Anthropocene 45 (2024) 100427

Contents lists available at ScienceDirect

Anthropocene

journal homepage: www.elsevier.com/locate/ancene

Saltwater intrusion and sea level rise threatens U.S. rural coastal landscapes and communities

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ARTICLE INFO

Keywords:
Coastal
Vulnerable
Rural
Rapid Change
Saltwater Intrusion
Sea Level Rise

ABSTRACT

The United States (U.S.) coastal plain is subject to rising sea levels, land subsidence, more severe coastal storms, and more intense droughts. These changes lead to inputs of marine salts into freshwater-dependent coastal systems, creating saltwater intrusion. The penetration of salinity into the coastal interior is exacerbated by groundwater extraction and the high density of agricultural canals and ditches throughout much of the rural U.S. landscape. Together saltwater intrusion and sea level rise (SWISLR) create substantial changes to the social-ecological systems situated along the coastal plain. Many scholars and practitioners are engaged in studying and managing SWISLR impacts on social, economic, and ecological systems. However, most efforts are localized and disconnected, despite a widespread desire to understand this common threat. In addition to variable rates of sea level rise across the U.S. outer coastal plain, differences in geomorphic setting, water resources infrastructure and management, and climate extremes are resulting in different patterns of saltwater intrusion. Understanding both the absolute magnitude of this rapid environmental change, and the causes and consequences for its spatial and temporal variation presents an opportunity to build new mechanistic models to link directional climate change to temporally and spatially dynamic socio-environmental impacts. The diverse trajectories of change offer rich opportunities to test and refine modern theories of ecosystem state change in systems with exceptionally strong socioecological feedbacks.

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https://doi.org/10.1016/j.ancene.2024.100427
Received 15 May 2023; Received in revised form 10 October 2023; Accepted 8 January 2024
Available online 13 January 2024

1. Introduction to saltwater intrusion and sea level rise (SWISLR)

The rising seas of our warming planet are flooding and salinizing low-lying coastal landscapes across the globe, with the impacts to landscapes and livelihoods extending well inland from coastal margins. The United States (U.S.) coastal plain, the low-lying areas adjacent to the coastline (typically <100 m elevation and <100 km inland from the coastline), is under threat of notable change due to global sea level rise (SLR). Because of regional variations throughout the U.S. coastal plain, risk is not uniform, with 90% of the coastline experiencing SLR levels that already exceed the global mean estimate of 0.2 m by 2040 (Jevrejeva et al., 2016) and current models suggesting that the mean high tide will inundate areas where 150–250 million people live by 2100 (Kulp and Strauss, 2019). In addition to gradual SLR, the extent of flooding associated with hurricanes, cyclones and typhoons (Woodruff et al., 2013) and the frequency of extreme precipitation events (Allan and Soden, 2008; Vousdoukas et al., 2018) are expected to increase as a result of warming ocean and atmospheric temperatures. SLR and coastal storm surge load marine salts into primarily freshwater coastal landscapes (Fig. 1). The resulting saltwater intrusion (SWI) has led to drastic outcomes such as forest mortality, crop failure, and degradation of drinking water (Tully et al., 2019a,b; White and Kaplan, 2017). SWI and SLR are intertwined and cannot be thought of as separate drivers of change. However, most of the literature focuses on SWI or SLR. Out of the 16,438 documents available on Scopus within the last 10 years related to SWI or SLR, only 361 (~2%) discuss both SWI and SLR. We review papers that show saltwater intrusion (SWI) and sea-level rise (SLR) (hereafter abbreviated as SWISLR) act in tandem to alter coastal systems, a term we will use throughout this paper to describe all landscapes of the lower U.S. coastal plains and the organisms and people that live and work within them.

Nomenclature

- SWISLR — saltwater intrusion and sea level rise
- Coastal Systems — inclusive of all landscapes of the lower U.S. coastal plains and the people that live and work within them
- Lower coastal plains — elevation of < 100 m above sea level and closer than 100 km from the U.S. coast
- Saltwater intrusion — Process by which saline water migrates into freshwater systems

Coastal systems have a disproportional global influence, with one recent estimate suggesting that they contribute about 77% of global ecosystem services and support about 41% of the global population (Martínez et al., 2007). The current literature on coastal systems is dominated by studies of cities and focuses on damage from extreme events and SLR risk, often neglecting the long term impacts of SWI (Hallegatte et al., 2013; Jeroen et al., 2014; Neumann et al., 2015). With the exception of research on marsh migration (e.g. (Fagherazzi et al., 2019) or land acquisition (e.g. (Johnson et al., 2019))less attention has been paid to rural coastal landscapes despite their large area (Bhattachan et al., 2018a; Small and Nicholls, 2003). While coastal populations are concentrated in cities, about 40% of the global population of coastal systems are rural residents (Kummu et al., 2016; McGranahan et al., 2007; Small et al., 2003). It is estimated that about 42% of the world's gross domestic product (GDP) is produced in coastal zones (Kummu et al., 2016), with much of this derived from farms, timber operations, and fisheries that operate in rural areas. In addition to these direct economic contributions, the estuarine and freshwater coastal wetlands that dominate coastal systems are recognized for their exceptional ecological value, providing a suite of critical ecosystem services including the sequestration and detoxification of pollutants, the provision of nursery habitat for many aquatic and terrestrial species, and flood protection (Barbier et al., 2011; Dahl and Stedman, 2013; Friess et al., 2020).

In the conterminous U.S. alone, without flood-defense structures, a 1-m increase in relative sea level is expected to convert 12,000–49,000 km^2 of dry land to intertidal land (Haer et al., 2013). This prediction of land conversion is a conservative estimate of the land that is likely to become salinized, as marine salts are delivered well inland of high tide lines during both storm surge and drought (Ardón et al., 2013; Tully et al., 2019a). Across coastal farm fields, timberlands and freshwater wetlands, SWISLR results in field abandonment (Gedan and Fernández-Pascual, 2019; Tully et al., 2019b), the creation of ghost forests (Kirwan and Gedan, 2019; Ury et al., 2021b; White et al., 2022), and freshwater wetland loss (Herbert et al., 2015; Manda and Klein, 2019a; Warnell et al., 2022). While investments in urban infrastructure are being considered as realistic options for reducing flooding in coastal cities (Hunt and Watkiss, 2011; Molinaroli et al., 2019), almost no consideration or investments in infrastructure to protect the full extent of rural coastal systems has occurred (Jurjonas et al., 2020; Sudol et al., 2023).

Historical water infrastructure investments in rural coastal landscapes have reduced flooding and enabled agricultural and timber operations, with the unintended consequence of increasing the extent of rural coastal systems currently vulnerable to SWISLR. The extensive construction of canals and navigation channels to facilitate drainage and shipping enables the inland movement of seawater through artificial drainage networks (Bhattachan et al., 2018; Manda et al., 2014; Poulter et al., 2008b; Rasmussen et al., 2013). Pumping of groundwater for freshwater supply can accelerate land subsidence leading to greater susceptibility to SWISLR (Eggleston and Pope, 2014). Thus in most coastal regions, impacts of SWISLR are seen in landscapes and river networks with a long history of substantial modification (Carter, 1975; Chapelle, 1986; Woodruff et al., 2018). Because of the long history of land use and water management in global coastal systems, the actual extent to which saltwater will affect coastal systems is highly dependent upon individual landowner decisions about water management (Bhattachan et al., 2018b; Poulter et al., 2008b) and government decisions about the maintenance and expansion of navigation and shipping channels (Carse and Lewis, 2017). To better understand coastal risk and make responsible infrastructure investments, SWISLR must be understood and modeled as a socio-ecological system (Adger et al., 2005).

The rates of relative sea level rise, groundwater withdrawals, and the frequency, intensity, and extent of droughts and floods vary widely across global coastal systems, thus the magnitude and extent of SWISLR impacts are highly heterogeneous. The impacts of SWISLR are consistent: inundation and salinization lead to reductions in agricultural yields and substantial reductions in coastal forest carbon stocks (Taillie et al., 2019a; Ury et al., 2020; Warnell et al., 2022), cause challenges to irrigation and drinking water supplies (Panthi et al., 2022), and threaten infrastructure, homes, livelihoods and lives (Hauer et al., 2021). Over time, in the absence of investment or intervention, SWISLR will convert a substantial proportion of modern coastal systems into open water, marsh, and abandoned fields and coastal communities (Fig. 2). SWISLR is already causing declines in agricultural yields (Tully et al., 2019b), extensive forest dieback (Kirwan and Gedan, 2019; White et al., 2022), and large-scale shifts in the extent and distribution of wetlands (Dahl and Stedman, 2013; Murray et al., 2022). SWISLR thus presents a major challenge for the rural coastal system communities whose livelihoods, water supplies, and landscapes are affected (Bhattachan et al., 2018; Tully et al., 2019b; Desmet et al., 2018).

The resulting loss of agricultural productivity, declines in water quality, and inundation are likely to differentially impact disadvantaged rural populations (Hauer et al., 2021; Handwerger et al., 2021; Rentschler et al., 2022). In the U.S. areas of higher sensitivity to future flood

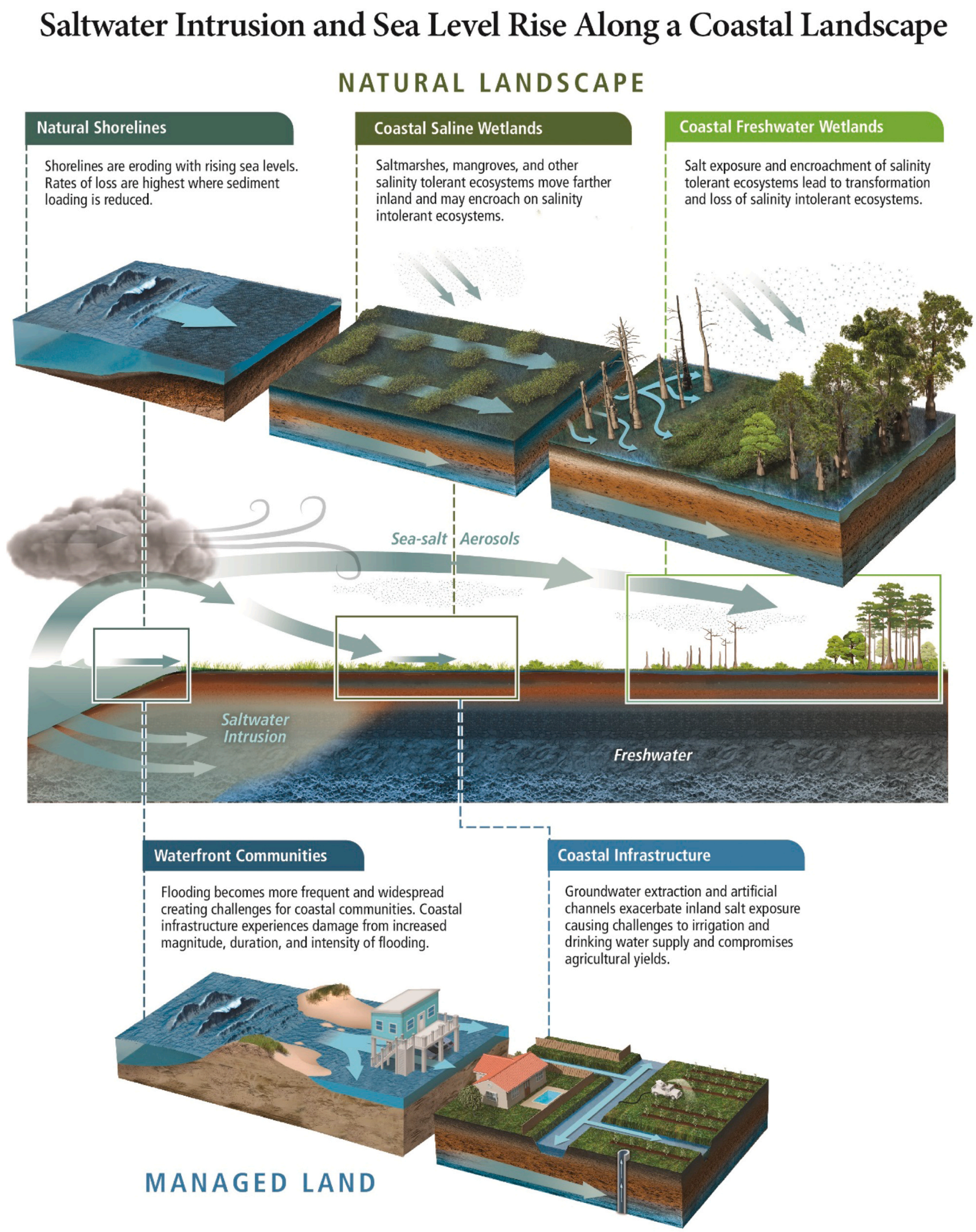

Fig. 1. Features of coastal SWISLR. The movement of saltwater into interior systems is shown by the light blue arrows. SLR causes the sea water-freshwater interface in both groundwater and surface waters to move upward and landward. Additionally, storms cause saltwater inundation onto freshwater landscapes and can spray salt inland. Both the natural and managed landscape, including coastal infrastructure like agricultural canals, can exacerbate SWISLR extent and influences of climate change stressors like drought. SWISLR impacts and extent depend on the type of land use being affected (e.g., agriculture and timberlands) and natural and anthropogenic features of the surrounding landscape.

