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Ghost forests created by the submergence of low-lying land are one of the most striking indicators of climate change along the Atlantic coast of North America. Although dead trees at the margin of estuaries were described as early as 1910, recent research has led to new recognition that the submergence of terrestrial land is geographically widespread, ecologically and economically important, and globally relevant to the survival of coastal wetlands in the face of rapid sea level rise. This emerging understanding has in turn generated widespread interest in the physical and ecological mechanisms influencing the extent and pace of upland to wetland conversion. Choices between defending the coast from sea level rise and facilitating ecosystem transgression will play a fundamental role in determining the fate and function of low-lying coastal land.

Sea level rise rates have been accelerating since the end of the 19th century, impacting low elevation land along coasts and estuaries around the world[1]. Sea level rise enhances flooding and saltwater intrusion, and threatens coastal communities, infrastructure, and ecosystems[2-4]. Ghost forests and abandoned farmland are striking indicators of sea-level driven land conversion. Dead trees and stumps surrounded by marshland, for example, represent relic forestland that has been replaced by intertidal vegetation. Similarly, bare soil and wetland plants at the edges of agricultural fields indicate the encroachment of wetlands into formerly productive farmland. These visual illustrations of land conversion are common along the North American Atlantic and Gulf of Mexico coasts, and reflect rapid ecosystem change and the inland migration of the intertidal zone in response to sea level rise (**Fig. 1**).

The ongoing conversion of uplands to wetlands is both economically and ecologically important. Eustatic sea level rise is predicted to rise between 0.4 - 1.2 m by 2100[5]. More than 600 million people live in low-lying coastal areas (<10 m elevation)[3], and approximately 50 million people live on land predicted to be permanently inundated with 0.5 m of sea level rise[6]. In the conterminous United States alone, 1m of relative sea level rise would convert approximately 12,000-49,000 km^2 of dry land to intertidal land without flood-defense structures[7,8]. Heavily populated, low-lying regions including subsiding deltas and island nations will be most affected[6]. In Egypt and Bangladesh, sea level rise could cause a 15-19% loss in habitable land and displace 13-16% of the population[9]. In the United States, residential property values may decrease with proximity to wetlands[10], and the conversion of uplands to wetlands is perceived as highly undesirable by many landowners[11]. On the other hand, the marshes and mangroves that replace inundated forests and farmland are considered among the most valuable ecosystems in the world because they improve water quality, reduce coastal erosion, protect against flooding, sequester carbon, and support marine fisheries[12]. Therefore, coastal sustainability in the face of sea level rise involves rapidly moving ecosystem boundaries and complex tradeoffs between the direct and indirect values of different land uses[13].

Although ghost forests first appeared in the scientific literature over a century ago[14] and are a prominent feature of many coastal and estuarine landscapes from the Atlantic Coast of Canada to the Gulf Coast of the United States [15-22], coastal change research has traditionally focused on more seaward environments, such as barrier islands, intertidal wetlands, and subtidal ecosystems[23,24]. Extensive research into those portions of the coastal landscape has identified a number of feedbacks between flooding, vegetation growth, and sediment transport that allows them to resist sea level rise until some threshold rate is exceeded. For example, marshes, mangroves, and oyster reefs are well known to resist sea level rise by accumulating sediment and growing vertically[24-26]. Although more work is needed to determine if analogous processes allow terrestrial land to resist sea level rise, observations of widespread land conversion[16,17,19] suggest terrestrial ecosystems largely lack mechanisms to engineer vertical soil growth. Therefore, forests and other terrestrial ecosystems are potentially more sensitive to sea level rise than better studied intertidal and subtidal portions of the coastal landscape[20].

Here, we review the natural and human mediated processes that influence sea-level driven land conversion. Although the review considers a variety of land types, we emphasize the conversion of forests to marshes because it is the most common and well-studied conversion, and because it produces ghost forests that are a striking visual indicator of sea-level driven land conversion. The first section illustrates that historical land submergence is geographically widespread, and has impacted terrestrial forests, agricultural fields, and developed landscapes alike. The second section discusses the ecological processes linking sea level rise and land conversion, such as plant population demography and community reorganization that shape the environmental consequences of land conversion. The third section argues that drowning of uplands is potentially the most important process determining future wetland area, and the fourth section considers the extent to which humans will prevent or facilitate coastal land submergence. The review ends with implications for land management, and highlights uncertainty in local flood defense strategy as the key knowledge gap limiting our ability to predict future sea-level driven land conversion and its impact on coastal ecosystems.

Extent and physical controls of historical land submergence

Ghost forests, abandoned agricultural fields, and other indicators of historical land submergence occur throughout low-lying and gently sloping portions of the Atlantic and Gulf coasts of North America[15-20] (**Fig. 1**). Land submergence is most extensive within the mid-Atlantic sea-level rise hotspot that stretches from North Carolina to Massachusetts, where relative sea level is rising three times faster than eustatic rates[27]. For example, 400 km^2 of uplands in the Chesapeake Bay region have converted to tidal marsh since the mid-1800s[19], and large tracts of hardwood and cedar forest death have been observed in Delaware Bay[16]. However, ghost forests are not confined to the sea level rise hotspot. Ghost forests have also been documented throughout the Florida Gulf Coast[17,18], the St. Lawrence estuary of Canada[15], and tidal freshwater forests in South Carolina, Georgia, and Louisiana[21,28]. There has been 148 km^2 of forest conversion over 120 years along the Florida Gulf Coast[17], and near complete loss of pine forests in the Lower Florida Keys[29]. Surprisingly, the phenomenon has not been widely documented on coastal plains outside of the United States. There are no reports of ghost forests from low-lying tropical regions where the phenomenon would be predicted, such as the Yucatan Peninsula, Mexico[30], or from the Pacific Ocean's western margin, such as along eastern China, due to the prevalence of seawalls there[31].

