Department of Science, Information Technology and Innovation

East Trinity Acid Sulfate Soil Remediation Project

Changes in Soil Properties after 13 Years of Remediation

Soil and Land Resources

Queensland Government

Prepared by

C.D. Smith, J. Manders and D. Brough

Soil and Land Resources
Science Division
Department of Science, Information Technology and Innovation
PO Box 5078
Brisbane QLD 4001

Disclaimer

Citation

Smith C.D., Manders J.A. and Brough D.M. (2016). East Trinity acid sulfate soil remediation project – Changes in soil properties after 13 years of remediation. (Department of Science, Information Technology and Innovation), Queensland Government, Brisbane.

Acknowledgements

This report has been prepared by the Department of Science, Information Technology and Innovation.
Field survey by J.A. Manders, D.T. Malcolm, L. O'Brien, K. Bryant, R. Willis, C.D. Smith

Summary

An acid sulfate soil remediation strategy commenced in 2001 at East Trinity, Cairns, North Queensland. The remediation strategy utilises natural wetland microbial processes that are turned on by the reintroduction of tidal inundation with the aid of buffering capacity of sea water and the addition of hydrated lime. The strategy is termed Lime Assisted Tidal Exchange (LATE) and employs controlled, daily tidal inundation over former tidal wetlands. The latter had become highly acidic as a consequence of drainage in the early 1970's. The acidification resulted from of the oxidation of pyrite (FeS_2), a naturally occurring mineral that accumulated in the marine sediments underlying the wetlands.

A soil survey was conducted to quantify changes in soil properties brought about by LATE. The results from this survey were compared to a survey carried out in 2001, before remediation commenced. Soil properties include measures such as field pH and a number of laboratory measures of acidity. Additionally, total sulfur was analysed. This survey re-sampled 95 sites originally sampled in 2001.

There has been a significant decrease in acidity to, or near to undisturbed levels. Field pH has improved by a substantial 2.5 units from a median pre-treatment figure of 4.0 to 6.5, shifting from a level that is toxic to most aquatic life. Total acidity (Titratable actual acidity) has been decreased by 89 per cent from 66 to 7 mol H^+/t soil. Oxidisable sulfur levels have increased in many areas indicating that the by-products of the original acidification process are now re-forming pyrite as the environmental processes revert to a more stable state.

Contents

List of tables

List of figures

List of plates

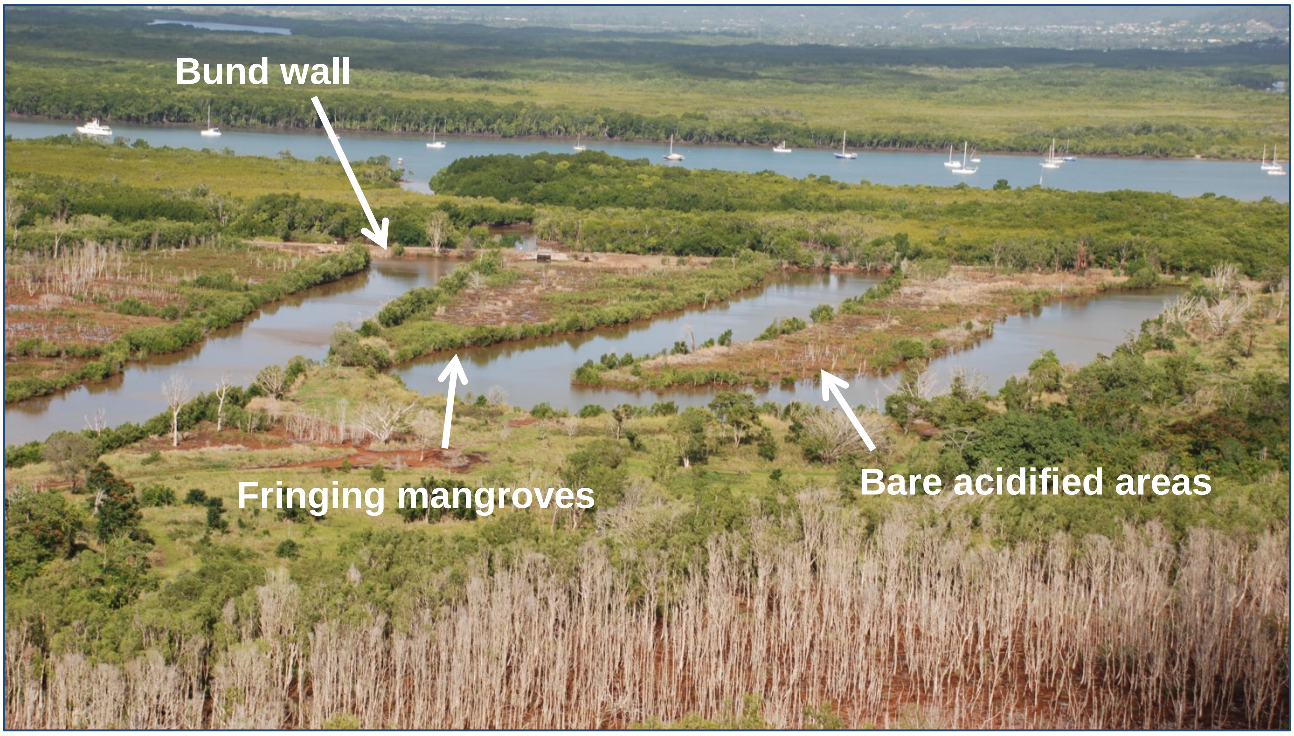


Plate 1. Lower Firewood Creek 2010 showing early mangrove re-vegetation in response to LATE. The cover photo is of the same area in 2013.

1 INTRODUCTION

East Trinity is an area of land located on the eastern side of Trinity Inlet, opposite the City of Cairns, North Queensland. Most of the 750 hectare former tidal wetland is underlain by pyrite (FeS_2) containing marine muds and sands. Pyrite is very stable in the absence of oxygen, such as under waterlogged soil conditions, but is highly unstable and prone to rapid oxidation when exposed to oxygen. The oxidation of pyrite is primary source of acidity that causes actual acid sulfate soil (ASS) formation and the related issue of acid mine drainage.

Tidal exclusion and drainage in the early 1970’s resulted in the oxidation of the pyrite thereby forming actual ASS resulting in the periodic release of sulfuric acid associated with drying and wetting cycles. Mangrove communities died and there were regular pulses of highly acidic water flowing from the site to Trinity Inlet.

An initial soil survey was carried out in 2001 as part of a program to guide an acid sulfate soil (ASS) remediation strategy at East Trinity (Smith et al. 2003). This recent survey was carried out in 2013 for the purpose of quantifying the change in soil parameters arising from the remediation strategy.

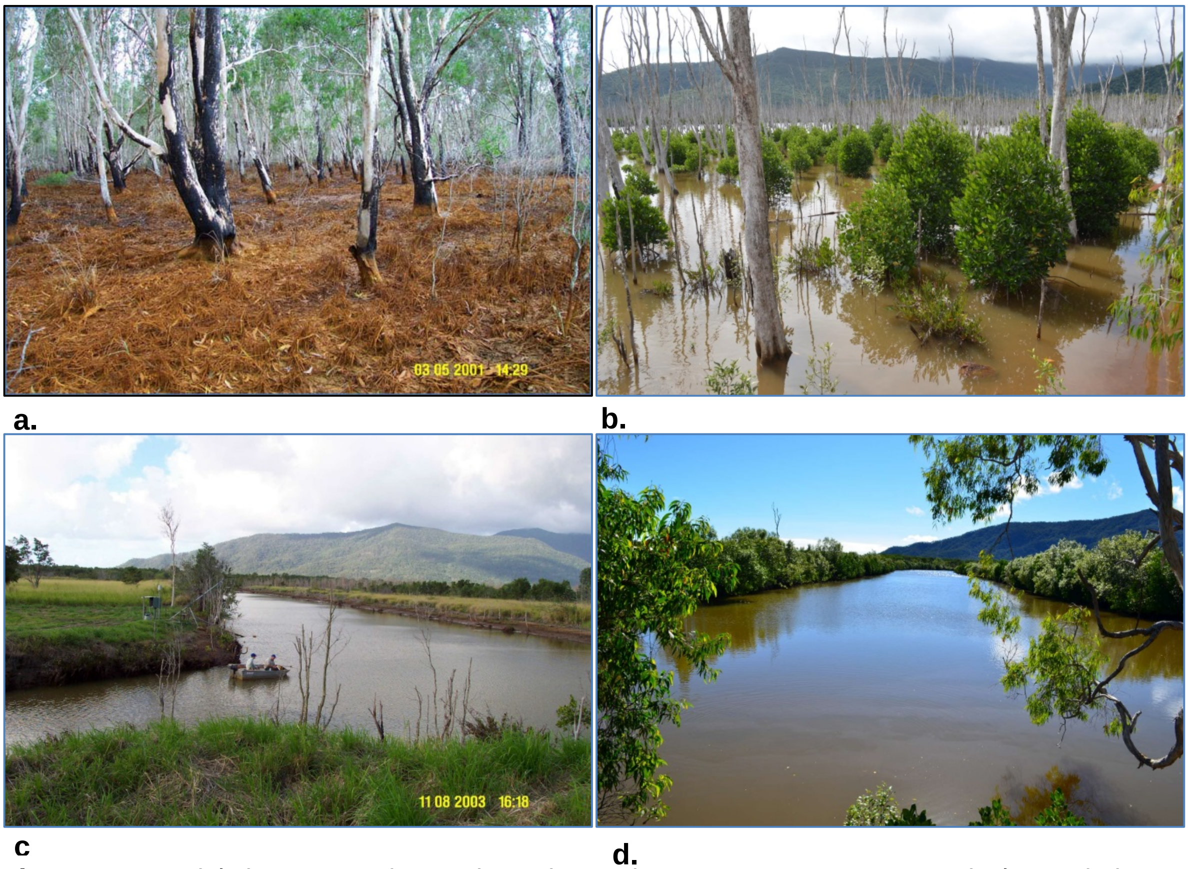


Plate 2. Terrestrial changes to Firewood Creek area in response to LATE. **a.** Typical post-drainage acidified landscape in May 2001 with iron staining on trunks of *Melaleucas* and understorey **b**. Mangrove *Rhizophora stylosa* regrowth, in same area as **a,** July 2013. **c**. Firewood Creek upstream from the bund wall, August 2003. **d**. Same area as **c**, showing mangrove regeneration on stream banks, June 2012.