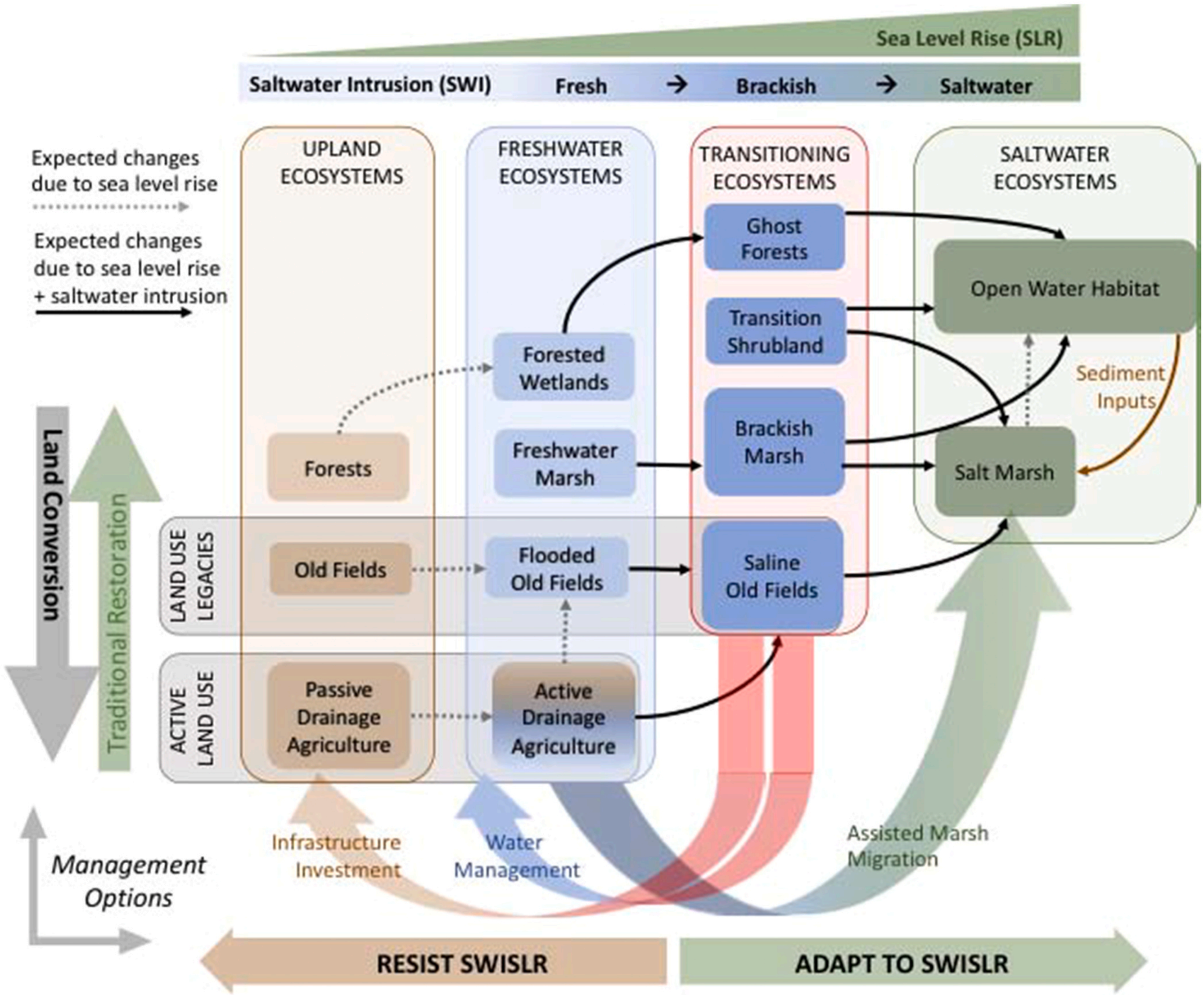

Fig. 2. Expected shifts in the distribution of dominant land cover types throughout the coastal plain due to prior land use, current management decisions, and the effects of sea level rise and saltwater intrusion.

risk were found to be concentrated in communities with higher Black populations (Wing et al., 2022). These environmental justice issues are not only driven by present-day processes associated with SWISLR, but are also the products of historical multi-generational factors involving land availability, bank and agency lending practices, and discriminatory exclusions by redlining (Hardy et al., 2017; Katz, 2021). Managers throughout the U.S. face the challenge of deciding whether and where to resist or adapt to SWISLR impacts (White and Kaplan, 2017) (Fig. 2). Making those management decisions requires better information about the socio-spatial-temporal dimensions of intersecting disadvantages in addition to current and future ecosystem vulnerability (O'Hare and White, 2018). The decisions that are made will alter patterns of vulnerability with feedback to climate change and future risks (Woodruff et al., 2018).

As described above, SWISLR is a rapid, high-magnitude change that is affecting coastal systems around the world. Meaningful management and adaptation decisions are necessary and need to be extended beyond population centers to include rural coastal landscapes. This review summarizes our current understanding of how SWISLR is affecting rural coastal systems and identifies critical knowledge gaps in our ability to predict and prepare for future coastal change.

2. Understanding SWISLR

SLR is typically modeled as a gradual, linear process, while SWI is variable and can be linear, oscillating, or episodic. For SLR, understanding the geology and geomorphology of a coastal region allows for prediction and visualization of the hazard across coastal systems. Geology and geomorphology can be generalized throughout regional or physiographic provinces for SLR modeling predictions (Braswell and Heffernan, 2019; Simon et al., 2004; Stein et al., 2008). Within these provinces vertical land movement, such as subsidence or isostatic rebound, combine to change the regional rates of relative SLR (Nicholls et al., 2021; Wöppelmann and Marcos, 2016). Understanding the bedrock geology of a region determines the sediment availability for creating depositional or erosional geomorphic landforms and, in turn, the hydrologic connectivity of the landscape (Arfib et al., 2007; Miller et al., 2013). SLR causes saline surface and groundwaters to penetrate into ecosystems, as well as extend the tidal freshwater zone upstream into former nontidal freshwaters (Ensign and Noe, 2018). Inundation can be predicted using SLR models and local topography, but SWI can occur well inland of the projected inundation due to many factors excluded from SLR models (Brinson et al., 1995; Kirwan et al., 2016; Panthi et al., 2022; Smith, 2013). Particularly in areas where topographic relief is low such as the Atlantic and Gulf Coast, additional drivers interact to exert strong control on the spatial extent, timing, and intensity of SWI. These drivers have been explored to lesser extent across broad spatial scales and include freshwater discharge (Bhattachan et al., 2018; MacCready, 2002), landscape connectivity (Bhattachan et al., 2018), wind and tides (Manda et al., 2014; Manda and Klein, 2019a, 2019b), vegetation (Möller et al., 2014), droughts and storms (Ardón et al., 2013; Michener et al., 1997; Prigent et al., 2007) and human alteration of these factors through land use change, coastal engineering, and groundwater pumping (Ardón et al., 2017; Bhattachan et al., 2018; Neville et al., 2023). Surface water and shallow groundwater also interact to influence the extent and intensity of SWI (Zhang et al., 2018). Due to the variety of drivers, the spatial extent of SWISLR is not well known.

Without a clear understanding of the full extent or a clear prediction of SWISLR, the consequences are harder to forecast. The inability to forecast the regional extent of SWISLR has led to localized studies, often with variable outcomes due to variations in the coastal landscapes. The hydrologic regime (Ardón et al., 2018; Helton et al., 2019), watershed characteristics (Noe et al., 2013), soil properties (Schoepfer et al., 2014; Steinmuller and Chambers, 2018), land use legacies (Ardón et al., 2017) and other human impacts (i.e., habitat loss, erosion, nutrient eutrophication and acidification, salinization and alkalinization of freshwater inflows) have been found to influence the inland extent of SWISLR at the local scale and cause variable ecosystem and socio-economic consequences. These variations - in exposure, vulnerabilities, and outcomes - highlight the need for interdisciplinary study and collaboration across jurisdictions to better prepare for the consequences.

2.1. Ecosystem consequences of SWISLR

At the beginning of this century, the coastal forests of the mid-Atlantic, southeastern, and Gulf Coast regions of the U.S. were identified as particularly vulnerable to the threat of SWISLR (Titus and Richman, 2001). SWISLR can cause coastal change that can be viewed in the context of ecosystem state change theories (Scheffer et al., 2001). Responses to a variety of SWISLR forces can lead to different trajectories of change. Conceptually, changes may be linear or involve thresholds that lead to abrupt non-linear transitions including regime shifts (Anderson et al., 2022; Ratajczak et al., 2018). These threshold responses may involve feedback that stabilize the new state and prohibit return to the initial state even if pre-transition conditions are re-established (Scheffer et al., 2009). SWISLR may also cause systems to "flicker" (Wang et al., 2012), alternating between ecosystem states (e.g., dominance by vegetation adapted to freshwater versus brackish water). While these dynamics related to crossing nonlinear thresholds including shifts to alternate states and/or flickering are known for some systems (Bestelmeyer et al., 2011), nonlinear change remains poorly understood in coastal ecosystems despite increased threats (McGlathery et al., 2013). In addition to these patterns, coastal ecosystems undergoing persistent and episodic intrusions may demonstrate variability associated with loss of resilience. Early warnings of change have been demonstrated in some field studies (e.g., (Carpenter et al., 2011; Wilkinson et al., 2018)) but remain poorly studied in coastal ecosystems (van Belzen et al., 2017). Dakos et al. (Dakos et al., 2008) suggest that slowing natural rates of change for a dynamic system could be one method for predicting ecosystem tipping points.

Ecosystem state changes caused by SWISLR can be seen through the dramatic shifts in plant communities along the coast (Krauss et al., 2018; Smith and Kirwan, 2021; Taillie et al., 2019b; Ury et al., 2019; White et al., 2022). At low projected rates of local SLR, in areas with a low gradient and no human interventions, salt marsh ecosystems may grow in size by moving inland at the expense of neighboring forest ecosystems (Feagin et al., 2010). With higher rates of local SLR, a high gradient of land surface, and inland human infrastructure, coastal marshes may shrink (Kirwan et al., 2016). Throughout these SLR and topography driven shifts, SWISLR is altering the soil salinity and biogeochemistry of the ecosystem through floods, droughts, and storms. Plant physiological responses to salt mimic hydraulic stress induced by extreme drought conditions (Volpe et al., 2011). It has seemed reasonable to predict that the traits most likely to modulate responses to salinity will be traits related to water stress. However, SWISLR has the possibility of causing ecosystem changes to the biogeochemical environment surrounding plant roots (Charles et al., 2019; Morrissey et al., 2014; Morrissey and Franklin, 2015; Neubauer et al., 2019; Solohin et al., 2020), and soil microbial communities (Rocca et al., 2020). Thus, researchers need to consider the interactions of carbon, nutrient, and water dynamics to fully model plant response to salinity (e.g., Ishtiaq et al., 2022). Additionally, the disruptions of plant-microbe associations in soil may also need to be considered in predicting plant responses to SWISLR (Huang et al., 2021; Pfennigwerth et al., 2018). Several plant stress studies have evaluated the tolerance of ecologically dominant and commercially important tree species to saltwater exposure (Ashraf and Harris, 2004; Kirwan et al., 2007; Krauss et al., 2007; Pezeshki, 1992; Poulter et al., 2008a; van Belzen et al., 2017), and few have considered the interactive effects of both flooding and salinity (Duberstein et al., 2020) or drought and salinity (Powell et al., 2016). Additional investigations examining the impacts of longer term biogeochemical changes that can be caused by SWISLR are needed.

Marine salts increase salinity, alkalinity, and sulfate concentrations resulting in feedbacks that alter the biogeochemical regime and land-ocean fluxes (Ardón et al., 2016; Helton et al., 2014; Tully et al., 2019a,b). The most well-documented effect of increased salinity is the mobilization of soil-bound ammonium and phosphate through cation exchange, which can increase nitrogen (N) and phosphorus (P) fluxes (Ardón et al., 2013; Herbert et al., 2018; NOE et al., 2013; Steinmuller and Chambers, 2018; Weston et al., 2010, 2006; Zhou et al., 2017); however, the magnitude of these responses is highly variable (Helton et al., 2019; Zhou et al., 2017). P concentrations may decrease with saltwater exposure through sorption and precipitation with cations (Jun et al., 2013) or increase with sulfide replacing iron-bound or calcium-bound P (Caraco et al., 1989; Flower et al., 2017; NOE et al., 2013). SWISLR can also exacerbate nutrient loading as saltwater can extract N and P from soils - N because of the elevated competition for exchange sites with sodium, calcium, and magnesium (Steinmuller and Chambers, 2018; Weston et al., 2010) and P due to iron reduction and competition with sulfur in the saltwater complex (Hartzell and Jordan, 2012; Jordan et al., 2008; NOE et al., 2013; Williams et al., 2014). Likewise SWISLR may alter dissolved organic carbon concentrations through physical interactions between cations and dissolved organic matter (DOM) (Ardón et al., 2016; Servais et al., 2020, 2019), or through long-term changes in plant communities and plant-soil feedbacks (Mueller et al., 2016; Stagg et al., 2018). Thus, the magnitude and effects of SWISLR on solute concentrations and potential associated land-sea biogeochemical fluxes may vary, and likely depend on the context within which SWISLR occurs. Part of what makes this particularly complicated to measure and model is that SWI, or the loading of salts, does not necessarily lead to soil salinization because the retention of salts depends to a large extent on the extent of dilution by precipitation and loss of salts through drainage. These changes in carbon and nutrient concentrations may result in changes in land-ocean biogeochemical fluxes, as well as shifts in the land-atmosphere exchange of greenhouse gasses (Ardón et al., 2018; Herbert et al., 2015; Ishtiaq et al., 2022; Lee et al., 2022; Tully et al., 2019b).

