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FEATURE

Salinity and acid sulfate soils of the Vietnam Mekong Delta: Agricultural management and adaptation

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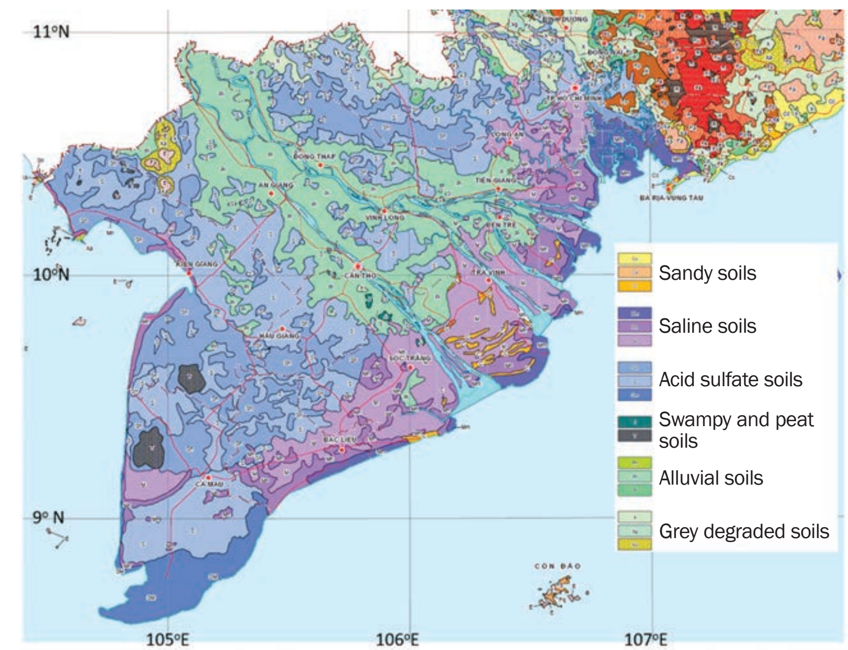
One of the largest concentrations of acid sulfate soils in the world is found in the Vietnam Mekong River Delta, a large low-lying river plain scarcely above sea level, covering 1.6 million ha (4.0 million ac; figure 1) (van Mensvoort 1996; Vietnam Ministry of Agriculture 1978; Huu et al. 2022). Acid sulfate soils have high concentrations of aluminum (Al), sulfates (SO_4^{2-}), and iron (Fe), and when drained produce sulfuric acid (H_2SO_4) that reduces soil pH below 4 (van Mensvoort 1996; Huu et al. 2022). These metals accumulate in the topsoil during the tropical dry season and are toxic to plant root growth and development and suppress yields making them some of the most difficult soils in which to grow agricultural crops. Yet, the Vietnam Mekong Delta produces 50% of Vietnam's rice crop; 95% of rice exports; 65% of aquaculture production; 60% of exported fish; and 70% of the country's fruit production (Loc et al. 2021). One of the keys to acid sulfate soil productivity is water-soil adaptive management that maintains crop-specific balance between reducing and oxidizing conditions in the plant rootzone at critical vegetative, bloom, and fruit development stages (Hanhart et al. 1997).

Figure 1

Saline and acid sulfate soils of the Vietnam Mekong Delta map. Saline soils of the Vietnam Mekong Delta peninsula are represented by dark purple (coastal mangrove soils) and two shades of lavender: strongly saline soils and moderate and slightly saline soils (lighter lavender). Acid sulfate soils are represented by shades of blue, with dark blue salt-affected potential acid sulfate soils where saltwater intrusion reaches into freshwater regions; mid-blues strongly acid sulfate soils; and lighter blue moderate and slightly sulfate soils. Alluvial soils (green), grey degraded soils, and grey degraded gleyic soils derived from old alluvium soil (very light green) are found along the mainstem Mekong and Bassac rivers and their distributaries. Scale 1:1,000,000. Image by Vietnam Ministry of Agriculture (1978).



