

CLIMATE CHANGE ADAPTATION IN ACID SULFATE LANDSCAPES

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ABSTRACT

Oxidation of sulfide minerals produces sulfuric acid and consequently creates Acid Sulfate Landscapes (ASLs), which represent one of the most degraded types of land-surface environments. Although acid sulfate-producing weathering is a naturally occurring process, it is markedly facilitated by human intervention. Mining is by far the dominant anthropogenic cause for the creation of inland acid sulfate footprints while land reclamation in coastal lowlands is the driver for the formation of coastal ASLs. The projected climate change highlights the possibility of an increase in the frequency and severity of extreme weather events such as droughts and heavy rains, which is likely to accelerate the acid generation in some circumstances and increase the frequency and magnitude of acid discharge. Sea level rise as a result of global warming will cause additional problems with the coastal ASLs. This is a review article. The following aspects are covered: (a) the overriding biogeochemical processes leading to acid sulfate-producing weathering, (b) a brief introduction to the inland acid sulfate landscapes, (c) a brief introduction to the coastal acid sulfate landscapes, (d) the likely impacts of climate change on ASLs and (e) the possible measures to combat climate change-induced environmental degradation in the identified key acid sulfate footprints. The projected climate change is like to significantly affect the acid sulfate landscapes in different ways. Appropriate management strategies and cost-effective technologies need to be developed in order to minimize the climate change-induced ecological degradation.

Keywords: Climate Change, Acid Sulfate Landscapes (ASLs), Acid Mine Drainage (AMD), Acid Sulfate Soils, Pyrite, Ecological Degradation

1. INTRODUCTION

The term “Acid Sulfate Landscapes” (ASLs) used in this article is referred to as land-surface environments that are affected by the oxidation of sulfide minerals. Oxidation of many metal sulfides leads to the generation of sulfuric acid and liberation of environmentally significant metals (Alpers and Blowes, 1994; Dinelli *et al.*, 2001; Lin and Lin, 2003; Audry *et al.*, 2005; Lee *et al.*, 2005; Lu *et al.*, 2011). This poses a major environmental threat in mined areas and coastal lowlands where sulfide minerals are present (Wilson and Hyne, 1997; DeNicola and Stapleton, 2002; Levings *et al.*, 2005). The soils formed from sulfidic parent materials are known as acid sulfate soils (mine site acid sulfate soils and coastal acid sulfate soils) and the process through which the acidic water discharges from the acid sulfate soils, mine spoils and tailings is referred to as acid drainage. Acid drainage from mine sites has been traditionally termed as Acid Mine Drainage (AMD) (Johnson and

Hallberg, 2005; Akcil and Koldas, 2006). More recently, the term “Acid Rock Drainage” (ARD) has also been used to cover acid drainage from naturally exposed rock formations that contain sulfide minerals (Mata *et al.*, 2002; Miller *et al.*, 2010).

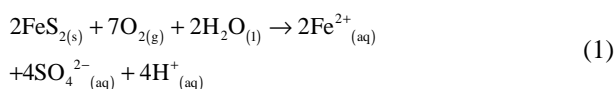
Global-scale observations of sulfide mineral-derived acid drainage indicate that the incidences of significant environmental damage in ASLs frequently occur during and immediately after the first heavy rainfall events following prolonged dry spells (Lin *et al.*, 2007; Macdonald *et al.*, 2007; Nordstrom, 2009). The projected climate change highlights the possibility of increase in the frequency and severity of extreme weather events such as droughts and heavy rains (Mirza, 2003; IPCC, 2007), which is likely to intensify the environmental damage in ASLs. The flushing of acid sulfate materials from acid sulfate soils and mine wastes will cause larger sudden increases in concentrations that will be an ever increasing danger to aquatic life with climate change (Nordstrom, 2009).