The pre-remediation survey in 2001 (Smith et al. 2003) involved coring at 85 locations to depths of 20 m. Sixty-three cores were taken along four transects that traversed the geomorphic complexity of the estuarine deposits. An additional 22 sites were strategically located to clarify and confirm the stratigraphic patterns elucidated from the transect data. The pre-remediation survey achieved an understanding of the surficial soil patterns and the deeper stratigraphic components of the Holocene period of deposition that was associated with sea level advance and retreat (Appendix 1). Soil sampling also established a relationship between soil properties and elevation, which, linked to the stratigraphic components, guided the remediation strategy. This initial survey established the following:

1. No acidified soil occurred above approximately 1 m Australian Height Datum (AHD) (pre-drainage aerial photography indicated that this area was dominated by mangrove communities).
2. The most concentrated zone of acidification occurred on land below 0.5 m AHD.
3. Self-neutralising ASS occurred at depths below 1 m AHD on land that previously supported samphire vegetation on salt flats.
4. Some of the land originally at 1 m AHD has irreversibly shrunk by up to a metre as a consequence of drainage.
5. Elongated curved sand ridges (cheniers) that occur across the site above the flat surface of the ASS are non-ASS.[1]

The remediation strategy involves an initial controlled re-introduction of daily tidal exchange with an added dose of hydrated lime to enhance the natural acid neutralising capacity of sea water. This strategy, referred to as lime assisted tidal exchange (LATE), has resulted in the return of mangroves (see Plates 1 and 2) and the return to normal water acidity levels.

LATE is the active phase of the remediation strategy. This stage of remediation is maintained until the pH of exiting waters stabilises to near background levels. At this stage any further acidity leaching from the soils is occurring at rates that can be neutralised by daily tidal flushing. To treat the remaining soil acidity a passive phase of remediation follows - daily tidal exchange without the addition of lime. This phase requires a continuing commitment as to limit tidal exchange would return the treated soils to an oxidising, acid producing condition.

This soil survey showed a decrease in soil acidity levels in response to LATE and 13 years of remediation. These soil tests have shown that field pH's as low as 3.0, recorded in 2001-2, have risen to above 5.5. This is remarkable soil remediation and represents a shift from an extreme to very minor acidity hazard. This has occurred within the land area subjected to LATE, that is, the controlled maximum level to which tidal inundation has occurred which is 0.5 m above the AHD. At this level most acidified soils on the site are subjected to tidal inundation, even though there is capacity to inundate a far larger area, were the full daily tidal flow allowed to enter the site in an unregulated manner.

The pre-remediation survey revealed that acidified soils occur beyond the 0.5 m AHD level to approximately 1 m AHD and can provide a source of acidity associated with natural wetting and drying cycles. Although this land is not being directly treated, it is potentially impacted by lateral

[1] The sand ridges are the result of accumulations created by repeated storm surges as the sea retreated from a high point approximately 6K yrs BP (Thom and Roy

ground water movement through sub-soil layers associated with seawater inundation. Importantly, water quality monitoring is not identifying any acidic discharge from the land above 0.5 m AHD. However, the impact of the remediation program on land above 0.5 m AHD has not been assessed. To obtain a comprehensive assessment of the status of all soils across the whole site, this survey aimed to document the change in soil parameters that have occurred over 13 years of lime assisted tidal exchange.

Freshwater Inundation

Not all of the land below 0.5 m AHD has been treated by tidal exchange alone. The area referred to as the ‘peat swamp’ occurs on the eastern margin of the site and adjacent to Hill’s Creek. This area was not responding to LATE. Located at the interface of tidal incursion and freshwater input from the mouth of the creek, and at the furthest extent from the lime dosing point, the daily tidal exchange process was thought to have little effect on the peat swamp soils.

A system for maintaining a high water level with freshwater was installed to address the acid sulfate soils at the upper-wetland ‘peat swamp’. The peat swamp was established in 2008 and further expanded in 2010. Water from Hill’s Creek was diverted into the upper part of the swamp through a pipe and drain system, and a containment bund was constructed across the lower end of the swamp. A slide gate in the bund allows water to slowly return to Hill’s Creek and hence maintain flow through the swamp. While not responding as rapidly as LATE treated soils, the peat swamp soils have now responded well to permanent freshwater inundation. Soils in the peat swamp have been assessed as part of this survey.

2 SOIL ASSESSMENT METHODOLOGY

2.1 Field

Eighty-five cores were described and sampled in pre-LATE field work during 2001. Post-LATE field work in 2013 re-sampled these pre-LATE sites. In addition, a number of sites of been monitored regularly for soil changes. Data from 10 of these acidity monitoring sites was added to the final data set. In all, data from 95 locations were assessed to quantify the changes to soil properties in response to the remediation program. In the period between the pre-LATE sampling and the present survey, 150 additional sites were described across the whole site. This data, together with 24 new cores taken in the 2013 was used to improve map boundary reliability in the present survey.

All field sampling and description was carried out according to:

- Australian Soil and Land Survey Field Handbook (National Committee on Soil and Terrain 2009)
- Guidelines for Sampling and Analysis of Lowland Acid Sulfate Soils in Queensland (Ahern et al. 1998)

In the 2013 survey, cores were taken to approximately 1 to 1.5 m depth using soil coring equipment including a Jarrett hand auger, sand and gouge augers. One or more samples for field and laboratory analysis were taken within each horizon (or soil layer) down the soil profile. Samples were taken to characterise all the oxidised horizons in the soil profile and from just into the underlying reduced horizon. Field pH was assessed at 0.1 m intervals down the profile using method 23Af (Rayment and Lyons, 2011)[2].

[2] Field pH (23Af) Field Measurement using a pH electrode on a 1:5 soil:water mixture.

2.2 Laboratory Analysis

Acid sulfate soil analyses quantify both potential and existing acidity. Undisturbed ASS that has not been oxidised has a dominance of potential acidity, principally in the form of pyrite (FeS_2). Potential acidity is assessed in the laboratory using methods such as the chromium reducible sulfur method (S_{CR}). Disturbed (or oxidised) ASS has actual acidity in the form of hydrogen, iron and aluminium ions, and is referred to as titratable actual acidity (TAA). This fraction is expressed as equivalent sulfur percentage (s-TAA), or as equivalent moles of hydrogen ions. Another oxidation product, jarosite, a prominent and characteristic feature for ASS that is typically evident to the naked eye as bright yellow soil mottles, is a less available source of acidity. Jarosite is referred to as retained acidity (s-S_{NAS}). Oxidised or actual ASS materials typically occur in the upper profile, overlying pyrite containing materials that remain anaerobic and reduced.

Field and laboratory pH is a measure of the hydrogen ion component of acidity, whereas titratable actual acidity (TAA) includes all forms of acidity, except that as jarosite**.** The impacts of LATE were assessed by:

a) The quantum of actual and retained acidity in the pre-LATE soils compared to that after 13 years of remediation and
b) Pre- and post-LATE sulfur per cent (%S).

The assessment of pre and post-sulfur content is of particular interest with respect to ASS remediation as demonstrated by Johnston et al. (2011) on the East Trinity site. This research has shown that LATE generates a biologically driven reductive dissolution process that eventually leads to the reformation of pyrite from the products of its original oxidation.

Analytical methods used in this survey are consistent with Rayment and Lyons (2011). They are also specified in the Acid Sulfate Soils Laboratory Methods Guidelines (Ahern et al. 2004). The analyses performed on samples taken during the pre- and post-LATE surveys are shown in Table 1.

Table 1. Analytical methods

ANALYTE	METHOD	SYMBOL & UNITS
Titratable Actual Acidity	s - 23F	s – TAA (equiv. %S)
Retained Acidity (Jarosite)	s - 20J	s - S_{NAS} (equiv. %S)
Existing Acidity (s-TAA + s-S_{NAS})		(equiv. %S)
Potential Sulfidic Acidity	22B	S_{CR} (%S)
Potential Sulfidic Acidity (some 2001 samples)	23E	S_{POS} (%S)
Laboratory pH	23A	pH_{KCl}
Net Acidity (S_{CR} + s-TAA + s-S_{NAS} - Acid Neutralising Capacity)		

2.3 Data Storage

All field and laboratory data are recorded in the Queensland Government's Soil and Land Information (SALI) database (Biggs et al. 2000). Terminology and codes in SALI are consistent with the Australian Soil and Land Survey Field Handbook (National Committee on Soil and Terrain 2009).

2.4 Treatment of Soil Profile Data for Mapping

Soils described in pre- and post-LATE sampling typically have up to four layers, or horizons, according with changes in soil morphological properties. Soil horizons vary in thickness, and hence there may be two or more samples from a very thick horizon. Tables 2 and 3 show examples of pre- and post-LATE profile data.

