Title: Saltwater Intrusion and Sea Level Rise threatens coastal landscapes and communities

Abstract

Globally the 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 landscape. Together saltwater intrusion and sea level rise (SWISLR) creates significant 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 outer coastal plain, differences in geomorphic setting, water resources infrastructure and management, and climate extremes are generating very 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 represents an opportunity to build and challenge new mechanistic models that 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.

KEYWORDS – Coastal, Vulnerable, Rural, Rapid Change

Definition Box:

SWISLR - saltwater intrusion and sea level rise.

Coastal Systems - inclusive of all landscapes of the lower 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 coast

Saltwater intrusion - Process by which saline water migrates into freshwater systems

1. INTRODUCTION to SWISLR

The rising seas of our warming planet are flooding and salinizing coastal plain landscapes across the globe, with the impacts to landscapes and livelihoods extending well inland from coastal margins. Global sea-level rise (SLR) risk is not uniform, with 90% of the coastline experiencing SLR levels that 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 and on top of this 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. The resulting saltwater intrusion (SWI) has lead to drastic outcomes such as forest mortality, crop failure, and degradation of drinking water (Tully et al., 2019a; White and Kaplan, 2017). We synthesize how saltwater intrusion (SWI) and sea-level rise (SLR) (hereafter abbreviated as SWISLR) are acting in tandem to alter coastal systems, a term we will use throughout this paper to describe all landscapes of the lower coastal plains (elevation of <100 m above sea level and closer than 100 km to the coast) and the organisms and people that live and work within them.

Placeholder Box

Figure 1. The Features of coastal SWISLR

NOTE - We have commissioned Hiram Henriquez of H2Hgraphics to create an educational figure that illustrates the complexity of the coastal landscape and the pressures of rising seas and salinization. This box is a placeholder. Henriquez has done many previous complex conceptual figures about wetlands and sea level rise is well qualified to create this figure.

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 (Martinez 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 leaving off the long term impacts from 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)) there has been far less attention paid to rural coastal landscapes despite their much larger area (Bhattachan et al., 2018a; Small and Nicholls, 2003). While it is true that 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, and flood protection (Barbier et al., 2011; Dahl and Stedman, 2013; Friess et al., 2020).

In the conterminous United States (US) 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). These represent conservative estimates 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., 2019). Across coastal farm fields, timberlands and freshwater wetlands, SWISLR results in field abandonment, the creation of ghost forests and freshwater wetland loss (Herbert et al., 2015; Kirwan and Gedan, 2019; Manda and Klein, 2019; Tully et al., 2019; Ury et al., 2021b; White et al., 2022). While significant investments in urban infrastructure are being considered as realistic options for reducing flooding in coastal cities (Hunt and Watkiss, 2011; Molinaroli et al., 2019), there has been almost no consideration of what infrastructure investments might protect the full extent of rural coastal systems (Jurjonas et al., 2020).

Historic 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, also 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 also 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 significant modification (Carter, 1975; Chapelle, 1986; Woodruff et al., 2018). Because of the long history of significant 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). In order 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 rate of 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 is highly heterogeneous. The impacts of SWISLR are consistent: inundation and salination lead to reductions in agricultural yields and substantial reductions in coastal forest carbon stocks (Taillie et al., 2019a; Ury et al., 2020) and challenge irrigation and drinking water supplies (Panthi et al., 2022). These impacts represent substantial threats to infrastructure, homes, livelihoods and lives (Hauer et al., 2021). Over time, in the absence of significant investment or intervention, SWISLR will convert a significant proportion of modern coastal systems into open water, marsh, and abandoned fields and coastal communities (Figure 2). SWISLR is already causing declines in agricultural yields (Tully et al., 2019), 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 significant challenge for the rural coastal system communities whose livelihoods, water supplies, and landscapes are affected (Bhattachan et al., 2018; Desmet et al., 2018; Tully et al., 2019b).