2.2. Socioeconomic consequences of environmental change

In addition to ecosystem consequences, SWISLR is affecting the socio-economic systems along the coast in diverse ways. Decision-makers – from public policy-makers to private households – require an understanding of how these factors interact and will continue to change, in order to manage and prepare for the future. SWISLR has myriad effects on coastal communities across the urban-rural gradient through direct and indirect impacts (Alameddine et al., 2017; Bhattachan et al., 2018b; Carse and Lewis, 2017; Lane et al., 2013). Coastal land loss due to SWISLR causes economic losses (Maldonado et al., 2019) and affects the social fabric and identity at the cultural, community, and individual level (Maldonado, 2014, 2015, 2018; Tully et al., 2019b). People rely on their surrounding environment for more than economic gain, and mental health impacts, such as grief and depression, may be experienced in coastal communities due to a "loss of place" (Albrecht et al., 2007). Shifts in population, policy changes, and other socioeconomic factors often cause reductions in income, changes in property values and social networks, and increases in the cost of insurance (Alameddine et al., 2017; Bhattachan et al., 2018b; Carse and Lewis, 2017) that often have disproportionate impacts on low income households and people of color (Hardy et al., 2017; Nance, 2015). SWISLR induced impacts can be exacerbated through variabilities in the social landscape. Social vulnerabilities are not equally distributed and can be particularly acute for rural agricultural communities (Bhattachan et al., 2018b; Jurjonas and Seekamp, 2018). SWI into aquifers harms drinking water supplies and agricultural crop production (Alameddine et al., 2017; Barlow and Reichard, 2009; Charles, 2012; Klassen and Allen, 2017; Michael et al., 2017; Tully et al., 2019b). These phenomena negatively impact human health and well-being, livelihoods, and economies (Bhattachan et al., 2018b; Bloetscher et al., 2016; Charles, 2012; Gutierrez and LePrevost, 2016). Communities, decision-makers, and individual property owners will be faced with difficult decisions about whether to adapt and invest in infrastructure and property protection or relocate (White and Kaplan, 2017). These decisions and their consequences are also influenced by a range of policies and institutions that can ease or exacerbate environmental and social outcomes (Bennett, 2018; Tully et al., 2019b). .

Coastal landscapes are important for Indigenous peoples worldwide, and many are facing the wide-reaching impacts of SWISLR. Some communities have occupied specific coastal territories since time immemorial, and others may claim coastal landscapes as part of their ancestral territories even though they are presently displaced from the coast because of social or environmental factors (Donatuto et al., 2014; Maldonado et al., 2014; Shreve, 2009). For example, in parts of the U.S. North Atlantic coastal plain, Lumbee, Coharie, and other Indigenous peoples presently located 100 km or more from the coast are still threatened by SWISLR. These communities claim parts of the Atlantic coastline within their ancestral territories (Lowery, 2018; North Carolina Commission of Indian Affairs, 1979). Cultural and historical resources within these territories are presently at risk of loss through shoreline erosion (Bhattachan et al., 2018; Lautzenheiser et al., 2011) and damage is possible to culturally-significant ecosystems such as forested coastal wetlands (Emanuel, 2019). In other coastal regions, indigenous culinary, consumptive, and cultural traditions have been the focus of revitalization efforts (e.g. (Lynn et al., 2014; Nabhan et al., 2010)). Efforts to strengthen and pass on these knowledge systems to future generations depend on the health and distribution of coastal ecosystems that provide habitat for shellfish, medicinal plants, and more used in these traditions (e.g., (Lynn et al., 2014; McCay et al., 2011)). These diverse knowledge systems are important for understanding the complexities surrounding SWISLR.

3. Research frontiers: a call for boundary crossing

Without new or altered water infrastructure to prevent it, the extent and duration of saltwater intrusion into coastal plain communities will increase under all realistic climate change scenarios. SWISLR is a complicated process and causes complicated issues throughout the coastal plain, as explained above. Therefore, gaining a holistic understanding is difficult because processes integral to SWISLR often exist at physical, social, and disciplinary boundaries. Much of the SWISLR research remains siloed, with only about 2% of SWISLR articles in Scopus being interdisciplinary research. There is a critical need to reconceptualize scientific frameworks in ways that center SWISLR. Additionally, SWISLR research requires communication and cooperation between many experts (including stakeholders) to address the physical, ecological, and socio-economic problems that arise. Due to the complexity of SWISLR related issues, research centered on SWISLR will require collaboration and buy-in from local communities to succeed.

SWISLR is a complex perturbation involving hydrologic, geomorphic, ecological, and socioeconomic feedbacks at the terrestrial-aquatic and freshwater-saltwater interfaces with tremendous consequences for the health and well-being of rural coastal residents. Predicting, managing, and adapting to rapid change in rural coastal landscapes requires rapid advances in transdisciplinary science and models (U.S. Department of Energy, 2017). Below, we identify six critical research frontiers that span the physical, ecological, and social sciences. These frontiers

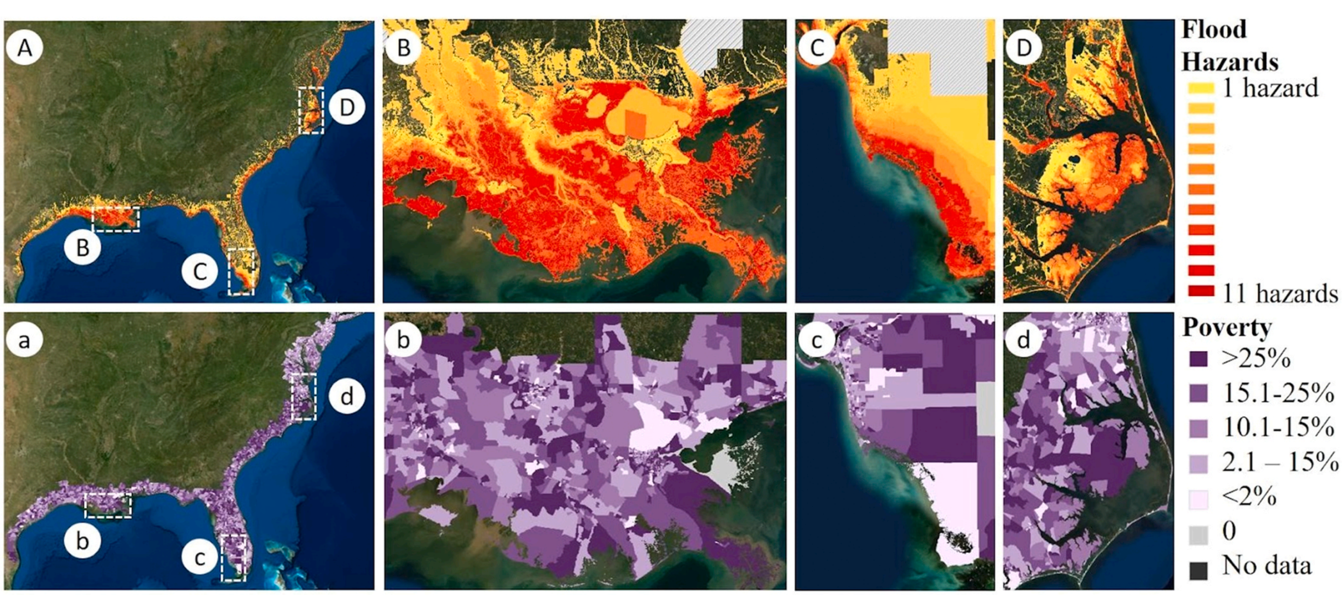

Fig. 3. Ecosystem and social vulnerabilities in the coastal plain ecoregion. This compilation of maps shows the number of potential flood hazards (top) and the percentage of people living below the poverty line for Census block groups (bottom) for the (Aa) entire North American coastal plain, (Bb) Gulf Coast of Louisiana, (Cc) southwest coast of Florida, and (Dd) coast of North Carolina. All maps are made from NOAAs Coastal Flood Exposure Mapper.

arose through discussions by members of the Coastal Futures Working Group and were reviewed among interdisciplinary SWISLR researchers. Each research frontier requires crossing physical, social, and disciplinary boundaries.

3.1. Who is engaged in decisions about climate risk prevention, climate adaptation, and SWISLR mitigation, and who is excluded?

3.1.1. Problem

To answer this question, implementing procedural and distributional justice in climate management is needed to cross the boundary of present systemic inequities (Schlosberg, 2007). We know that while many groups are having the conversation about how to carry out risk prevention, adaptation and SWISLR mitigation efforts, not all groups are involved in planning climate risk prevention or are consulted. This has a twofold impact: it excludes valuable voices and perspectives while also creating the conditions for already vulnerable groups to shoulder the bulk of the consequences of SWISLR. We know from research conducted on climate change risk and impact that there is an uneven distribution of both across differently situated populations (Barnett, 2020; Collins, 2010; Faber, 2015; Hardy et al., 2017; Leichenko and Silva, 2014; Thomas et al., 2019). Some communities experience more resource, livelihood, and cultural losses than others (Adger et al., 2013; McDowell et al., 2016; McNeeley and Lazrus, 2014; Thomas et al., 2019). This is related to physical climate change and more specifically, SWISLR events, but is driven by social practices and historical practices of exclusion (Ciplet et al., 2015; Graham et al., 2015; Hardy et al., 2017; Martinich et al., 2013; Marzeion and Levermann, 2014). Even as a number of organizations at national, regional, and local scales develop resources to mitigate the impacts; access to, and knowledge about, those resources is inconsistent across impacted communities (Shearer, 2012; Thomas et al., 2019). Mitigation plans may not take into account the lived experience of SWISLR impacts, missing out on key areas of intervention that may be needed if communities are to be best prepared to respond to SWISLR. Uneven access to climate change mitigation and adaptation resources has at its foundation long-standing structural oppression based on race, class, gender, ability and their intersections (Heynen et al., 2007; Mastaler, 2019; Nesmith et al., 2020; Sanders, 2020; Sultana, 2014). Thus, strategies developed may sometimes have the impact of increasing inequality (Atteridge and Remling, 2018; Thomas and Warner, 2019). These groups are underrepresented in decision-making processes, their knowledge is under-valued, and simultaneously, they experience the bulk of the impacts of climate change (Adger et al., 2011; Lazrus, 2016, 2015). These groups are often situated in livelihood activities, such as agriculture, fishing, or forestry that are steadily experiencing the effects of SWISLR (Hardy et al., 2017; Thomas et al., 2019).

3.1.2. Call to action

To include the perspectives of vulnerable communities, researchers can start advancing toward a solution by documenting what is missing in existing data-sets through examining access to data, reviewing consultation methods, determining place-specific exclusionary practices and vulnerabilities, and creating a pathway for conducting new and impactful research on climate change and SWISLR. However, proximate problems should be accounted for before these actions are taken. Many vulnerable communities are not able to give their attention to SWISLR or other climate concerns because of pressing economic and/or social issues. How is it that vulnerable communities can give their attention to SWISLR mitigation, if they are struggling to maintain their livelihoods or experiencing exclusion or discrimination? What institutions could identify and offset this bias? More work needs to be done with the communities being impacted. A focus on creating a common vocabulary that is attentive to cultural, economic, and political differences between stakeholders seeking to mitigate the impacts of SWISLR and communities experiencing those impacts is needed to better communicate existing issues.

3.2. What areas have recently undergone and are currently vulnerable to significant ecosystem transitions as a result of SWISLR?

3.2.1. Problem

Geographic and spatial boundaries must be crossed to gain a clear understanding of the extent of SWISLR. There has been some success crossing spatial boundaries through remote sensing: the transitions between land cover types, ecosystem types, and salinization in agriculture systems have been successful at local scales, and regional synthesis to reveal 'hotspots' of change (Chen et al., 2022; Ury et al., 2021; White et al., 2022). However, the drivers of coastal vegetation change remain an area of uncertainty. For example, at large spatial scales and at fine spatial resolutions, it is challenging to attribute the ultimate cause of vegetation mortality; how can we identify whether vegetation has died because of flood stress, salt stress, disturbance, or due to other resource limitations? Maps of key drivers such as soil salinity, inundation frequency, and human-made infrastructures remain unavailable at the regional scale in many areas. In addition, due to the limited timespan of remote sensing datasets, it is challenging to track the temporal trajectories of ecosystems that have been going through SWISLR. Understanding the temporal trend of these SWISLR-impacted ecosystems is crucial to modeling.

The research community is poorly equipped at present because the best models for understanding rapid environmental change (i.e., earth surface models and economic forecasting models) do not interact. People and decision making are not included in earth surface models and environmental change is not included in the economic models. Model capabilities are limited to interfaces – be they aquatic-terrestrial / freshwater-saltwater / urban-rural because models are generally developed to determine boundaries. By its very nature SWISLR is model defying – by both penetrating and shifting boundaries. To manage, adapt, and predict SWISLR impacts, we need to develop models that cross boundaries.