The mapped soil units have been characterised according to the degree of change in soil acidity levels in response to LATE. To do so, it was necessary to ascribe a single value to each pre and post set of soil profile data for respective soil properties. To average all values in each horizon would give a biased result because of the variation within horizons, significant changes across sharp horizon boundaries and varying horizon depths. The alternative method adopted was the equal-area spline (Bishop et al., 1999; Malone et al., 2009).

The equal-area spline de-convolves (assimilates) horizon-based observations of a soil profile by interpolating the data to derive values at 1 cm depth intervals. The algorithm of Malone et al. (2009) was applied to generate an integrated curve from the profile data. The curve may slightly underestimate or overestimate the actual values down the profile. The equal area spline smooths the curve so that for each horizon, the area of over-prediction equals the area of under-prediction. In this way the mean of the attribute for each horizon, and hence the profile, is maintained. An example of the technique is shown in Figure 1 of Bishop et al., (1999).

The de-convolution creates two useful effects. It provides a finely resolved common basis (a value for each 1 cm increment) to which horizon-based observations can be compared and the interpolated values can be ‘re-convolved’ to customised depth intervals.

The spline data 1 cm increments for the pre and post sites were averaged to the depth of the reduced horizon (lower depth of the B horizon) that was established during pre-LATE sampling. This allows data to be excluded from the un-oxidised soil layer, to reduce the noise associated with sampling method and spatial variability between pre and post assessment. This approach anchors the comparison of pre- and post-LATE changes to the base condition of the pre-LATE oxidised soil layer. It was necessary to amend the raw data in the application of the spline in a select few cases to enable comparison. For example, if data was absent in the horizon above the reduced layer, the spline will erroneously assume the value of the reduced layer for that horizon. This has been corrected by inserting either a representative value in the existing horizon, or a very narrow (false horizon) with a value. For example, a zero value for potential sulfur percentage has been inserted in the horizon above the reduced layer for some sites. This is done in a small number of occasions only, and where clear there was a clear justification either from indicators such as soil morphology, field pH and the data, or from similar adjacent sites.

Where TAA is high and field pH is >7 in treated soils, oxidation of the sample has very likely occurred subsequent to sampling as a consequence of the oxidation of very reactive acid volatile sulfur compounds. In a few minor cases where this has obviously occurred, the TAA results have been excluded on the following grounds:

- pH_{KCl} is more than 1 unit less than field pH, and
- pH_{KCl} is <5, and
- TAA has increased over time after treatment

The delta or change value was used as the basis for portraying the responses to LATE in map form. For example, thirteen map units were delineated in the Treated Sulfidic soil category. An average delta value was ascribed to the map unit if more than one site occurred. Delta values of actual acidity, for example, range from 0.1%S to 0.45 %S across the treated map units. Each map unit was coloured according to its delta value.

Figure 1 and Tables 2-4 demonstrate the process of characterising a map unit according to pre- and post-LATE analysed soil properties. A spline curve is generated from the soil profile values for each soil site in the map unit with pre and post treatment data (Table 2 and 3). The average of the 1 cm spline values to the depth of the reduced layer produces a single profile value for each soil core. All the single profile values in a map unit are then averaged for the pre- and post-LATE results respectively. The difference between these two averages is the delta value for the map unit (see Table 4).

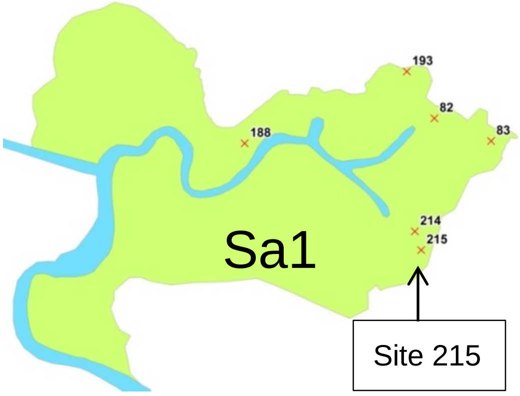


Figure 1. A typical map unit (Sa1-Sulfidic, undergoing active treatment) containing 6 locations with pre- and post-LATE data.

Table 2. Site 215 field pH pre-treatment

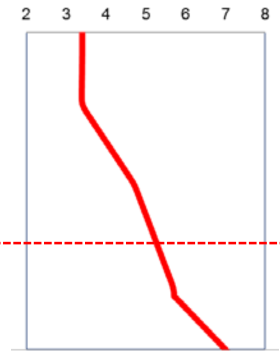
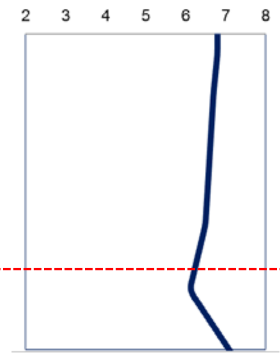
Horizon Depth	Name	pH Depth	Field pH	Spline Curve	Single Profile Value*
0.00-0.30	A1	0.10 0.30	3.4 3.4		4.22
0.30-0.90	B2	0.60	4.7		
0.90-1.20	2C	1.00 1.20	5.7 7		

Table 3. Site 215 field pH post-treatment

Horizon Depth	Name	pH Depth	Field pH	Spline Curve	Single Profile Value*
0.00-0.05	A11				6.60
0.05-0.20	A12	0.10	6.8		
0.20-0.60	B21a	0.25 0.50	6.7 6.6		
0.60-0.85	B22a	0.75	6.5		
0.85-1.15	C1	1.10	6.1		

*The average of the 1 cm spline values to the reduced layer (0.9 m)

Table 4. Field pH and calculation of delta value for the map unit

Site Number	pH Pre-LATE	pH Post-LATE	Delta pH
82	3.18	6.41	
83	3.69	6.26	
188	4.86	6.20	
193	4.05	5.58	
214	4.90	7.13	
215	4.22	6.60	
Average	**4.15**	**6.36**	**2.2**

2.5 Mapping Units

Holocene geomorphology and elevation were used to define the high level mapping units. These units were further subdivided into component mapping units on the basis of tidal exchange limits, sulfuric/sulfidic status and other soil characteristics. Individual map units with similar characteristics were grouped into defined mapping units as explained below and listed in Table 5.

Table 5. Mapping units and codes

PRIMARY MAPPING UNITS	COMPONENT MAPPING UNITS	CODE
The final (cutting and back-filling) phase of Holocene deposition (former mangrove communities)	Sulfidic, Active Treatment, 0.0 - 0.3 m AHD - Land undergoing LATE.	Sa1
	Sulfidic, Active Treatment, 0.3 - 0.5 m AHD - Land undergoing LATE.	Sa2
	Sulfidic, Passive Treatment, 0.0 - 0. 5 m AHD - Land undergoing passive treatment, formerly actively treated	Sp3
	Sulfuric, Not Treated, 0.3 - 0.5 m AHD[1]	Ant2
	Sulfuric Not Treated, 0.5 – 1 m AHD[2]	Ant4
Central bay, Holocene marine muds (former samphire communities)	Sulfidic, self-neutralising, 0.5 – 1 m AHD	Sn4
	Sulfidic, self-neutralising, >1 m AHD	Sn5
	Sulfidic, self-neutralising, 0.5 – 1 m AHD residual acidity at depth	Snr4
Chenier ridges	Non-sulfidic cheniers, > 1 m AHD, sulfidic at depth	Sch5
Land above 1 m AHD	Surface terrestrial material, sulfidic at depth	S5
Land above 2 m AHD (terrestrial deposition)	Non Sulfidic, >2 m AHD, terrestrial	N6

[1]Land between 0.3 and 0.5 m AHD in the Magazine Creek area has been excluded from treatment

[2]This untreated category is still acid producing and hence termed 'sulfuric'. The treated categories were formerly acid producing but are now dominantly 'sulfidic', meaning they have reverted to potential acid sulfate soils. These treated soils will remain effectively non-acid producing if kept wet under a normal tidal regime.

The soils on land up to an elevation of approximately 1 m AHD (former mangrove communities) are derived from sulfidic sediments associated with the final depositional phase as the shoreline retreated from 1 m higher to the present level. This and the other geomorphic and elevation defined units have been delineated, subdivided and coded as described in Table 5.

The accepted stratigraphic model of Graham and Larsen (2003) indicates that the first depositional phase was associated with shoreline advance. This transgressive depositional phase commenced approximately seven thousand years ago when sea levels reached their present level at the end of the last ice age (Grindrod and Rhodes 1984). Sea levels then rose to approximately 1 m higher than present. This shoreline advance ceased approximately six thousand years ago (Thom and Roy 1982; Chappell 1983) and created a blanket of sediment and an aquatic wedge. A period of stability ensued during which a second depositional phase (referred to as estuary bay marine muds) occurred when sediments infilled the wedge of water above the transgressive sediments. These sediments are pyritic (sulfidic) but are self-neutralising if oxidised as they contain microscopic calcitic organisms, *foraminifera* (Chaproniere 2002). As mentioned above, the final depositional phase occurred when the shoreline subsequently retreated to the present level as a result of hydro-isostatic uplift of the Cairns coast (Chappell et al.,1982; Hopley 1982). Components of the estuary bay sediments remained intact, whereas other areas were eroded and replaced with back-filling with pyritic sediments.

The sediments that were not eroded have subsequently been covered by material from only the highest tides. These areas have become hyper-saline and colonised by samphire vegetation communities. The surface of these sediments occurs predominantly at an elevation of 1 to 1.5 m AHD.

The sandy chenier ridges formed by storm surge action are non-sulfidic, but can overlie sulfidic material. The surface of the chenier ridges occurs from 1.5 to 2.5 m AHD.

