The Invisible Flood: The Chemistry, Ecology, and Social Implications of Coastal Saltwater Intrusion

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Saltwater intrusion is the leading edge of sea-level rise, preceding tidal inundation, but leaving its salty signature far inland. With climate change, saltwater is shifting landward into regions that previously have not experienced or adapted to salinity, leading to novel transitions in biogeochemistry, ecology, and human land uses. We explore these changes and their implications for climate adaptation in coastal ecosystems. Biogeochemical changes, including increases in ionic strength, sulfidation, and alkalinization, have cascading ecological consequences such as upland forest retreat, conversion of freshwater wetlands, nutrient mobilization, and declines in agricultural productivity. We explore the trade-offs among land management decisions in response to these changes and how public policy should shape socioecological transitions in the coastal zone. Understanding transitions resulting from saltwater intrusion—and how to manage them—is vital for promoting coastal resilience.

Keywords: climate change, land use management, salinization, saltwater intrusion, sea-level rise

Saltwater intrusion—the landward movement of seawater—has numerous, complex consequences for coastal ecosystems and communities, which can and should be distinguished from the impacts of flooding due to sea-level rise. Saltwater intrusion may precede tidal inundation of low-lying uplands, and dramatically changes the chemistry of tidal freshwater wetlands. Although there always has been a swath of coastal land adapted to salt, interactions among sea-level rise, climate change and coastal water infrastructure is causing saltwater to reach areas with human and ecological communities that have not experienced or adapted to salinity, leading to novel biogeochemical, ecological, and human land use transitions.

Recent studies have documented increases in storm-driven flooding, and higher-amplitude tidal inundation is associated with sea-level rise, which affects private property and public infrastructure (Moftakhari et al. 2015). Studies also have considered the impacts of coastal inundation on ecosystems and protected lands (Epanchin-Niell et al. 2017). However, the effects of saltwater intrusion, particularly on ecosystem services, have received less attention, perhaps because shifts in water chemistry are invisible to the general public. Marine salt inputs to previously freshwater-dominated systems have profound impacts on ecosystem biogeochemistry, leading to coastal forest loss, species invasions, reductions in agricultural productivity, declines in

coastal water quality, and marsh migration. Understanding these biogeochemical and ecosystem changes is critical for predicting the full impacts on society and identifying how people and communities can best adapt.

To improve our understanding of coastal saltwater intrusion, we first describe the climatic and anthropogenic drivers of saltwater intrusion and its global extent, identify the chemical alterations that accompany salinization, and synthesize the ecological consequences. We then examine the social impacts, including how individual landowners and managers may respond, and the role for public policy in shaping socioecological transitions in the coastal zone.

Drivers of saltwater intrusion

Saltwater intrusion and the degree of upland salinization are driven by five main factors: the position of sea-level relative to the land and water table, the frequency and magnitude of storms and tides, the frequency and duration of drought, water use (e.g., surface and groundwater withdrawals for drinking water and irrigation), and hydrologic connectivity (e.g., tide gates, levees, agricultural, diversions, and roadside ditches, and canals; figure 1). Because each of these five factors are themselves variable in space, time, frequency, and duration, the process of ecosystem salinization is extremely dynamic and can occur slowly or quickly, depending on the unique combination of drivers acting on any particular
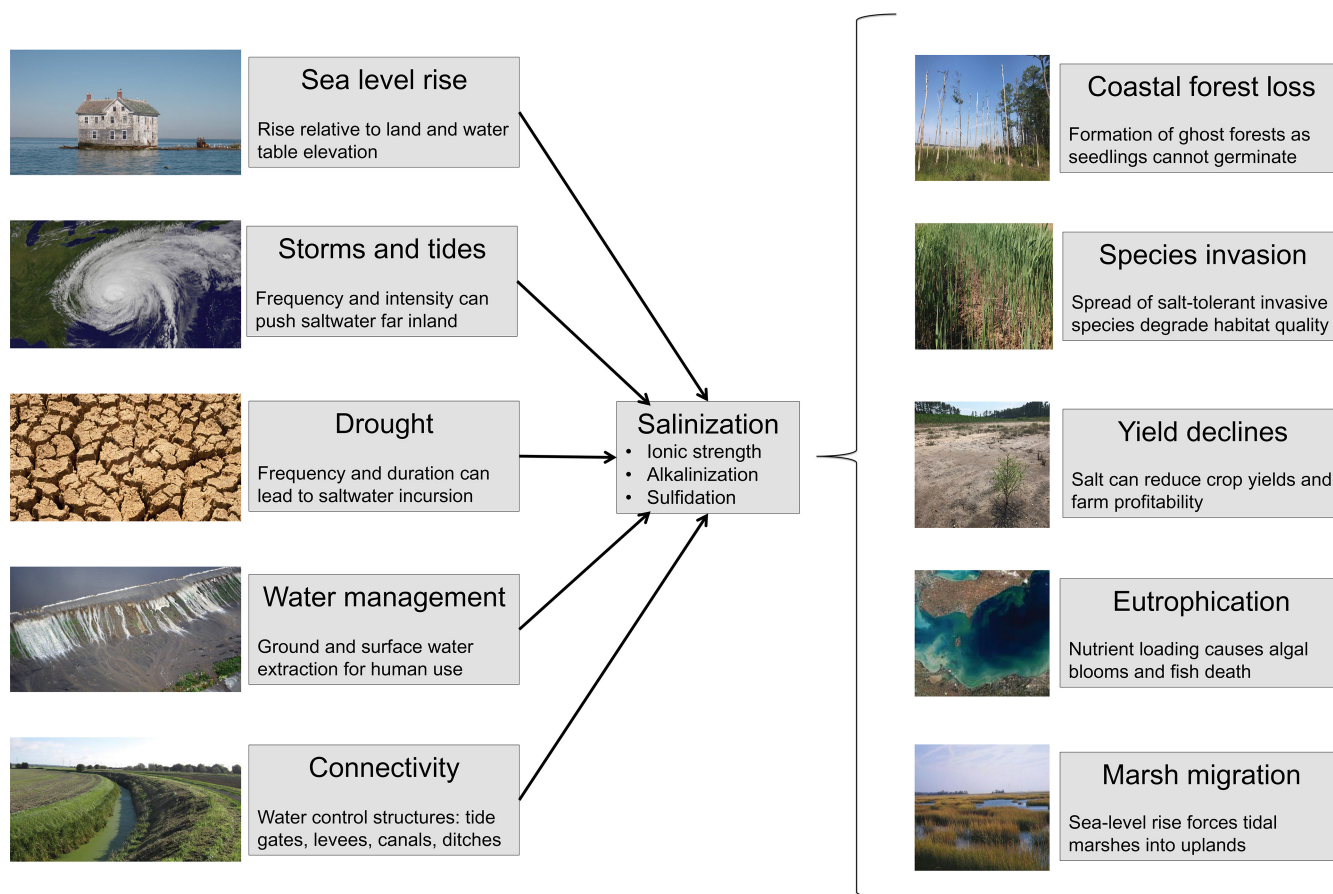
Figure 1. Drivers of salinization in uplands, three primary components of salinization, and their effects on biogeochemistry, plant communities, and ecosystem services.