3.2.2. Call to action

We need more information on the hazard of SWISLR and the potential outcomes to identify vulnerable areas. It is crucial to provide data on the spatio-temporal changes of the coastal ecosystems beyond land cover and use types, but also productivity, structure, and biodiversity. In addition, high resolution data on inundation frequency and human-made infrastructure are important. Therefore, efforts are needed to share data in accessible ways (Wilkinson et al., 2016), including providing training opportunities about spatial data interpretation to local communities. In addition to data needs, centering these models on SWISLR or community concerns would help cross spatial and social boundaries. A key step is to learn from a local community about what data/information they would like to know, and how remote sensing can provide them that information. Using this as a first step will help in creating purpose driven models to identify local vulnerabilities, which can potentially help community and stakeholders come to local solutions.

3.3. How are water management and climate change interacting to determine the magnitude, extent, and duration of saltwater intrusion?

3.3.1. Problem

Humans have altered the hydrologic connections across much of the North American coastal plain. Over a century of development has degraded many of the coastal ecosystems (Gedan et al., 2009; Gittman et al., 2015) and substantially altered coastal hydrology (Gregory, 2006; Werner and McNamara, 2007). While there is enhanced potential for SWISLR to become more severe, the actual extent to which saltwater will affect the U.S. coastal plain is highly dependent upon human decisions about water. To better understand how water management and climate change are interacting, communication is needed and the discipline boundary between hydrology and policy/management needs to be crossed.

The influence of water management infrastructure on SWISLR extent is variable, and the spatial extent of water management infrastructure is not well known (Neville et al., 2023). Due to the long and changing history of human land use, there is not a clear record of all the human infrastructure present along the U.S. coastal plain. Remote sensing and imagery mapping applications have the potential to help map out human infrastructure, as seen in the creation of the Global River Obstruction Database (Yang et al., 2022). However, these global databases lack spatial resolution to identify smaller infrastructure (Neville et al., 2023), which can either enhance the spatial extent of SWISLR by allowing salty water to flow inland along natural drainage networks (Bhattachan et al., 2018) or constrain flow through control technologies, such as gates, culverts, dikes, and berms (Rodríguez et al., 2017; Sandi et al., 2018). New digital elevation models derived from high resolution LIDAR imagery have the potential to improve the mapping of the altered human hydrologic network in coastal landscapes (Lang et al., 2012). Thus, predicting the timing, magnitude, and duration of saltwater intrusion events will require models that integrate water infrastructure (canals systems, dikes, levees) and water management (pumps, check dams, irrigation, groundwater extraction), in addition to SLR, rainfall-runoff relationships, evapotranspiration, and natural geomorphology.

3.3.2. Call to action

Land use history and change complicates hydrology and the potential extent of SWISLR due to human modification. To properly predict SWISLR and its consequences, a comprehensive data collection of water management infrastructure is necessary. The lack of a database of coastal water management structures, and a meta-analysis of salinization trends of freshwater coastal ecosystems by SWISLR, hinders development of predictive tools. A compilation and synthesis of long-term data on water salinity in tidal freshwater and oligohaline zones within the U.S. coastal plain is needed before identifying how human modification influences SWISLR. Compiled salinity, discharge, water level, and biogeochemical concentration datasets paired with consistent ancillary datasets (e.g., soil properties, land use history, topography) are needed to explain and predict spatiotemporal patterns in salinity and biogeochemical response direction and magnitude. Paired soil surface, groundwater, and surface water salinity monitoring in different land uses are required to understand how salinity moves across aquatic-terrestrial systems. Once management structures are identified across the coastal plain, and salinity trends are mapped, interactions between human modification and SWISLR can be better understood.

3.4. What are the consequences of SWISLR for farms and coastal fisheries?

3.4.1. Problem

SWISLR will impact a significant proportion of U.S. cropland, and farmers have limited methods to adapt to SWISLR. Currently, ~11% of the U.S. land area in the coastal plain is cultivated and about 55,850 ha (138,000 acres) of this farmland is within 0.9 m (3 ft) of projected SLR (Sweet et al., 2017; Gibson et al., 2021). These farmlands sit between developed uplands and tidal creeks and may serve as the last line of defense. A large portion of the farmland in the coastal plain is artificially drained to remove water from saturated soils (Edwards and Thurman, 2022). These drainage canals and ditches can have shallow gradients and provide a pathway for higher salinity water to move inland.

Few crops can grow in sustained soil conditions of greater than 2 ppt salinity (Tanji et al., 2002), however salinity levels between 4 and 13 ppt are regularly measured on salt-intruded farms (de la Reguera et al., 2020; Tully et al., 2019b). Salinization of fields harms the typical corn (Zea mays L.)-soy (Glycine max (L.) Merr.) rotations (McNulty et al., 2015) and in some cases, 100% crop failure has been observed (Tully et al., 2019b). SWISLR impacts on farmlands also have downstream consequences for fisheries and aquatic ecosystems. The application of fertilizer N and P (either mineral or organic) to farmlands over prior decades has led to a build-up of nutrients in the soil. These "legacy" nutrients can be remobilized years, or even decades, after application, supplying a persistent, but unpredictable, source of N and P downstream to waterways (Ardón et al., 2013; Sharpley et al., 2013). Excess nutrient loading has substantially degraded coastal freshwater and marine water quality across the U.S. Atlantic and Gulf of Mexico coastal plain including eutrophication, hypoxia, and harmful algal blooms (Boesch, 2019; Paerl et al., 2001, 2018) that affect local fisheries and aquatic ecosystems.

There are several ways in which farmers respond to the effects of SWISLR on their farmlands. (1) Farmers engage in physical adaptation by managing water and salinity through the installation of tide gates or on-field amendments. Tide gates are water control structures that mitigate the upslope movement of saltwater from the sound/ocean, while allowing freshwater to flow freely to the ocean (White and Kaplan, 2017). Farmers apply gypsum or other amendments to their fields to improve soil structure, with the addition of gypsum requiring more freshwater applications to leach excess salts from the soil (Mukhopadhyay et al., 2021). (2) Farmers adapt their crop choice by planting alternate crops or plants more robust to salinity (Ventura et al., 2015; Voutsina et al., 2015), or by converting their operations to aquaculture (Mukhopadhyay et al., 2021). Further, farmers can also adopt climate-smart or more resilient practices that address challenges related to climate change (Food and Agriculture Organization of the United Nations, 2021). (3) Farmers abandon their land entirely and cease agricultural production (Gedan and Fernández-Pascual, 2019), potentially receiving payments for conservation easements (Rissman et al., 2015) or putting the field to another (less valuable) economic purpose.

3.4.2. Call to action

To answer this complex question collaboration across disciplines are needed. Landowners, farmers, and fishers need access to information and resources to better understand when and how to respond to SWISLR. Predictions of the spatial extent of SWISLR will help landowners plan better for the future. Specifically, maps are needed that overlap the predicted extent of SWISLR with property and farm land. Currently no maps exist that allow farmers to make informed decisions about how to manage SWISLR. SWISLR is a moving edge, and better spatial predictions will help us manage the current and future edge.

Information and technical assistance for land conversion is necessary for coastal landowners and managers. Collaborations across state-lines will enable researchers, farmers, and land managers to learn how different groups are dealing with SWISLR. This will help encourage knowledge-sharing and identify gaps in knowledge and technical capacity (e.g. how to grow alternative crops or convert vulnerable fields to salt tolerant wetland species).

3.5. How is SWISLR affecting the structure, biodiversity, and function of ecological systems?

SWISLR represents extreme stress to many plants, leading to two coordinated changes, inland range expansions of more salt-tolerant plant species and inland retreat of less salt-tolerant species. Among the most visually obvious impacts of SWISLR on coastal ecology is the loss of shoreline and marsh through subsidence and the transition of coastal freshwater forested wetlands to ghost forests (Fig. 4.) (Anderson et al., 2022; Bernhardt, 2022; Osland et al., 2022; Taillie et al., 2019a; Ury et al., 2021b; Weston, 2014; White et al., 2022). Because pollinators, herbivores, and other animal dispersers tend to have specialized diet and habitat requirements, changing plant communities result in shifts in the communities of the animals that depend directly on them (Hunter et al., 2015; Taillie et al., 2019c). The transition from coastal forests to ghost

Fig. 4. Shoreline loss and inland ghost forests from coastal NC. Photos by ES Bernhardt.

forest to marsh can be associated with substantial loss of total carbon stocks due to replacement ofaboveground biomass of coastal forested wetlands (Smart et al., 2020; Smith and Kirwan, 2021), direct changes in soil chemistry and hydrology (Ardón et al., 2018; Ury et al., 2021a) and plant mediated feedbacks (Lerdau and Slobodkin, 2002). Further, increased abundance of standing dead trees (snags) in ghost forests has been shown to increase ecosystem greenhouse gas emissions (Martinez et al., 2022; Martinez and Ardón, 2021). Predicting the effects of SWISLR on coastal ecological systems is extremely challenging, given that: (1) salinization includes multiple vectors of chemical change; (2) salinization impacts and retention are contingent upon the hydrologic setting and soil characteristics; and (3) many of the microbial responses to salinization that determine soil C turnover are themselves contingent upon plant responses (Herbert et al., 2015; Tully et al., 2019b).

3.5.1. Call to action

To better understand SWISLR impacts to ecological systems we first need to find a generalization of patterns found within existing studies. This synthesis of ecological SWISLR impacts will help identify whether the extent of physiological responses to salt stress are consistent within species and across developmental stages, and what factors best explain the diversity of biogeochemical responses to SWISLR at broad geographic scales. The impacts can then be predicted with mechanistic models to determine which plant traits predict sensitivity to salt-stress across species, and whether these are consistent across different plant functional types. These models would enhance existing or future hydrologic models used for predicting ecosystem consequences of SWISLR, including the dynamics of transitions and recovery of ecosystems. In tandem with these first two priorities is the need for collaboration between ecosystem scientists to develop and implement standardized sampling and measurement methods. Along with identifying the patterns of ecosystem response and incorporating those relationships into mechanistic models, a synthesis of methods used in ecosystem science could be created and analyzed to identify the best-practices for future research. All three priorities are necessary to cross the ecosystem-specific and spatial-centric boundaries that currently limit our understanding of ecosystem response to SWISLR.

3.6. How are coastal communities interpreting, responding to, and managing for SWISLR impacts and risk?

3.6.1. Problem

SWISLR threatens communities located along the low-lying coastal plain in diverse ways, creating complicated problems to address. As with many climate change risks, variations in the ecological and social landscape create unique vulnerabilities that make SWISLR impacts unequal across the landscape, often disproportionately impacting low income families, the elderly, and people of color (Harlan et al., 2019; Wing et al., 2022). Households respond to these impacts and risks by making decisions about their property at a parcel scale which have direct and indirect consequences to the surrounding ecosystem, neighborhood decisions, and future populations (Cook et al., 2012; Scyphers et al., 2015). Geography and historical landscape decisions have been found to influence exposure and social vulnerability, with historic exclusionary housing policies (redlining) causing neighborhoods to see increased risk of flooding, and historic draining of agricultural land through ditches being more vulnerable to SWISLR impacts (Bhattachan et al., 2018; Katz, 2021). Adaptation to impacts and risk is not distributed equally across the U.S. coastal plain due to the (typically) high costs of adaptation options available, resulting in low income and rural communities with a high risk of SWISLR, without options to increase their resiliency (Gittman et al., 2015; Schlosberg, 2007). Understanding how coastal communities are impacted, and their responses is a vital first step in planning for SWISLR adaptation (Cook et al., 2012; Douglas et al., 2012). Wide variations in social vulnerability, exposure, and historical adaptation actions presents governance institutions at a variety of levels, from local to national, with numerous challenges, including: creating a widely-accepted definition of the nature and scope of the problem, coordinating adaptation actions, achieving buy-in from differentially affected communities, and ensuring the equitable allocation of resources.

3.6.2. Call to action

Discipline and governance barriers strongly affect how we identify, record, study, and communicate SWISLR impacts. Scholars from a wide range of social science disciplines have studied human dimensions of SLR, with less work devoted specifically to the social aspects of SWI. To answer the question, "how are coastal communities interpreting, responding to, and managing for SWISLR impacts and risk?", we can combine the expertise of multiple disciplines (including those taking social, ecological, economic, health, and infrastructure perspectives) (Bloetscher et al., 2016). In doing so, we can incorporate local and traditional knowledge into research, planning and decision making (Dolan and Walker, 2006; Lesen, 2015). These multi-discipline teams can then better synthesize a wide range of studies that have investigated the human dimensions of SWISLR. This synthesis would help highlight human impacts of SWISLR, adaptation actions in light of SWISLR, and institutional barriers and opportunities for governance that effectively address SWISLR. Once a synthesis is complete, community leaders and decision-makers need to be involved to adequately share the knowledge collected and to develop innovative strategies for incorporating diverse types of knowledge into decision-making around mitigation, restoration, adaptation, and retreat. Creating an integrative and collaborative approach will enable the development of strategies for weighing management and response options ranging from status quo to restoration, to retreat.