Land between 1 and 2 m AHD typically has non-sulfidic material to a depth of 1.5m, below which an approximately 1 m thick sulfidic layer occurs. The surface material is dominantly of terrestrial origin.

Land above 2 m AHD is non-sulfidic of terrestrial origin.

Appendix 1 depicts the depositional components described above in a stratigraphic diagram derived from the deep drilling carried out in 2001 (Graham and Larsen 2003; Smith et al., 2003).

Each of the mapping units described in Table 5 will have one or more occurrences. Each occurrence is referred to as a map unit or unique map area (UMA). The ninety-five comparative sites occur in the following mapping units and associated UMA’s.

- Actively and Passively Treated Sulfidic soils (Sa1-3) (35 sites,13 UMA’s)
- Non-treated, Sulfuric soils (Ant2, Ant4) (31 sites,12 UMA’s)
- Non- treated, Sulfidic self-neutralising soils (Sn4,Sn5, Snr4) (29 sites,16 UMA’s

Appendixes 2 and 3 are maps portraying the changes in field pH and existing acidity respectively across the defined mapping units.

3 RESULTS AND DISCUSSION

3.1 Impacts of LATE

The pre- and post-LATE data from the single profile value are summarised in Tables 6 and 7 for the three mapping units associated with Holocene sediments. Table 6 expresses the laboratory data as %S, whereas Table 7 expresses the same data as mol H^+/t.

The field pH data indicate an acidity reduction in the Sulfidic Treated areas (Sa, Sp) of 2.5 units compared to a very minor acidity increase in the Sulfuric Untreated (Ant) areas of 0.1 units. As would be expected, the Sulfidic Self Neutralising category with little pre-LATE acidity has not altered.

The decrease in Titratable Actual Acidity results reinforces the positive benefits of LATE on the treated land. Median TAA has been reduced by 89 per cent from 0.107 to 0.012 %S or 66 to 7 mol H^+/t soil. A slight reduction in TAA has occurred in the untreated (Ant2, Ant4) areas. These latter soils would be expected to continue to oxidise and produce acid and acidic by-products, but under the passive tidal regime these by-products are being neutralised. Field observations confirm the impact of tidal water inundation on these soils. Most notable is the weathering of jarosite in the wet sub-soil layers of the untreated soils located near to the limit of tidal exchange. This arguably is the consequence of lateral sub-surface seepage of saline ground water from the tidal inundation treated areas to the adjacent soils. The fact that no overall increase in retained (jarositic) or net acid soluble sulfur (NAS) in the sulfuric untreated areas has occurred also suggests that saline groundwater may be impacting these soils.

A substantial decrease in jarosite or retained acidity has occurred in the treated areas. This, together with the substantial increase in sulfur levels, supports the conclusions of Johnston et al. (2011) that reductive dissolution of jarosite and reformation of pyrite is occurring in response to LATE.

Figures 2 and 3 are plots of the range of pre- and post-LATE data for field pH and TAA based on single profile values calculated from the equal area spline. For both pH and TAA, the plots portray manifest improvement in soils in the treated area.

Figure 4 displays the entire range of results for all the selected soil parameters for the treated land only. It is based on every value encountered above the reduced level in every profile as opposed to a single spline value for the whole soil profile.

Pre-LATE sampled sites that are now below the permanent tidal level (< 0.0 m AHD) were not resampled due to inaccessibility, danger from crocodiles, and the difficulty in obtaining a sample under water. A reasonable assumption is that these inundated areas would now be in a reduced state given that treated areas from 0.0 to 0.5 m AHD have been shown in this survey to be in a fully or significantly reduced state.

Table 6. Selected analytes expressed as per cent sulfur are given for treated and untreated areas at different elevation.

MAP AREAS		SPLINE DATA TO REDUCED LAYER															Elevation AHD
		Field pH			TAA (%S)			NAS (%S)			Existing Acidity (%S)			Potential (%S)			
		Pre	Post	Δ	Pre	Post	Δ	Pre	Post	Δ	Pre	Post	Δ	Pre	Post	Δ	
Sulfidic, Treated (Sa and Sp units)	Median	3.9	6.5	2.6	0.107	0.012	-0.095	0.231	0.034	-0.197	0.338	0.046	-0.292	0.178	0.292	0.114	<0.5 m
Sulfidic, Not Treated (Ant units)	Median	4.5	4.4	-0.1	0.140	0.101	-0.039	0.091	0.091	0.000	0.231	0.192	-0.039	0.267	0.074	-0.193	0.5-1 m
Sulfidic, Self-Neutralising, Not Treated (Sn units)	Average[1]	6.7	6.6	-0.1	0.007	0.007	0.000	0.018	0.009	-0.009	0.025	0.016	-0.009	0.110	0.076	-0.034	0.3->1 m

[1] An average was calculated for this mapping unit as only three profiles were sampled

Table 7. Selected analytes expressed as mol H^+/t.

MAP AREAS		SPLINE DATA TO REDUCED LAYER												Elevation AHD
		TAA (mol H+/t)			NAS (mol H+/t)			Existing Acidity (mol H+/t)			Potential (mol H+/t)			
		Pre	Post	Δ	Pre	Post	Δ	Pre	Post	Δ	Pre	Post	Δ	
Sulfidic, Treated	Median	67	7	-59	144	21	-123	211	29	-182	111	182	71	<0.5 m
Sulfidic, Not Treated	Median	87	63	-24	57	57	0	144	120	-24	167	46	-120	0.5-1 m
Sulfidic, Self-Neutralising, Not Treated	Average[1]	4	4	0	11	6	-6	16	10	-6	69	47	-21	0.3->1 m

[1] An average was calculated for this mapping unit as only three profiles were sampled.

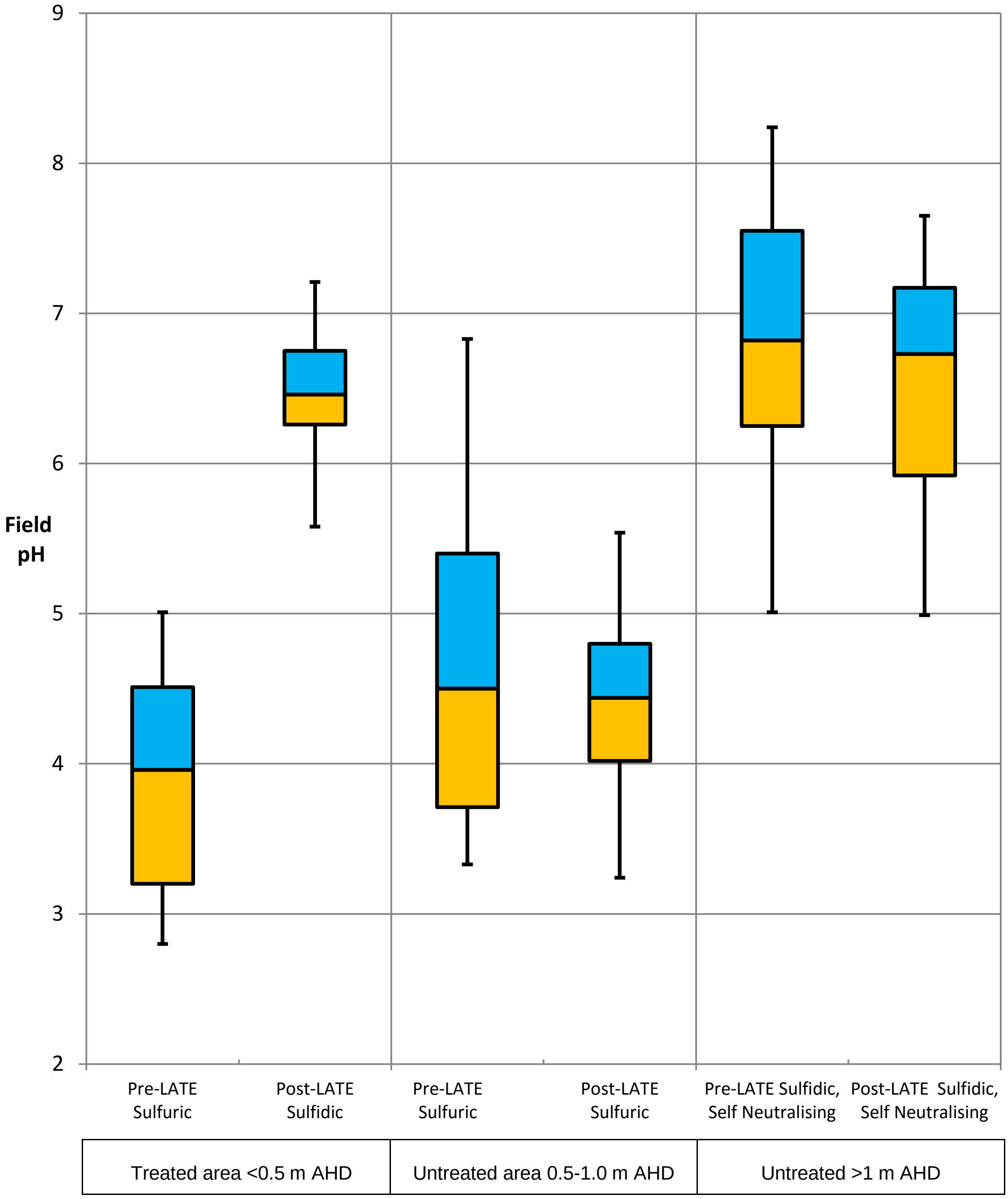


Figure 2. Field pH values pre- and post-LATE for sulfidic, sulfuric and sulfidic self-neutralising sites are shown based on a single profile value calculated from 1 cm spline data above the reduced layer. The box shows the 25th and 75th percentiles and median, and the whiskers shows the values at the 0 and 100th percentiles.