location. For example, sea salts may be delivered slowly to coastal ecosystems through groundwater exchange, surface water mixing, and tidal pumping or rapidly during extreme events like hurricanes and tsunamis.

The penetration of saltwater into surface and groundwaters is enhanced by relative sea-level rise, which reflects the combined effects of changes in the elevation of the ocean surface (2.8–3.6 millimeters per year globally since 1993; Nerem et al. 2018) and vertical movements of the land surface (e.g., subsidence of 1–3 millimeters per year across North American Coastal Plain; Karegar et al. 2016). Prolonged droughts can increase the extent of saltwater intrusion (sometimes referred to as *incursion*; Ardón et al. 2013) and increase the peak salinity of high tides or of rivers during low flows (Neubauer and Craft 2009). Ground- and surface-water extraction for human consumption, irrigation, or industry can greatly accelerate the otherwise slow rate of saltwater intrusion attributed to sea-level rise (White and Kaplan 2016), and can play a more important role in aquifer salinization than sea-level rise (Ferguson and Gleeson 2012).

The frequency and intensity of storms and tides affect how far saltwater is pushed into uplands and whether water control structures such as levees and tide gates are overtopped (Yang et al. 2018). When overtopped, water control structures can trap marine salts just as effectively as they prevent saltwater intrusion during lower flows. In all cases, ecosystems that are hydrologically connected to saline coastal waters are more likely to have saltwater intrusion (figure 2). Many coastal landscapes that were hydrologically altered to promote drainage or enable navigation are now subject to saltwater intrusion. In Louisiana, for example, thousands of kilometers of canals were cut and dredged by oil, gas, and pipeline companies to allow industrial access to the marsh and now provide a conduit for saltwater to flow into low-salinity regions (Poulter et al. 2008, Bhattachan et al. 2018). Similarly, in northern Italy, agricultural irrigation and drainage channels, constructed to move freshwater to fields, now serve the reverse—and unintended—purpose of facilitating salinization (Antonellini et al. 2008).