4. Conclusions

Under all realistic climate change scenarios, the extent and duration of SWISLR into coastal plain systems will increase substantially. The associated rising water tables, further inland extent of saline ground and surface waters, and more frequent extreme events are already placing stress on coastal systems. These stressors are responsible for systematic shifts such as the creation of ghost forests (White et al., 2022) and rapid demographic change (Kummu et al., 2016) and without new or altered water infrastructure to prevent SWISLR - natural ecosystems, infrastructure, food production, and livelihoods are at risk. To intelligently confront and respond to SWISLR, scholars and stakeholders can reframe the way many conceptualize the effects of climate change, moving from the question of "when might long-term inundation occur?" to "when and how might salinization affect lands prior to, during, and after inundation?" and "what land and water management options will minimize the potential for catastrophic outcomes from regime shifts?" As landscapes transform in response to SWISLR, and in advance of rising seas, we argue that the sustainability of coastal systems hinges largely on developing sophisticated understanding of the coupled human and natural processes influencing salinization of surface water, ground water, and adjacent lands. Although the examples provided in this manuscript focus on the North American Coastal Plain, SWISLR is a global problem and better understanding relies on engaging the widest possible diversity of voices, and educating the widest possible diversity of coastal communities and decision makers. Both efforts will rely heavily on building a robust and diverse network of engaged experts and improving access to information regarding pertinent research and management activities of all interested individuals. Facilitating and sharing diverse knowledge when confronting SWISLR will help cross boundaries associated with current SWISLR research and management efforts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

This paper arose from discussions of the Coastal Futures Working Group supported by the University of Virginia's Environmental Resilience Institute Water Futures Initiative and was further refined by members of the National Science Fund Dynamics of Integrated Socio-Environmental Systems SWISLR Research Cordination Network Steering Committee members which supported lead author KLO during the preparation of this manuscript (NSF 2108286). All authors contributed to the framing and editing of this paper. We are grateful for the generous input from Larry Band, Bryan Davis, Karen McGlathery, and Mike Pace of UVA, Pat Megonigal from the Smithsonian Environmental Research Center, and Ben Poulter from NASA Goddard during early discussions of this paper. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This is publication #1676 from the Institute of Environment at Florida International University.

References

Adger, W.N., Hughes, T.P., Folke, C., Carpenter, S.R., Rockström, J., 2005. Social-ecological resilience to coastal disasters. Science. https://doi.org/10.1126/science.1112122.

Adger, W.N., Barnett, J., Chapin III, F.S., Ellemor, H., 2011. This must be the place: underrepresentation of identity and meaning in climate change decision-making. Glob. Environ. Polit. 11, 1–25.

Adger, W.N., Barnett, J., Brown, K., Marshall, N., O'brien, K., 2013. Cultural dimensions of climate change impacts and adaptation. Nat. Clim. Chang. 3, 112–117.

Alameddine, I., Jawhari, G., El-Fadel, Mutasem, 2017. Social Perception of Public Water Supply Network and Groundwater Quality in an Urban Setting Facing Saltwater Intrusion and Water Shortages. Environ. Manag. 59, 571–583.

Albrecht, G., Sartore, G.-M., Connor, L., Higginbotham, N., Freeman, S., Kelly, B., Stain, H., Tonna, A., Pollard, G., 2007. Solastalgia: the distress caused by environmental change. Australas. Psychiatry 15 (Suppl 1), S95–S98.

Allan, R.P., Soden, B.J., 2008. Atmospheric warming and the amplification of precipitation extremes. Science.

Anderson, S.M., Ury, E.A., Taillie, P.J., Ungberg, E.A., Moorman, C.E., Poulter, B., Ardón, M., Bernhardt, E.S., Wright, J.P., 2022. Salinity thresholds for understory plants in coastal wetlands. Plant Ecol. 223, 323–337.

Ardón, M., Morse, J.L., Colman, B.P., Bernhardt, E.S., 2013. Drought-induced saltwater incursion leads to increased wetland nitrogen export. Glob. Chang. Biol. 19, 2976–2985.

Ardón, M., Helton, A.M., Bernhardt, E.S., 2016. Drought and saltwater incursion synergistically reduce dissolved organic carbon export from coastal freshwater wetlands. Biogeochemistry 127. https://doi.org/10.1007/s10533-016-0189-5.

Ardón, M., Helton, A.M., Scheuerell, M.D., Bernhardt, E.S., 2017. Fertilizer legacies meet saltwater incursion: challenges and constraints for coastal plain wetland restoration. Elem. Sci. Anth 5.

Ardón, M., Helton, A.M., Bernhardt, E.S., 2018. Salinity effects on greenhouse gas emissions from wetland soils are contingent upon hydrologic setting: a microcosm experiment. Biogeochemistry 140, 217–232.

Arfib, B., de Marsily, G., Ganoulis, J., 2007. Locating the Zone of Saline Intrusion in a Coastal Karst Aquifer Using Springflow Data. Ground Water 45, 28–35.

Ashraf, M., Harris, P.J.C., 2004. Potential biochemical indicators of salinity tolerance in plants. Plant Sci. https://doi.org/10.1016/j.plantsci.2003.10.024.

Atteridge, A., Remling, E., 2018. Is adaptation reducing vulnerability or redistributing it? Wiley Interdiscip. Rev. Clim. Change 9, e500.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81, 169–193.

Barlow, P.M., Reichard, E.G., 2009. Saltwater intrusion in coastal regions of North America. Hydrogeol. J. 18, 247–260.

Barnett, J., 2020. Global environmental change II: political economies of vulnerability to climate change. Prog. Hum. Geogr., 0309132519898254

Bennett, N.J., 2018. Navigating a just and inclusive path towards sustainable oceans. Mar. Policy 97, 139–146.

Bernhardt, E., 2022. Coastal freshwater wetlands squeezed between migrating salt marshes and working lands. Sci. Adv. 8, eadd1628.

Bestelmeyer, B.T., Ellison, A.M., Fraser, W.R., Gorman, K.B., Holbrook, S.J., Laney, C.M., Ohman, M.D., Peters, D.P.C., Pillsbury, F.C., Rassweiler, A., Schmitt, R.J., Sharma, S., 2011. Analysis of abrupt transitions in ecological systems. Ecosphere 2, art129.

Bhattachan, A., Emanuel, R.E., Ardón, M., Bernhardt, E.S., Anderson, S.M., Stillwagon, M.G., Ury, E.A., BenDor, T.K., Wright, J.P., 2018. Evaluating the effects of land-use change and future climate change on vulnerability of coastal landscapes to saltwater intrusion. Elem. (Wash., DC 6, 62.

Bhattachan, A., Jurjonas, M.D., Moody, A.C., Morris, P.R., Sanchez, G.M., Smart, L.S., Taillie, P.J., Emanuel, R.E., Seekamp, E.L., 2018a. Sea level rise impacts on rural coastal social-ecological systems and the implications for decision making. Environ. Sci. Policy. https://doi.org/10.1016/j.envsci.2018.10.006.

Bhattachan, A., Jurjonas, M.D., Moody, A.C., Morris, P.R., Sanchez, G.M., Smart, L.S., Taillie, P.J., Emanuel, R.E., Seekamp, E.L., 2018b. Sea level rise impacts on rural coastal social-ecological systems and the implications for decision making. Environ. Sci. Policy 90, 122–134.

Bloetscher, F., Polsky, C., Bolter, K., Mitsova, D., Garces, K.P., King, R., Carballo, I.C., Hamilton, K., 2016. Assessing potential impacts of sea level rise on public health and vulnerable populations in Southeast Florida and providing a framework to improve outcomes. Sustain. (Switz.) 8. https://doi.org/10.3390/su8040315.

Boesch, D.F., 2019. Barriers and bridges in abating coastal eutrophication. Front. Mar. Sci. 6, 123.

Braswell, A.E., Heffernan, J.B., 2019. Coastal Wetland distributions: delineating domains of macroscale drivers and local feedbacks. Ecosystems. https://doi.org/10.1007/s10021-018-0332-3.

Brinson, M.M., Christian, R.R., Blum, L.K., 1995. Multiple states in the sea-level induced transition from terrestrial forest to estuary. Estuaries 18, 648–659.

Caraco, N.F., Cole, J.J., Likens, G.E., 1989. Evidence for sulphate-controlled phosphorus release from sediments of aquatic systems. Nature 341, 316–318.

Carpenter, S.R., Cole, J.J., Pace, M.L., Batt, R., Brock, W.A., Cline, T., Coloso, J., Hodgson, J.R., Kitchell, J.F., Seekell, D.A., Smith, L., Weidel, B., 2011. Early warnings of regime shifts: a whole-ecosystem experiment. Science 332, 1079–1082.

Carse, A., Lewis, J.A., 2017. Toward a political ecology of infrastructure standards: or, how to think about ships, waterways, sediment, and communities together. Environ. Plan. A 49, 9–28.

Carter, L.J., 1975. Agriculture: a new frontier in coastal north Carolina. Science 189, 271–275.