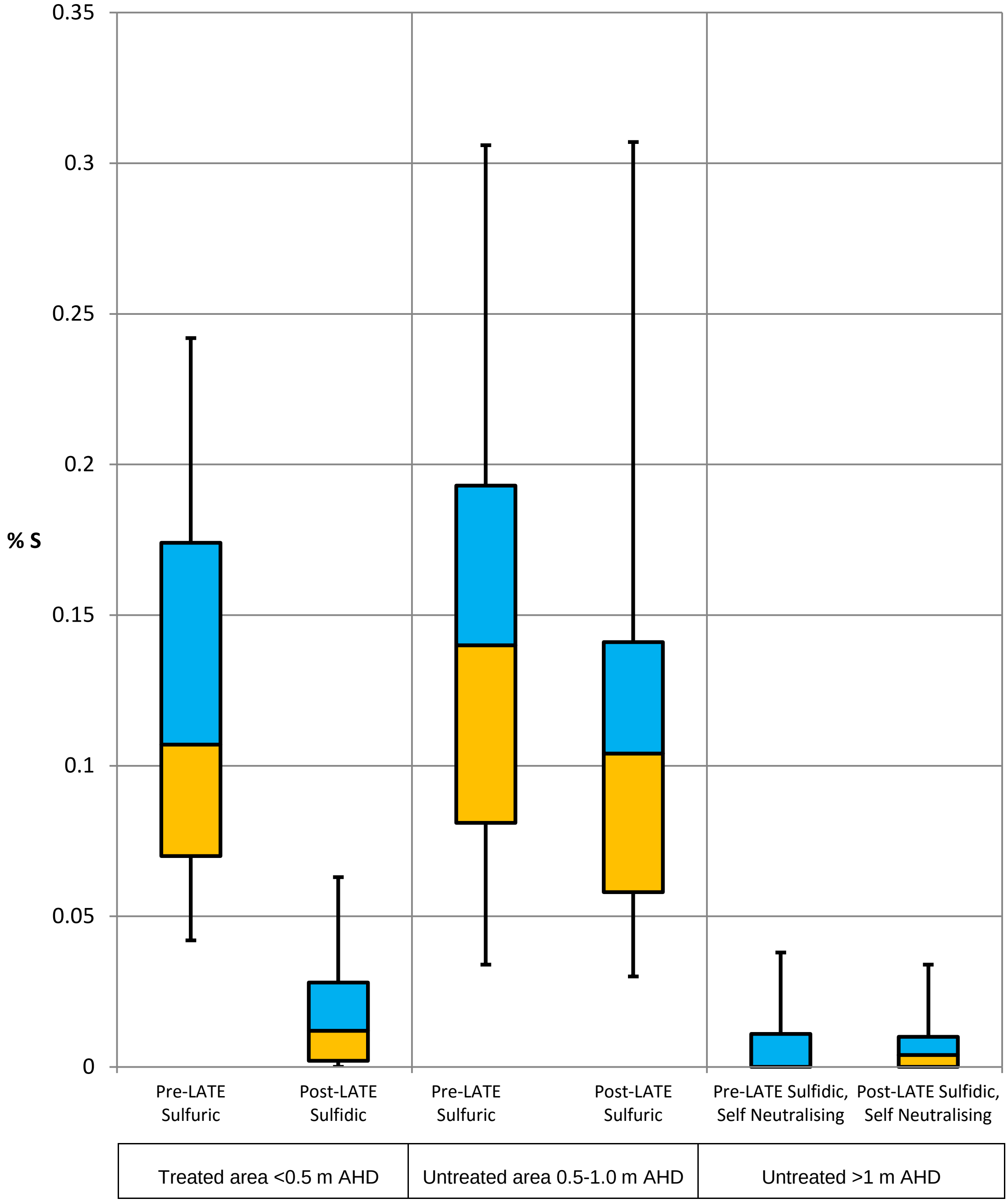


Figure 3. TAA values pre- and post-LATE for sulfidic, sulfuric and sulfidic self-neutralising sites are shown based on a single profile value calculated from 1 cm spline data above the reduced layer. The box shows the 25th and 75th percentiles and median, and the whiskers shows the values at the 0 and 100th percentiles.

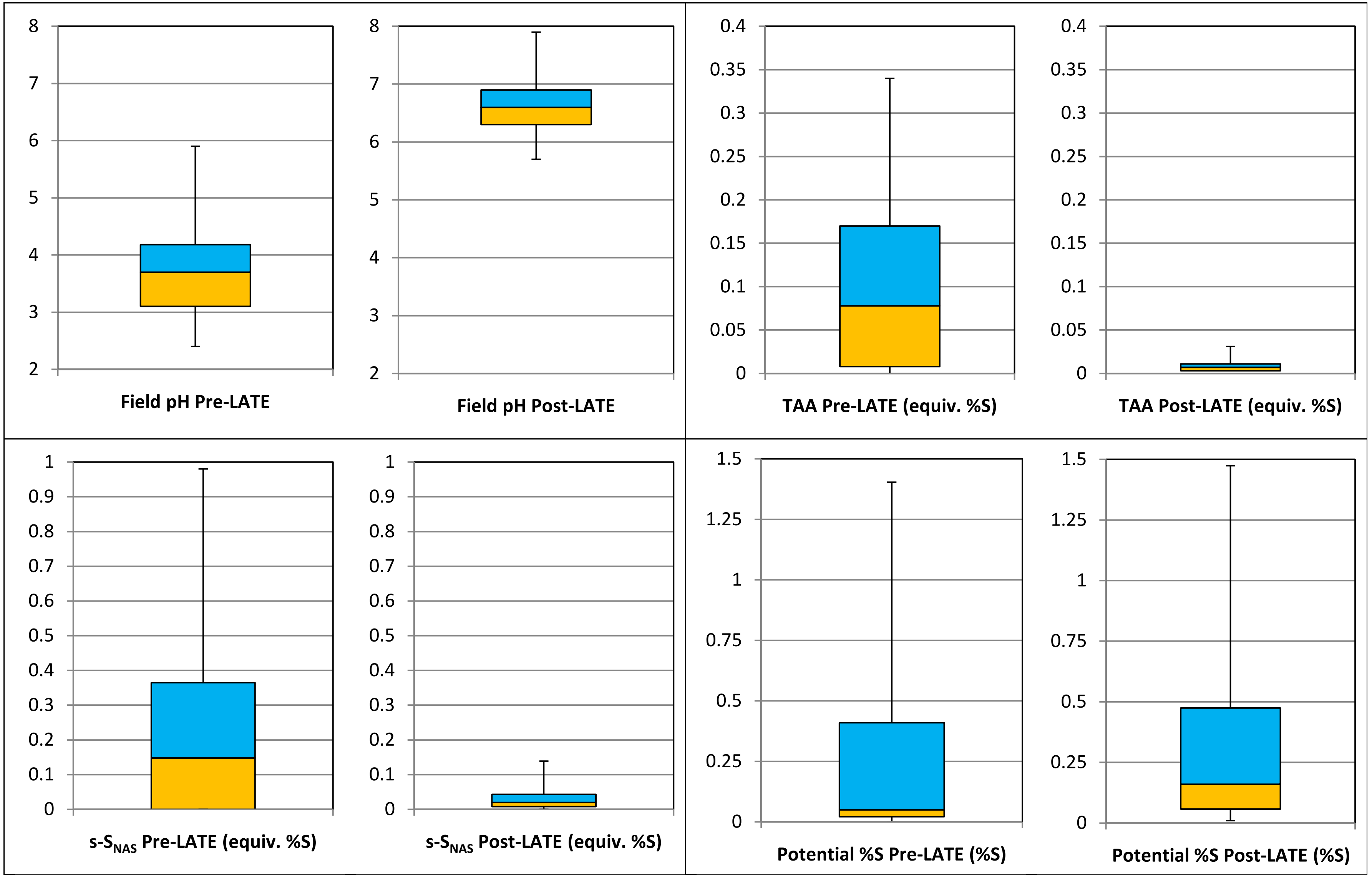


Figure 4. Distribution of pre- and post-LATE raw values throughout the profile above the reduced layer for field pH and selected analytes within treated areas. The box shows the 25th and 75th percentiles and median, and the whiskers shows the values at the 0 and 100th percentiles.

3.2 Freshwater Treatment

Freshwater inundation has brought about a dramatic change to the ‘peat swamp’ with respect to vegetation (Plate 3) and field pH (Figure 5a). However, laboratory results indicate that these soils have not responded in the same way as the LATE treated soils. Figures 5a to 5f show data from four sampling periods for site 86 in the ‘peat swamp’ as follows:

Figures 5a and 5b, portray a contrast in 2012 results between field pH and pH_{KCl}. Field pH shows that a substantial decrease in hydrogen ion acidity has occurred in response to freshwater inundation. However, the low laboratory pH_{KCl} for the same sample indicates that the presence of acid volatile material in the sample that has apparently oxidised in the period between sampling and laboratory analysis. This component means that these soils will very rapidly produce significant quantities of acid on drying. This has not been the case with soils that undergone significant periods of LATE. However, with a longer period of inundation, the acid volatile component may decline or be eliminated. Importantly, as long as the peat swamp is kept inundated, the acid volatile material will not produce acid.

Figure 5c shows the degeneration of jarosite whereas Figure 5d indicates the associated accumulation of sulfur, arguably as a result of reductive dissolution of the jarosite.

a.

b.

c.

d.