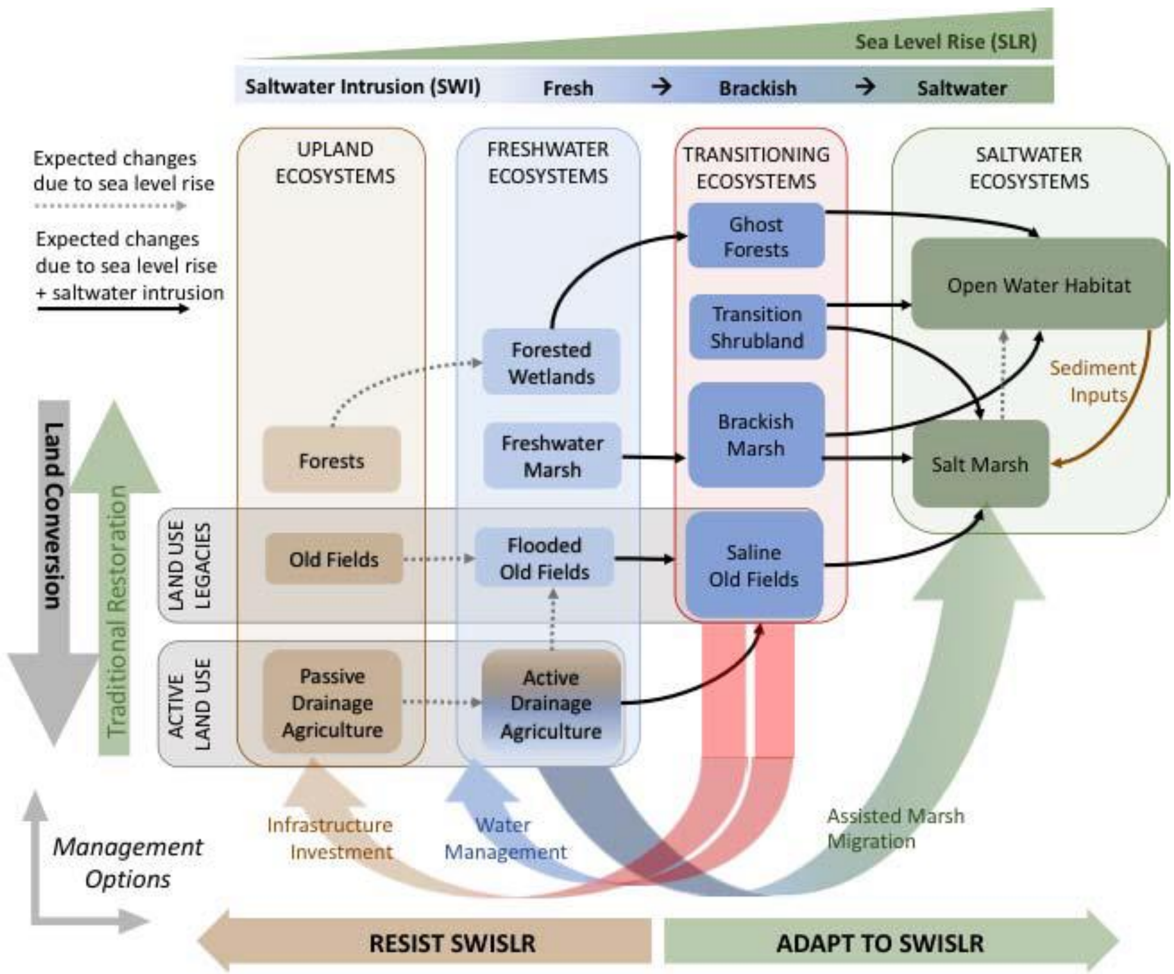

Figure 2. Expected shifts in the distribution of dominant land cover types throughout the coastal plain due to prior land use, current management decisions, and the effects of sea level rise and saltwater intrusion.

