	4.9-5.0	MC	8.8	8.4	<0.02							
946	0.9-1.0	FS	6.2	5.4	<0.02							
	1.9-2.0	FS	6.6	5.6	<0.02							
	2.9-3.0	FS	6.7	5.6	<0.02							
	3.9-4.0	FS	7.0	5.9	<0.02							
	4.9-5.0	FS	8.3	7.2	<0.02							
	5.9-6.0	FS	8.3	7.5	<0.02							
947	0.9-1.0	FS	7.1	7.0	<0.02							
	1.9-2.0	FS	8.4	8.9	<0.02							
	2.9-3.0	FS	8.0	8.4	<0.02							
	3.9-4.0	FS	8.2	8.8	<0.02							
	4.9-5.0	FS	8.1	8.8	<0.02							
	5.9-6.0	FS	8.2	8.5	<0.02							
948	1.9-2.0	FS	8.3	8.3	<0.02							
	2.9-3.0	FS	8.3	8.0	<0.02							
	3.7-3.8	FSL	7.1	3.8	<0.02							
	3.9-4.0	FSLC	7.5	6.5	0.02							
	4.4-4.5	FSLC	7.4	7.0	0.05							
	4.9-5.0	LC	6.9	0.8	0.79							
949	1.9-2.0	FS	8.4	8.7	<0.02							
	2.9-3.0	FS	8.5	8.7	<0.02							
	3.9-4.0	FS	8.5	8.7	<0.02							
	4.4-4.5	LC	7.5	4.3	<0.02							
	4.7-4.8	HC	7.5	7.1	<0.02							
950	0-0.1	LC	6.1	3.8	0.11							
	0.2-0.3	LC	6.2	3.3	0.16							
	0.4-0.5	LC	6.2	0.9	0.91							
	0.9-1.0	LC	6.2	0.7	3.2							
	1.4-1.5	FSLC	6.2	1.0	1.5							
951	0-0.1	LC	6.8	5.3	<0.02							
	0.5-0.6	FS	5.7	5.2	<0.02							
	0.9-1.0	FS	6.2	5.3	<0.02							
	1.4-1.5	LC	7.4	6.3	<0.02							
	1.7-1.8	LC	7.3	6.1	<0.02							

Site	Depth (m)	Texture	pH_F	pH_{FOX}	S_{CR} % S	s-ANC_{BT} % S	TAA mol H^+/t	TPA	TSA	S_{POS} % S	S_{NAS} % S	s-ANC % S
952	0.9-1.0	CFS	5.4	5.1	<0.02							
	1.9-2.0	CFS	6.0	5.6	<0.02							
	2.9-3.0	FS	7.2	8.3	<0.02							
	3.4-3.5	FS	7.7	8.5	<0.02							
	3.9-4.0	FS	7.8	6.7	0.3	6.8						
	4.4-4.5	MHC	8.1	7.5	0.06							
953	0.9-1.0	FS	7.3	6.1	<0.02							
	1.9-2.0	FS	8.2	6.6	<0.02							
	2.7-2.8	S	7.3	8.2	<0.02							
	2.9-3.0	FS	7.8	5.1	1.1	2.4						
	3.4-3.5	MHC	7.9	5.9	0.34							
954	0.9-1.0	CFS	6.7	6.7	<0.02							
	1.9-2.0	CFS	6.8	6.5	<0.02							
	2.9-3.0	CFS	6.2	7.0	<0.02							
	3.9-4.0	FS	7.8	7.2	<0.02							
	4.4-4.5	FS	7.9	6.6	0.31	2.8						
	4.9-5.0	FS	8.1	6.3	0.37	2.9						
955	0.9-1.0	CFS	5.5	5.2	<0.02							
	1.9-2.0	FS	6.7	6.6	<0.02							
	2.9-3.0	FS	7.4	7.0	<0.02							
	3.4-3.5	FS	7.5	6.6	0.06	3.8						
	3.9-4.0	FS	7.8	4.9	0.34	2.6						
	4.4-4.5	FSCL	7.9	6.3	0.25	1.9						
	4.9-5.0	FSCL	7.4	5.6	0.25	2.7						
	5.1-5.2	MC	8.6	8.0	<0.02							
956	0.9-1.0	CFS	6.3	6.5	<0.02							
	1.9-2.0	FS	7.6	7.8	<0.02							
	2.9-3.0	FS	7.8	6.6	<0.02	1.2						
	3.4-3.5	FS	7.8	6.0	0.23	3.7						
	3.9-4.0	FS	8.1	6.0	0.15	2.7						
	4.2-4.3	MC	8.0	7.7	<0.02							
957	0.9-1.0	CFS	6.2	5.4	<0.02							
	1.9-2.0	FS	6.1	5.7	<0.02							