This review article covers the following aspects: (a) the overriding biogeochemical processes leading to acid sulfate-producing weathering, (b) a brief introduction to the inland acid sulfate landscapes, (c) a brief introduction to the coastal acid sulfate landscapes, (d) the likely impacts of climate change on ASLs and (e) the possible measures to combat climate change-induced environmental degradation in the identified key acid sulfate footprints.

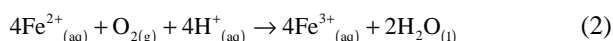
2. ACID SULFATE PRODUCING WEATHERING

Oxidation of certain sulfide mineral types results in the production of acid sulfate materials. The common acid-generating sulfide minerals include pyrite (FeS_2), pyrrhotite (Fe_{1-x}S), chalcopyrite (CuFeS_2), marcasite (FeS_2), sphalerite (ZnS) and arsenopyrite (FeAsS) (Jennings *et al.*, 2000; Jiang *et al.*, 2008).

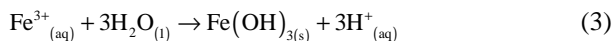
Pyrite is the most abundant sulfide mineral in the Earth's surface environments (Alpers and Blowes, 1994). In a global-scale, oxidation of pyrite is the most important process leading to the formation of ASLs. The primary oxidant driving pyrite oxidation is molecular oxygen (O_2), which plays a direct role in pyrite oxidation at the initial stage of pyrite weathering under circumneutral pH conditions, as described by the following chemical equation:



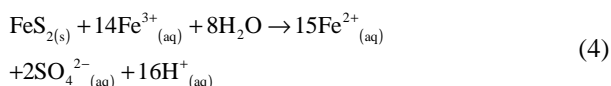
The aqueous ferrous ion (Fe^{2+}) generated from Equation 1 may be subsequently oxidized to ferric ion (Fe^{3+}) by molecular oxygen, as shown below:



The aqueous Fe^{3+} produced from Equation 2 and 3 can then hydrolyze to generate hydrogen ion (H^+) and consequently cause decrease in pH:



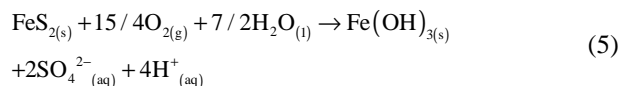
When pH is sufficiently low to maintain Fe^{3+} solubility, Fe^{3+} acts as a more effective oxidant for pyrite oxidation, as expressed by the following overall chemical Equation:



Oxidation of the aqueous Fe^{2+} by O_2 to produce Fe^{3+} is very slow under acidic conditions but the process can

be catalyzed by iron-oxidizing bacteria (Singer and Stumm, 1970; Olson, 1991), which are commonly present in the natural environments where pyrite occurs.

Overall, the microbially mediated oxidation of pyrite can be expressed by the following general chemical Equation:



Therefore, the oxidation of each mole of pyrite produces two moles of sulfuric acid and one mole of iron hydroxide upon its complete weathering.

3. INLAND ACID SULFATE LANDSCAPES

Inland acid sulfate landscapes are associated with near-surface geological formations that contain acid-producing sulfide minerals. Exposure of sulfidic rocks on the land surface could be part of the natural geomorphic evolution, leading to acid generation and translocation to downstream areas (Grant and Newell, 1993; Neubert *et al.*, 2011). However, human intervention such as mining and large construction activities can dramatically facilitate these processes (Jamieson *et al.*, 2005; Johnson and Hallberg, 2005; Nieto *et al.*, 2007).

Mining is by far the dominant anthropogenic cause for the formation of inland ASLs. In 1989, it was roughly estimated that ca. 19,300 km of streams and rivers and ca. 72,000 ha of lakes and reservoirs worldwide had been seriously damaged by mine effluents (Johnson and Hallberg, 2005). Mining projects have been rapidly increased in the recent two decades, especially in countries experiencing rapid economic growth such as in China. Many mines in the developing countries are operated without sufficient environmental management measures in place or no environmental management measure adopted at all in the cases of illegal mining (Lin *et al.*, 2007). The extent of AMD-induced ecological degradation could be far larger than two decades ago.