More than 50 years ago vast areas of this delta were covered permanently by wetlands, brackish lagoons, tidal marshes, and mangrove forests. The prevailing winds of the southwest monsoon season brought predictable continuous heavy rains, a consistent 20-fold increase in Mekong River discharge and extensive prolonged flooding inundating lowlands for months (Adamson et al. 2009; Taylor 2014; Ngan et al. 2018). The monsoon is followed by a dry season when the rains stop and farmers adapt their cropping systems by growing flooded rice (*Oryza sativa* L.) varieties in the wet season and digging ditches and canals to drain the floodwater and convey fresh water from the Mekong (Song Tien) and Bassac (Song Hau) rivers and their tributaries to their fields for dry season crop irrigation. A changing climate—sea level rise, a stronger and increasingly variable SW monsoon, and more frequent and prolonged drought (Adamson et al. 2009)—in concert with amplified tidal effects and saltwater intrusion reaching 50 to 130 km (31 to 81 mi) upstream into the main rivers since February of 2020 threaten freshwater resources (Loc et al. 2021; World Bank 2022). A growing population, land use decisions, saline soils, loss of mangrove coastal protection, degraded wetlands, water and sediment flow dynamics affected by upstream dams, and mining of river sediments are challenging delta agriculture capacities to continue to provide an abundance of food and nutrition

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security and rural livelihoods (World Bank 2022; Loc et al. 2021). According to the World Bank (2022), Vietnam is among the world's most vulnerable climate risk countries, ranked 13th among 180 countries by Germanwatch Global Climate Risk Index 2000 to 2019.

In response to these changing conditions, the delta floodwater control system is being modified to encourage farmers to diversify their cropping systems and be more attentive to the environmental impacts of agriculture (Luu et al. 2022). Vietnam Resolution 120/2017/NQ-CP, issued in 2017, promotes "living with floods," "uncertainty adaptation," and nature-based approaches for addressing climate change and upstream development (Luu et al. 2022). Delta farmers are challenged to make a living under these stressful and uncertain conditions. They continue to seek innovative water management and drainage approaches and adapt cropping systems to changing soil-water conditions, building on their accumulated local knowledge and scientific findings gained from laboratory and field experiments. Understanding the chemical and biogeophysical properties and pedogenic processes of acid sulfate soils, developing climate-flexible crops and management systems as well as increasing crop genetic tolerances to Al and salt concentrations are foundational to effective delta agricultural adaptation.

TRANSFORMING A LARGE TROPICAL DELTA INTO AN AGRICULTURAL LANDSCAPE

Fresh water for agriculture and drinking has for centuries been scarce during the long five-month dry season with saline water incursions making the acidic delta soils less productive for crops and the shallow ground water salty and not safe for cooking or drinking (Taylor 2014). Historically this wild, untamed, vast floodplain was sparsely settled with agriculture and small settlements on marine sandy coastal dunes—fresh water oases—created as flooding and river sediments built out the delta. It was not until the French colonization (1800s) and Vietnamese state (1980s) undertook large irrigation programs to construct canals to channel fresh water from the Mekong and Bassac rivers to reduce water and soil salinity that agricultural systems replaced the wetland ecosystem (Taylor 2014; Luu et al. 2022).

At first natural waterways were straightened and deepened, and then connected by canals. The French Colonial Government set about clearing forests and draining wetlands to turn the underutilized and agriculturally unproductive soils into rice production. These sparsely populated, densely vegetated acid sulfate lands were used by resistance fighters as hideouts during the US Vietnam War (1961 to 1973). After the war, the Vietnam state established large-scale state farms (1,000 to 10,000 ha [2,471 to 24,710 ac]) to increase the delta population and alleviate serious food shortages (van Mensvoort 1996). Newly resettled farmers were inexperienced in managing waterlogged acid sulfate soils to make them productive, and the state farms were inadequately funded with a shortage of knowledge and equipment resources as well as insufficient farm workers for large-scale parcels. Excess water on the landscape in monsoon season alternating with dry season freshwater scarcity made delta living conditions harsh, and most of these collective farms failed to grow enough food for farmers to make a living (van Mensvoort 1996).