	2.9-3.0	FS	7.5	6.8	<0.02							
	3.4-3.5	FS	7.7	6.3	0.19	2.9						
	3.9-4.0	FS	7.8	5.5	0.17	0.83						
	4.4-4.5	MHC	8.4	5.3	0.07							
958	0.9-1.0	CFS	6.2	7.2	<0.02							
	1.9-2.0	FS	7.1	7.2	<0.02							
	2.7-2.8	FS	6.9	5.4	0.28	3.2						
	2.9-3.0	FS	7.2	6.2	0.08	1.7						
	3.4-3.5	FS	7.5	3.5	0.76	0.9						
	3.9-4.0	LC	7.1	1.0	1.2							
	4.4-4.5	LC	7.1	1.3	2.1							
	4.9-5.0	LC	7.1	1.3	1.2							
959	0.4-0.5	LC	4.5	3.7	<0.02		12	<10	<10	<0.01	<0.01	<0.01
	0.7-0.8	LC	3.9	3.4	<0.02		13	<10	<10	<0.01	<0.01	<0.01
	0.9-1.0	FSLC	5.9	5.3	<0.02							
	1.4-1.5	FSLC	5.9	2.6	0.02							
	1.9-2.0	FSLC	6.1	1.6	0.72							
	2.4-2.5	FSLC	6.2	1.2	0.65	0.67						
	2.9-3.0	FS	6.6	5.6	0.41	1.4						
960	0-0.1	ZLC	6.3	4.0	0.49							
	0.2-0.3	ZLC	7.0	1.0	1.2							
	0.5-0.6	ZLC	7.0	5.4	0.91	1.2						
	0.9-1.0	ZLC	6.7	5.7	0.7	1.7						
	1.4-1.5	ZLC	6.6	5.7	0.61	1.3						

Site	Depth (m)	Texture	pH_F	pH_{FOX}	S_{CR} % S	s-ANC_{BT} % S	TAA mol H^+/t	TPA	TSA	S_{POS} % S	S_{NAS} % S	s-ANC % S
961	0.9-1.0	MC	5.2	5.0	<0.02							
	1.4-1.5	LMC	5.7	5.3	<0.02							
962	0-0.1	LC	6.5	6.8	<0.02							
	0.4-0.5	LC	6.4	0.8	4.0							
	0.9-1.0	LC	6.6	0.8	2.2							
963	0-0.1	LC	6.2	1.6	4.3							
	0.4-0.5	LC	6.3	1.1	2.7							
	0.9-1.0	LC	6.7	0.7	1.5							
964	0-0.1	LC	6.7	6.2	0.04							
	0.5-0.6	ZLC	5.5	5.0	<0.02							
	0.9-1.0	ZLC	5.7	1.5	1.8							
	1.4-1.5	ZLC	6.1	1.4	1.0							
965	0.9-1.0	MC	7.7	8.1	<0.02							
	1.9-2.0	FSLC	7.7	7.3	<0.02							
	2.7-2.8	FSLC	7.7	7.3	<0.02							
966	0.9-1.0	CFS	6.4	6.1	<0.02							
967	0-0.1	LC	6.0	0.9	0.32							
	0.4-0.5	LC	6.1	0.9	0.74							
	0.9-1.0	LC	6.3	0.7	1.0							
968	0.5-0.6	LC	6.8	6.0	<0.02							
	0.9-1.0	LC	6.6	5.8	<0.02							
	1.4-1.5	LC	6.4	5.5	<0.02							
	1.9-2.0	ZLC	6.1	1.1	1.3							
	2.4-2.5	S	6.4	4.7	<0.02							
	2.9-3.0	S	6.6	4.5	<0.02							
969	0-0.1	LC	6.2	5.2	0.02							
	0.4-0.5	LC	6.3	4.6	<0.02							
	0.9-1.0	ZLC	6.4	1.6	2.5							
970	0.9-1.0	FS	6.4	6.2	<0.02							
	1.9-2.0	LC	7.2	6.1	<0.02							
	2.4-2.5	LC	6.4	5.4	<0.02							
	2.9-3.0	ZLC	6.3	1.1	2.1							
	3.4-3.5	FS	7.3	1.3	1.2							
971	0-0.1	LMC	5.6	5.1	<0.02							
	0.5-0.6	LC	5.1	4.7	<0.02							
	0.9-1.0	LMC	5.8	6.0	<0.02							
	1.9-2.0	MHC	7.1	6.3	<0.02							
	2.2-2.3	LMC	6.9	6.1	<0.02							
972	0-0.1	ZLC	6.7	1.5	3.5							
	0.4-0.5	ZLC	6.5	1.2	1.1							
	0.9-1.0	ZLC	6.6	1.4	2.6							
	1.4-1.5	ZLC	6.8	0.8	1.9							