Depending on the type of ore, the method used for mining, the abundance of sulfide minerals and the dominant type of sulfide mineral, the characteristics of acid sulfate footprints created by mining operations could vary markedly from place to place.

3.1. Acid Sulfate Footprints Associated with Metal Ore Mining

Many economic metal ore deposits such as iron, copper, gold, lead and zinc are associated with large amounts of pyrite, pyrrhotite and arsenopyrite. In many cases, the copper and zinc ores themselves are acid-generating sulfide minerals. The oxidation of these sulfide minerals not only produces sulfuric acid but also

mobilizes substantial amounts of heavy metals that are originally bound to these minerals. Depending on the geological conditions, the ores may be extracted by different methods, which determine the type, size and distribution of mining footprints.

Open-pit mining is a common practice for metal ore extraction. This method involves the removal of soil and rocks (overburden) overlying the ore body. The bottom of mine pits usually extends below the groundwater table. Therefore, groundwater tends to flow into the mine pit. To allow mining to take place, the water needs to be pumped out of the pit. If sulfide minerals are present and oxidized, this could cause marked off-site ecological impacts. An acidic pit lake usually forms at some point in time after mine closure (Geller *et al.*, 2012). The acidic, metal-rich lake water can generate plumes of polluted groundwater which migrate down-gradient into the surrounding aquifers (Younger *et al.*, 2002).

In many historical mines, the overburden materials were dumped in the areas near the mine pits. Accelerated oxidation of sulfate minerals in the waste soil/rock stockpiles results in rapid acid generation, which inhibits colonization of natural plants. The lack of vegetative cover makes the soil more easily eroded. Therefore, waste soil/rock dumps are an important source of acid mine drainage, as well as sulfide mineral-containing sediments to the downstream areas. With increased environmental concerns, safe storage of waste soils/rocks are now legally required in most countries. Usually, the sulfidic waste soil/rock materials are stored in purpose-built storage facilities with a liner on the bottom to prevent seepage of acidic water down to the adjacent aquifers and a capping layer of good soil to allow the establishment of vegetative cover after the capacity of the overburden storage facility is used up. Acid neutralizing agents and fertilizers are frequently applied to create more favourable conditions for vegetation establishment (Brown *et al.*, 1997; Gatzweiler *et al.*, 2001; Bleeker *et al.*, 2002; Xenidis *et al.*, 2002; Maddocks *et al.*, 2004; Ram *et al.*, 2006; Liu *et al.*, 2009; Padmavathiamma and Li, 2010).

Where underground mining is practiced, the volume of waste rocks is markedly reduced, especially when waste rocks are used to backfill the mine voids. During mining operations, water in the mine tunnel needs to be pumped out, which could have off-site environmental impacts. Nowadays, on-site treatment of acidic mine water is part of the routine operations in many active mines in order to meet the legal requirements. After mine closure, the abandoned underground mine workings are flooded if its elevation is below the water table. The acidic water in the abandoned underground mine workings can then become a source of contaminants to the adjacent surface water and groundwater, depending on the geomorphic and geological conditions.

Another important mine footprint is tailings dam/impoundment that is designed to contain the residues of ore processing. Mine tailings materials are usually of fine-grained and consequently have a large specific area. Sulfide mineral particles in such small sizes are usually highly reactive. In order to minimize the oxidation of sulfide minerals in the tailings dam, a layer of cover water needs to be maintained to reduce the level of dissolved oxygen in the water-sediment interface.

In some mines, mud-retaining impoundments or sedimentation ponds are also constructed to intercept the sediments and mine water from the waste soil/rock dumps, as well as the mined land surfaces. However, due to high sedimentation rate, the holding capacity of these facilities could be rapidly reduced, resulting in overflowing of acidic mine water into the downstream areas, especially during and after heavy rainfall events (Lin *et al.*, 2007). This may be a worse scenario since the total amounts of acid and toxic materials in the dam water, after accumulation during a longer period, are much greater, as compared to direct discharge from the mine spoil stockpiles.