Widespread evidence of saltwater intrusion

Saltwater intrusion has been documented in coastal regions across the globe (Barlow and Reichard 2010, Herbert et al. 2015), and its impact on human water resources is a growing threat. Worldwide, about 40 percent of the human population lives within 100 kilometers of a coastline and relies on coastal freshwater aquifers for drinking water (Kummu et al. 2016). Small changes in salinity can render water
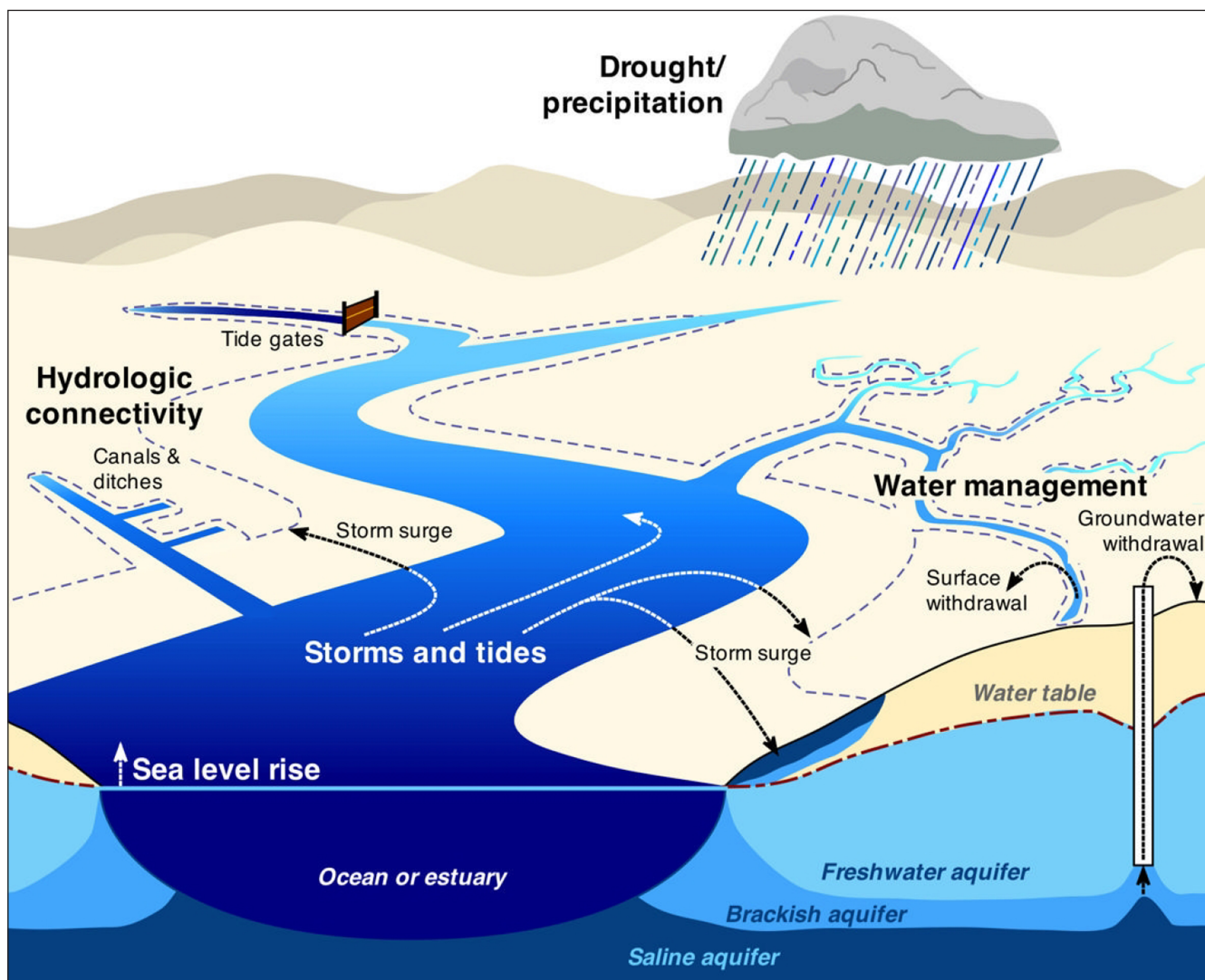
Figure 2. Illustration of shallow coastal system undergoing saltwater intrusion. Coastal saltwater intrusion (dashed lines) is caused by relative sea-level rise, water management (e.g., water withdrawals), the connectivity of creeks and ditches to the source of saltwater, the frequency of rainfall and drought events, and storms and tides.

undrinkable, because drinking chloride concentrations above 250 milligrams per liter (salinity of approximately 0.5 parts per thousand) in drinking water can cause hypertension and stroke (Vineis et al. 2011). Hundreds of groundwater wells in coastal countries such as Cyprus, Mexico, Oman, and Israel have been closed because of saltwater intrusion (Barlow and Reichard 2010). The 2004 earthquake and tsunami that devastated the province of Aceh, Indonesia, salinized drinking water sources both near the coast and inland (Fesselet and Mulders 2006). Bangladesh and Vietnam, the fourth and fifth largest producers of rice in the world, are extremely vulnerable to saltwater intrusion from sea-level rise, freshwater withdrawals, and tropical storms (Mahmuduzzaman et al. 2014) endangering global food security. In the Tropical Pacific, the Carteret Islands have become increasingly uninhabitable because of rising sea levels and saltwater intrusion,

which have resulted in declines in agricultural productivity and evacuation to nearby Papua New Guinea (Green 2016). In Los Angeles, water management practices to stave off saltwater intrusion in freshwater aquifers include artificial recharge using imported freshwater (Johnson and Whitaker 2003). In South Florida the Biscayne aquifer must be protected from saltwater intrusion, which otherwise would jeopardize the drinking water of 8 million people in metropolitan Miami (Barlow and Reichard 2010). In other regions affected by coastal saltwater intrusion, people rely on deep wells or reverse osmosis water supply systems to continue to inhabit and farm affected lands (Alameddine et al. 2018). Effects of salinization of drinking water is significant and immediately impactful, whereas other effects of saltwater intrusion are less obvious, because they result from slower biogeochemical and ecological changes that nonetheless

Box 1. Biogeochemical effects of salinization.

Increased ionic strength
- Osmotic stress → plant stress or death
- Ion exchange → nutrient mobilization

Alkalinization
- pH change → phosphorus release from acid soils
- Clay dispersion → prevent drainage
- Cation bridging → change carbon dynamics

Sulfidation
- High sulfate → reduced carbon storage
- Sulfide toxicity → plant stress/death
- Formation of iron-sulfur minerals → phosphorus release

have important ramifications for human society and adaptive responses.