Observations of historical land submergence indicate that topography and relative sea level rise are the two most important controls on the rate of lateral forest retreat[32]. Migration rates are substantially lower in U.S. Pacific Coast and New England estuaries (<10 cm yr^{-1})[33,34] than in the mid-Atlantic coastal plain (up to 7 m yr^{-1})[16,19,35] where rates of land conversion are inversely correlated with slope[16,19]. Although mortality of canopy trees may depend on punctuated disturbance events such as storms and therefore lag behind sea level rise[30,36], land conversion is tightly tied to sea level over decadal timescales[16,18,30] . For example, the elevation of coastal treelines has increased in parallel with late-Holocene sea level rise, and lateral rates of forest retreat are 2-14 times higher than pre-industrial rates[20,35] (**Fig. 2**).

The conversion of agricultural fields and residential lawns to wetlands is less visually striking than ghost forests, as one herbaceous plant community is replaced by another, but is much more economically damaging. Marshes migrate rapidly into urban and suburban lawns, where mowed marshes look similar to mowed lawns[37]. Abandonment of agricultural land due to salinization is prevalent in low elevation coastal regions around the world, including large areas of North Carolina[38,39], Italy[40], Mexico[41], and Bangladesh[42]. In Bangladesh, saltwater intrusion has salinized 10,000 km^2 of land in the last 4 decades, including an estimated 3,000 km^2 of arable land[42]. Bangladeshi farmers responded by increasing fertilizer applications to compensate for losses in yields, switching crops, and converting 1,380 km^2 of farmland to shrimp ponds[42]. Sea level rise is forecasted to result in major losses in agricultural area over the next century in nations with agricultural production in deltaic or coastal regions (e.g. 1,000 km^2 will be lost within the Pearl River Delta region of China)[43]. The Mekong Delta of Vietnam stands to be one of the most affected areas in the world, where losses in rice production threaten global food supply[44].

Ecological processes linking sea level and land conversion

Dead trees underlain by wetland vegetation are a striking final indicator of uplands that have been displaced by sea level rise and saltwater intrusion (**Fig. 3**). However, the creation of ghost forests and the wholesale reorganization of ecosystems begins with more subtle changes that can be anticipated with a deeper understanding of the ecological processes that link sea level rise and land conversion. In the early stages of groundwater salinization, live trees may exhibit reduced sap flow[45] and annual growth[46,47] though reduced growth is not always observed[34,48]. During the next phase of ghost forest formation, forest distress becomes more visible. Young trees die conspicuously and tree recruitment ceases[30,46] (**Fig. 3a**). Because recruitment ceases prior to the death of mature trees[30,46,48], tree age distributions skew towards older trees at lower elevations[36,46], and relict trees stand as ghost forests in waiting[18]. Salt tolerant species establish in the understory as adult trees die[30], aided by increased light penetration and seed delivery from storm wrack deposits[49]. Shrubs often dominate the transition from forest to tidal wetland[18,21,50] (**Fig. 3b**). Of the 148 km^2 of converted forest land in Big Bend, Florida, 55% converted to marsh, while 45% converted to a shrub-dominated habitat[17] that persisted for 20 years[18]. These areas may be particularly persistent in formerly agricultural areas, where land is graded flat during cultivation. Finally, dead tree trunks and stumps persist in tidal marshes for decades, a lasting remnant of the forests displaced by sea level rise and saltwater intrusion (**Fig. 3c**).

Upland ecosystem mortality is driven by the synergistic impacts of salinity and inundation, which are more challenging for plants than either stress alone[21,51-53]. Generally, plants that tolerate flooding are more resistant to low level salinity stress[21]. Variation in stress tolerances between plant species can explain differences in the rate of transition of different forest types. For example, in Delaware Bay, Atlantic white cedar (*Chamaecyparis thyoides*) forests died back at faster rates than hardwood forests (typical species: red maple [*Acer rubrum*], sweetgum [*Liquidambar styraciflua*], blackgum [*Nyssa sylvatica*]). Eastern redcedar (*Juniperus virginiana*) is among the most tolerant tree species; the species outlasted loblolly pine (*Pinus taeda*), winged elm (*Ulmus alata*), and Florida maple (*Acer floridanum*) during forest dieback in Florida[54]. Trees and crops are most vulnerable to salinity stress during germination and as seedlings[51,55,56]. Mortality of relatively salt-tolerant tree seedlings occurs when salinity exceeds about 5 ppt[57], and most crops cannot tolerate sustained salinities over 2 ppt[58,59].