The most significant off-site impact of acid mine drainage is the ecological degradation of the receiving streams, lakes and estuaries (Nieto *et al.*, 2007; Shipp and Zierenberg, 2008; Bae *et al.*, 2010). In areas where the mines are in close proximity to human habitats, the mine water or mine water-affected stream water is used for irrigation purposes. This could cause severe contamination of soils and shallow groundwater. The edible portions of crops grown on the mine water-contaminated soils frequently have elevated concentrations of heavy metals (Lin *et al.*, 2005), which could cause human health problems. Where drinking water is extracted from the contaminated shallow aquifer, the well water could also be the source of human health problems (Chen *et al.*, 2007).

3.2. Acid Sulfate Footprints Associated with Coal Mining

Unlike metal ore deposits, coal strata tends to have much simpler mineralogical composition with pyrite being the only sulfide mineral present in significant amount. Consequently, AMD from coal mines frequently has relatively low levels of heavy metals although some coals may contain high concentration of arsenic and selenium (Speight, 2005). Due to the nature of sedimentary deposit, coal-borne pyrite frequently appears as microcrystals in a framboidal structure, which can be more easily weathered, as compared to large pyrite cubes encountered in hard rocks. Depending on the occurrence depth of a coal deposit and other conditions, different methods are used to extract the coal. Surface mining is usually used for coal deposit that occurs at a depth less than 50 m. Similar to open-pit

metal ore mining, open-pit coal mining also creates acid sulfate pit lakes (Radhakrishnan *et al.*, 2011) and waste soil/rock dumps. Modern surface coal mining frequently uses non-sulfidic overburden materials to backfill the mine pits, as practiced in strip mining. This minimizes the possibility of directly exposing sulfide minerals on the land surface.

Underground mining is usually used for extracting coal from deeply occurring coal seams. This mining method tends to have minimal disturbance to the land surface but may have adverse impacts on the quality of groundwater and become a source of acid mine drainage.

Coal refuse (tailings) from the coal preparation plant usually contains elevated concentration of pyrite and thus represent a significant acid sulfate footprint associated with coal mining (Olyphant *et al.*, 1991), especially during the earlier days when these materials were not stored properly.

3.3. Inland Acid Sulfate Soils

In arid and semi-arid areas that are subject to prolonged droughts, inland acid sulfate soils may develop from the dried wetlands where iron sulfides are formed and accumulated under previous anaerobic conditions (Fitzpatrick *et al.*, 1996; Hall *et al.*, 2006; Lamontagne *et al.*, 2006).

In a global scale, inland acid sulfate soil area does not represent a major ASL. However, in certain area such as in the outback Australia, it could have a significant impact on the local ecosystem (McCarthy *et al.*, 2006).

4. COASTAL ACID SULFATE LANDSCAPES

Coastal acid sulfate landscapes occur in the areas where existing and past pyritic sediments are present. These include mangrove tidal flats, coastal salt marshes and coastal floodplains/deltas. Globally, ASS are mainly distributed in Southeast Asia and Australia with paddy rice cultivation being the predominant uses of ASS in the former (e.g., Dent and Pons, 1995; Minh *et al.*, 1997) and sugarcane farming and cattle grazing being the important agricultural use in the latter (mainly in the Queensland and northern NSW coastal areas) (e.g., Lin and Melville, 1994; Lin *et al.*, 1998a; Cook *et al.*, 2000). There are about 24 million ha of coastal acid sulfate soil around the world (Sullivan, 2004). The location of coastal acid sulfate soils often coincides with high population density areas (Ljung *et al.*, 2009). As such, coastal acid sulfate soils not only impact on ecosystems but also pose a threat to human society. It was conservatively estimated that there are over 4 million ha of ASS present along the Australia's coast. ASS-derived environmental degradation is so great that the problem has been causing conflicts among different sectors of communities (White *et al.*, 1996).