Biogeochemical effects of salinization from saltwater intrusion

The movement of saltwater into terrestrial freshwater systems alters the composition of porewater in upland and wetland soils. Seawater is a complex solution; on average, it has around 400 times more salt than freshwater, with the base cations (calcium, magnesium, sodium, potassium) and sulfate ions accounting for 44% of total marine salts. To better describe how salinization is changing upland chemistry, we detail the process of salinization in three independent but co-occurring chemical alterations: an increase in ionic strength, alkalinization, and sulfidation (box 1).

Increase in ionic strength. As saltwater intrudes into freshwater systems, the ionic strength of surface water or soil porewater increases. Regardless of the specific ionic composition, increases in ionic strength cause osmotic stress for organisms not adapted to saltwater. High salt concentrations essentially draw water out of plant cells. This process is particularly damaging to plant seeds, which imbibe water prior to germination. High osmotic stress prevents tree regeneration in coastal forests (Williams et al. 1999). In soils, an increase in ionic strength increases ion exchange, affecting the release of nutrients such as nitrogen and phosphorus (Weston et al. 2006). For example, multiple studies have shown that saltwater intrusion promotes ammonium liberation from soil particles because of the elevated competition for exchange sites with sodium, calcium, and magnesium (Weston et al. 2010, Steinmuller and Chambers 2018). In nitrogen-limited coastal systems, this leads to eutrophication of estuaries (Ardón et al. 2013).

Alkalinization. The ionic composition of seawater determines the alkalinity, or the *amount* of base cations in solution. The link between salinization and alkalinization has been described in United States stream waters polluted by salts from road deicing, irrigation, and other human activities

(Kaushal et al. 2018), and the same general phenomenon acts in coastal lands affected by saltwater intrusion. Saltwater introduces large quantities of calcium and magnesium carbonates, which can change the potential for acid neutralization in soils and affect phosphorus availability (Weston et al. 2006, Chambers et al. 2011). In upland soils, such as those found in agricultural fields, an increase in sodium may also lead to clay dispersion, effectively changing the soil structure by plugging soil pores and impeding water infiltration and drainage (Rengasamy et al. 1984), which can delay planting and dramatically reduce yields.

Finally, the intrusion of alkaline saltwater can induce cation bridging, or bonds between cations and dissolved organic matter, which creates flocculent organic matter. This process reduces the microbial use of dissolved organic carbon and may lead to increased carbon sequestration and burial (Ardón et al. 2016). For example, in the Florida Everglades, flocculant organic matter is a primary detrital energy source, and plays a critical role in food webs (Sanchez and Trexler 2016). Therefore, increased concentrations of base cations through saltwater intrusion can change ecosystem carbon dynamics with consequences for ecosystem productivity and carbon storage.

Sulfidation. Sulfidation is the increase in sulfide stored in ecosystems following saltwater intrusion. Seawater contains relatively high concentrations of sulfate, which is reduced under low-oxygen conditions in the microbial metabolic pathway of sulfate reduction to sulfide. Sulfidation is unlikely after brief episodes of flooding with seawater, but occurs with chronic intrusion (figure 3). The increased availability of sulfate can drive shifts in microbial organic matter mineralization pathways (e.g., from methane production to sulfate reduction) and have major impacts on ecosystem carbon storage (Weston et al. 2011, Neubauer 2013). Furthermore, the reduced form of sulfur produced from chronic intrusion, hydrogen sulfide (H_2S), is toxic to plants and other organisms and can drive shifts in plant community composition and productivity (Lamers et al. 2013). If iron is present in the ecosystem, sulfide can also react to form pyrite and other precipitates, reducing sulfide toxicity and storing the sulfur compounds in the ecosystem (Sjøgaard et al. 2016). Therefore, free H_2S formation is unlikely after brief episodes of flooding with seawater, but occurs with chronic intrusion once the H_2S buffering capacity of the soils is depleted (figure 3). This buffering capacity will vary among systems because of differences in sedimentation rates, iron and organic matter availability, and microbial activity (Heijs and van Gemerden 2000). Nevertheless, saltwater intrusion may eventually consume available iron (Schoepfer et al. 2014), and free sulfides can accumulate in soils or sediments until the system is "fully sulfidized" (figure 3).