By the mid-1980s irrigation projects expanded throughout the delta to create a freshwater network across the entire peninsula with sluice gates that protected the waterway grid from saline intrusion and reengineered the waterscape to drain and control water for rice agriculture (Taylor 2014). Rice establishes and grows well in waterlogged environments but is sensitive to salinity with an electric conductivity (EC_{SPE}) threshold of 3 dS m^{-1} (Korres et al. 2022). The saline delta rivers, wetlands, and marshes were converted into perennial freshwater zones. This reduced the seasonal variation in water flow patterns, converted the flood plain into regulated canals, dykes, and polders that irrigated agriculture, and prevented annual flood waters from submerging fields (and sediments from replenishing soil fertility) (Luu et. 2022).

Today's Vietnam Mekong Delta agricultural landscape is built on managing and controlling the quantity and distribution of water year round (flooding, irrigation, fresh and saline waters) in alluvial and acid sulfate soils (figure 2). Water control projects consist of high dyke and flood control, salinity control to enable freshwater agriculture, and salinity control in brackish water aquaculture (Ngan et al 2018). Canals that link to the Bassac and Mekong main stem rivers and their distributaries are used to provide fresh water to agriculture and settlements. During the rainy season, many of these same canals are used to drain the land and release flood waters back into rivers and the West and East China Seas (Ngan et al 2018; Hanhart et al. 1997). Extensive agricultural drainage ditches and canals lower the water table and speed up hydrologic exchanges between the coastal landscape and the ocean which can increase salt concentration (Tully et al. 2019). Sluice gates allow fields to drain after flooding and during low tide and are closed during the dry season and high tide to prevent saltwater from moving into canals and waterways used to drain agricultural fields (figure 2).

ACID SULFATE SOILS OF THE VIETNAM MEKONG DELTA

Acid sulfate soils occupy more than 40% of the Vietnam Mekong Delta (figure 1). Soils are characterized by high Al, Fe, and SO_4^{2-} concentrations and low pH 2.7 to 3.5, >0.5 mol Fe^{2+} and 0.05 mol Al^{3+} m^{-3}. A large portion of these soils are underwater annually for several months during the monsoon season. Sea level rise, seasonal and increasingly variable cyclones, coastal storms, and high tides flood coastal regions and push seawater upriver mixing with fresh water. The onset of the dry season is accompanied by receding waters and shifting salinity concentrations in the waterways with sluice gates and dyke systems built to irrigate and drain the interior landscape and control salinity intrusion. Drought periods can exacerbate saltwater intrusion into coastal groundwater tables as freshwater flow rates decrease and allow saline water to move further inland (Tully et al. 2019). Saltwater intrusion, the landward movement of saltwater, alters soil geochemistry and changes soil porewater chemistry, soil pH, and other characteristics

Figure 2

This sluice gate in Soc Trang Province, Vietnam, connects a main canal to the South China Sea and controls saltwater tidal inflow and flooding outflow. Open sluice gates allow fields to drain after heavy rains and flooding and are closed during high tide to prevent saltwater from moving into canals and waterways used to irrigate agricultural fields.

that affect agricultural cropping systems, species composition, and ecosystem services (Tully et al. 2019)

Alternating aerobic-anerobic conditions in tidal marshes, saltwater wetlands, drainage ditches and canals, and other waterlogged saline soils and sediments are typical environments where acid sulfate soils form (van Mensvoort 1996; Hanhart et al. 1997). Saline wetlands, estuaries, tidal basins, and other marine influenced subaqueous soil environments are ideal for pyrite (FeS_2) to form from Fe-containing soils and sediments exposed to sea water (a source of SO_4^{2-}), decomposing organic matter, and sulfur (S)-reducing bacteria. Tidal movements expose waterlogged soil briefly to air at neap tide allowing the FeS to oxidize to FeS_2 at the very top of the soil surface. As the waters recede they take the neutral buffering bicarbonate (HCO_3^-) ions with them turning the soils acidic (van Mensvoort 1996). When aerobic conditions are introduced via engineered ditches and drainage systems, FeS_2 is oxidized to H_2SO_4 to a much deeper depth and forms a soil sulfuric horizon consisting of soluble forms of Al^{3+}, SO_4^{2-}, and Fe^{2+} (figure 3).