The transition of uplands to wetlands can be either gradual or punctuated by disturbance events such as hurricanes, fires, and insect outbreaks. Pulses of high salinity water during storms often trigger mortality[60,61]. Although storm waters recede in hours, salinity effects can linger for years to decades in the groundwater[62,63], and individual storms have lasting impacts on tree growth[47]. Storm floods can reach tens of kilometers inland and are accompanied by wind, erosion, and wrack disturbances. Correspondingly, shifts in upland land cover occur suddenly, when storm-related disturbance destroys an upland ecosystem[61]. In the absence of major disturbance, change may occur more gradually, as elevated groundwater salinities slowly take their toll on a plant community that is intolerant to salinity. Moreover, the impact of storms increases with sea level rise, leading to the progressive inland retreat of upland ecosystems through time[15]. Terrestrial water budgets can also affect the rate of change, as saltwater intrusion resulting from sea level rise is exacerbated by drought[54], surface and groundwater withdrawals[41], and hydrological connectivity from dams, ditching, and canals[64].

Ecosystem transitions affect the provision of ecosystem services, though the exact nature of these shifts varies based on tradeoffs in services between upland and wetland ecosystems[13,65]. Tidal wetlands exhibit much higher areal rates of carbon sequestration and storage than terrestrial environments[7]. Therefore, the conversion of forests and croplands to tidal wetlands will increase total carbon sequestration of a region, provided that gains are not offset by concurrent losses in tidal wetland area (***next section***). Similarly, upland conversion of agricultural lands, a nutrient source to adjacent waterways and estuaries[66], to tidal wetlands, a nutrient sink[12], should ultimately increase nutrient uptake. During transition, however, salinization of uplands can result in short-lived[21] releases of massive amounts of legacy nutrients that have accumulated in cultivated soils over prior decades. In North Carolina, saltwater intrusion into former farmland is predicted to release 18 x 10^6 kg ammonium, or approximately half the annual ammonium flux of the Mississippi River to the Gulf of Mexico[39]. In

Maryland, high releases of phosphate occur during saltwater intrusion into agricultural land[67]. These nutrient releases contribute to coastal eutrophication and associated algal blooms and dead zones[68].

Upland conversion may reduce biodiversity provisioning, as wetland migration represents an opportunity for invasive species expansion. In Delaware Bay, 30% of converted forest area became native tidal marsh habitat, while 60% became dominated by the invasive common reed (*Phragmites* australis)[16]. The conversion of uplands to the invasive common reed during ghost forest formation is of particular concern for Atlantic tidal marsh endemic species with narrow habitat requirements, such as the diamondback terrapin (*Malaclemys* terrapin)[69] and the saltmarsh sparrow (*Ammodramus caudacutus*) predicted to go extinct by 2030 due to sea level rise[70]. In Florida, the invasive Brazilian pepper (*Schinus terebinthifolius*) inhabits a similar niche to the common reed in that it outcompetes native species in the ecotone and exhibits wide salinity tolerance, and is also expected to spread during upland conversion[18,71]. Thus, sea-level driven land conversion will effect both the composition and function of the coastal landscape.

Implications for the survival of adjacent wetlands

The conversion of uplands to wetlands is a primary mechanism for wetland survival in the face of sea level rise, and counterintuitively leads to predictions that wetlands may expand with sea level rise under certain conditions[2,8,17]. At the most basic level, wetlands must migrate to higher elevations faster than they erode laterally and drown vertically in order to maintain their size[32]. Although marshes and mangroves build soil vertically, there are limits to the rate of sea level rise that wetlands can survive in place. Numerical models predict that maximum possible vertical accretion rates overlap with the range of predicted sea level rise rates for 2100 (generally 5-30 mm/yr)[72], and observations of wetland drowning indicate that these limits have already been exceeded in some places[73,74]. When these threshold rates of sea level rise are exceeded, wetlands must migrate laterally into submerging uplands to survive.

Historical observations and simple analyses of coastal topography indicate that upland drowning has the potential to create large areas of new wetlands that are comparable in size to existing wetlands. For example, historical maps of the Chesapeake Bay suggest that approximately 1/3 of all marshland today formed as a result of migration into drowning uplands since the mid-19th Century, and that upland drowning compensated for historical erosion of marshes in the region[19]. On the Florida Gulf Coast, marsh formation in submerging uplands has outpaced historical loss, and led to net marsh expansion[17]. More work is needed to infer how future sea level rise will alter the timescales associated with wetland loss and migration, but these historical trends together with observations of ghost forests underlain by marsh vegetation, suggest that wetland migration can occur on the decadal-century timescales relevant to wetland loss. Across the conterminous United States, there are ~26,000 km^2 of saline wetlands[75], and sea level rise of 1.2 m would inundate ~12,000-49,000 km^2 of uplands[7]. Thus, the formation of new wetlands in drowning uplands has the potential to compensate for even large losses of existing wetlands.

Rates of marsh migration generally increase in parallel with sea level rise[20,35,37], but existing marsh is relatively resistant to sea level rise because enhanced flooding leads to faster vertical accretion[76]. Upland migration, therefore, allows marshes to potentially expand, rather than contract, in response to sea level rise[13,76]. Numerical modeling suggests that marshes adjacent to gently sloping uplands will expand under moderate increases in sea level rise, followed by inevitable contraction when high rates of sea level rise lead to widespread drowning of existing marshland[76]. The particular rate of sea level rise that leads to a transition from marsh expansion to marsh contraction depends principally on the slope of adjacent uplands[32], anthropogenic barriers to migration[77], and factors such as tidal range and sediment supply that control the resistance of existing marsh to sea level rise and edge erosion[24]. Nevertheless, numerical models that consider both dynamic marsh accretion and the potential for marshes to migrate inland suggest that many marshes will expand under moderate rates of sea level rise, and then contract under higher rates[13,76,78,79] (**Fig. 4**).