The resulting loss of agricultural productivity and declines in water quality are likely to differentially impact disadvantaged rural populations and communities (Hauer et al., 2021). Studies have already shown inundation disproportionately impacts poorer communities and countries globally (Handwerger et al., 2021; Rentschler et al., 2022). In the U.S., specifically, areas of higher sensitivity to future flood 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 multi-generational factors involving land availability, bank and agency lending practices, and red-lining (Hardy et al., 2017; Katz, 2021). Managers throughout the region face the challenge of deciding whether and where to resist or adapt to SWISLR impacts (White and Kaplan, 2017) (Figure 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, where ~41% of the global population lives. Meaningful management and adaptation decisions are necessary and must 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 much more variable and can be linear, oscillating, or episodic. For SLR, understanding the geology and geomorphology of the coast allows us to predict and display the hazard across coastal systems. The broad aspects of geology and geomorphology are similar or generalizable throughout regional or physiographic provinces (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 SLR rates (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 that are typically ignored in SLR models (Brinson et al., 1995; Kirwan et al., 2016; Panthi et al., 2022; Smith, 2013). Particularly in areas where topographic relief is low, e.g. the U.S. Coastal Plain, 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, 2019), 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 & alkalinization of freshwater inflows) have been found to influence the inland extent of SWISLR at the local level and cause variable ecosystem and socio-economic consequences. These variations - in exposure, vulnerabilities, and outcomes - highlight the need for interdisciplinary study and boundary defying collaboration in order 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 US 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. (2008) suggest that a slowing down in the 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 have often been viewed through the lens of hydraulic stress equivalent to 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 the roots (Charles et al., 2019; Morrissey et al., 2014; Morrissey and Franklin, 2015; Neubauer et al., 2019; Solohin et al., 2020), and the microbial communities (Rocca et al., 2020). Thus, researchers should 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), but few have considered the interactive effects of both flooding and salinity (Powell et al., 2016) or drought and salinity, and none have examined the impacts of longer term biogeochemical changes that can be caused by SWISLR.

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). 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 direction of SWISLR on solute concentrations and potential associated land-sea biogeochemical fluxes may vary, and likely depends 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 – both policy-makers and 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 damages (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, 2018, 2015, 2014; Tully et al., 2019b). People rely on their surrounding environment for more than economic gain, and mental health impacts may be experienced in coastal communities due to a loss of place, such as grief, depression, and others (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 due harms both 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 invest in infrastructure and property protection or to make the hard choices to adapt 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 across scales (Bennett, 2018; Tully et al., 2019b).

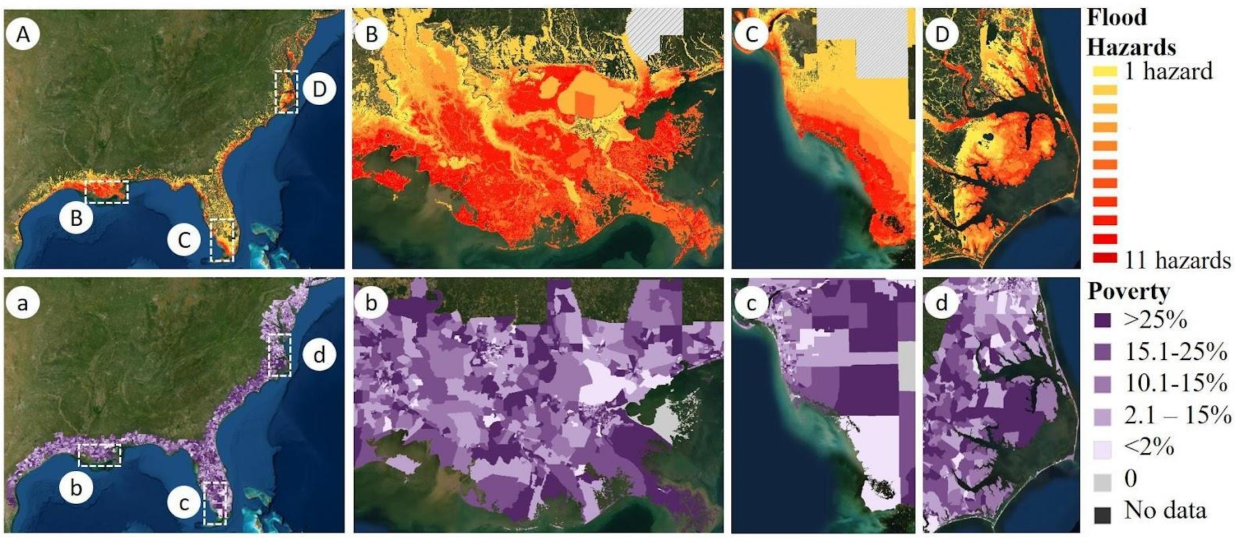

Figure 3**.** Ecosystem and Social vulnerabilities in the Coastal Plain ecoregion. This compilation of maps show flood hazard (top) and poverty (bottom) for the (Aa) entire North American Coastal Plain, (Bb) Gulf Coast of Louisiana, (Cc) southwest coast of Florida, and (Dd) coast of North Carolina. All maps are made from NOAAs Coastal Flood Exposure Mapper.