In the Mekong Delta during the dry season the acid sulfate soil oxidizes causing a dramatic drop in pH and an increase in ferrous iron (Fe^{2+}) and SO_4^{2-} in the soil solution (Hanhart et al. 1997). The drop in pH along with salt stress on agricultural crops can reduce germination rates and productivity (Tully et al. 2019). Although Al is usually insoluble, in pH soils below 4.5, clay silicate minerals dissolve releasing soluble Al^{3+} into the soil solution making Al toxicity one of the biggest limitations to growing crops in acid sulfate soils (Le Van and Masuda 2004; Hanhart et al. 1997). During the dry season, when the soil is exposed to air, FeS_2 oxidizes and lowers soil pH, resulting in Al becoming soluble, causing severe Al toxicity that inhibits root growth and impacts plant cell functioning (Le Van and Masuda 2004).

Hanhart et al. (1997) reported that surface water management can alleviate nutritional deficiencies caused by Al and Fe toxicity aggravated by FeS_2 oxidation and improve yields in acid sulfate soils. Replacing continuous submergence rice crops with alternate wet-dry irrigation intervals, midseason drainage, or raised beds can address some of the adverse conditions of acid sulfate soils (Hanhart et al. 1997; Minh et al. 1997a, 1997b; Le Van and Masuda 2004). Lateral ditches and raised beds using alternating wet-dry interval irrigation to correspond with critical plant development periods have expanded delta cropping systems from "rice only" to diversified annual and perennial cropping systems.

RAISED BEDS IN ACID SULFATE SOILS

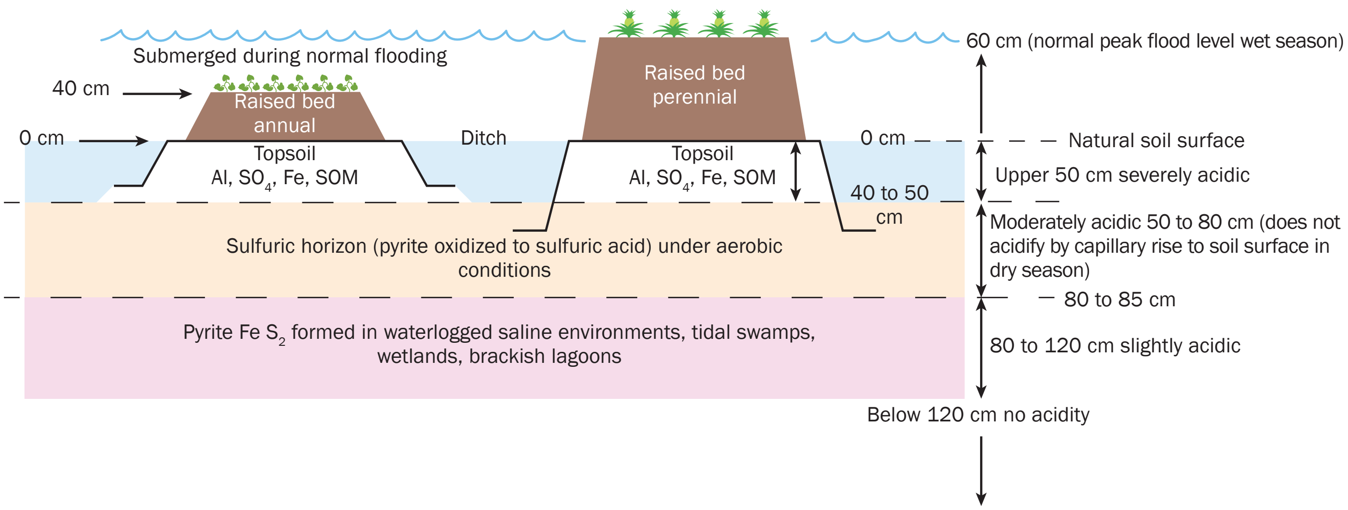
A primary goal of acid sulfate soil-water management is to maintain "a delicate balance between reducing and oxidizing conditions in the rootzone" (Hanhart et al. 1997), paying attention to root Al, Fe, and SO_4^{2-} stress, plant growth stages, bloom, preharvest, and harvest. This "delicate balance" varies by crop and cultivar and entails improving tolerance to salt stress and removing or minimizing soluble Al and Fe while managing the soil-water environment.