Plate 3. Visual change to Hills Creek peat swamp over time in response to freshwater inundation. **a.** Aerial view of the peat swamp in 2006 showing M*elaleuca* die off and iron staining**. b**. Typical understorey view in 2006 showing highly acidic surface water and iron stained soils**. c**. Aerial view of the peat swamp in 2013 showing vegetation recovery and absence of iron staining. **d.** Same view as b in May 2015.

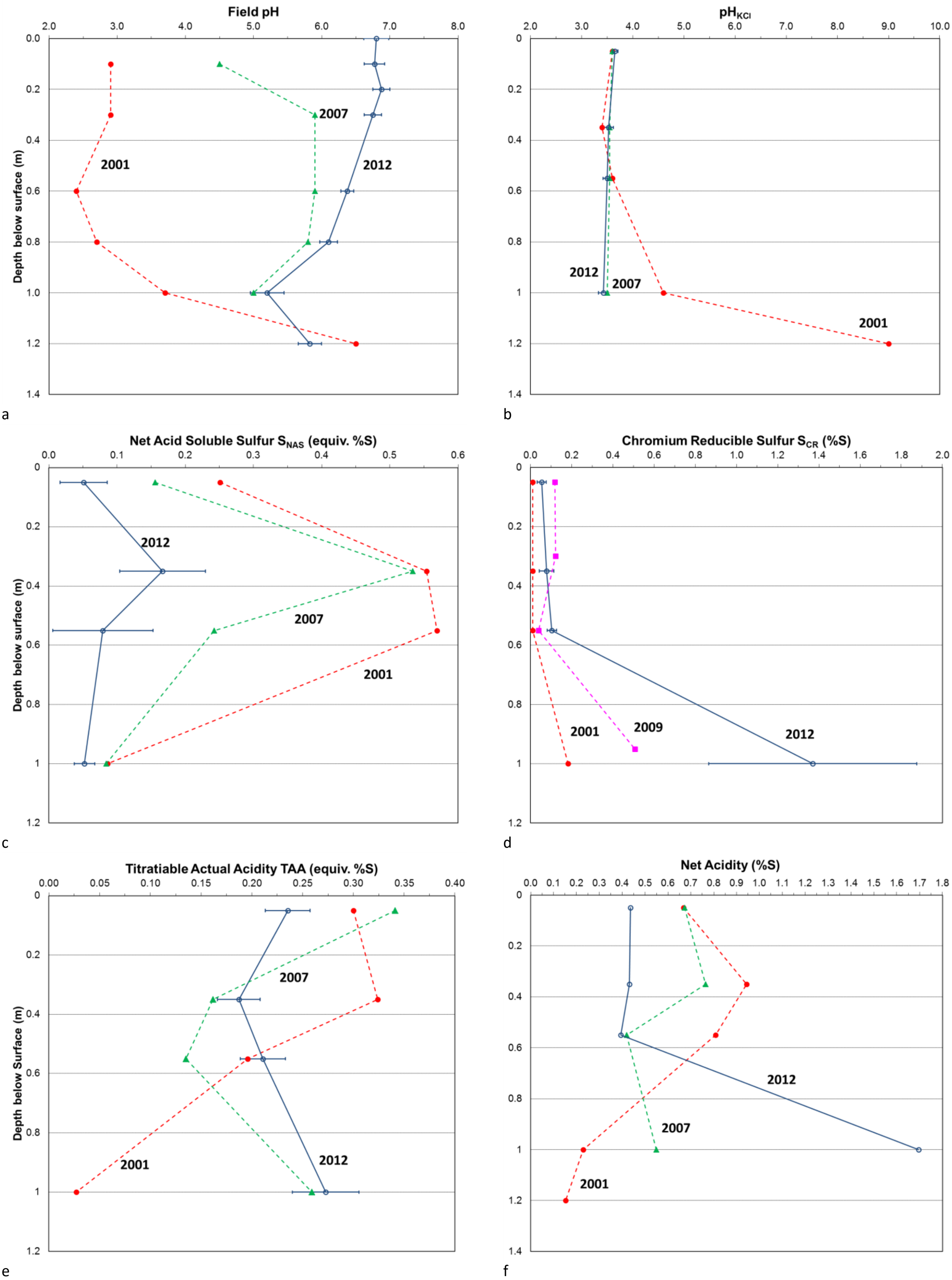


Figure 5. Site 86, Peat swamp before and after freshwater inundation. **a**. Field pH (1:5 soil:water mixture) **b**. pH_{KCl} **c.** Retained Acidity (measured as Net Acid Soluble Sulfur S_{NAS}**)** **d.** Potential %S (measured as S_{CR}) e. Actual Acidity (measured as Titratable Actual Acidity TAA) f. Net Acidity = Potential+Actual+Retained-ANC

The results for TAA in the 0 to 0.2 m layer indicate a decrease in all forms of actual acidity (hydrogen ions, iron, aluminium and organic matter) from 0.3 %S in 2001 to 0.23 %S in 2012. Hydrogen ion levels measured as field pH have been reduced by 30 per cent by 2007 and are near to background levels by 2012. Jarosite decreased in a similar way to inconsequential levels from 0.25 %S in 2001 to 0.05 %S in 2012. These changes represent a major remediation of the acid sulfate soils in the wetland.

TAA in the 0.2 to 0.4 m layer decreased from 0.35 %S in 2001 to 0.152 %S in 2007 and then increases marginally to 0.157 %S in 2012. In contrast, jarosite levels barely decreased from 0.55 %S to 0.525 %S in 2007, but then decrease substantially to 0.16 %S by 2012. Hydrogen ions (field pH) decrease substantially by 2007 to near background levels and reach background levels by 2012. The sharp drop in TAA in this layer in 2007 is therefore likely associated with a decrease in hydrogen ion concentration.

TAA in the 0.4 to 0.6 m layer has decreased from 0.2 %S in 2001 to 0.13 %S by 2007, and then increased to 0.21%S by 2012. The jarosite in this layer has now halved from 0.55 %S to 0.24 %S by 2007, and has almost disappeared by 2012 (Figure 5c). Hydrogen ion levels (field pH) in contrast have already reached background levels by 2007. This suggests that the TAA level in this layer in 2007 is associated mainly with iron species. One likely source of this acidity is from the breakdown of jarosite. The increase in TAA in this layer from 2007 to 2012 may then be explained by the further breakdown of jarosite and a reduction of ferric ion.

4 CONCLUSION

The remarkable results from this soil survey provide one of the lines of evidence that lime assisted tidal exchange has successfully remediated a substantial area of acid sulfate soils. Before remediation, this land had become severely degraded and was a chronic source of acid and toxic metals that drained into Trinity for over 30 years. The success of the remediation has been documented using changes in soil properties that have occurred over a 13 year period. In particular, Titratable Actual Acidity has been decreased by 89 per cent to near background levels.

In addition to reducing or eliminating soil acidity, this survey also provides evidence of soil chemical and biological processes that are returning, or have returned soils to their former reduced state as demonstrated by the disappearance of jarosite and the reformation of pyrite. This provided a valuable quantification of the full magnitude and rates of rehabilitation on this site. Beyond the immediate value in improving the local environment of this important wetland habitat, the LATE demonstration site has provided an international demonstration and fundamental understanding of these processes which will inform the remediation of other areas.

This survey has also expanded the value of this remediation strategy by providing quantified evidence of the potential for freshwater remediation. While there are differences in soil responses to permanent freshwater inundation, the end results show a similar magnitude of soil acidity remediation. Unlike soils subjected to long term seawater inundation, the freshwater soils contain acid volatile material which can rapidly oxidise and produce acid on drying. With a longer period of inundation, this material may decline or be eliminated. Importantly, the maintenance of inundated conditions will prevent any acidification.

The successful remediation of the soils is one of the environmental benefits of the remediation. Other studies into water quality, vegetation (Newton et al. 2014) and mangrove community regeneration, aquatic (Sheaves and Abrantes 2015) and avian (Smith and Venables 2014) species are either completed or underway. A synthesis of all of these lines of evidence will give a rich picture of the environmental changes from the remediation.

REFERENCES

Ahern CR, Ahern MR and Powell B (1998). *Guidelines for Sampling and Analysis of Lowland Acid Sulfate Soils (ASS) in Queensland*. Department of Natural Resources, Indooroopilly, Queensland, Australia.

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

Biggs AJW, Kidston EM, Searle RD, Wilson PL, Grundy MJ, Heiner IJ, Smith CD, and Sweeney C (2000). :SALI – The soil and landform information system for Queensland", *Proceedings of Soil 2000: New horizons for a New Century. Australian and New Zealand Second Joint Soils Conference. New Zealand society of Soil Science, Christchurch, 3-8 December 2000, pp.19.*

Bishop TFA, McBratney AB and Laslett GM (1999). *Modelling soil attribute depth functions with equal-area quadratic smoothing splines.* Geoderma, 91, 27-45*.*

Chappell J (1983) Evidence of smoothly falling sea level relative to North Queensland, Australia, during the past 6,000 yr. *Nature*, 302: 406-408

Chappell J, Rhodes EG, Thom BG and Wallensky E (1982). Hydro-isostasy and the sea-level isobase of 5500 B.P. in North Queensland, Australia. Marine Geology 49: 81–90

Chaproniere GCH (2002). Foraminiferal biostratigraphy of sample ETA 62-5.1m Department of Geology, ANU, Canberra. CSIRO Land and Water, Australia.

Graham TL and Larsen RM (2003). Acid Sulfate Soil and Stratigraphic Investigation: East Trinity, Cairns, Queensland. GC Report 2003-2-III31 for Department of Natural Resources & Mines, Queensland.