973	0-0.1	LMC	5.3	4.4	<0.02							
	0.9-1.0	MHC	6.8	6.3	<0.02							
	1.9-2.0	FSLMC	6.2	6.5	<0.02							
974	2.9-3.0	FS	7.4	6.6	<0.02							
	3.9-4.0	FS	6.7	6.3	<0.02							
	4.4-4.5	FS	6.7	6.3	<0.02							
	4.7-4.8	MHC	7.3	6.5	<0.02							
975	0.9-1.0	MC	7.5	7.2	<0.02							
	1.7-1.8	MC	7.4	7.7	<0.02							
	2.4-2.5	MC	7.2	7.7	<0.02							
976	0-0.1	LC	6.8	6.9	<0.02							
	0.2-0.3	ZLC	5.9	1.5	0.78							
	0.5-0.6	ZLC	5.6	1.5	1.4							
	0.9-1.0	ZLC	6.2	1.5	3.4							

Site	Depth (m)	Texture	pH_F	pH_{FOX}	S_{CR} % S	s-ANC_{BT} % S	TAA mol H^+/t	TPA	TSA	S_{POS} % S	S_{NAS} % S	s-ANC % S
977	0-0.1	FSLC	7.0	7.3	<0.02							
	0.4-0.5	LC	5.9	5.7	<0.02							
	0.9-1.0	LC	6.2	1.0	1.1							
	1.4-1.5	MHC	6.4	5.4	<0.02							
978	0-0.1	LC	5.3	4.5	<0.02							
	0.4-0.5	LC	4.5	5.2	<0.02		10					
	0.7-0.8	LC	3.9	4.7			19	16	<10	<0.02	<0.01	<0.01
	0.9-1.0	LC	4.5	4.9	<0.02		<10					
	1.4-1.5	LC	5.6	1.4	1.6							
979	0-0.1	ZLC	4.0	3.5			45	<10	<10	<0.01	<0.01	<0.01
	0.5-0.6	LC	4.0	4.0			35	15	<10	<0.01	<0.01	<0.01
	0.9-1.0	LC	3.8	4.1			27	16	<10	<0.01	0.09	<0.01
	1.2-1.3	LC	4.0	3.8			19	13	<10	0.01	0.11	<0.01
	1.4-1.5	LC	6.2	5.6	<0.02							
	1.9-2.0	MC	6.7	8.2	<0.02							
980	0-0.1	LC	4.4	3.7	<0.02		13					
	0.5-0.6	LC	3.5	3.6			59	54	<10	0.02	0.01	<0.01
	0.9-1.0	LC	3.3	3.3			65	49	<10	0.02	0.15	<0.01
	1.4-1.5	LC	3.3	2.9			66	91	25	0.03	0.27	<0.01
	1.9-2.0	LC	3.4	1.5			57	67	10	0.03	0.15	<0.01
	2.4-2.5	MC	3.6	2.7	0.06		61					
981	0-0.1	ZLC	6.0	2.8	0.71							
	0.4-0.5	ZLC	6.1	0.9	2.6							
	0.9-1.0	ZLC	6.3	1.0	1.7							
982	0-0.1	LC	6.0	3.3	<0.02							
	0.4-0.5	LC	3.2	3.5	<0.02		38	79	41	<0.01	<0.01	<0.01
	0.6-0.7	LC	3.8	3.0	<0.02		36	136	100	0.02	0.01	<0.01
	0.9-1.0	LC	4.0	3.6	<0.02		39	141	102	0.03	0.07	0.01
	1.1-1.2	LC	4.7	1.9	0.32		23					
	1.4-1.5	LMC	6.6	2.1	0.86							
983	0-0.1	LMC	6.4	5.7	<0.02							
	0.5-0.6	MC	7.2	6.3	<0.02							
	0.9-1.0	MC	7.3	6.4	<0.02							
984	0-0.1	LC	4.7	4.1	<0.02		28					
	0.2-0.3	LC	3.9	3.3			24	14	<10	0.03	0.17	<0.01
	0.5-0.6	LC	4.0	3.2	<0.02		16	83	67	0.03	0.1	<0.01
	0.9-1.0	ZLC	4.3	3.2			23	11	<10	0.03	0.06	0.01
	1.4-1.5	ZLC	4.5	1.6	0.89		25					
985	0-0.1	LC	7.5	6.8	<0.02							
	0.5-0.6	LMC	7.2	7.5	<0.02							
986	0-0.1	ZLC	6.8	1.9	1.0							
	0.2-0.3	ZLC	6.7	1.2	15.6							
	0.5-0.6	ZLC	6.8	1.2	16.6							
987	0-0.05	MC	7.1	5.9	<0.02							
	0.9-1.0	MC	7.9	5.7	<0.02							
	1.9-2.0	MHC	7.4	6.3	<0.02							