These types of simple landscape models based on topography and land use have thus far assumed a binary response of land types to sea level rise (e.g. complete conversion of inundated forestland and no conversion of inundated urban land, ***next section***), and that wetlands will migrate into uplands as soon as they become sufficiently inundated (e.g. without ecological lags, ***previous section***). Other work identifies additional caveats. For example, the response of low-lying land to sea level rise will vary both within and across regions[19,80-82], where regions with steep upland topography and anthropogenic barriers to migration may see near complete loss of marshes[81]. In places where marshes persist, the proportion of flood-tolerant vegetation types will increase[78,79,81] and newly created wetlands may themselves be vulnerable to sea level rise[10]. Salt water intrusion into freshwater soils increases organic matter decomposition rates so that soil elevation loss could limit wetland migration and/or survival in submerging forests with organic rich soils[4,28]. Finally, interactions between multiple facets of climate change and socioeconomic factors (e.g. changing hurricane frequencies and flood protection strategies) may influence sea-level driven land conversion in unanticipated ways. Nevertheless, recent global modeling suggests wetland migration into submerging uplands is the single biggest factor influencing wetland area through time, and that global wetland area could increase by up to 60% by 2100 for a 1.1 m sea level rise (**Fig. 5**).

Opportunities and barriers to coastal land submergence

Although there is abundant land that could be inundated by sea level rise, anthropogenic structures and coastal development may prevent land conversion in many regions of the world. Ghost forests, abandoned farmland, and other indicators of land submergence are most common in the Southeastern and mid-Atlantic United States, in part because these coastal regions are largely rural and devoid of large, systematic flood control structures outside of major cities. In contrast, ghost forests are rare in Western Europe and China because extensive seawalls and dykes protect uplands from sea level rise and coastal flooding[31,84]. Large flood control structures are less common in the United States, but migration of wetlands into submerging uplands may instead be prevented by local barriers including berms, bulkheads, roads, ditches with floodgates, and impervious surfaces[80,85]. For example, 42% of all land less than 1 m above spring high water is currently developed along the U.S. Atlantic coast, whereas less than 10% is currently protected against development[86].

Human impacts are typically perceived as barriers to wetland migration, but people also facilitate sea-level driven land conversion, and the net-impact can be difficult to discern. Historical marsh migration rates likely decrease with the degree of coastal development in the Chesapeake Bay region, but the relationship is weak and highly site specific[19,85]. Elsewhere, suburban lawns convert to marsh as quickly as adjacent forests[37], and reclaimed agricultural areas are particularly susceptible to salinization and land conversion[40]. Wetland restoration projects commonly remove berms to reconnect agricultural fields and other land types with tidal flooding[87,88]. Barrier removal has mixed effects. Since barriers enhance land subsidence and limit sedimentation, the land behind the barriers may require substantial restoration to be suitable for wetlands[87-90]. Indeed, accidental or poorly planned breaches after significant subsidence can rapidly drown wetlands[89]. In other cases, large levees are carefully removed or moved further inland to create wetlands that contribute to natural flood protection in a concept known as nature-based engineering or managed realignment[84,90] (**Fig. 5a**). Finally, human actions sometimes unintentionally accelerate land submergence by increasing rates of saltwater intrusion via groundwater withdrawal and/or subsidence[4,91] or building canals that input saltwater[64]. Nevertheless, anthropogenic barriers block substantial wetland migration today in many regions[80,81], and wholesale submergence and abandonment of low-lying coastal land is unlikely because in most cases the cost of conventional flood control structures is far less than the cost of economic damages associated with flooding[92].

The United States Gulf Coast represents an interesting case study for how population growth and flood-control structures might interact to determine the extent of upland land conversion (**Fig. 6a**). This region contains approximately 50% of U.S. saline wetlands[75], high variability in human population densities and rates of relative sea level rise, and the most extensive flood protection system in the United States[77,82,93]. Analysis of topography and land use across the entire U.S. Gulf Coast indicate that 39,000 km^2 of land is vulnerable to submergence under a 1.2 m sea level rise, and that barriers projected under population growth will prevent conversion in an additional 6,000 km^2 [77]. This work highlights that there are strong spatial gradients in both opportunities and barriers to migration within the Gulf Coast region, such that the absence of land conversion in highly urbanized areas may result in large reductions in local wetland area[77,82]. Nevertheless, these analyses have three fundamental implications at the regional scale. First, current and projected barriers to wetland migration are small relative to the total amount of land available for migration (~15%), such that the total area of land that will be inundated will be large regardless of protection of urban areas. Second, only 35% of land available for migration is currently owned by government and private conservation organizations[77], suggesting that most land conversion will take place on private land and depend on local decisions not fully considered in analyses based on urbanization and levee construction. Finally, the area of land potentially available for saline wetland migration (39,000 km^2)[77] is nearly three times the area of land currently occupied by saline wetlands on the Gulf Coast (13,600 km^2)[75] and larger than the current extent of saline wetlands in the entire conterminous United States (26,000 km^2). Together, these observations emphasize that sea-level driven land conversion will be widespread and a fundamental determinant of wetland area at regional scales, even in the presence of urban barriers.