Grindrod J and Rhodes EG (1984). Holocene sea-level history of a tropical estuary: Missionary Bay, North Queensland. In: Thom BG (ed) Coastal Geomorphology in Australia. Academic Press Australia, p. 151-178.

Hopley D (1982). The geomorphology of the Great Barrier Reef : quaternary development of coral reefs. Wiley, New York

Johnston SG, Keene AF, Bush RT, Burton ED, Sullivan LA, Isaacson LS, McElnea AE, Ahern CR, Smith CD and Powell B (2011). Iron geochemical zonation in a tidally inundated acid sulfate soil wetland. Chemical Geology 280, 257–270.

Malone BP, McBratney AB, Minasny B, and Laslett GM (2009). *Mapping continuous depth functions of soil carbon storage and available water capacity.* Geoderma, 154, 138-152.

National Committee on Soil and Terrain (NCST) (2009). *Australian Soil and Land Survey Field Handbook.* 3rd Edition, CSIRO Publishing, VIC.

Newton MR, Addicott EP and Bannink PJ (2014). Vegetation Survey of the East Trinity Reclamation Site: November 2014. Queensland Herbarium, Queensland Department of Science, Information Technology, Innovation and the Arts, Brisbane.

Rayment GE and Lyons DJ (2011). Soil Chemicals Methods – Australia. Volume 3 in the Australian Soil and Land Survey Series. CSIRO Publishing, Collingwood, VIC. Australia.

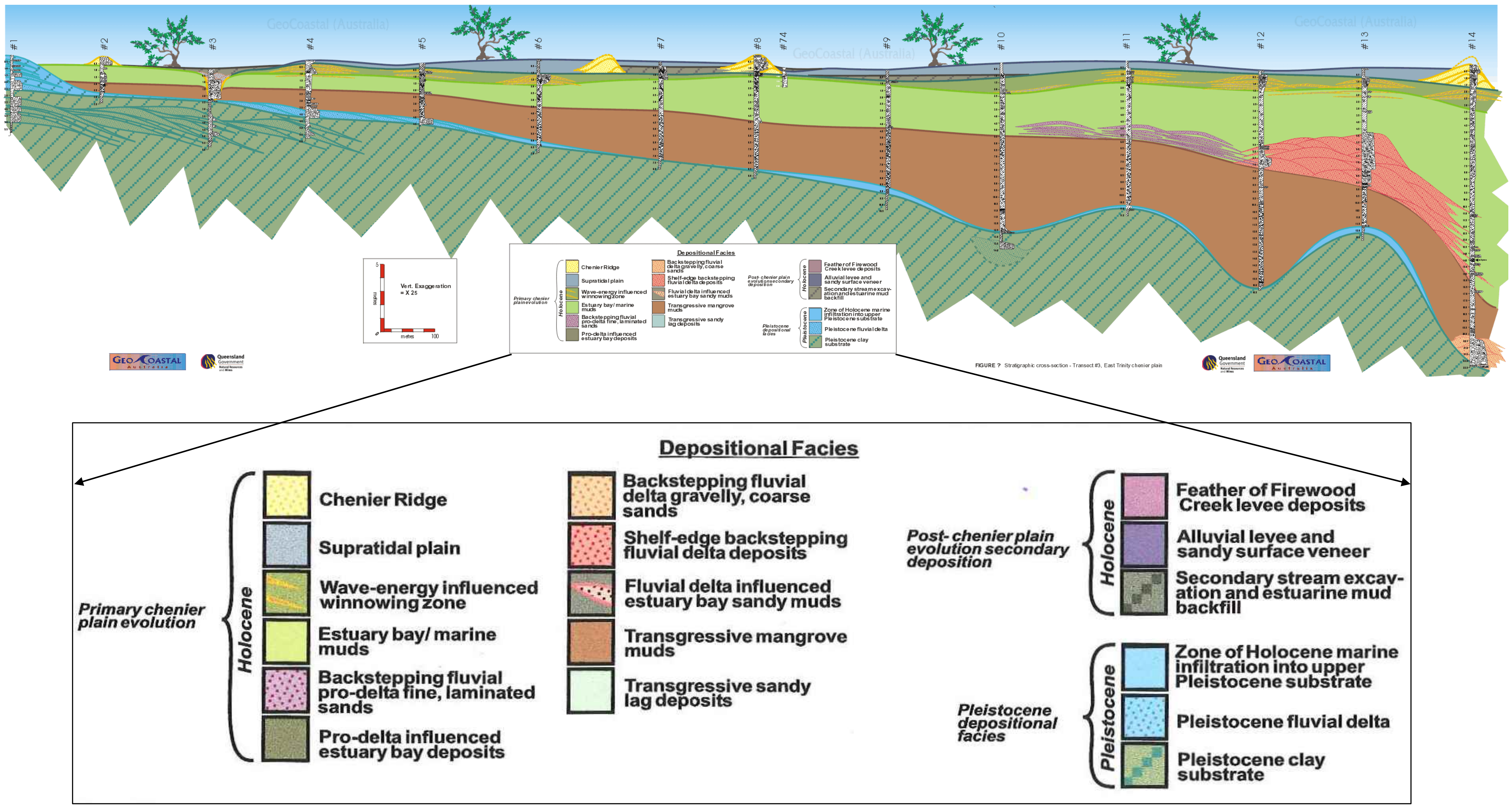
Sheaves M and Abrantes K (2015). Fish and crustacean communities of East Trinity 15 years after remediation of acid sulfate soils. Estuary and Coastal Wetland Ecosystems Research, James Cook University. Townsville.

Smith CD, Graham TL, Barry EV, Adams JJ and Ahern CR (2003). Acid Sulfate Soil and Stratigraphic Assessment. In: *Demonstration of Management and Rehabilitation of Acid Sulfate Soils at East Trinity: Technical Report.* Smith CD, Martens MA, Ahern CR, Eldershaw VJ, Powell B, Barry EV and Hopgood GL (eds). Department of Natural Resources and Mines, Indooroopilly, Queensland, Australia.

Smith GC and Venables BL (2014). Birds of East Trinity Inlet – Acid-Sulphate Remediation Project. Department of Science, Information Technology, Innovation and the Arts. Brisbane.

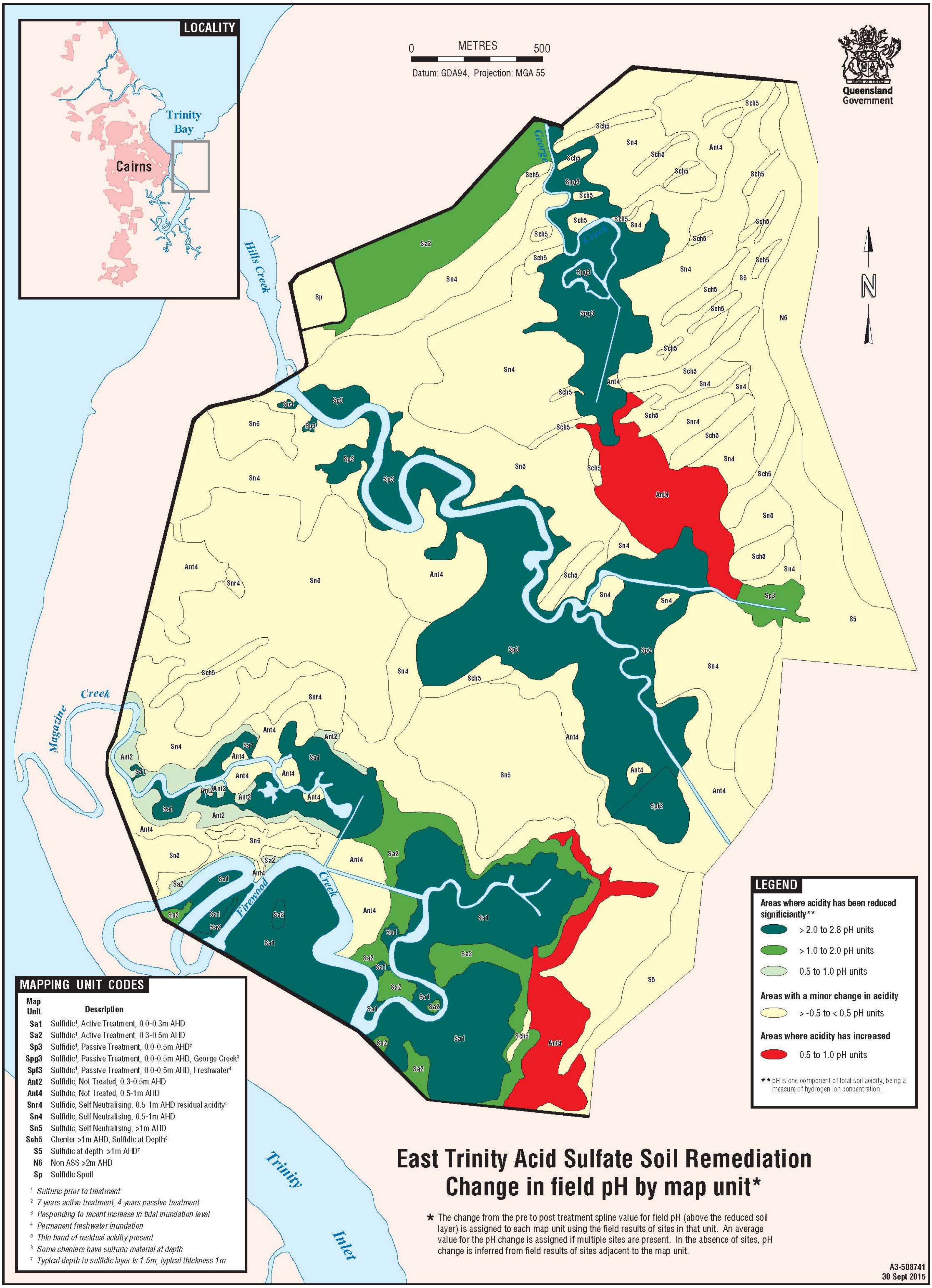
Thom BG and Roy P (1985). Relative sea levels and coastal sedimentation in southeast 2253 Australia in the Holocene. Journal of Sedimentary Petrology 55, 257-264.