Sulfidation can play an important role in other biogeochemical reactions, notably phosphorus cycling and the release of phosphorus to coastal waters. In nonsaline systems, biologically available phosphate is largely bound
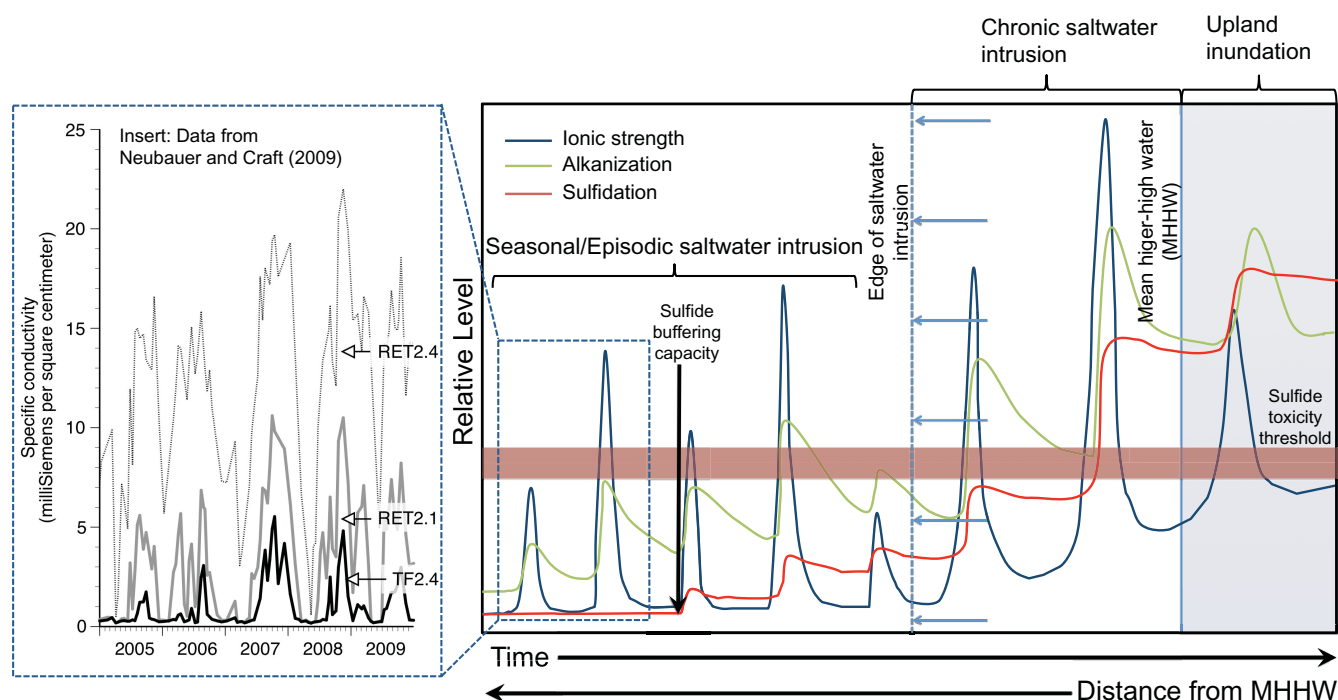
Figure 3. Conceptual diagram of the changes in ionic strength (solid black line in print/blue line online), alkalinization (gray dotted line in print/green line online) and sulfidation (solid gray line in print/red line online) that are likely to occur as systems salinize. Shaded region represents upland regions that experience tidal inundation and the dashed grey line (blue line online) represents the moving edge of saltwater intrusion. The dotted horizontal line represents the point above which a freshwater system experiences sulfide toxicity. Moving along the x-axis can be viewed as changes at a locale over time as sea levels rise or as differences in dynamics across a spatial gradient extending inland from the coast (i.e., distance from mean higher high water, MHHW). Insert (dashed box in print/dashed blue box online) highlights data on salinity from the Potomac River at three stations ranging from seaward (dashed and grey lines, RET2.4 and RET2.1) to landward (solid black line, TF2.4). Similar to ionic strength, salinity returns to zero (data from Neubauer and Craft 2009).

in iron mineral precipitates (Jordan et al. 2008, Hartzell et al. 2017). During sulfidation, iron consumed in reactions with sulfides is no longer available to bind to phosphate, thus increasing water column phosphorus concentrations. Because of the important role of iron as a sink for sulfide, the reactive iron content of soil could be a good predictor of the timescale over which sulfidation will lead to plant community changes and phosphorus loading into waterways.

Dynamics of salinization. We present a conceptual model of expected changes from salinization as the edge of saltwater intrusion moves across a landscape (figure 3). Changes in ionic strength may be pulsed within a given system as fluctuations in freshwater inputs (e.g., via rainfall or river flow) can dilute seawater or drought can concentrate salts (figure 3). However, over time, ionic strength of the system will likely increase, as is evinced by increased salinity in the Delaware River (Ross et al. 2015), James, and Chikahominy Rivers over the twenty-first century (Rice et al. 2012). Alkalinization of a system will likely track increases in ionic strength (especially sodium concentrations), and trends in alkalinity will depend on the initial buffering capacity of the system (Kaushal et al. 2018). Sulfidation will increase

more rapidly on reaching the sulfide buffering capacity threshold, although some degree of buffering may continue as a result of organic inputs (Heijs and van Gemerden 2000, Valdemarsen et al. 2009, Duan and Kaushal 2015). As soils periodically dry, some of the sulfides oxidize back to sulfate, partly reacidifying the soil (Luther et al. 1986), leading to interannual variation in pH and dissolved sulfide concentrations (figure 3). Overall, ecosystems may remain more sulfidic and alkaline following pulsed salinity events, even if the ionic strength has returned to (near) freshwater levels. This "memory" may result in more rapid alkalinization and sulfidation following subsequent saltwater intrusion events, such that seasonal saltwater intrusion may have a cumulative impact on ecosystem biogeochemistry, eventually tipping the system into a new state (e.g., forested wetland to brackish wetland).

Ecological consequences of saltwater intrusion

Biogeochemical changes in ionic strength, alkalinization, and sulfidation due to saltwater intrusion cascade into ecosystem changes. Soil microbial communities can shift following salinization (e.g., Herbert et al. 2015, Chambers et al. 2016, Dang et al. 2019 and the citations therein). Although

plants vary widely in their tolerances to high sulfide concentrations and salinity, few nonadapted plant species can tolerate waterlogged and saline environmental conditions (Lamers et al. 2013). Therefore, saltwater intrusion can drive inland retreat of upland plant communities and landward migration of coastal plant communities (Brinson et al. 1995) far in advance of regular tidal inundation with seawater (Brinson et al. 1995, Krauss et al. 2009, Antonellini and Mollema 2010). The pace and trajectory of plant community shifts will depend on the rate of saltwater intrusion as well as factors such as soil type, geomorphology, and hydrologic connectivity. In addition, upland ecosystems and land use can either constrain or facilitate community shifts. Below, we examine the transitions in coastal ecosystems occurring in response to saltwater intrusion, to highlight its far-reaching effects and repercussions for coastal ecosystems and ecosystem services.