The concentration of pyrite in estuarine sediments is closely related to organic carbon content and sedimentation rate (Lin *et al.*, 1998b). Substantial amounts of pyrite (up to 10%) can be accumulated in mangrove sediments in locations with low sedimentation rate (e.g., in Fiji Islands, unpublished data). In contrast, in rapidly expanding deltaic areas with high sedimentation rate, the concentration of pyrite in the sediments is generally very low (Lin and Melville, 1994). Like coal strata, pyrite in estuarine sediments usually appears as microcrystals in a framboidal structure and therefore is subject to rapid oxidation when exposed to atmosphere.

The distribution of coastal acid sulfate soils coincides with the estuarine areas that attract human settlement. Human activities involving excavation of pyritic estuarine sediments such as road construction, urban development and fish pond farming could expose pyritic sediments on the land surface. This causes acceleration of pyrite oxidation and therefore creates acid sulfate footprints. While pyrite oxidation in coastal floodplain may take place as a naturally occurring process in certain physiographic settings, agricultural practice could dramatically intensify the process (Lin and Melville, 1993; 1994).

In particular, sugarcane farming requires intensive land drainage to allow sugarcane plants to grow. This, combined with the floodgate control measures to prevent the brackish/saline estuarine water from penetrating into the field drains, leads to lowering of watertable in the ASS-containing floodplains and consequently induces/enhances pyrite oxidation in the subsoil layers to produce sulfuric acid. The discharge of acid sulfate materials from sugarcane acid sulfate soils into the adjacent estuarine waterways during flood events acidifies the estuarine water and causes damage to the aquatic ecosystems (Lin *et al.*, 2004; Macdonald *et al.*, 2004).

5. LIKELY IMPACTS OF CLIMATE CHANGE AND POSSIBLE RESPONSE MEASURES

Acid sulfate landscapes are fragile ecosystems that are subject to further environmental damage under a changing climate. The increased temperature as well as more frequent and severe droughts and floods will have complex impacts on ecological processes in ASLs. It is not intended in this presentation to cover all possible scenarios that are likely to be encountered in a more variable climate. Instead, some key ASLs are identified and discussed below.

5.1. Mine Pit Lakes

Sulfide minerals exposed on the pit walls are a major source of acid and metals upon oxidation. Since

the oxidation rate of sulfide minerals tends to increase with increasing temperature (Schoonen *et al.*, 2000), acid generation is likely to be enhanced under climate change in some circumstances. Climate is the single most important factor affecting the hydrological processes associated with a mine pit lake (Castendyk and Eary, 2009). Increased precipitation is likely to cause rise in the lake water level, which poses a risk of contaminating surface water and shallow groundwater.

For mine pit lakes with a high risk of causing off-site environmental impacts, it may be necessary to adopt appropriate remediation methods for minimizing acid generation from the pit walls and detoxifying the lake water. A few methods for mine pit lake remediation have been proposed (Castendyk and Eary, 2009). The rehabilitation efforts can also make beneficial utilization of pit lakes possible (Castendyk and Eary, 2009). This is particularly relevant to the dryland areas where water resources are scarce (Kumar *et al.*, 2009).

5.2. Underwater-Stored Mine Tailings

In practice, underwater storage methods have been used for disposal of mine tailings that are potentially acid-producing. Tailings Storage Facilities (TSFs) are designed to contain and keep the tailings materials under a layer of water in order to minimize contacts of sulfide minerals with oxygen. However, the engineering design of many TSFs in existing mines might not take into account the potential effects of climate change. It is likely that during future prolonged drought events, the strong evaporation rate will result in a thinner than designed layer of overlying water in the TSFs or even temporary drying out of the TSFs, leading to enhanced oxidation of sulfide minerals contained in the TSFs.