Chapelle, S.E.G., 1986. Maryland, a history of its people. Johns Hopkins University Press.
Charles, A., 2012. People, oceans and scale: governance, livelihoods and climate change adaptation in marine social–ecological systems. Curr. Opin. Environ. Sustain. 4, 351–357.
Charles, S.P., Kominoski, J.S., Troxler, T.G., Gaiser, E.E., Servais, S., Wilson, B.J., Davis, S.E., Sklar, F.H., Coronado-Molina, C., Madden, C.J., Kelly, S., Rudnick, D.T., 2019. Experimental saltwater intrusion drives rapid soil elevation and carbon loss in freshwater and brackish everglades marshes. Estuaries Coasts 42, 1868–1881.
Chen, B.J.W., Teng, S.N., Zheng, G., Cui, L., Li, S.-P., Staal, A., Eitel, J.U.H., Crowther, T. W., Berdugo, M., Mo, L., Ma, H., Bialic-Murphy, L., Zohner, C.M., Maynard, D.S., Averill, C., Zhang, J., He, Q., Evers, J.B., Anten, N.P.R., Yizhaq, H., Stavi, I., Argaman, E., Basson, U., Xu, Z., Zhang, M.-J., Niu, K., Liu, Q.-X., Xu, C., 2022. Inferring plant–plant interactions using remote sensing. J. Ecol. 110, 2268–2287.
Ciplet, D., Roberts, J.T., Khan, M.R., 2015. Power in a warming world: The new global politics of climate change and the remaking of environmental inequality. MIT Press.
Collins, T.W., 2010. Marginalization, facilitation, and the production of unequal risk: the 2006 Paso del Norte Floods. Antipode 42, 258–288.
Cook, E.M., Hall, S.J., Larson, K.L., 2012. Residential landscapes as social-ecological systems: a synthesis of multi-scalar interactions between people and their home environment. Urban Ecosyst. 15, 19–52.
Dahl, T.E., Stedman, S.-M., 2013. Status and trends of wetlands in the coastal watersheds of the Conterminous United States 2004 to 2009. US Department of the Interior, US Fish and Wildlife Service and National ….
Desmet, K., Kopp, R., Kulp, S., Nagy, D.K., Oppenheimer, M., Rossi-Hansberg, E., Strauss, B., 2018. Evaluating the Economic Cost of Coastal Flooding. https://doi.org/10.3386/w24918.
Dolan, A.H., Walker, I.J., 2006. Understanding vulnerability of coastal communities to climate change. Relat. Risks. J. Coast. Res. 1316–1323.
Donatuto, J., Grossman, E.E., Konovsky, J., Grossman, S., Campbell, L.W., 2014. Indigenous community health and climate change: integrating biophysical and social science indicators. Coast. Manag. 42, 355–373.
Douglas, E.M., Kirshen, P.H., Paolisso, M., Watson, C., Wiggin, J., Enrici, A., Ruth, M., 2012. Coastal flooding, climate change and environmental justice: Identifying obstacles and incentives for adaptation in two metropolitan Boston Massachusetts communities. Mitig. Adapt. Strateg. Glob. Change. https://doi.org/10.1007/s11027-011-9340-8.
Duberstein, Jamie A., Krauss, Ken W., Baldwin, Michael J., Allen, Scott T., Conner, William H., Salter, John S., Miloshis, Michael, 2020. Small gradients in salinity have large effects on stand water use in freshwater wetland forests. . Ecol. Manag. 473 (October), 118308.
Edwards, E.C., Thurman, W.N., 2022. The institutional costs of adaptation: agricultural drainage in the United States. Work. Pap. Ser. https://doi.org/10.3386/w30081.
Eggleston, J., Pope, J.P., 2014. Land Subsidence and Relative Sea-level Rise in the Southern Chesapeake Bay Region. United States Geological Survey.
Emanuel, R.E., 2019. Water in the lumbee world: a river and its people in a time of change. Environ. Hist. Durh. N. C. 24, 25–51.
Ensign, S.H., Noe, G.B., 2018. Tidal extension and sea-level rise: recommendations for a research agenda. Front. Ecol. Environ. 16, 37–43.
Faber, J.W., 2015. Superstorm sandy and the demographics of flood risk in New York City. Hum. Ecol. 43, 363–378.
Fagherazzi, S., Anisfeld, S.C., Blum, L.K., Long, E.V., Feagin, R.A., Fernandes, A., Kearney, W.S., Williams, K., 2019. Sea level rise and the dynamics of the marsh-upland boundary. Front. Environ. Sci. Eng. China 7, 25.
Feagin, R.A., Luisa Martinez, M., Mendoza-Gonzalez, G., Costanza, R., 2010. Salt marsh zonal migration and ecosystem service change in response to global sea level rise: a case study from an urban region. Ecol. Soc.
Flower, H., Rains, M., Lewis, D., Zhang, J.-Z., Price, R., 2017. Saltwater intrusion as potential driver of phosphorus release from limestone bedrock in a coastal aquifer. Estuar. Coast. Shelf Sci. 184, 166–176.
Food and Agriculture Organization of the United Nations, 2021. Climate-smart agriculture case studies 2021: Projects from around the world. Food & Agriculture Org.
Friess, D.A., Yando, E.S., Alemu, J.S., Wong, L., Soto, S.D., Bhatia, N., 2020. Ecosystem Services and Disservices of Mangrove Forests and Salt Marshes. In: Hawkins, S.J., Allcock, A.L., Bates, A.E., Evans, A.J., Firth, L.B., McQuaid, C.D., Russell, B.D., Smith, I.P., Swearer, S.E., Todd, P.A. (Eds.), Oceanography and Marine Biology: An Annual Review, Oceanography and Marine Biology - An Annual Review. CRC Press, London, England, pp. 107–141.
Gedan, K.B., Fernández-Pascual, E., 2019. Salt marsh migration into salinized agricultural fields: a novel assembly of plant communities. J. Veg. Sci., jvs.12774
Gedan, K.B., Silliman, B.R., Bertness, M.D., 2009. Centuries of human-driven change in salt marsh ecosystems. Ann. Rev. Mar. Sci. 1, 117–141.
Gibson, N., McNulty, S., Miller, C., Gavazzi, M., Worley, E., Keesee, D., Hollinger, D., 2021. Identification, mitigation, and adaptation to salinization on working lands in the U.S. Southeast. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC. https://doi.org/10.2737/srs-gtr-259.
Gittman, R.K., Fodrie, F.J., Popowich, A.M., Keller, D.A., Bruno, J.F., Currin, C.A., Peterson, C.H., Piehler, M.F., 2015. Engineering away our natural defenses: an analysis of shoreline hardening in the US. Front. Ecol. Environ. 13, 301–307.
Graham, S., Barnett, J., Fincher, R., Mortreux, C., Hurlimann, A., 2015. Towards fair local outcomes in adaptation to sea-level rise. Clim. Change 130, 411–424.
Gregory, K.J., 2006. The human role in changing river channels. Geomorphology 79, 172–191.
Gutierrez, K., LePrevost, C., 2016. Climate justice in rural Southeastern United States: a review of climate change impacts and effects on human health. Int. J. Environ. Res. Public Health 13, 189.
Haer, T., Kalnay, E., Kearney, M., Moll, H., 2013. Relative sea-level rise and the conterminous United States: consequences of potential land inundation in terms of population at risk and GDP loss. Glob. Environ. Change 23, 1627–1636.
Hallegatte, S., Green, C., Nicholls, R.J., Corfee-Morlot, J., 2013. Future flood losses in major coastal cities. Nat. Clim. Change 3, 802–806.
Handwerger, L.R., Sugg, M.M., Runkle, J.D., 2021. Present and future sea level rise at the intersection of race and poverty in the Carolinas: a geospatial analysis. J. Clim. Change Health 3, 100028.
Hardy, R.D., Milligan, R.A., Heynen, N., 2017. Racial coastal formation: the environmental injustice of colorblind adaptation planning for sea-level rise. Geoforum 87, 62–72.
Harlan, S.L., Sarango, M.J., Mack, E.A., Stephens, T.A., 2019. A survey-based assessment of perceived flood risk in urban areas of the United States. Anthropocene 28, 100217.
Hartzell, J.L., Jordan, T.E., 2012. Shifts in the relative availability of phosphorus and nitrogen along estuarine salinity gradients. Biogeochemistry 107, 489–500.
Hauer, M.E., Hardy, D., Kulp, S.A., Mueller, V., Wrathall, D.J., Clark, P.U., 2021. Assessing population exposure to coastal flooding due to sea level rise. Nat. Commun. 12, 6900.
Helton, A.M., Bernhardt, E.S., Fedders, A., 2014. Biogeochemical regime shifts in coastal landscapes: the contrasting effects of saltwater incursion and agricultural pollution on greenhouse gas emissions from a freshwater wetland. Biogeochemistry 120, 133–147.
Helton, A.M., Ardón, M., Bernhardt, E.S., 2019. Hydrologic context alters greenhouse gas feedbacks of coastal wetland salinization. Ecosystems. https://doi.org/10.1007/s10021-018-0325-2.
Herbert, E.R., Boon, P., Burgin, A.J., Neubauer, S.C., Franklin, R.B., Ardón, M., Hopfensperger, K.N., Lamers, L.P.M., Gell, P., 2015. A global perspective on wetland salinization: ecological consequences of a growing threat to freshwater wetlands. Ecosphere 6, art206.
Herbert, E.R., Schubauer-Berigan, J., Craft, C.B., 2018. Differential effects of chronic and acute simulated seawater intrusion on tidal freshwater marsh carbon cycling. Biogeochemistry 138, 137–154.
Heynen, N., McCarthy, J., Prudham, S., Robbins, P., 2007. Neoliberal Environments: False Promises and Unnatural Consequences. Routledge.
Huang, K., Kardol, P., Yan, X., Luo, X., Guo, H., 2021. Plant–soil biota interactions explain shifts in plant community composition under global change. Funct. Ecol. 35, 2778–2788.
Hunt, A., Watkiss, P., 2011. Climate change impacts and adaptation in cities: a review of the literature. Clim. Change 104, 13–49.
Hunter, E.A., Nibbelink, N.P., Alexander, C.R., Barrett, K., Mengak, L.F., Guy, R.K., Moore, C.T., Cooper, R.J., 2015. Coastal vertebrate exposure to predicted habitat changes due to sea level rise. Environ. Manag. 56, 1528–1537.
Ishtiaq, K.S., Troxler, T.G., Lamb-Wotton, L., Wilson, B.J., Charles, S.P., Davis, S.E., Kominoski, J.S., Rudnick, D.T., Sklar, F.H., 2022. Modeling net ecosystem carbon balance and loss in coastal wetlands exposed to sea-level rise and saltwater intrusion. Ecol. Appl. 32, e2702.
Jeroen, C.J., Wouter Botzen, W.J., Emanuel, K., Lin, N., de Moel, H., Michel-Kerjan, E.O., 2014. Evaluating flood resilience strategies for coastal megacities. Science 344, 473–475.
Jevrejeva, S., Jackson, L.P., Riva, R.E.M., Grinsted, A., Moore, J.C., 2016. Coastal sea level rise with warming above 2C. Proc. Natl. Acad. Sci. 113, 13342–13347.
Johnson, K.A., Wing, O.E.J., Bates, P.D., Fargione, J., Kroeger, T., Larson, W.D., Sampson, C.C., Smith, A.M., 2019. A benefit–cost analysis of floodplain land acquisition for US flood damage reduction. Nat. Sustain. 3, 56–62.
Jordan, T.E., Cornwell, J.C., Boynton, W.R., Anderson, J.T., 2008. Changes in phosphorus biogeochemistry along an estuarine salinity gradient: The iron conveyer belt. Limnol. Oceanogr. 53, 172–184.
Jun, M., Altor, A.E., Craft, C.B., 2013. Effects of increased salinity and inundation on inorganic nitrogen exchange and phosphorus sorption by tidal freshwater floodplain forest soils, Georgia (USA). Estuaries Coasts 36, 508–518.
Jurjonas, M., Seekamp, E., 2018. Rural coastal community resilience: assessing a framework in Eastern North Carolina. Ocean Coast. Manag. 162, 137–150.
Jurjonas, M., Seekamp, E., Rivers, L., Cutts, B., 2020. Uncovering climate (in)justice with an adaptive capacity assessment: a multiple case study in rural coastal North Carolina. Land Use Policy 94, 104547.
Katz, L., 2021. Formerly Redlined Areas Have 25% More Home Value At High Flood Risk [WWW Document]. Redfin News. URL https://perma.cc/W7PP-9KH5 (Accessed 15 February 2023).
Kirwan, M.L., Gedan, K.B., 2019. Sea-level driven land conversion and the formation of ghost forests. Nat. Clim. Chang. 9, 450–457.
Kirwan, M.L., Kirwan, J.L., Copenheaver, C.A., 2007. Dynamics of an estuarine forest and its response to rising sea level. J. Coast. Res. https://doi.org/10.2112/04-0211.1.
Kirwan, M.L., Walters, D.C., Reay, W.G., Carr, J.A., 2016. Model of marsh erosion and migration. Geophys. Res. Lett. 43, 4366–4373.
Klassen, J., Allen, D.M., 2017. Assessing the risk of saltwater intrusion in coastal aquifers. J. Hydrol. 551, 730–745.
Krauss, K.W., Chambers, J.L., Creech, D., 2007. Selection for salt tolerance in tidal freshwater swamp species: Advances using baldcypress as a model for restoration. In: Ecology of Tidal Freshwater Forested Wetlands of the Southeastern United States. Springer Netherlands, Dordrecht, pp. 385–410.
Krauss, K.W., Noe, G.B., Duberstein, J.A., Conner, W.H., Stagg, C.L., Cormier, N., Jones, M.C., Bernhardt, C.E., Graeme Lockaby, B., From, A.S., Doyle, T.W., Day, R. H., Ensign, S.H., Pierfelice, K.N., Hupp, C.R., Chow, A.T., Whitbeck, J.L., 2018. The role of the upper tidal estuary in wetland blue carbon storage and flux. Glob. Biogeochem. Cycles 32, 817–839.