Coastal forest loss. Salinity stress can lead to coastal tree death. Large areas of forest can be killed by salt deposited by a single storm event (Middleton 2016), but incremental forest retreat also contributes to landscape change (DeSantis et al. 2007). One early sign of salinity stress in trees is reduced sap flow during periods of drought or high salinity (Teobaldelli et al. 2004). In general, forest regeneration is more sensitive to salinity and associated flooding than mature tree mortality (Williams et al. 1999, Kirwan et al. 2007), because seedlings of flood-tolerant trees require moist, but not chronically flooded, soils for germination (Conner et al. 2007). Often, habitat conversion will occur many years after regeneration has ceased in stressed areas, when mature trees are killed by a saltwater intrusion event associated with a drought or large storm (e.g., Hurricane Sandy; Middleton 2016). Colonization by salt-tolerant vegetation follows forest death (Williams et al. 1999).

The rate of forest retreat varied with upland slope, climate conditions, and forest type (Smith 2013). For example, in the Big Bend region of Florida, 148 square kilometers of coastal palmetto, bottomland, pineland, and mixed forest converted to transitional and tidal marsh between the late 1800s and 1995, resulting in a lateral retreat of 4.2 meters per year (Raabe and Stumpf 2015), with forest replacement accelerating during a multiyear drought (Williams et al. 1999, DeSantis et al. 2007). Along tidal tributaries to the Delaware Bay, Smith (2013) observed a lateral retreat in coastal hardwood and Atlantic cedar swamp forests of 1.8 meters per year between 1930 and 2006. In contrast, there was no detectable forest retreat or mortality related to saltwater intrusion from 1974 to 2010 in southern New England, where upland slopes are steeper (Field et al. 2016).

Different sensitivities of tree species to flooding and salinity stresses also result in differential forest retreat. In the subtropics, inland forests of loblolly pine (*Pinus taeda*), winged elm (*Ulmus alata*), and Florida maple (*Acer floridanum*) were more sensitive, whereas juniper palmetto (*Juniperus virginiana* and *Sabal palmetto*) forests were more resistant

(DeSantis et al. 2007). Similarly, Smith (2013) found higher rates of migration in Atlantic white cedar (*Chamaecyparis thyoides*) than in hardwood forest (*Acer rubrum*, *Liquidambar styraciflua*, *Nyssa sylvatica*, and *Quercus* spp.). Where a single vulnerable tree species is planted for harvest in plantations, we expect to see more uniform tree mortality relative to more diverse coastal forests.

Freshwater wetland conversion. Salinity is an important ecological structuring agent in estuarine wetland plant communities. In response to saltwater intrusion, downriver and more salt-tolerant tidal wetland plant species can shift upriver, with brackish plants replacing oligohaline plant communities (Schuyler et al. 1993) and oligohaline plants replacing tidal freshwater plant communities (Perry and Hershner 1999). Long-term saltwater intrusion experiments in tidal freshwater wetlands produce a reduction in diversity (Neubauer et al. 2013). Saltwater intrusion reduces tidal freshwater forest tree height and basal area (Krauss et al. 2009) and, ultimately, converts tidal forest to more salt-tolerant emergent marsh over the course of a decade or more (Craft 2012, White and Kaplan 2016).

Expansion of invasive species. Given the habitat preferences of some widespread invasive plant species for moderate salinity (e.g., salt cedar *Tamarix chinensis*; Cui et al. 2010) and the high salinity tolerance of others (e.g., *Schinus terebinth*, Ewe and da Silveira Lobo Sternberg 2007; *Casuarina* spp., Potgieter et al. 2014; *Triadica sebifera*, Conner et al. 2007), and many prominent invasive species are likely to expand their ranges in coastal areas because of saltwater intrusion.

In the eastern United States, the invasive haplotype of *Phragmites australis* is positioned to be a dominant species in salt-affected, retreating coastal ecosystems. It grows at the upland edge of tidal wetlands, is relatively salt-tolerant and is highly opportunistic (Chambers et al. 2008). In Delaware Bay, roughly half of the area of forest retreat now accommodates *P. australis*–dominated marsh (Smith 2013). In contrast, in lawns transitioning because of saltwater along the Connecticut coast, private landowners are inadvertently controlling the spread of *P. australis* through mowing (Anisfeld et al. 2017). During marsh migration, *P. australis* is replacing native high marsh species and contributing to coastal squeeze of native tidal marsh communities. In temperate Atlantic Coast marshes, *P. australis*' expansion will most affect the high marsh dominant *Spartina patens*. A *S. patens*–associated endemic species, the saltmarsh sparrow, *Ammodramus caudacutus*, is predicted to go extinct within the next several decades (Field et al. 2016). In summary, with increasing saltwater intrusion, many salt-tolerant invasive species are poised to colonize new areas and expand their range.