The characteristics of acid sulfate soils, delta water management, and soil leaching processes provide a framework for adaptive management options and land use redesign. One way to improve soil quality and crop yield in acid sulfate soils is to leach high SO_4^{2-}, Al, and Fe concentrations out of the rootzone (Minh et al. 1997a, 1997b). Soil beds raised (figure 3) above the natural soil surface built from sediments excavated from adjacent lateral ditches can improve the drainage and leach toxic minerals from the plant root zone (Minh et al. 1997a, 1997b). The depth to the acid sulfate horizon, depth to water table during growing season, the role of capillary rise, the specific crop grown, and the time and cost of labor influence the height of the constructed raised beds. Evapotranspiration will pull water upwards during the dry season, potentially leaving behind Na_2SO_4 and other salts. The higher the raised bed, the thicker the zone of leaching will be and distance to the water table and sulfidic materials, thus increasing the available soil volume for roots.

Freshly excavated soil deposited as ridges or shaped into raised beds create a network of macropores between soil clods that enable water to flow through the topsoil and bypass the unsaturated soil matrix. Water moving through the macropores of newly constructed raised beds can quickly

Figure 3

Raised bed schematic of upland crops grown in acid sulfate soils. Adapted from van Mensvoort (1996), Minh et al. (1997), and Hanhart et al. (1997). Graphic by Cruz Dragosavac Designs.



remove/leach soluble Al and other soluble substances from the surface of the soil clods into the drainage/irrigation ditch (figure 4). Flushing raised beds with fresh water (water low in electrical conductivity and dissolved metals) two or three times before a crop is planted removes additional toxic substances that can affect crop roots and plant development. Soil Al, Fe, and SO_4^{2-} concentrations are flushed with fresh water in annual raised bed systems that are submerged during normal flooding and then planted after the flooding recedes. The raised bed is rebuilt with topsoil after each monsoon flooding, then an annual crop is transplanted into the bed to grow; harvest occurs during the dry season with the cycle annually repeated (Minh et al. 1997a)

Throughout the season, rain and/or freshwater irrigation consolidates and crusts over the soil surface in the raised bed, and mesopores form as crop roots grow and decay. This reduces the number of water-conducting macropores and slows the movement of water through the soil profile reducing Al leaching (figure 5). Dry intervals increase Al^{3+} concentrations in the soil with infiltration after each precipitation event removing some salts but at slower rates. When fresh water removes the Al from the soil it concentrates in the outflow to the ditch and can increase contamination in irrigation water downstream (Minh et al.1997a).

Multiple-year, perennial raised beds with deeper roots are built higher than annual beds (figure 3). Constructed from topsoil and sulfuric horizon soils while deepening ditches and clearing sediments during the dry season, the beds are left fallow during the following rainy season, flushing out Al and other salt concentrations. The use of the sulfuric horizon soil brings higher concentrations of Al and SO_4^{2-} to the raised bed and lowers the pH. After year 1 planting, development, bloom, fruiting, and harvest, the soil on the raised beds are not disturbed, and a perennial crop is grown on the raised bed for several years. The raised beds are 20 to 30 cm (8 to 12 in) above normal peak flood levels so the crop is not submerged (Minh et al. 1997b).

Figure 4

Can Tho University graduate students sample acid sulfate soils in a raised chili pepper bed prepared for planting, located between flooded rice fields and a water chestnut field in Soc Trang Province, Vietnam Mekong Delta, December of 2022.

Figure 5
Raised watermelon beds, Vietnam Mekong Delta, December of 2022. Raised beds enable upland crops to be grown in delta acid sulfate soils.