Moving beyond static models based on topography and land use is difficult because adaptation to coastal flooding depends not only on the rate of sea level rise, but also on a variety of human decisions influenced by complex socio-economic factors. There are strong landowner attitudes against wetland migration[11] (**Fig. 6b**), growing coastal populations[94], and it is economically rational to build flood defense structures for most of the world's coasts[92]. On the other hand, rising sea level and energy costs suggest that building and maintenance costs will increase through time, such that conventional engineering may be unsustainable in the long term[95,96]. Rising costs may especially prevent engineering solutions in developing countries and poorer regions[3]. Interestingly, highly developed deltaic regions, including the Mississippi, Rhone, and East Asian deltas, are the most vulnerable to rising energy costs[96]. Therefore, regions with large areas of currently protected land are also the most likely to incorporate nature-based engineering approaches that would allow submergence of some land for the first time in centuries[84,90].

While the factors that contribute to flood defense are ultimately quite complex, levees generally occur where population densities in the 100 year coastal flood plain exceed 20 people per km^2, and global modeling suggests this threshold represents a key determinant of wetland fate under sea level rise and population growth[83]. Lower population thresholds, reflecting nature based engineering, lead to wetland expansion, whereas higher thresholds, reflecting conventional engineering, lead to wetland contraction (**Fig. 5b**). Therefore, decisions to defend or abandon portions of the coast represent a fundamental, if not primary, determinant of coastal submergence and the migration of wetlands into uplands[24,83].

Recommendations for future research

Our review suggests that widespread sea-level driven submergence of low-lying land will continue in the future, even under scenarios of coastal population growth and large-scale defense of urban areas. However, land conversion will largely take place on privately owned land[82,86], where landowner attitudes and adaptation efforts suggest local resistance[70]. We therefore pose the following 3 questions to guide future research and land management decisions:

1. Is land conversion inevitable on privately owned, rural land? Research in the last 5 years has identified and mapped large barriers to wetland migration such as urban land and publically owned levees at regional scales[77,80-82]. However, the majority of vulnerable land is located on private property in rural areas[38,82,87]. Future research should investigate the efficacy of local and privately maintained barriers such as berms, ditches, and secondary roads, and the probability and consequences of barrier failure. Barriers influence the adaptive capacity of coastal systems by enhancing land subsidence and limiting sedimentation. Therefore, this research should quantify key thresholds in the timing of barrier removal/failure that minimize both the cost of abandoned land and the cost of restoration. Government

and conservation organizations are increasingly preserving wetland "migration corridors," but understanding of if and how landowners influence land submergence will help prioritize conservation efforts.

2. Can transitional land uses and nature-based engineering compensate for tradeoffs between private property and ecosystem service values? Sea-level driven land conversion leads to simultaneous loss in value for private landowners and gain in ecosystem services for the general public[19,97]. Future research should focus on whether transitional land and water management decisions, such as planting salt-tolerant crops[98], leasing land to hunt clubs, early harvest of susceptible timber lands, and groundwater manipulations[4] could significantly offset economic losses and influence the function of newly forming wetlands. Future research should also consider the viability of nature-based engineering, where limited wetland migration could simultaneously enhance natural flood protection and reduce levee maintenance costs[84,97].

3. How can policy incentives shape the future of coastal upland conversion? Programs in the United States that provide assistance or recommendations to landowners affected by sea level rise are few and harshly criticized for providing perverse subsidies[99] and benefiting repeatedly flood damaged and reconstructed properties[100]. Programs such as the USDA's Conservation Reserve Program, that subsidize remediating salinity damage on farm fields, could be repurposed as instruments for adaptation to sea level rise. Regional predictions for tidal wetland habitat gain or loss should set the context for management and policy incentives to either prioritize wetland migration or upland protection[100].

In summary, our review highlights extensive sea-level driven land conversion, marked by ghost forests and abandoned agricultural land that represent relict features of a rapidly submerging coast. Accelerated sea level rise over the next 80 years could potentially create new wetlands equivalent in size to current wetlands, even under scenarios of coastal population growth and urban levee construction. These changes will happen disproportionately on rural and private lands where efforts to prevent or promote land conversion are poorly understood. Given the extent of historical change, the magnitude of forecasted change, and an unpredictable human response, sea-level driven land submergence is likely to lead to wholesale reorganization of coastal ecosystems and economies within this century.

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Figures

Figure 1. ***Geographic distribution of sea-level driven land conversion in North America.*** Clockwise from top left: Red spruce ghost forest and buried stumps, New Brunswick, Canada; Atlantic white cedar ghost forest in New Jersey; Salt damaged agricultural field in Virginia, where white and gray areas represent bare ground, and yellow-red colors represent stressed crops; Palm tree ghost forest in Florida. Photo sources: D. Johnson, K. Able, Google Earth, and A. Langston.