Agricultural productivity decline and field conversion. Very few crops can grow in sustained conditions of greater than 2 parts per thousand salinity (Tanji and Kielen 2002), which is substantially below the salinity levels in many salt-intruded

fields (Tully et al. 2019). For example, crops such as corn (*Zea mays* L.) and soy (*Glycine max* (L.) Merr.) have suffered yield declines with saltwater intrusion (McNulty et al. 2015). Because of the episodic nature of saltwater intrusion and the variation in tolerance of crops, coastal croplands can exhibit gradual or sudden declines in productivity (Tanji and Kielen 2002). When farming practices of tillage or herbicide application continue during the initial stages of saltwater intrusion, fields often exhibit large bare areas in which crops cannot tolerate the saline conditions and the farm practices kill colonizing noncrop plants. Abandoned, salinized farmland, which has high nutrient levels (e.g., nitrogen and phosphorus), low organic matter, and a seed bank of opportunistic annuals, can be rapidly colonized by annual graminoids and herbs, including many agricultural weed species (Voutsina et al. 2015). On the arid Pacific Coast of Baja California, for example, abandoned agricultural land is rapidly colonized by the invasive and highly salt-tolerant ice plant, *Mesembryanthemum crystallinum* (Meyer et al. 2016).

Ecological changes from saltwater intrusion in agricultural lands are further shaped by past land use. The presence of tide gates influences the timing of transition for managed uplands. Drainage ditches and tile drainage, installed to divert excess freshwater, often serve as conduits for saltwater as land subsides or sea levels rise (Bhattachan et al. 2018). When impoundments fail, agricultural lands may convert to open water, as they did in Delaware, where over half of tidal wetlands were once impounded (Smith et al. 2017). Even small-scale land management may affect ecosystems exposed to saltwater intrusion. For example, heavy equipment tracks can create microtopography on graded fields, fostering wetter areas that may become salt pannes and pools as abandoned agricultural lands convert to wetlands.

Nutrient leaching and runoff from salt-intruded agricultural land will complicate nutrient management efforts in the coastal zone. Saltwater can extract legacy nitrogen and phosphorus from agricultural soils long after farmlands have been abandoned. Even years after restoring wetlands, legacy nutrients may be transported into ditches connected to tidal creeks draining into estuaries during times of drought and enhanced saltwater incursion (Ardón et al. 2013). Estuarine eutrophication can lead to harmful algal blooms, ecosystem state shifts (e.g., transitioning from oligotropic to eutrophic), and declines in valuable fisheries and is the subject of major regulatory efforts that may be stymied by unanticipated nutrient loading from coastal salt-damaged fields as saltwater intrusion moves across the landscape.

Social implications and adaptive responses to saltwater intrusion

The ecological outcomes of saltwater intrusion are additionally shaped by feedbacks among natural and human-driven processes. Land managers and society are affected by and must prepare for saltwater intrusion, which affects biodiversity, ecosystem services, and human well-being. Responses may differ among land managers, and these adaptation responses can affect the ecological trajectories of coastal systems. The management choice that is in the best interest of a particular land manager often may not provide the greatest benefits to society (e.g., Borchert et al. 2018). For a range of potential adaptation responses to saltwater intrusion, we describe potential costs and benefits that private land managers might consider, as well as the expected returns to society from each choice (table 1). We highlight several such examples below.

Adaptation to saltwater intrusion in coastal forests. Coastal forests may be managed for a variety of values, including timber harvest revenues, biodiversity provisioning, recreation (e.g., hiking, hunting), and aesthetic values (Burkhard et al. 2012). Saltwater can lead to forest death, thereby reducing the range of values described above. In addition, invasive species may invade salt-damaged land (Smith 2013), further reducing biodiversity and recreational values. In contrast to inaction, land managers could enhance one-time timber revenues by harvesting at-risk timber earlier than they otherwise would. Clearing forest in the path of migrating marsh may also provide salt marsh conservation benefits. Therefore, early harvest may promote a range of values provided by wetlands, including enhanced biodiversity, carbon storage, nutrient buffering, and improved water quality, as well as private gains.

Management of invasive species in salt-intruded forestlands could provide additional benefits to society, through improved habitat quality, but might not provide net benefits to a private land manager, depending on the values they derive from the land. A land manager may seek to maximize recreational hunting benefits, which can be reduced by nonnative plant invasions, but they would likely weigh the additional value against his private costs of control. If private incentives are insufficient to induce invasive species control on private lands, but societal benefits would outweigh the costs, then policy intervention may be warranted, which could be achieved through public invasive species control programs or incentives to landowners (Epanchin-Niell et al. 2010).

Adaptation to saltwater intrusion in tidal freshwater wetlands. In the absence of active management, freshwater tidal wetlands affected by saltwater intrusion are expected to transition to oligohaline or brackish tidal marsh. Preferences for particular wetland types may differ among landowners, depending on aesthetic or recreational preferences. Public preferences for freshwater wetlands may depend on the ability of freshwater wetland species to shift inland, the remaining extent of freshwater tidal wetlands, and the particular species that depend on the systems. Options for preserving freshwater wetlands typically involve major changes in the use and flow of freshwater. For example, freshwater diversions have been used to connect or reconnect coastal floodplain wetlands with their river channel to mimic historical flooding and sediment delivery in places such as the Mississippi River delta, China, and Texas, with varying outcomes (White and

Table 1. Public and private costs and benefits of landowner management responses to saltwater intrusion.

