Climate change: a frontier for acid sulfate soil research

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Abstract
Sea-level is predicted to continue to rise this century, threatening the integrity of coastal floodplains throughout the world. The low-lying elevation of much of the 17 million ha of acid-sulfate soils that occur worldwide, renders these landscapes particularly vulnerable to the impacts of climate change. Acid sulfate soils landscapes are regulated by redox driven biogeochemical processes that are sensitive to watertable dynamics, tidal exchange and temperature. The increased likelihood of extreme weather events such as drought and floods and rising global temperatures are directly relevant to the redox and hydrological processes that influence acid sulfate soil behaviour and their impact on the environment. This paper examines aspects of climate change and highlights some of the key challenges for acid sulfate soil research.

Keywords
Pyrite; iron sulfides; monosulfides; wetlands; sulfuric.

Introduction
Dealing with global warming, climate change and rising sea-levels has been described by international leaders as possibly the largest moral and environmental dilemma of our time. The low-lying elevation of much of the 17 million ha of coastal acid sulfate soils (CASS), render these landscapes particularly vulnerable to rising sea-levels. Being landscape systems dominated by redox processes that are sensitive to watertable dynamics, the increasing likelihood of extreme weather events such as drought and floods as predicted by climate scientist (IPCC 2007) will also affect how CASS behave and impact the environment. Major shifts in fundamental coastal acid sulfate soil biogeochemistry and hydrology are anticipated, yet the consequences of global climate change to soil and water quality in these landscapes are largely unexplored.

Climate change is dependent on a complexity of regional factors and its impacts will vary across the globe (IPCC 2007). Even within continents the predicted impacts on weather patterns and sea-level are diverse. It is anticipated that tropical regions will experience increasing rainfall and more frequent cyclones. Other areas will become increasingly prone to extreme droughts. Understanding these potential impacts of climate change on CASS landscapes is particularly important, given the utility of these areas for agriculture and urban communities, their unique capacity to cause extreme environmental degradation, and their sensitivity to climatic factors such as temperature and hydrology and susceptibility to sea-level inundation. There is a strong and expanding fundamental knowledge of processes in CASS landscapes, but limited studies to date that consider the impacts of climate change. This paper examines some of the key issues of climate change of relevance to ASS.

Climate change
The predicted impacts of climate change are warmer conditions, an increasing proportion of rainfall to occur from heavy falls, increasing occurrence of drought in many regions, increasing frequency of intense tropical cyclones, and incidents of extreme high seas (e.g. tsunamis, storm surges) (IPCC 2007). All of these predicted impacts of climate change have direct relevance to CASS landscapes, through either exacerbating oxidation by drought, re-instating reductive geochemical processes or changing the export and mobilisation of contaminants. The potential impacts of climate change vary between regions (IPCC 2007), and for CASS, the relative importance of any one of these issues will vary depending on landscape elevation and latitude. Specific land management factors such as man-made drainage will also affect how climate change impacts CASS. These issues are discussed in the following sections.

Sea-level rise
Tidal inundation of CASS is capable of shifting the geochemical regime from oxidising and acidifying, to reductive and neutralising system. This has been examined experimentally and recently demonstrated on a field scale by our research group at East Trinity, north-eastern Australia (Johnston *et al*. 2009). The CASS at

East Trinity oxidised and acidified in the 1970s, when developers installed a 7 km long seawall, tidal gates, drained and cleared 740 ha of tidal wetland to grow sugarcane. This dewatered underlying sulfidic soils, exposing and oxidising iron sulfide minerals, resulting in slugs of highly acidic water as low as pH 2.5, crop failure, fish kills and major impacts on neighbouring wetlands (Johnston *et al*. 2009). Tidal inundation of this site commenced incrementally in 2001–02, and now most of the formerly acidified areas across the site are regularly inundated by tidal waters.

Microbial driven reductive geochemical processes have established quickly at East Trinity, much of the acidity has been naturalised in the soil profile (Figure 1), dramatically improving surface and groundwater water quality (Johnston *et al*. 2009). The site has reverted from a once chronic and severely acidic condition to a situation where acidic discharges are now very rare (Johnston *et al*. 2009). The geochemical transition at the East Trinity site caused by seawater inundation has initiated extensive reductive dissolution of Fe (III) oxide minerals, resulting in very high concentrations of pore water Fe^{2+} (>2000 mg L-1) in the former sulfuric horizons and thick accumulations of reactive Fe (III)-oxide minerals at the ground surface (Figure 2). Iron reduction at this scale has a range of geochemical consequences, such as the mobilisation of arsenic and other contaminant metals (Burton *et al*. 2008). The longer term consequences of tidal inundation are the focus of current research at the East Trinity study site.

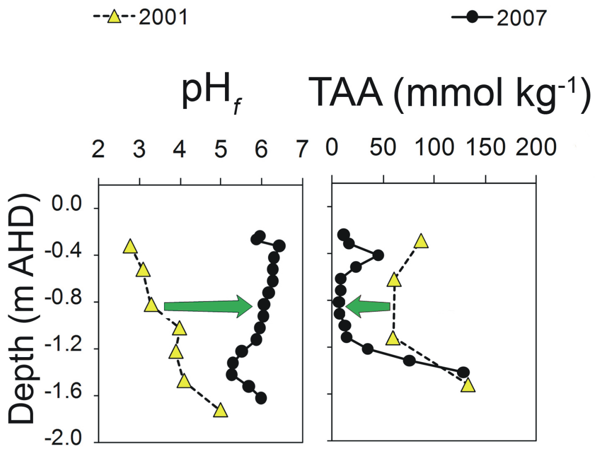

Figure 1. Changes in soil pH and Total Actual Acidity (TAA), for a former sulfuric soil horizon at the East Trinity Wetland, Cairns, Eastern Australia, showing a dramatic increase in soil pH and decrease in TAA after 6 years of permanent tidal inundation (adapted from Johnston *et al*. 2009).