Measures to counteract drought-induced oxidation of sulfide minerals in TSFs could include methods that can be used to avoid the occurrence of massive oxidation of sulfide minerals prior to water level re-rise or re-inundation of the TSF. Possible options are:

- No action if the dry interval is not sufficiently long to allow the development of massive microbially catalyzed oxidation of sulfide minerals and
- Application of chemical agents to impede oxidation of sulfide minerals

It was proposed that sodium oleate and phosphates be used to inhibit pyrite oxidation by passivating the mineral surfaces (Nyavor and Egiebor, 1995; Jiang *et al.*, 2000). However, these techniques may be more suitable for treating materials with a high proportion of sulfide minerals such as sulfide ore concentrate. Application of such methods to tailings that contain a relatively small proportion of sulfide minerals is probably not cost-effective.

Bactericides have also been used to inhibit the growth of iron and sulfide-oxidizing bacteria that play an important role in microbially-enhanced oxidation of sulfide minerals (Rastogi, 1996). This method only has short-term effects on suppressing the microbial activities (Johnson and Hallberg, 2005). Nevertheless, for temporary control of the growth of iron and sulfide-oxidizing bacteria, as required in the current circumstances, the anti-bacteria method may be appropriate.

Another potential method for impeding oxidation of sulfide minerals is to top-dress acid neutralizing materials on the drying tailings materials to halt pH drop (Mylona *et al.*, 2000; Mata *et al.*, 2002). This reduces the level of aqueous Fe^{3+} that triggers catalyzed oxidation of sulfide minerals (Moses *et al.*, 1987; Rimstidt and Newcomb, 1993; Janzen *et al.*, 2000).

The fundamental knowledge that is required for evaluation of these options includes:

- How long does it take to create a sufficiently acidic pH by abiotic oxidation of sulfide minerals to allow microbially-catalyzed oxidation to take place when no actions are taken?
- Can other oxidants rather than molecular oxygen e.g., rainwater-borne H_2O_2 play roles in the oxidation of sulfide minerals?
- What are the effects of bactericides or added acid-neutralizing materials on preventing the tailings from acidification?

These are among the research issues that need to be addressed in order to develop cost-effective measures for climate change adaptation.

5.3. Sulfidic Mine Spoils

For surface mining, overburden materials (mine spoils) are usually disposed of on land surfaces. In mines where environmental management plan is implemented, mine spoils are usually stored in a dedicated storage facility with a layer of sealing materials (or capping materials) to minimize the penetration of air and water into the mine spoils. However, cracking of sealing layers could occur in areas experiencing acute dry and wet seasons (Johnson and Hallberg, 2005). This is likely to be intensified with climate change, potentially initiating oxidation of sulfide minerals in the originally sealed mine spoil storage facilities.

Where no environmental management plan is in place, mine spoils are often stockpiled on the land surfaces without any treatment. This is common in historical mines and many current mines especially in the developing countries (Sracek *et al.*, 2006; Lu *et al.*, 2010). Consequently, the sulfide minerals in mine waste stockpiles are subject to rapid oxidation and acid production. These acidic, metal-rich mine spoil

stockpiles act as major sources of AMD. Given the practical difficulties entailed in inhibiting the formation of AMD at sources, treatment of mine water using either active or passive systems has been the major counteracting measures for AMD remediation in the developed world (Johnson and Hallberg, 2005; Gazea *et al.*, 1996; Sheoran and Sheoran, 2006; Kleiv and Thornhill, 2008) while in many developing countries, acidic mine water is directly discharged into streams (Naicker *et al.*, 2003; Lin *et al.*, 2007). With climate change, the volume of mine water and loadings of acids and metals during extreme flood events may exceed the designed capacity of mine water treatment facilities, resulting in the entry of untreated mine water into downstream areas. For mines without mine water treatment facilities, more severe environmental damage is expected.