Kulp, S.A., Strauss, B.H., 2019. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat. Commun. 10, 4844.
Kummu, M., de Moel, H., Salvucci, G., Viviroli, D., Ward, P.J., Varis, O., 2016. Over the hills and further away from coast: global geospatial patterns of human and environment over the 20th–21st centuries. Environ. Res. Lett. 11, 034010.
Lane, K., Charles-Guzman, K., Wheeler, K., Abid, Z., Graber, N., Matte, T., 2013. Health effects of coastal storms and flooding in urban areas: A review and vulnerability assessment. J. Environ. Public Health. https://doi.org/10.1155/2013/913064.
Lang, M., McDonough, O., McCarty, G., Oesterling, R., Wilen, B., 2012. Enhanced detection of wetland-stream connectivity using LiDAR. Wetlands 32, 461–473.
Lautzenheiser, L., Bamann, S.E., Gosser, D.C., 2011. Now you see it; now you don't. Coastal erosion and coastal cottages: twenty years of cultural resource management. In: Ewen, C.R., Whyte, T.R., Davis Jr, R.P.S. (Eds.), The Archaeology of North Carolina: Three Archaeological Symposia. North Carolina Archaeological Council, pp. 13–11.
Lazrus, H., 2015. Risk perception and climate adaptation in Tuvalu: a combined cultural theory and traditional knowledge approach. Hum. Organ. 74, 52–61.
Lazrus, H., 2016. Drought is a relative term:" drought risk perceptions and water management preferences among diverse community members in Oklahoma, USA. Hum. Ecol. 44, 595–605.
Lee, D.Y., Kominoski, J.S., Kline, M., Robinson, M., Roebling, S., 2022. Saltwater and nutrient legacies reduce net ecosystem carbon storage despite freshwater restoration: insights from experimental wetlands. Restor. Ecol. 30 https://doi.org/10.1111/rec.13524.
Leichenko, R., Silva, J.A., 2014. Climate change and poverty: vulnerability, impacts, and alleviation strategies. Wiley Interdiscip. Rev. Clim. Change 5, 539–556.
Lerdau, M., Slobodkin, L., 2002. Trace gas emissions and species-dependent ecosystem services. Trends Ecol. Evol. 17, 309–312.
Lesen, A., 2015. Scientists, Experts, and Civic Engagement: Walking a Fine Line. Ashgate Publishing, Ltd.
Lowery, M.M., 2018. Lumbee Indian.: Am. Struggl. UNC Press Books.
Lynn, K., Daigle, J., Hoffman, J., Lake, F., Michelle, N., Ranco, D., Viles, C., Voggesser, G., Williams, P., 2014. The impacts of climate change on tribal traditional foods. In: Maldonado, J.K., Colombi, B., Pandya, R. (Eds.), Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions. Springer International Publishing, Cham, pp. 37–48.
MacCready, P., 2002. Estuarine adjustment to changes in river flow and tidal mixing. J. Phys. Oceanogr. 29, 708–726.
Maldonado, J.K., 2014. A multiple knowledge approach for adaptation to environmental change: lessons learned from coastal Louisiana's tribal communities. J. Polit. Ecol. 21, 61.
Maldonado, J.K., 2015. Chapter 12 - Everyday Practices and Symbolic Forms of Resistance: Adapting to Environmental Change in Coastal Louisiana. In: Shroder, J. F., Collins, A.E., Jones, S., Manyena, B., Jayawickrama, J. (Eds.), Hazards, Risks and Disasters in Society. Academic Press, Boston, pp. 199–216.
Maldonado, J.K., 2018. Seeking Justice in an Energy Sacrifice Zone: Standing on Vanishing Land in Coastal Louisiana. Routledge.
Maldonado, J.K., Shearer, C., Bronen, R., Peterson, K., Lazrus, H., 2014. The impact of climate change on tribal communities in the US: displacement, relocation, and human rights. In: Maldonado, J.K., Colombi, B., Pandya, R. (Eds.), Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions. Springer International Publishing, Cham, pp. 93–106.
Maldonado, J.K., Maldonado, J.K., Adamo, S., de Sherbinin, A., Akers, D., Albrecht, G., Sartore, G.-M., Connor, L., Higginbotham, N., Freeman, S., et al., 2019. Ecological Migrants. In: Seeking Justice in an Energy Sacrifice Zone: Standing on Vanishing Land in Coastal Louisiana. Cambridge University Press Washington, DC, pp. 1–5.
Manda, A.K., Giuliano, A.S., Allen, T.R., 2014. Influence of artificial channels on the source and extent of saline water intrusion in the wind tide dominated wetlands of the southern Albemarle estuarine system (USA). Environ. Earth Sci. 71, 4409–4419.
Manda, A.K., Klein, W.A., 2019a. Adaptation strategies to address rising water tables in coastal environments under future climate and sea-level rise scenarios. Coast. Zone Manag. https://doi.org/10.1016/b978-0-12-814350-6.00017-3.
Manda, Alex K., Klein, Wendy A., 2019b. Adaptation strategies to address rising water tables in coastal environments under future climate and sea-level rise scenarios. Coast. Zone Manag. https://doi.org/10.1016/b978-0-12-814350-6.00017-3.
Martinez, M., Ardón, M., 2021. Drivers of greenhouse gas emissions from standing dead trees in ghost forests. Biogeochemistry 154, 471–488.
Martinez, M., Ardón, M., Carmichael, M.J., 2022. Identifying sources and oxidation of methane in standing dead trees in freshwater forested wetlands. Front. Environ. Sci. Eng. China 9. https://doi.org/10.3389/fenvs.2021.737379.
Martínez, M.L., Intralawan, A., Vázquez, G., Pérez-Maqueo, O., Sutton, P., Landgrave, R., 2007. The coasts of our world: Ecological, economic and social importance. Ecol. Econ. 63, 254–272.
Martinich, J., Neumann, J., Ludwig, L., Jantarasami, L., 2013. Risks of sea level rise to disadvantaged communities in the United States. Mitig. Adapt. Strateg. Glob. Change 18, 169–185.
Marzeion, B., Levermann, A., 2014. Loss of cultural world heritage and currently inhabited places to sea-level rise. Environ. Res. Lett. 9, 034001.
Mastaler, J.S., 2019. Social justice and environmental displacement. Environ. Justice 12, 17–22.
McCay, B.J., Brandt, S., Creed, C.F., 2011. Human dimensions of climate change and fisheries in a coupled system: the Atlantic surfclam case. ICES J. Mar. Sci. 68, 1354–1367.
McDowell, G., Ford, J., Jones, J., 2016. Community-level climate change vulnerability research: trends, progress, and future directions. Environ. Res. Lett. 11, 033001.
McGlathery, K., Reidenbach, M., D'Odorico, P., Fagherazzi, S., Pace, M., Porter, J., 2013. NonlineaR Dynamics and Alternative Stable States in Shallow Coastal Systems. Oceanography 26, 220–231.
McGranahan, G., Balk, D., Anderson, B., 2007. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environ. Urban. https://doi.org/10.1177/0956247807076960.
McNeeley, S.M., Lazrus, H., 2014. The cultural theory of risk for climate change adaptation. Weather, Clim., Soc. 6, 506–519.
McNulty, S., Weiner, S., Myers, J.M., Farahani, H., Fouladbash, L., Marshall, D., Steele, R. F., 2015. Southeast regional climate hub assessment of climate change vulnerability and adaptation and mitigation strategies. Agric. Res. Serv. 2015, 1–61.
Michael, H.A., Post, V.E.A., Wilson, A.M., Werner, A.D., 2017. Science, society, and the coastal groundwater squeeze. Water Resour. Res. 53, 2610–2617.
Michener, W.K., Blood, E.R., Bildstein, K.L., Brinson, M.M., Gardner, L.R., 1997. Climate change, hurricanes and tropical storms, and rising sea level in coastal wetlands. Ecol. Appl. 7, 770–801.
Miller, K.G., Kopp, R.E., Horton, B.P., Browning, J.V., Kemp, A.C., 2013. A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast. Earths Future 1, 3–18.
Molinaroli, E., Guerzoni, S., Suman, D., 2019. Do the adaptations of venice and miami to sea level rise offer lessons for other vulnerable coastal cities? Environ. Manag. 64, 391–415.
Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., Van Wesenbeeck, B.K., Wolters, G., Jensen, K., Bouma, T.J., Miranda-Lange, M., Schimmels, S., 2014. Wave attenuation over coastal salt marshes under storm surge conditions. Nat. Geosci. 7, 727–731.
Morrissey, E.M., Franklin, R.B., 2015. Evolutionary history influences the salinity preference of bacterial taxa in wetland soils. Front. Microbiol. 6, 1013.
Morrissey, E.M., Gillespie, J.L., Morina, J.C., Franklin, R.B., 2014. Salinity affects microbial activity and soil organic matter content in tidal wetlands. Glob. Chang. Biol. 20, 1351–1362.
Mueller, P., Jensen, K., Megonigal, J.P., 2016. Plants mediate soil organic matter decomposition in response to sea level rise. Glob. Chang. Biol. 22, 404–414.
Mukhopadhyay, R., Sarkar, B., Jat, H.S., Sharma, P.C., Bolan, N.S., 2021. Soil salinity under climate change: challenges for sustainable agriculture and food security. J. Environ. Manag. 280, 111736.
Murray, N.J., Worthington, T.A., Bunting, P., Duce, S., Hagger, V., Lovelock, C.E., Lucas, R., Saunders, M.I., Sheaves, M., Spalding, M., Waltham, N.J., Lyons, M.B., 2022. High-resolution mapping of losses and gains of Earth's tidal wetlands. Science 376, 744–749.
Nabhan, G.P., Walker, D., Moreno, A.M., 2010. Biocultural and ecogastronomic restoration: the renewing america's food traditions alliance. Ecol. Restor. 28, 266–279.
Nance, E., 2015. Exploring the impacts of flood insurance reform on vulnerable communities. Int. J. Disaster Risk Reduct. 13, 20–36.
Nesmith, A.A., Schmitz, C.L., Machado-Escudero, Y., Billiot, S., Forbes, R.A., Powers, M. C.F., Buckhoy, N., Lawrence, L.A., 2020. Environmental Injustice: Transformative Change Toward Justice. In: The Intersection of Environmental Justice, Climate Change, Community, and the Ecology of Life. Springer, pp. 39–56.
Neubauer, S.C., Piehler, M.F., Smyth, A.R., Franklin, R.B., 2019. Saltwater intrusion modifies microbial community structure and decreases denitrification in tidal freshwater marshes. Ecosystems 22, 912–928.
Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J., 2015. Future coastal population growth and exposure to sea-level rise and coastal flooding–a global assessment. PLoS One 10, e0118571.
Neville, J.A., Emanuel, R.E., Ardón, M., Pavelsky, T., 2023. Location and design of flow control structures differentially influence salinity patterns in small artificial drainage systems. J. Water Resour. Plan. Manag. 149, 05023002.
Nicholls, R.J., Lincke, D., Hinkel, J., Brown, S., Vafeidis, A.T., Meyssignac, B., Hanson, S. E., Merkens, J.-L., Fang, J., 2021. A global analysis of subsidence, relative sea-level change and coastal flood exposure. Nat. Clim. Chang. 11, 338–342.
Noe, G.B., Krauss, K.W., Lockaby, B.G., Conner, W.H., Hupp, C.R., 2013. The effect of increasing salinity and forest mortality on soil nitrogen and phosphorus mineralization in tidal freshwater forested wetlands. Biogeochemistry 114, 225–244.
North Carolina Commission of Indian Affairs, 1979. A historical perspective about the indians of north carolina and an overview of the commission of Indian affairs. N. C. Hist. Rev. 56, 177–187.
O'Hare, P., White, I., 2018. Beyond "just" flood risk management: the potential for—and limits to—alleviating flood disadvantage. Reg. Environ. Change. https://doi.org/10.1007/s10113-017-1216-3.
Osland, M.J., Chivoiu, B., Enwright, N.M., Thorne, K.M., Guntenspergen, G.R., Grace, J. B., Dale, L.L., Brooks, W., Herold, N., Day, J.W., Sklar, F.H., Swarzenzki, C.M., 2022. Migration and transformation of coastal wetlands in response to rising seas. Sci. Adv. 8, eabo5174.
Paerl, H.W. et al, Bales, J.D., Ausley, L.W., Buzzelli, C.P., Crowder, L.B., Eby, L.A., Fear, J.M., Go, M., Peierls, B.L., Richardson, T.L., Ramus, J.S., M.Go, Richardsoni, T.L., Ramus¶, J.S., 2001. Ecosystem impacts of three sequential hurricanes (Dennis, Floyd and Irene) on the United State's largest lagoonal estuary, Pamlico Sound, NC. Proceedings of the National Academy of Science 98, 5655–5660.
Paerl, H.W., Otten, T.G., Kudela, R., 2018. Mitigating the expansion of harmful algal blooms across the freshwater-to-marine continuum. Environ. Sci. Technol. 52, 5519–5529.
Panthi, J., Pradhanang, S.M., Nolte, A., Boving, T.B., 2022. Saltwater intrusion into coastal aquifers in the contiguous United States - a systematic review of investigation approaches and monitoring networks. Sci. Total Environ. 836, 155641.