Figure 2. Photos illustrating the abundance of iron in the shallow groundwater and as surface precipitate accumulations at East Trinity, resulting from tidal inundation triggered microbial reduction of iron minerals within the deeper, former sulfuric soil layers.

Tidal inundation at East Trinity has also triggered a succession of floodplain vegetation communities towards more salt tolerant species. Vegetation types vary in their supply of labile organic carbon for reductive iron-sulfur cycling. Distinctive relationships are known to occur between vegetation types and liability of organic carbon (Blodau and Peiffer 2003; Johnston *et al.* 2003). The magnitude of vegetation change and indirect effects on CASS are still largely unquantified.

Periodic sea-water inundation

CASS are prone to pulse events of saline water intrusion, due to extreme tides, storm surge and tsunamis.

These events are generally short-lived and do not shift systems from oxidative to reductive geochemical condition. The inundation of acidic soils with saline water has a number of important possible direct effects that include: 1) Enhancing the release of acidity as Al^{3+} via cation exchange processes, which may then acidify surface or downstream waters (Wright *et al.* 1988); 2) Enhancing the release of Fe (Portnoy and Giblin 1997). Cyclic redox transformations of Fe greatly influence the acidity, chemistry and oxygenation status of overlying waters (Burton *et al.* 2006); 3) Enhancing the release of nutrients into pore waters, particularly NH_4 (Portnoy and Giblin 1997).

Recent research by our group at Southern Cross University has examined the response of a range of CASS to short-term saline water inundation. The results of this research are being presented in detail at the 19th World Congress on Soil Science (Wong *et al*. submitted). Saline water generally causes a rapid displacement of acidic metal cations and metal contaminants, resulting in lower pH and increased metal contents in surface waters. The potential for greater release of acidity and contaminants by periodic saline water ingress will be enhanced under the currently predicted changing climate scenario of increasing storm surges and extreme high tides.

Increasing frequency of extreme weather events: droughts and floods

Drought

The effects of prolonged drought on the further oxidation and acidification of CASS have been examined for agricultural areas (e.g. Wilson *et al*. 1999). Drought can exert its greatest impact on already drained and therefore, hydrologically stressed CASS landscapes. Interestingly, Wilson *et al*. (1999) found that in periods of drought, water quality in agricultural field drains improved. This was attributed to an inversion of the hydraulic gradients caused by crop water use, lowering the groundwater to below the drainage system and effectively preventing seepage. However, when rainfall does return and droughts break, extremely poor quality can result. It is well known that 'first-flush' flood events in CASS cause the greatest impact (Sammut *et al*. 1996).

Exposure of unoxidised sulfidic soils by extreme drought is an emerging concern in drought prone regions. In their natural state, CASS landscapes are characteristically waterlogged, and drought has rarely been considered a significant threat. However, water capture and irrigation have reduced the discharge of most major catchments throughout the world, particularly at critically dry periods. Demand for secure water in developing nations is increasing and regulation of river flows is continuing (e.g. the Mekong). The vulnerability of drying out water bodies that currently prevent subaqueous sulfidic soil materials from oxidising is largely unknown. With higher temperatures, increasing evaporative losses, less rainfall and greater demand on water resources under a changing climate, subaqueous sulfidic areas that are currently protected by natural water bodies will become increasingly susceptible to exposure by drought. An insight to the potential scale of drought triggered CASS impacts is currently provided in the Murray-Darling river basin of Australia, arguably one of the most highly regulated and stressed major river systems. An extreme drought period that has dominated the catchment since the year 2000, has lowered lake water levels, exposing thousands of hectares of sulfidic shoreline and lake-bed sediments (Fitzpatrick *et al*. 2008). These sediments are beginning to oxidise and acidify, and predictions indicate that water levels will continue to drop for the next couple of years. Climate change predicts a greater occurrence of drought, the vulnerability of subaqueous ASS and potential consequences to water quality have not been systematically assessed.

Floods

Biogeochemical processes occurring in CASS landscapes exert a controlling influence on drainage water quality (Burton *et al.* 2006). Catastrophic fish kills as a result of extreme deoxygenation and/or acidification can result from large flood events (Bush *et al*. 2004; Sammut *et al.* 1996; Johnston *et al*. 2004). In isolation, it would seem reasonable to expect that an increase the frequency of flood events will increase the environmental and agronomic impact from CASS. However, there is a range other factors that may contribute to the magnitude of floodwater impacts, such as the abundance of monosulfidic black ooze (MBO) in drains and seasonality. Deoxygenation is known to be far more intense during summer floods due to the more rapid decomposition of floodplain vegetation (Johnston *et al*. 2004). A consideration of how contaminants accumulate in the soil profile and how MBO materials accumulate in drains between floods, and the influence of seasonality is required to begin to understand how future climate change may affect flood induced impacts in CASS landscapes.

Conclusions

Climate change is predicted to causes many environmental impacts that have direct relevance to CASS. Our scientific understanding of the chemical, biological and hydrological processes in CASS indicates that climate change will have an impact on these soils and CASS landscapes. However, advancing our understanding of these impacts will require new science that integrates the key areas of understanding the influence of climate change on the parameters which govern them. This is a critical and emerging frontier for acid sulfate soil research.

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