Aluminum-tolerant crops like pineapple cultivar (*Ananas comosus* [L.] Merrill), a perennial fruit, tolerate low pH and high levels of soluble soil Al, grow well in low soil fertility, and are fairly well adapted to acid sulfate soils (Le Van and Masuda 2004). Pineapple roots are shallow, spreading laterally 1 to 1.5 m (3.3 to 4.9 ft) and 15 to 30 cm (6 to 12 in) deep, making it well suited for deep-ditch raised bed management (figure 6) (Minh et al 1997b, Nga and van Meenvoort 1997). Pineapple has benefited from efforts to select plants with the ability to exclude Al from entering the root apex and root hairs (Le Van and Masuda 2004). Root elongation and color are two practical plant response indicators of Al toxicity that are useful to farmers in regulating field drainage in acid sulfate soils (Hanhart et al. 1997; LeVan and Masuda 2004). Saline-tolerant fruit culture (Loc et al. 2021), including Al-tolerant mango (*Mangifera indica* L.) and pineapple cultivars and salt-tolerant coconut (*Cocos nucifera* L.) crops, in delta soils are diversifying current cropping systems.

MICROBIOLOGY OF ACID SULFATE SOILS

The relationships among soil organic matter (SOM), pH, microbial activity, and alternating aerobic-anerobic soil conditions are important areas of research for future crop adaptation.

Sulfate, a major component of seawater is reduced to sulfide (S^{2-}) by microbial activity. Sulfide inhibits nitrification and denitrification (Tully et al. 2019). Soil microbes raise soil pH, drive SO_4^{2-} reduction, break down plant residues, and serve as an additional buffer to prevent acidification when the soil dries (Mosley et al. 2017).

Organic matter accumulates in frequently saturated soils with slower decomposition rates than when exposed to air (Tully et al. 2019). The presence of SOM regulates concentrations of Al by retaining the ions and reducing leaching (Nga and van Meenvoort 1997). SOM is the fuel that feeds microbial activity (and SO_4^{2-} reduction). When SOM availability is limited, soil microbial action slows or decreases.

Low pH and metal toxicities inhibit plant growth, change the soil structure, affect the diversity of microorganisms, and impact plant available nitrogen (N), phosphorus (P), and other nutrients. Nitrogen and P are critical nutrients in plant cell division, root development, and plant growth, and improve crop photosynthesis increasing plant tolerance to abiotic and biotic stresses. Plant rhizosphere microorganisms affect plant growth and yields (Huu et al. 2022). Beneficial bacteria have mechanisms that stimulate plant growth by increasing the availability of nutrients such as N, P, and silicon (Si) and improving

Figure 6
The pineapple, which has shallow roots that spread laterally, is grown in raised beds in saline acid sulfate soils of the Vietnam Mekong Delta, December of 2022. Pineapple is a high value fruit crop with higher tolerance for salt than many delta crops.

pest and disease resilience (Huu et al. 2022; Nguyen et al. 2023).

Phosphorus is insoluble (Fe-P) when soil pH is less than 4. However, P solubilizing bacteria release organic acids during the microbial metabolism processes and increase soil pH. Evaluations of several strains of purple nonsulfur bacteria (PNSB) in the 0 to 20 cm (0 to 8 in) layer of acid sulfate soil have shown that application of *R. sphaeroides* P solubilizing strains increased P availability for plant use (Luu et al. 2022). These bacteria solubilize Al-P and Fe-P compounds, making P available for root growth, leaf and flowering, and fruit development. Mango, pineapple, and rice growth, yields, and soil health have shown improvements from the use of PNSB as a biofertilizer. PNSB solubilizing microbes are active in both aerobic and anerobic environments, making them well suited to the delta's wet-dry cycles. Use of PNSB reduced soil legacy P, improved fertilizer efficiency, and offers an alternative to synthetic fertilizers with potential to reduce negative impacts of P loss on water quality (Luu et al. 2022).

Mekong Delta research on microbial biopesticides for vegetable crops has shown capacity to improve pest, disease, and yield in green onions (*Allium*) and an increase in soil pH after two consecutive crops compared to the control (Nguyen et al. 2023). A five-spice biopesticide product of garlic (*Allium sativum* L.), chili (*Capsicum*), ginger (*Zingiber officinale*), onion, and lemongrass (*Cymbopogon*) resulted in significant increase in the number of soil bacteria such as beneficial N-fixing bacteria, phosphate (PO_4^{3-})-solubilizing bacteria, and Si-solubilizing bacteria compared to the control.