988	0.9-1.0	FS	8.0	8.3	<0.02							
	1.9-2.0	FS	8.2	8.5	<0.02							
	2.9-3.0	FS	8.2	8.5	<0.02							
	3.9-4.0	FS	7.6	7.6	<0.02							
	4.9-5.0	FS	7.9	7.9	<0.02							
	5.9-6.0	FS	8.3	8.7	<0.02							
	6.9-7.0	FS	8.1	8.4	<0.02							
989	0.9-1.0	FS	7.1	6.9	<0.02							
	1.9-2.0	FS	7.4	6.8	<0.02							
	2.9-3.0	FS	8.1	8.6	<0.02							

Site	Depth	Texture	pH_F	pH_{FOX}	S_{CR}	s-ANC_{BT}	TAA	TPA	TSA	S_{POS}	S_{NAS}	s-ANC
	(m)				% S	% S	mol H^+/t			% S	% S	% S
989 con't	3.9-4.0	FS	8.5	8.9	<0.02							
	4.9-5.0	FS	8.0	9.0	<0.02							
	5.9-6.0	FS	7.8	8.6	<0.02							
	6.9-7.0	FS	8.2	8.5	<0.02							
	8.3-8.4	MHC	8.8	7.3	<0.02							
990	0.9-1.0	FS	8.6	7.4	<0.02							
	1.9-2.0	FS	8.5	6.9	<0.02							
	2.9-3.0	FS	8.6	6.8	<0.02							
	3.9-4.0	FS	8.6	6.6	<0.02							
	4.9-5.0	FS	8.7	6.9	<0.02							
	5.9-6.0	KS	8.7	8.6	<0.02							
	6.9-7.0	FS	8.8	7.0	<0.02							
	7.9-8.0	FS	8.9	7.1	<0.02							
	8.9-9.0	FS	9.0	9.2	<0.02							
	9.9-10.0	FS	8.9	9.1	<0.02							
	10.9-11.0	FS	8.9	9.1	<0.02							
	11.9-12.0	FS	8.8	9.1	<0.02							
991	0.9-1.0	FS	7.3	6.5	<0.02							
	1.9-2.0	FSLC	7.6	6.3	<0.02							
	2.9-3.0	MC	6.7	5.3	<0.02							
992	0-0.1	ZLC	6.9	3.0	0.49							
	0.4-0.5	ZLC	7.0	1.4	1.3							
	0.9-1.0	ZLC	7.0	1.6	1.9							
	1.4-1.5	ZLC	6.8	1.8	0.8							
993	0-0.05	LC	7.7	6.6	<0.02							
	0.2-0.3	LC	5.3	4.5	<0.02							
	0.4-0.5	ZLC	5.5	1.4	1.5							
	0.8-0.9	LMC	6.6	1.7	2.2							
994	0.9-1.0	FS	8.5	7.0	<0.02							
	1.9-2.0	FSLC	8.5	7.3	<0.02							
	2.9-3.0	FSLC	6.6	5.7	<0.02							
	3.9-4.0	FSCL	6.2	5.1	<0.02							
	4.9-5.0	MC	7.2	7.6	<0.02							
	5.9-6.0	MC	6.5	6.5	<0.02							
995	0.5-0.6	LMC	6.0	5.0	<0.02							
	0.9-1.0	LC	5.7	4.0	<0.02							
	1.4-1.5	LC	5.4	2.7	<0.02		27					
	1.9-2.0	ZLC	5.3	2.2	<0.02		32					
	2.4-2.5	ZLC	5.1	1.3	0.97		24					
	2.9-3.0	ZLC	5.4	1.3	1.7							
	3.4-3.5	ZLC	5.8	1.4	0.65							
	3.9-4.0	MHC	6.7	7.3	<0.02							
996	0.2-0.3	MC	5.6	1.4	<0.02							
	0.9-1.0	MHC	6.8	5.9	<0.02							
	1.9-2.0	MC	7.3	5.9	0.16							
997	0-0.1	ZLC	7.1	7.1	<0.02							
	0.4-0.5	ZLC	6.5	1.0	1.6							
	0.9-1.0	ZLC	6.4	1.0	1.7							
	1.4-1.5	ZLC	6.4	1.1	0.9							
	1.9-2.0	ZLC	6.5	1.0	1.9							
998	0-0.1	LC	6.0	4.6	0.16							
	0.4-0.5	ZLC	6.2	0.9	3.1							
	0.9-1.0	ZLC	6.3	1.1	1.8							
999	0-0.1	LMC	7.8	7.5	<0.02							
	0.9-1.0	MC	7.4	6.6	<0.02							
	1.6-1.7	LMC	7.4	7.9	<0.02							

ISBN 978-1741729283