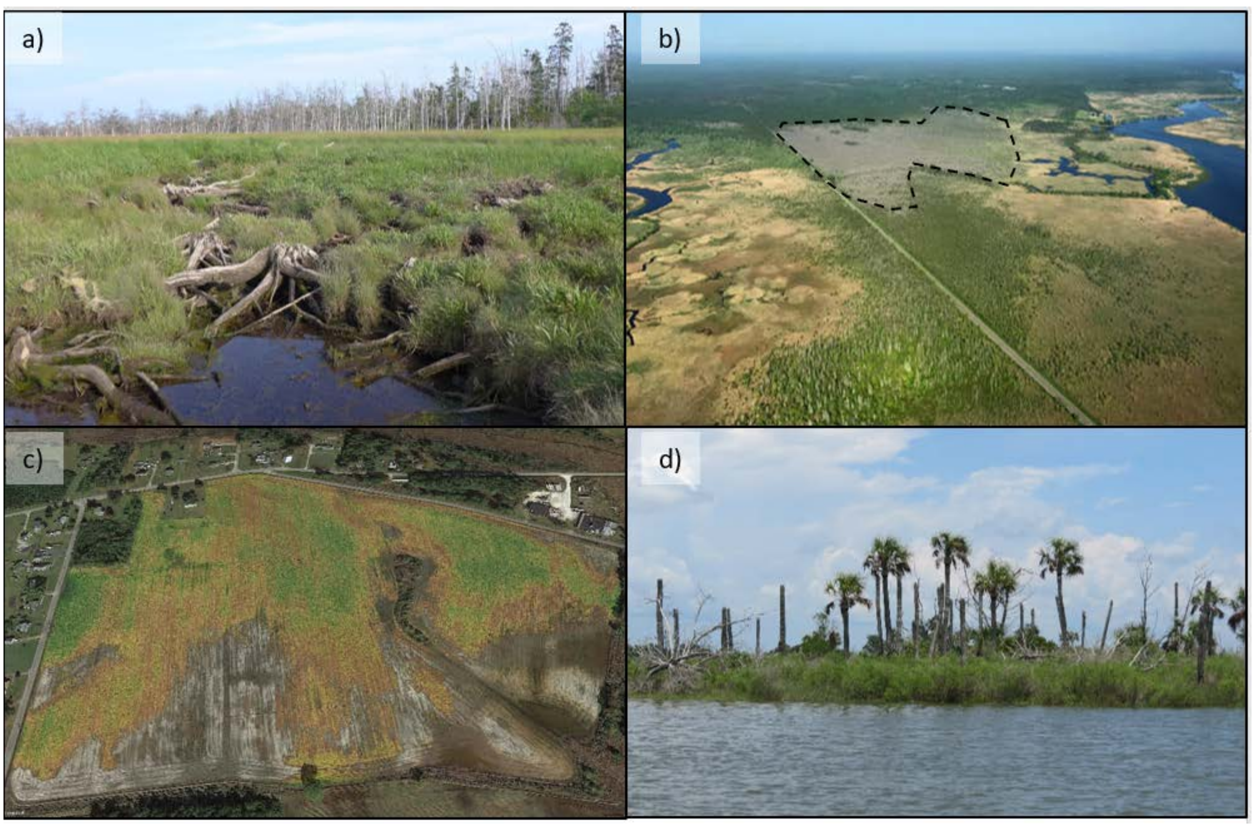

Figure 2. ***Accelerating forest retreat rates.*** Lateral forest retreat rates for 5 U.S. mid-Atlantic sites, where gold bars represent late-Holocene rates (pre-1875 CE) inferred from sediment cores and historical maps, and green bars represent modern rates (post-1875 CE) inferred from historical maps and aerial photographs. 1875 CE was chosen to approximate the initiation of accelerated sea level rise on the Atlantic coast[1]. Modern forest retreat rates are 2-14 X higher than late-Holocene rates, and generally increase through time. Source: Ref [20].