Stroud and Manefield (2014) found that Actinobacteria was a major component of acid sulfate soil horizons in Australia. All soil horizons contained d-proteobacteria and a-proteobacteria. Splitting the phylum Chloroflexi into classes revealed that the Chloroflexi class was a dominate group in the acid sulfate soils, and the phylum Acidobacteria in soil horizons was dominated by Holophagae. The phylum Firmicutes was dominated by the classes Bacilli and Clostridia across all the acid sulfate soils, with the class Nitrospira low in abundance. This is the group that contains acidophilic Fe(II)-oxidizing bacteria (*Leptospirillum* sp.), the most important phylotype in acid sulfate soils. The abundance of this group may be determined by pH due to their limited metabolic capacity (derives energy solely from Fe(II) oxidation) and adaptability under extremely acidic environments (pH < 4).

Although little is known about acid-tolerant Fe(II) oxidizers, around 22 are acidophilic Fe(II)-oxidizing species across four phyla (Bonnefoy and Holmes 2012) with only Firmicutes, and Alicyclobacillus detected in these soils. Chloroflexus was highly abundant in the acid sulfate soil horizons, but its role in Fe cycling is not well understood. However, research from microbial mat zones indicated a positive relationship to zones of enriched Fe(II) oxidation and the fully sequenced C*hloroflexus aurantiacus* (Trouwborst et al. 2007). More research is needed to understand acid sulfate microorganisms and roles they play in regulating plant nutrient uptake.

IMPROVING PLANT SALINITY AND ALUMINUM TOLERANCE

Saline and freshwater wetland soils accumulate plant residues in the soil surface horizon and have a permanently submerged reduced gleyed horizon where Fe sulfide minerals (FeS_2) are present (Ponnamperuma 1972). These anaerobic, submerged soils are neutral and can support salt-tolerant plants. However, upland plants have a greater variance in their resistance to saturated soils and waterlogging. This resistance has been linked to root capacity to oxidize the rhizosphere and ability to withstand short periods of soil submergence (Ponnamperuma 1972).

When soil salt solution exceeds the osmotic pressure in plant cells, the plant has decreased root capacity to absorb minerals like Ca, potassium (K), and water. High salt concentrations restrict soil water absorption and inhibit seed germination (Adil et al. 2023).

Salinity stress on plant metabolic processes affect osmotic processes, specific ion toxicity by disturbing the sodium (Na^+)/Ca^{2+} ratio, nutrition imbalance, and oxidation stress, which lead to decreased photosynthesis and plant productivity (Adil et al. 2023). Increasing plant available Si has been found to improve the salt tolerance of some crops such as rice, tomatoes (*Solanum lycopersicum* L.), and sugarcane (*Saccharum*) grown in saline soils. A growing body of microbial research on Si applications is finding a small increase in soluble Si by specific microorganisms can significantly enhance salt tolerance in some crops including improved seed access to soil water, structure of leaf cells, and photosynthetic activity. Solubilized Si helps adjust water uptake by roots enabling plants to maintain water balance and improve drought tolerance. One silicate-solubilizing bacteria (SSB) study on rice cultivars grown in salt-affected soil under greenhouse conditions in two consecutive seasons evaluated the efficacy of five SSB, *Ochrobactrum ciceri* TCM_39 (TCM_39), *Microbacterium neimengense* MCM_15 (MCM_15), *Klebsiella aerogenes* LCT_01 (LCT_01), *Citrobacter freundii* RTTV_12 (RTTV_12), and *Olivibacter jilunii* PTST_30 (PTST_30), isolated from bamboo, sugarcane, rice planted soils, earthworm intestine, and earthworm feces as bacterial sources (Nguyen and Tran 2023). Researchers found SSB improved rice salt-tolerant capability, growth, and yield when grown in salt-affected soils.