To minimize the climate change-induced further environmental damage in this type of ASLs, a “source control” approach needs to be adopted. In-situ acid neutralization of the acidic topsoils for vegetation establishment has been a major research effort for rehabilitation of exposed mine spoils in recent decades (Brown *et al.*, 1997; Gatzweiler *et al.*, 2001; Bleeker *et al.*, 2002; Xenidis *et al.*, 2002; Maddocks *et al.*, 2004; Ram *et al.*, 2006; Liu *et al.*, 2009; Padmavathamma and Li, 2010). However, there has so far been limited success in large-scale application of such technologies. There has been insufficient in-depth research conducted to unveil the biogeochemical processes accompanied with various remediation methods.

The research aspects that need to be addressed in order to improve the fundamental understanding of these biogeochemical processes may include:

- Mechanisms and kinetics of acid neutralization, particularly decomposition of jarosites, deprotonation of variably-charged colloids and desorption of exchangeable aluminium under alkaline conditions;
- Evolution of iron/sulfide-oxidizing microbial community as pH increase during acid neutralization of the mine spoils; and
- Potential roles of neutrophilic iron-oxidizing bacteria in oxidation of sulfide minerals

5.4. Coastal Acid Sulfate Landscapes

Perhaps the most vulnerable coastal acid sulfate footprints are among those containing pyritic soil materials that are directly exposed on the land surfaces such as road base, fishpond bunds and other construction sites as a result of land excavation activities. For such areas, complete neutralization of the acidity is necessary to prevent future environmental damage to be induced by climate change. For broadacre agricultural lands, it is economically unfeasible to completely neutralize the acidity in the soils. Therefore, alternative strategies need to be developed.

Among various modes of agricultural uses, sugarcane farming appears to be the one that is most sensitive to the climate change. The acidity in many acid sulfate soils under sugarcane production is in dynamic equilibrium except during drought spells, which accelerate pyrite oxidation and consequently acid generation in the soil profiles. The newly produced acid materials are ready to be exported to estuarine aquatic systems during major flood events following heavy rains. The potential increases in the length and frequency of droughts, as well as extreme rainfall events are expected to have significant impacts on the sugarcane production and estuarine ecosystems due to the possible increase in acid production rate in acid sulfate sugarcane soils and more frequent acid flush into the adjacent estuarine waterways.

In addition, the elevation of many coastal acid sulfate soils is either slightly higher or below the sea level. In a longer term, the projected sea level rise as a result of global warming could eventually make the sugarcane farming economically unviable due to the high costs associated with the additional engineering work to maintain a low watertable in the soils. To develop appropriate strategies and cost-effective methods for adapting to the possible environmental changes due to climate variability, the following measures are considered:

- Change from deep drainage system to shallow drainage system, coupled with alternative cropping system may be an option for climate change adaptation in this type of ASLs. This alternative water management strategy will slow down watertable lowering during extended dry spells and consequently reduce acid generation rate
- Trash retention: To change pre-harvest sugarcane burning to green harvesting with at least 50% of sugarcane trash being retained in the field. Methods can be developed to optimise the conditions for rapid decomposition of the sugarcane residues, which will create a healthy topsoil layer and also raise the elevation of the land
- Raised bed: use single row spaces and plant the crop at ground level, followed by soil mounding over the top of the cane sets. This will increase the thickness of unsaturated topsoil layer and also reduce nitrous gas emission, through selected compaction of interspaces and trash retention
- Slot drainage and in-drain acid neutralization: to accelerate removal of surface water during high rainfall events and following flooding and eliminate toxic materials in the drain water before discharging into estuarine waterways
- Introduction of water- and acid-tolerant sugarcane cultivars to allow sugarcane production in the acid sulfate soils with relatively high watertable conditions, as to be caused by sea level rise and increases in major rain events

6. CONCLUSION

The projected climate change is like to significantly affect the acid sulfate landscapes in different ways. Increase in the frequency and severity of extreme weather events such as droughts and heavy rains will accelerate acid generation in some circumstances and increase the frequency and magnitude of acid discharge from acid sulfate footprints into the surrounding areas, causing further damage to the already fragile ecosystems. Appropriate management strategies and cost-effective technologies need to be developed in order to minimize the climate change-induced ecological degradation.

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