Appendix 1

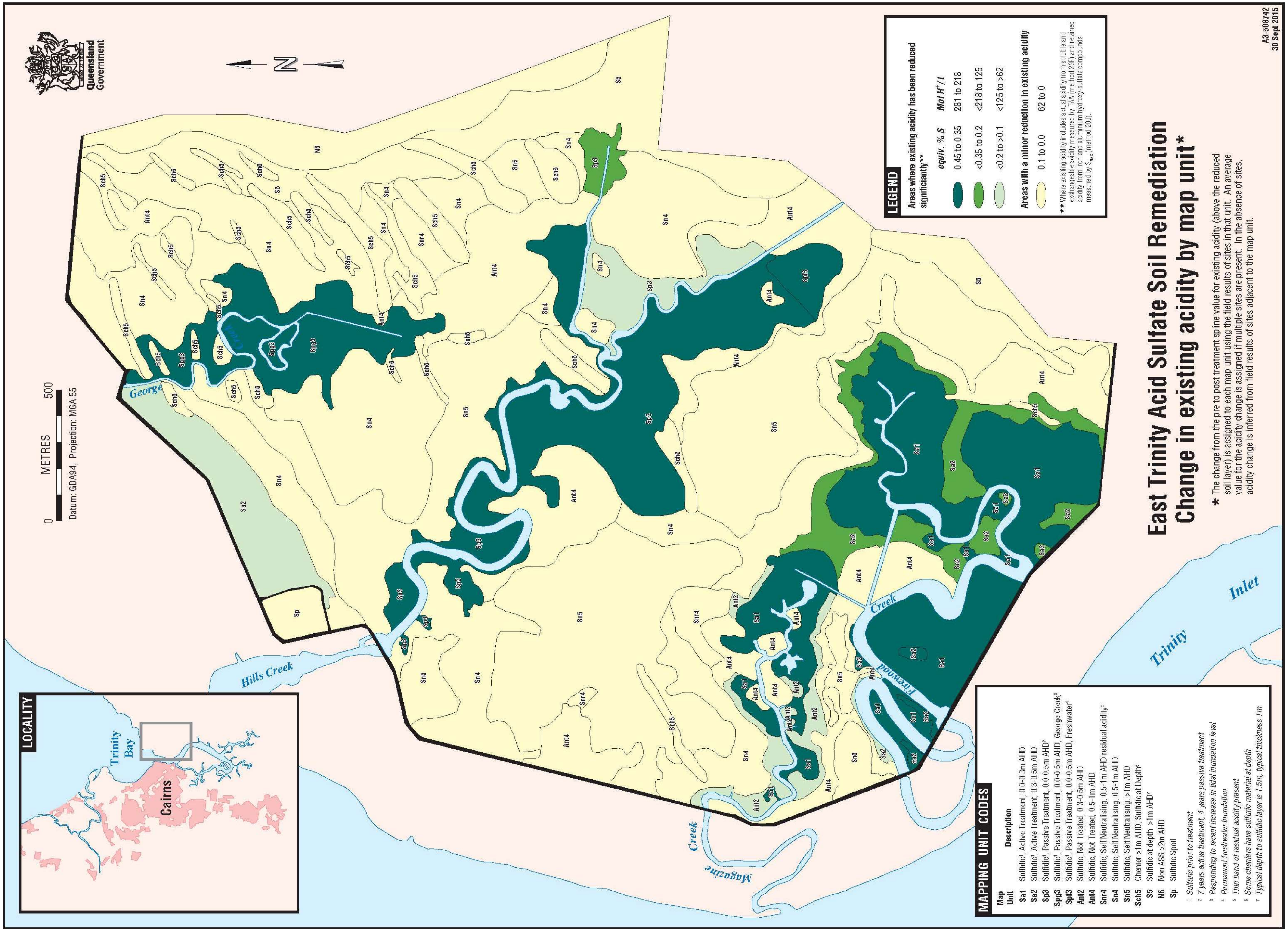


Stratigraphic cross-section along Transect 3, East Trinity – (Graham and Larsen 2003; Smith et al., 2003)

Appendix 2


LOCALITY
Trinity Bay
Cairns
0 METRES 500
Datum: GDA94, Projection: MGA 55
Queensland Government
N
Hills Creek
George Creek
Magazine Creek
Firewood Creek
Trinity Inlet
LEGEND
Areas where acidity has been reduced significantly**
> 2.0 to 2.8 pH units
> 1.0 to 2.0 pH units
0.5 to 1.0 pH units
Areas with a minor change in acidity
> -0.5 to < 0.5 pH units
Areas where acidity has increased
0.5 to 1.0 pH units
** pH is one component of total soil acidity, being a measure of hydrogen ion concentration.
MAPPING UNIT CODES
Map Unit Description
Sa1 Sulfidic[1], Active Treatment, 0.0-0.3m AHD
Sa2 Sulfidic[1], Active Treatment, 0.3-0.5m AHD
Sp3 Sulfidic[1], Passive Treatment, 0.0-0.5m AHD[2]
Spg3 Sulfidic[1], Passive Treatment, 0.0-0.5m AHD, George Creek[3]
Spf3 Sulfidic[1], Passive Treatment, 0.0-0.5m AHD, Freshwater[4]
Ant2 Sulfidic, Not Treated, 0.3-0.5m AHD
Ant4 Sulfidic, Not Treated, 0.5-1m AHD
Snr4 Sulfidic, Self Neutralising, 0.5-1m AHD residual acidity[5]
Sn4 Sulfidic, Self Neutralising, 0.5-1m AHD
Sn5 Sulfidic, Self Neutralising, >1m AHD
Sch5 Chenier >1m AHD, Sulfidic at Depth[6]
S5 Sulfidic at depth >1m AHD[7]
N6 Non ASS >2m AHD
Sp Sulfidic Spoil
1 Sulfuric prior to treatment
2 7 years active treatment, 4 years passive treatment
3 Responding to recent increase in tidal inundation level
4 Permanent freshwater inundation
5 Thin band of residual acidity present
6 Some cheniers have sulfuric material at depth
7 Typical depth to sulfidic layer is 1.5m, typical thickness 1m
East Trinity Acid Sulfate Soil Remediation
Change in field pH by map unit*
* The change from the pre to post treatment spline value for field pH (above the reduced soil layer) is assigned to each map unit using the field results of sites in that unit. An average value for the pH change is assigned if multiple sites are present. In the absence of sites, pH change is inferred from field results of sites adjacent to the map unit.
A3-508741
30 Sept 2015

Appendix 3


East Trinity Acid Sulfate Soil Remediation
Change in existing acidity by map unit*
* The change from the pre to post treatment spline value for existing acidity (above the reduced soil layer) is assigned to each map unit using the field results of sites in that unit. An average value for the acidity change is assigned if multiple sites are present. In the absence of sites, acidity change is inferred from field results of sites adjacent to the map unit.
LEGEND
Areas where existing acidity has been reduced significantly**
equiv. % S
Mol H+/t
0.45 to 0.35
281 to 218
<0.35 to 0.2
<218 to 125
<0.2 to >0.1
<125 to >62
Areas with a minor reduction in existing acidity
0.1 to 0.0
62 to 0
** Where existing acidity includes actual acidity from soluble and exchangeable acidity measured by TAA (method 23F) and retained acidity from iron and aluminium hydroxy-sulfate compounds measured by S_NAS (method 20J).
MAPPING UNIT CODES
Map Unit
Description
Sa1 Sulfidic1, Active Treatment, 0.0-0.3m AHD
Sa2 Sulfidic1, Active Treatment, 0.3-0.5m AHD
Sp3 Sulfidic1, Passive Treatment, 0.0-0.5m AHD2
Spg3 Sulfidic1, Passive Treatment, 0.0-0.5m AHD, George Creek3
Spf3 Sulfidic1, Passive Treatment, 0.0-0.5m AHD, Freshwater4
Ant2 Sulfidic, Not Treated, 0.3-0.5m AHD
Ant4 Sulfidic, Not Treated, 0.5-1m AHD
Snr4 Sulfidic, Self Neutralising, 0.5-1m AHD residual acidity5
Sn4 Sulfidic, Self Neutralising, 0.5-1m AHD
Sn5 Sulfidic, Self Neutralising, >1m AHD
Sch5 Chenier >1m AHD, Sulfidic at Depth6
S5 Sulfidic at depth >1m AHD7
N6 Non ASS >2m AHD
Sp Sulfidic Spoil
1 Sulfuric prior to treatment
2 7 years active treatment, 4 years passive treatment
3 Responding to recent increase in tidal inundation level
4 Permanent freshwater inundation
5 Thin band of residual acidity present
6 Some cheniers have sulfuric material at depth
7 Typical depth to sulfidic layer is 1.5m, typical thickness 1m
LOCALITY
Trinity Bay
Cairns
METRES
0
500
Datum: GDA94, Projection: MGA 55
Queensland Government
N
George Creek
Hills Creek
Firewood Creek
Magazine Creek
Trinity Inlet
A3-508742
30 Sept 2015