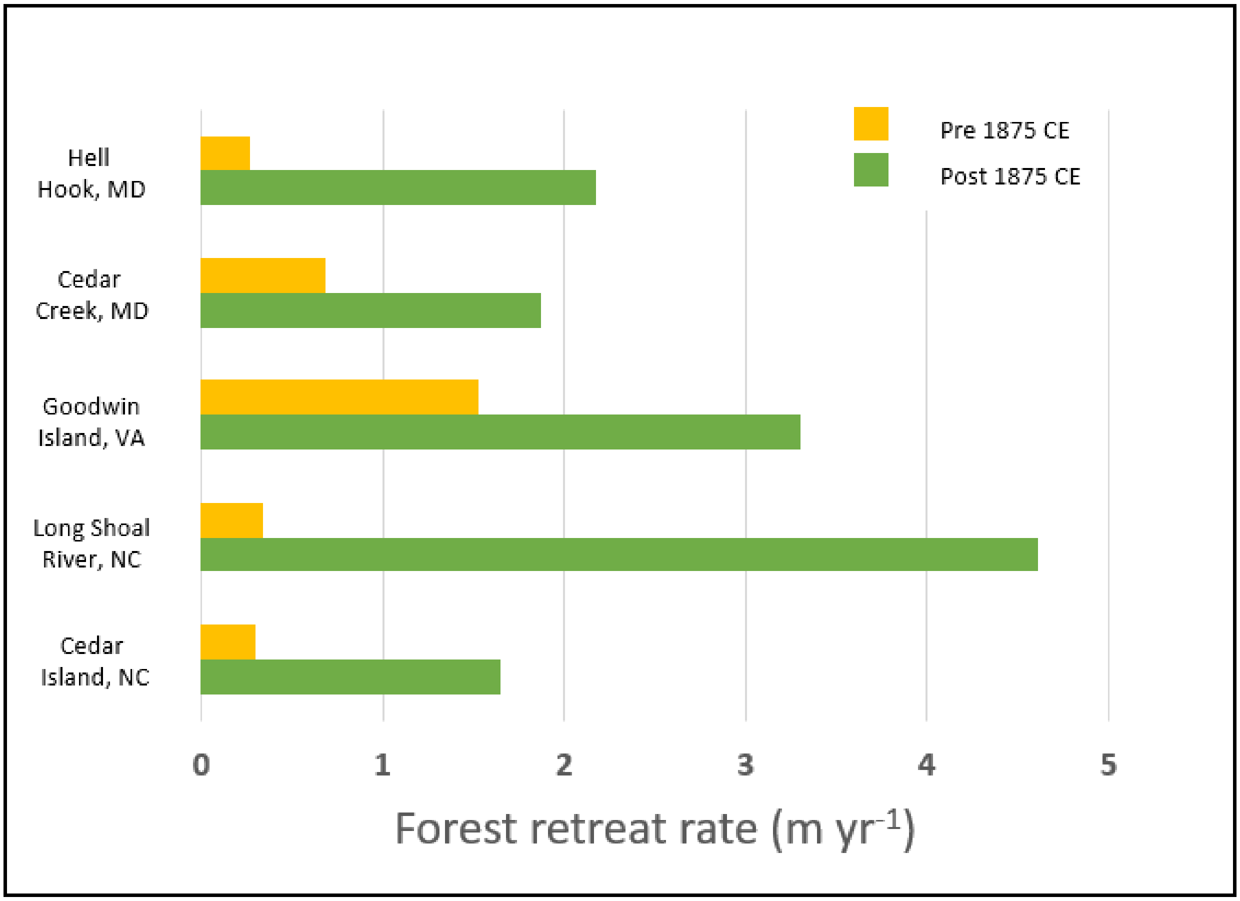

Figure 3. ***Stages of ghost forest creation.*** Photos show forest to marsh conversion in the Chesapeake Bay region (Maryland, USA), characterized by *(a)* death of tree saplings, *(b)* opening of canopy and invasion of *Phragmites* and shrubs, *(c)* adult tree death and conversion to marsh, indicated by stumps in foreground and ghost forest in background. Photo sources: K. Gedan, M. Sall, and L. Schepers.

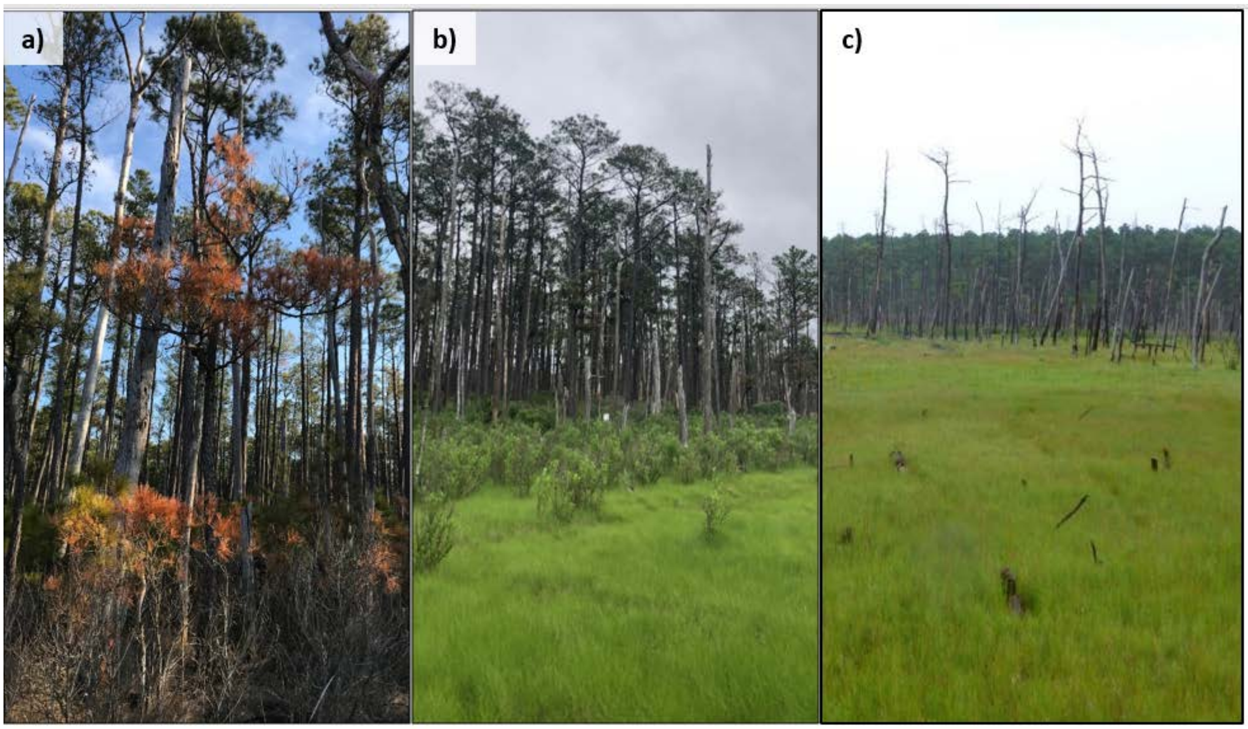

Figure 4. ***Effect of topographic slope and human impacts on marsh size*.** a) Model simulations showing change in marsh width (dMW/dt) for different rates of sea level rise (SLR) and slopes of adjacent land (colored lines). For gently sloping, natural coasts, marshes expand with increasing sea level rise rates until a threshold rate of sea level rise is exceeded. Marshes inevitably decline in size when uplands are steep or protected by anthropogenic barriers (black line represents case with no migration). Source: Ref [76]. b) steep uplands prevent landward marsh migration and favor small and/or shrinking marshes (Bay of Fundy, Nova Scotia). c) Gently sloping uplands facilitate landward marsh migration and favor large and/or expanding marshes (Chesapeake Bay, MD). Photo sources: M. Kirwan and L. Schepers.