Pezeshki, S.R., 1992. Response of Pinus taeda L to soil flooding and salinity. Ann. Des. Sci. For. 49, 149–159.
Pfennigwerth, A.A., Van Nuland, M.E., Bailey, J.K., Schweitzer, J.A., 2018. Plant–soil feedbacks mediate shrub expansion in declining forests, but only in the right light. J. Ecol. 106, 179–194.
Poulter, B., Christensen, N.L., Qian, S.S., 2008a. Tolerance of Pinus taeda and Pinus serotina to low salinity and flooding: Implications for equilibrium vegetation dynamics. J. Veg. Sci. 19, 15–22.
Poulter, B., Goodall, J.L., Halpin, P.N., 2008b. Applications of network analysis for adaptive management of artificial drainage systems in landscapes vulnerable to sea level rise. J. Hydrol. 357, 207–217.
Powell, A.S., Jackson, L., Ardón, M., 2016. Disentangling the effects of drought, salinity, and sulfate on baldcypress growth in a coastal plain restored wetland. Restor. Ecol. 24, 548–557.
Prigent, C., Papa, F., Aires, F., Rossow, W.B., Matthews, E., 2007. Global inundation dynamics inferred from multiple satellite observations, 1993-2000. J. Geophys. Res. D: Atmos. 112, 1993–2000.
Rasmussen, P., Sonnenborg, T.O., Goncear, G., Hinsby, K., 2013. Assessing impacts of climate change, sea level rise, and drainage canals on saltwater intrusion to coastal aquifer. Hydrol. Earth Syst. Sci. 17, 421–443.
Ratajczak, Z., Carpenter, S.R., Ives, A.R., Kucharik, C.J., Ramiadantsoa, T., Stegner, M.A., Williams, J.W., Zhang, J., Turner, M.G., 2018. Abrupt change in ecological systems: inference and diagnosis. Trends Ecol. Evol. https://doi.org/10.1016/j.tree.2018.04.013.
Dakos, V., Scheffer, M., van Nes, E.H., Brovkin, V., Petoukhov, V., Held, H., 2008. Slowing down as an early warning signal for abrupt climate change. Proc. Natl. Acad. Sci. U. S. A. 105, 14308–14312.
de la Reguera, E., Veatch, J., Gedan, K., Tully, K.L., 2020. The effects of saltwater intrusion on germination success of standard and alternative crops. Environ. Exp. Bot. 180, 104254.
Rentschler, J., Salhab, M., Jafino, B.A., 2022. Flood exposure and poverty in 188 countries. Nat. Commun. 13, 3527.
Rissman, A.R., Owley, J., Shaw, M.R., Thompson, B.B., 2015. Adapting conservation easements to climate change. Conserv. Lett. 8, 68–76.
Rocca, J.D., Simonin, M., Bernhardt, E.S., Washburne, A.D., Wright, J.P., 2020. Rare microbial taxa emerge when communities collide: freshwater and marine microbiome responses to experimental mixing. Ecology 101, e02956.
Rodríguez, J.F., Saco, P.M., Sandi, S., Saintilan, N., Riccardi, G., 2017. Potential increase in coastal wetland vulnerability to sea-level rise suggested by considering hydrodynamic attenuation effects. Nat. Commun. 8 https://doi.org/10.1038/ncomms16094.
Sanders, M.C., 2020. Equity in addressing climate change: using law and policy to serve frontline communities. Traumatology.
Sandi, S.G., Rodríguez, J.F., Saintilan, N., Riccardi, G., Saco, P.M., 2018. Rising tides, rising gates: the complex ecogeomorphic response of coastal wetlands to sea-level rise and human interventions. Adv. Water Resour. 114, 135–148.
Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., Walker, B., 2001. Catastrophic shifts in ecosystems. Nature 413, 591–596.
Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Dakos, V., Held, H., van Nes, E.H., Rietkerk, M., Sugihara, G., 2009. Early-warning signals for critical transitions. Nature 461, 53–59.
Schlosberg, D., 2007. Defining Environmental Justice: Theories, Movements, and Nature. Oxford University Press.
Schoepfer, V.A., Bernhardt, E.S., Burgin, A.J., 2014. Iron clad wetlands: Soil iron-sulfur buffering determines coastal wetland response to salt water incursion. J. Geophys. Res.: Biogeosciences 119. https://doi.org/10.1002/2014JG002739.
Scyphers, S.B., Picou, J.S., Powers, S.P., 2015. Participatory conservation of coastal habitats: the importance of understanding homeowner decision making to mitigate cascading shoreline degradation. Conserv. Lett. https://doi.org/10.1111/conl.12114.
Servais, S., Kominoski, J.S., Charles, S.P., Gaiser, E.E., Mazzei, V., Troxler, T.G., Wilson, B.J., 2019. Saltwater intrusion and soil carbon loss: Testing effects of salinity and phosphorus loading on microbial functions in experimental freshwater wetlands. Geoderma 337, 1291–1300.
Servais, S., Kominoski, J.S., Coronado-Molina, C., Bauman, L., Davis, S.E., Gaiser, E.E., Kelly, S., Madden, C., Mazzei, V., Rudnik, D., Santamaria, F., Sklar, F.H., Stachelek, J., Troxler, T.G., Wilson, B.J., 2020. Effects of saltwater pulses on soil microbial enzymes and organic matter breakdown in freshwater and brackish coastal wetlands. Estuaries Coasts 43, 814–830.
Sharpley, A., Jarvie, H.P., Buda, A., May, L., Spears, B., Kleinman, P., 2013. Phosphorus legacy: overcoming the effects of past management practices to mitigate future water quality impairment. J. Environ. Qual. 42, 1308.
Shearer, C., 2012. The social construction of alaska native vulnerability to climate change. Race, Gend. Cl. 19, 61–79.
Shreve, B.G., 2009. From time immemorial": the fish-in movement and the rise of intertribal activism. Pac. Hist. Rev. 78, 403–434.
Simon, A., Dickerson, W., Heins, A., 2004. Suspended-sediment transport rates at the 1.5-year recurrence interval for ecoregions of the United States: transport conditions at the bankfull and effective discharge? Geomorphology 58, 243–262.
Small, C., Nicholls, R.J., 2003. A global analysis of human settlement in Coastal Zones. J. Coast. Res 19, 584–599.
Small, C., Nicholls, R.J., Smallt, C., Nichollst, R.J., 2003. A global analysis of human settlement in coastal zones. Source.: J. Coast. Res. J. Coast. Res. 19, 584–599.
Smart, L.S., Taillie, P.J., Poulter, B., Vukomanovic, J., Singh, K.K., Swenson, J.J., Mitasova, H., Smith, J.W., Meentemeyer, R.K., 2020. Aboveground carbon loss associated with the spread of ghost forests as sea levels rise. Environ. Res. Lett. 15, 104028.
Smith, A.J., Kirwan, M.L., 2021. Sea level-driven marsh migration results in rapid net loss of carbon. Geophys. Res. Lett. 48 https://doi.org/10.1029/2021gl092420.
Smith, J.A.M., 2013. The role of phragmites australis in mediating inland salt marsh migration in a mid-atlantic estuary. Cit.: Smith JAM PLoS ONE 8. https://doi.org/10.1371/journal.pone.0065091.
Solohin, E., Widney, S.E., Craft, C.B., 2020. Declines in plant productivity drive loss of soil elevation in a tidal freshwater marsh exposed to saltwater intrusion. Ecology 101, e03148.
Stagg, C.L., Baustian, M.M., Perry, C.L., Carruthers, T.J.B., Hall, C.T., 2018. Direct and indirect controls on organic matter decomposition in four coastal wetland communities along a landscape salinity gradient. J. Ecol. 106, 655–670.
Stein, S., Systems, H., Halbach, P.E., Tunnicliffe, V., Hein, J.R., Johnson, H., Becker, K., Herzen, R.V., Baross, J., Delaney, J., Juteau, T., Fisher, A., Waldhause, F., Bohnenstiehl, D., Weekly, R., Kim, W., Hayba, D.O., Schultz, A., Driesner, T., Geiger, S., Heinrich, C., Matthai, S., Janecky, D., Rosenberg, N., Boulegue, J., Genthon, P., Rabinowicz, M., Sanford, W., Neuzil, C., 2008. References and Notes 1. Science 1828–1831.
Steinmuller, H.E., Chambers, L.G., 2018. Can saltwater intrusion accelerate nutrient export from freshwater wetland soils? an experimental approach. Soil Sci. Soc. Am. J. 82, 283.
Sudol, T.A., Miller Hesed, C.D., Clark, J.M., Moser, F.C., 2023. Resisting-accepting-directing sea level rise on the Chesapeake Bay: Agricultural producers' motivations and actions. J. Environ. Manage. 332, 117355.
Sultana, F., 2014. Gendering climate change: Geographical insights. Prof. Geogr. 66, 372–381.
Sweet, W.V., Kopp, R.E., Weaver, C.P., Obeysekera, J., Horton, R.M., Thieler, E.R., Zervas, C., 2017. Global and Regional Sea Level Rise Scenarios for the United States. NOAA.
Taillie, P.J., Moorman, C.E., Poulter, B., Ardón, M., Emanuel, R.E., 2019a. Decadal-scale vegetation change driven by salinity at leading edge of rising sea level. Ecosystems 22, 1918–1930.
Taillie, P.J., Moorman, C.E., Poulter, B., Ardón, M., Emanuel, R.E., 2019b. Decadal-scale vegetation change driven by salinity at leading edge of rising sea level. Ecosyst. 1–13.
Taillie, P.J., Moorman, C.E., Smart, L.S., Pacifici, K., 2019c. Bird community shifts associated with saltwater exposure in coastal forests at the leading edge of rising sea level. PLOS ONE. https://doi.org/10.1371/journal.pone.0216540.
Tanji, K.K., Kielen, N.C., Food and Agriculture Organization of the United Nations, 2002. Agricultural drainage water management in arid and semi-arid areas. Food and Agriculture Organization of the United Nations.
Thomas, K., Hardy, R.D., Lazrus, H., Mendez, M., Orlove, B., Rivera-Collazo, I., Roberts, J.T., Rockman, M., Warner, B.P., Winthrop, R., 2019. Explaining differential vulnerability to climate change: a social science review. Wiley Interdiscip. Rev. Clim. Change 10, e565.
Thomas, K.A., Warner, B.P., 2019. Weaponizing vulnerability to climate change. Glob. Environ. Change 57, 101928.
Titus, J.G., Richman, C., 2001. Maps of lands vulnerable to sea level rise: modeled elevations along the US Atlantic and Gulf coasts. Clim. Res. 18, 205–228.
Tully, K., Gedan, K., Epanchin-Niell, R., Strong, A., Bernhardt, E.S., BenDor, T., Mitchell, M., Kominoski, J., Jordan, T.E., Neubauer, S.C., Weston, N.B., 2019a. The invisible flood: the chemistry, ecology, and social implications of coastal saltwater intrusion. Bioscience 69, 368–378.
Tully, K.L., Weissman, D., Wyner, W.J., Miller, J., Jordan, T., 2019b. Soils in transition: saltwater intrusion alters soil chemistry in agricultural fields. Biogeochemistry 142, 339–356.
U.S. Department of Energy, 2017. Research Priorities to Incorporate Terrestrial-Aquatic Interfaces in Earth System Models: Workshop Report. U.S. Department of Energy.
Ury, Emily, A., Yang, Xi, Wright, Justin P., Bernhardt, Emily S., 2021. Rapid deforestation of a coastal landscape driven by sea level rise and extreme events. Ecol. Appl.: A Publ. Ecol. Soc. Am. April, e2339.
Ury, E.A., Anderson, S.M., Peet, R.K., Bernhardt, E.S., Wright, J.P., 2019. Succession, regression and loss: does evidence of saltwater exposure explain recent changes in the tree communities of North Carolina's Coastal Plain? Ann. Bot. https://doi.org/10.1093/aob/mcz039.
Ury, E.A., Anderson, S.M., Peet, R.K., Bernhardt, E.S., Wright, J.P., 2020. Succession, regression and loss: does evidence of saltwater exposure explain recent changes in the tree communities of North Carolina's Coastal Plain? Ann. Bot. 125, 255–264.
Ury, E.A., Wright, J.P., Ardón, M., Bernhardt, E.S., 2021a. Saltwater intrusion in context: soil factors regulate impacts of salinity on soil carbon cycling. Biogeochemistry 157, 215–226.
Ury, E.A., Yang, X., Wright, J.P., Bernhardt, E.S., 2021b. Rapid deforestation of a coastal landscape driven by sea level rise and extreme events. Ecol. Appl., e2339
van Belzen, J., van de Koppel, J., Kirwan, M.L., van der Wal, D., Herman, P.M.J., Dakos, V., Kéfi, S., Scheffer, M., Guntenspergen, G.R., Bouma, T.J., 2017. Vegetation recovery in tidal marshes reveals critical slowing down under increased inundation. Nat. Commun. 8, 15811.
Ventura, Y., Eshel, A., Pasternak, D., Sagi, M., 2015. The development of halophyte-based agriculture: past and present. Ann. Bot. 115, 529–540.
Volpe, V., Manzoni, S., Marani, M., Katul, G., 2011. Leaf conductance and carbon gain under salt-stressed conditions. J. Geophys. Res. 116, G04035.
Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L. P., Feyen, L., 2018. Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. Nat. Commun. 9, 2360.

Voutsina, N., Seliskar, D.M., Gallagher, J.L., 2015. The Facilitative Role of Kosteletzkya pentacarpos in Transitioning Coastal Agricultural Land to Wetland During Sea Level Rise. Estuaries Coasts 38, 35–44.
Wang, R., Dearing, J.A., Langdon, P.G., Zhang, E., Yang, X., Dakos, V., Scheffer, M., 2012. Flickering gives early warning signals of a critical transition to a eutrophic lake state. Nature 492. https://doi.org/10.1038/nature11655.
Warnell, K., Olander, L., Currin, C., 2022. Sea level rise drives carbon and habitat loss in the U.S. mid-Atlantic coastal zone. PLOS Clim. 1, e0000044.
Werner, B.T., McNamara, D.E., 2007. Dynamics of coupled human-landscape systems. Geomorphology 91, 393–407.
Weston, N.B., 2014. Declining sediments and rising seas: an unfortunate convergence for tidal wetlands. Estuaries Coasts 37, 1–23.
Weston, N.B., Porubsky, W.P., Samarkin, V. a, Erickson, M., Macavoy, S.E., Joye, S.B., 2006. Porewater stoichiometry of terminal metabolic products, sulfate, and dissolved organic carbon and nitrogen in estuarine intertidal creek-bank sediments. Biogeochemistry 77, 375–408.
Weston, N.B., Giblin, A.E., Banta, G.T., Hopkinson, C.S., Tucker, J., 2010. The effects of varying salinity on ammonium exchange in estuarine sediments of the Parker River, Massachusetts. Estuaries Coasts 33, 985–1003.
White, E., Kaplan, D., 2017. Restore or retreat? saltwater intrusion and water management in coastal wetlands. Ecosyst. Health Sustain. 3, e01258.
White, E.E., Ury, E.A., Bernhardt, E.S., Yang, X., 2022. Climate change driving widespread loss of coastal forested wetlands throughout the north american coastal plain. Ecosystems 25, 812–827.
Wilkinson, G.M., Carpenter, S.R., Cole, J.J., Pace, M.L., Batt, R.D., Buelo, C.D., Kurtzweil, J.T., 2018. Early warning signals precede cyanobacterial blooms in multiple whole-lake experiments. Ecol. Monogr. 88, 188–203.
Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R., Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S., Heringa, J., 't Hoen, P.A.C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., Mons, B., 2016. The FAIR guiding principles for scientific data management and stewardship. Sci. Data 3, 160018.
Williams, A.A., Lauer, N.T., Hackney, C.T., 2014. Soil phosphorus dynamics and saltwater intrusion in a florida estuary. Wetlands 34, 535–544.
Wing, O.E.J., Lehman, W., Bates, P.D., Sampson, C.C., Quinn, N., Smith, A.M., Neal, J.C., Porter, J.R., Kousky, C., 2022. Inequitable patterns of US flood risk in the Anthropocene. nature climate change.
Woodruff, J.D., Irish, J.L., Camargo, S.J., 2013. Coastal flooding by tropical cyclones and sea-level rise. Nature 504, 44–52.
Woodruff, S., BenDor, T.K., Strong, A.L., 2018. Fighting the inevitable: infrastructure investment and coastal community adaptation to sea level rise. Syst. Dyn. Rev. 34, 48–77.
Wöppelmann, G., Marcos, M., 2016. Vertical land motion as a key to understanding sea level change and variability. Rev. Geophys. 54, 64–92.
Yang, X., Pavelsky, T.M., Ross, M.R.V., Januchowski-Hartley, S.R., Dolan, W., Altenau, E. H., Belanger, M., Byron, D., Durand, M., Van Dusen, I., Galit, H., Jorissen, M., Langhorst, T., Lawton, E., Lynch, R., Mcquillan, K.A., Pawar, S., Whittemore, A., 2022. Mapping flow-obstructing structures on global rivers. Water Resour. Res. 58 https://doi.org/10.1029/2021wr030386.
Zhang, Y., Li, W., Sun, G., Miao, G., Noormets, A., Emanuel, R., King, J.S., 2018. Understanding coastal wetland hydrology with a new regional-scale, process-based hydrological model. Hydrol. Process. 32, 3158–3173.
Zhou, M., Butterbach-Bahl, K., Vereecken, H., Brüggemann, N., 2017. A meta-analysis of soil salinization effects on nitrogen pools, cycles and fluxes in coastal ecosystems. Glob. Chang. Biol. 23, 1338–1352.