Biochemical and physiological research evaluating salt and Al tolerance in pineapple cultivars is finding significant differences in detection of Al in the soil and accumulation of Al in roots among cultivars (Le Van and Masuda 2004). Low Al accumulation in roots accompanied by increased Al tolerance suggests an Al exclusion mechanism in the roots triggered by exposure to soil Al (LeVan and Masuda 2004). This type of research lays the groundwork for improved plant breeding and technologies that target development of plants with root systems able to exclude Al and minimize salt impacts on plant water uptake.

These are the kind of innovations that will be needed to simultaneously manage water-soil relationships in acid sulfate soils, improve agricultural capacities to produce food and nutrition, enable farmers to make a living, and ensure the integrity of unique delta ecosystems.

LIVING WITH SALINITY: AGRICULTURAL ADAPTATIONS TO SALINE ACID SULFATE SOILS

One meter (3.3 ft) of sea-level rise would inundate 79% of Ca Mau and 76% of Kien Giang provinces in the Vietnam Mekong Delta. The World Bank (2022) predicts that without adaptation, 45% of the delta will be affected by salinity. Below are eight recommendations to guide Vietnam Mekong Delta policymakers, scientists, local leaders, and farmers in effectively adapting and living with salinity while continuing to make acid sulfate soils productive and delta ecosystems sustainable and healthy:

1. widen the adoption of diversified cropping systems and landscape and farm level management practices that are better adapted to acid sulfate soils and increasing salinization;
2. increase research, field evaluations, and applications on soil microorganisms and the role of organic residue management, and improve plant genetic diversity to mitigate and increase crop tolerance to saline acid sulfate soils and saltwater;
3. increase freshwater flows and aquifer recharge to offset saltwater intrusion;
4. proactively prepare and protect lands and settlements to increase resilience against tropical cyclones; drought-flooding extremes; and soil, coastal, and riverbank erosion;
5. manage pesticide and fertilizer use to meet crop nutrient needs while simultaneously reducing and eliminating pesticide and fertilizer contamination of soil, ditches, canals, and rivers;
6. restore and maintain wetlands and mangrove forests as multibenefit resources;
7. enable delta farmers and fishers to make a living that supports their households; and
8. restrict new development in eco-sensitive and fragile environmental regions, and strengthen and enforce land use regulations.

CONCLUSION: UNCERTAINTY ADAPTATION

The 1980s "rice first" policy promoted engineered ditches, canals, and sluice gates that provided freshwater irrigation, managed flooding, eliminated saltwater intrusion and drained acid sulfate soils to reclaim thousands of hectares for the intensification of rice production (Olson and Morton 2018; Ngan et al. 2018; Luu et al. 2022). While Vietnamese Mekong Delta farmers have learned over the decades to manage flood-drought cycles in acid sulfate soils, the increasing instability in global climate and local weather conditions present new levels of uncertainty and adaptation challenges. The repeated rapid oxidation of sulfidic materials in acid sulfate soils when exposed to air from drainage, drought, and resubmergence during flooding increases soil acidity, slows soil microbial respiration, increases FeS_2 buildup leading to reduced agriculture productivity, degrades surface water quality, and makes aquatic ecosystems vulnerable (Tully et al. 2019; Mosley et al. 2017).

A changing climate has altered the predicable delta wet-dry seasonal regimes and made it more difficult for farmers to grow traditional rice crops. Climate change, sea level rise, human land use management, increased population, and the rise in food and nutrition insecurity is again challenging the region to ratchet up their adaptation and agricultural production strategies to ensure food and nutrition security, ecosystem well-being, and that Vietnamese farmers are able to make a living.

Local and indigenous farmer knowledge and university scientific research have combined to create innovative land management approaches, engineer extensive water management projects, and develop salt-tolerant crop varieties to make acid sulfate soils agriculturally productive. Continuous research and experimentation will be needed to respond and prepare for present and future uncertainties.

Adaptive integration of biogeophysical, pedogenic, and social knowledge is critical in deepening understanding of landscape and local surface level drainage impacts and soil-water relationships under increasingly variable conditions. Observing and learning more about the connections and synergies among rates of percolation, soil management effects on macropores and mesopores, the role of bypass flows in raised bed soil leaching processes, densities and types of beneficial bacteria in productive soils, and plant breeding for salt tolerance will be essential to living with uncertainty and strengthening delta sustainability and resilience.

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