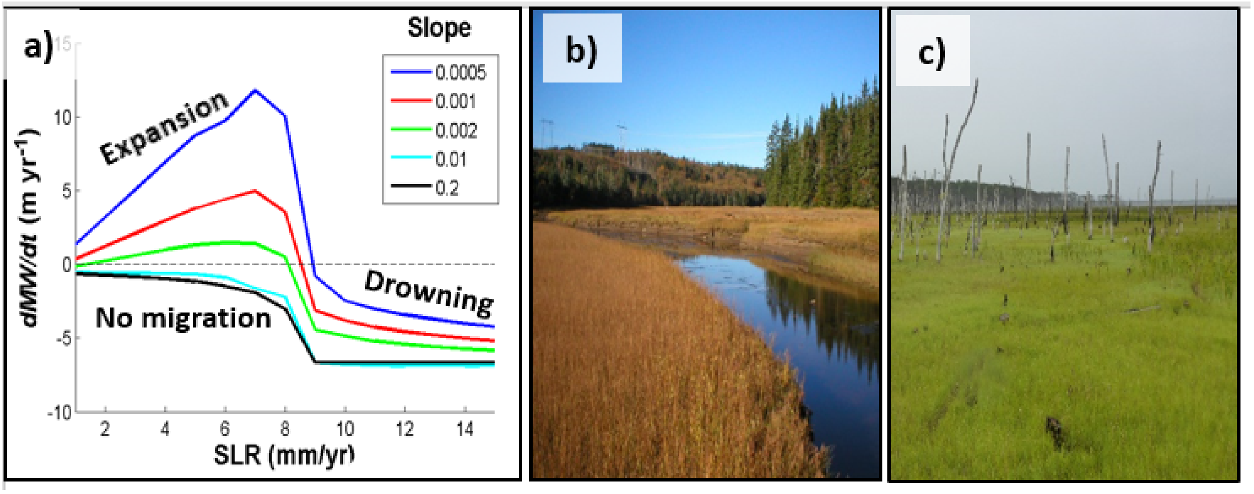

Figure 5. ***Effect of flood defense strategy and land conversion on wetland size.*** a) Nature-based engineering to create marsh in front of leveed agricultural fields in the Wash Estuary, U.K. The levee was intentionally breached in 2002, marsh vegetated colonized naturally, and now protects the more inland levee. Photo source: U.K. Environment Agency. b) Modeled global wetland area for the IPCC RCP 8.5 sea-level rise scenario. Colors represent different flood-defense scenarios, where the model assumes no landward wetland migration where the projected human population in the 100 year floodplain exceeds 5–20 people km^{-2} (red, reflecting business as usual), 20–150 people km^{-2} (pink), and 150–300 people km^{-2} (yellow, reflecting extensive nature-based engineering). Source: Ref [83].

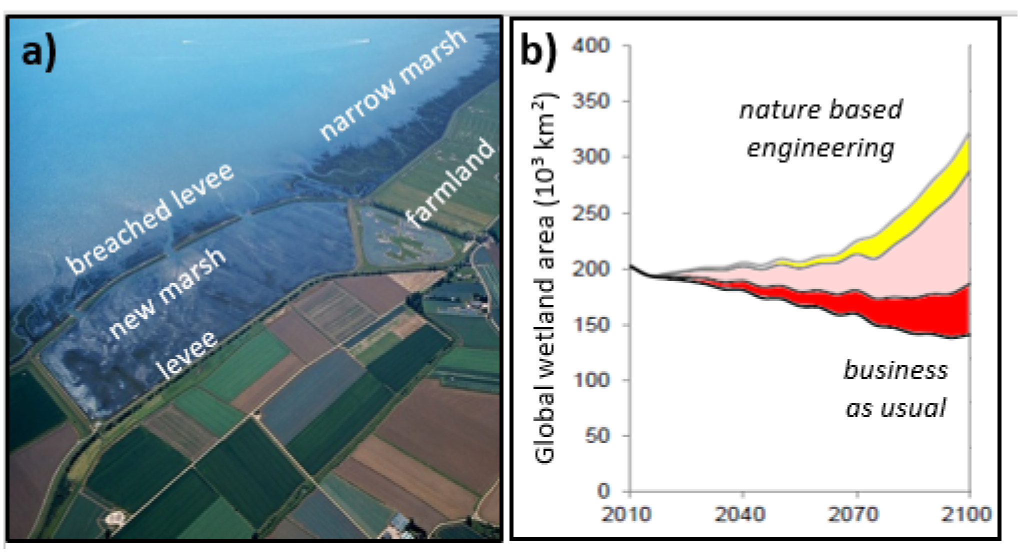

Figure 6. ***Land conversion in the face of human barriers.*** a) Projected urban barriers and opportunities for wetland migration for U.S. Gulf Coast estuaries (Borchert et al., 2018). Opportunities for wetland migration are an order of magnitude greater than urban barriers to migration in each estuary, and potential wetland migration increases with increasing sea level rise scenario (top to bottom). b) Preferences of 1002 landowners regarding conservation easements to allow marsh migration in the Northeastern U.S. Responses are strongly unlikely (SU), unlikely (U), neutral (N), likely (L), and strongly likely (SL). Source: Ref [11].