Consequence of saltwater intrusion	Management response	Public outcome	Private outcome
Coastal forest loss	Nonaction	• Delay tidal marsh migration • Biodiversity reductions due to species invasions	• Lose land and profit

	Early timber removal	• Promote tidal marsh migration
		  ◦ Carbon storage
		  ◦ Nutrient buffering
		  ◦ Improve water quality
			• Avoided harvest value losses

	Control invasive species	• Improved habitat quality • Enhanced biodiversity	• Enhanced recreation or hunting value • Financial costs of invasive control
Tidal freshwater wetland loss	Nonaction	• Transition from freshwater to saline marsh ◦ In some places, freshwater wetlands are an imperiled habitat • Loss of biodiversity and shift in species distributions	• Change in recreational value, e.g., shifts from freshwater to saltwater birds
	Management of water inflows and outflows	• Conserve freshwater wetlands • Impede tidal marsh migration • Incur upstream consequences of water management ◦ Water available for power generation, drinking water, etc.	• Sustain recreational value of freshwater wetland • Incur financial cost of constructing water control structures
Crop yield decline	Nonaction	• Eutrophication due to continued or increased fertilizer applications	• Yield declines • Profit loss
	Plant alternative crops (e.g., salt-tolerant)	• Promote rural economy • Potential nutrient remediation • Delay tidal marsh migration	• Sustained yield • Incurred costs of skill or equipment acquisition • Continued investments in agricultural production
	Abandon fields	• Legacy nutrient release • Promote tidal marsh migration and associated benefits	• Yield forfeit • Avoided investment in marginal land
	Enroll land in conservation easements	• Legacy nutrient release • Promote tidal marsh migration and associated benefits	• Yield forfeit • Avoided investment in marginal land • Alternative revenue source • Hunting value

Note: Nonaction scenarios report future trends compared to today. Other management responses are compared to the future nonaction scenario.

Kaplan 2016). Increased stream flow, which may be achieved by modifying water withdrawal or delivery, can also mitigate saltwater intrusion impacts (figure 2; Kaplan et al. 2010). Such changes in water management often require built infrastructure or widespread behavioral changes in water use across communities, which typically cannot be implemented by a single private land manager.

Adaptation to saltwater intrusion in coastal agricultural land. As saltwater intrusion on agricultural lands has led to crop productivity declines, land managers have responded in several ways, including abandoning land or enrolling it in easements, adding water control structures (White and Kaplan 2016), switching to alternative crops (Ventura et al. 2015, Voutsina et al. 2015), adjusting agricultural inputs (e.g., fertilizer and pesticides; Khanom 2016), and applying gypsum to displace sodium ions and improve drainage (Amezketa et al. 2005). Adaptation choices include the types of management changes and the timing of those changes. Some choices may require land managers to weigh costs and benefits only in the short-term (e.g., annual crop

or agricultural input choices), whereas others may require evaluation over the long-term (e.g., investments in new farm equipment or participation in a habitat restoration programs).

A farmer facing reduced crop yields because of saltwater intrusion may switch to more salt-tolerant or lower-input crops (e.g., soybeans or sorghum) to increase profitability. This decision would likely weigh differences in expected profitability, accounting for any upfront costs of transitioning to a new crop (e.g., costs of acquiring new skills or equipment). The primary societal benefits of this type of transition likely would stem from support of the rural economy. However, if adoption of low-input crops (e.g., biomass crops, such as switchgrass [*Panicum*] and silvergrass [*Miscanthus*]) could also reduce legacy nutrients in the soils, this could provide potentially large public benefits in terms of reduced impacts from eutrophication, which is estimated to cause $81 billion to $441 billion per year in environmental damages across aquatic systems in the United States (Sobota et al. 2015). Identification of profitable crops that could also provide environmental

benefits would help better align private and public interests. Alternatively, a farmer may stop farming salt-intruded fields to avoid economic losses resulting from poor yields. Field abandonment may provide public benefits by allowing landward migration of wetlands, therefore maintaining the ecosystem services and biodiversity benefits wetlands provide (Borchert et al. 2018).

Other options are to enroll abandoned agricultural lands in conservation easements or to restore wetland vegetation and control invasive species. Landowners might be motivated to restore wetland vegetation to obtain tax savings or other financial incentives or to obtain recreational opportunities such as hunting. As the productivity of agricultural land declines with saltwater intrusion, the opportunity cost of engaging in conservation or other land uses also declines, reducing the needed incentives to restore wetlands. However, federal, state, or local governments, or nongovernmental organizations may want to target incentives to enhance the transition of coastal farmland to wetland.

Managing the invisible flood

Understanding feedbacks among biogeochemical factors, ecological processes, and human responses to coastal saltwater intrusion is key for predicting and managing changes in coastal systems as sea levels rise. Adaptation to climate risks including sea-level rise associated inundation and saltwater intrusion can be hindered by knowledge gaps, financial resource constraints, social and cultural barriers, transaction costs, and institutional barriers. Also, because public and private benefits from the implementation of adaptation strategies often differ, incentive programs and public investments may be important for influencing coastal land management to bring about desired social and ecological outcomes. The collaboration of diverse disciplines and stakeholders is needed to improve our understanding of saltwater intrusion drivers and consequences. This understanding is critical for communities that are developing coastal policies that enhance long-term resilience in this era of rapid global change.

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