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 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 presently risk loss through shoreline erosion (Bhattachan et al., 2018; Lautzenheiser et al., 2011) and damage to culturally-significant ecosystems such as forested coastal wetlands (Emanuel, 2019). In other coastal regions, indigenous culinary, consumption, 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 (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 significantly under all realistic climate change scenarios. We must transform the way scientists and stakeholders 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 inundation?" and "What land and water management options will minimize the potential for catastrophic regime shifts?" As coastal plain landscapes worldwide transform in response to and, in advance of rising seas, we argue that sustainability of these coastal landscapes depends largely on developing a sophisticated scientific understanding of the coupled human and natural processes influencing salinization of surface waters and adjacent lands. However, gaining this understanding is difficult since processes integral to SWISLR often exist at physical, social, and disciplinary boundaries. There is a critical need to reconceptualize scientific frameworks (including models, remote sensing, etc.) in ways that center SWISLR. Additionally, SWISLR research requires communication and cooperation between myriad 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 need collaboration and buy-in from local communities for success.

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. Each research frontier requires us to cross 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?

Problem

In order to answer this question, scholars should implement procedural and distributional justice to cross the boundary of systemic inequities present in climate management (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 have a seat at the climate risk prevention table 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 significant 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 historic 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).

Call to Action

To include the perspectives of vulnerable communities researchers can start 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 in order to better communicate the issues currently in place.

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

Problem

Geographic and spatial boundaries must be crossed in order 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 are still unavailable at the regional scale. In addition, due to the limited time-span 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 our 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. No models are very good at dealing with interfaces - be they aquatic-terrestrial / freshwater-saltwater / urban-rural because models like boundary conditions. By its very nature SWISLR is model defying - both penetrating and shifting boundaries. To manage, adapt, and predict SWISLR impacts, we need to develop models that cross boundaries.

Call to Action

We need more information on the hazard of SWISLR and the potential outcomes in order 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 should be made to share data in an accessible way (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?

Problem

Humans have altered the hydrologic connections across much of the outer Coastal Plain. In the North American Coastal Plain (NACP), for example, over a century of development has degraded coastal ecosystems (Gedan et al., 2009; Gittman et al., 2015) and significantly 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 Coastal Plain is highly dependent upon individual landowner decisions about water management (Bhattachan et al., 2018b; Poulter et al., 2008b) and federal government decisions about the maintenance and expansion of navigation and shipping channels (Carse and Lewis, 2017). In order to better understand how water management and climate change are interacting, communication is needed and the discipline boundary between hydrology and policy/management needs crossing.

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 coastal plain. Remote sensing and tools such as Google Earth Engine 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 still miss smaller infrastructure (Neville et al., 2023), which can either enhance the spatial extent of SWISLR by “short circuiting” natural drainage networks (Bhattachan et al., 2018) or constrain these processes through flow 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 sea level rise, rainfall-runoff relationships, evapotranspiration, and natural geomorphology.

Call to Action

Land use history and change complicates hydrology and the potential extent of SWISLR due to human modification. In order to properly predict SWISLR, and its consequences, an extensive collection of water management infrastructure should be created. We not only lack a database of coastal water management structures, but currently we lack a meta-analysis of salinization trends of freshwater coastal ecosystems by SWISLR as well. Therefore, work should be done to compile and synthesize long-term data on water salinity in tidal freshwater and oligohaline zones of the Coastal Plain before identifying how human modification influences SWISLR. We need salinity, discharge, water level, and biogeochemical concentration datasets paired with consistent ancillary datasets (e.g., soil properties, land use history, topography) to explain and predict spatiotemporal patterns in salinity and biogeochemical response direction and magnitude. We need paired soil surface, groundwater, and surface water salinity monitoring in different land uses to understand how salinity moves across aquatic-terrestrial systems. Once management structures are identified across the coastal plain, and salinity trends are mapped, then the interactions between human modification and SWISLR can be better understood.

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

Problem

SWISLR will impact a significant proportion of US cropland, and farmers have limited methods to adapt to SWISLR. Currently, ~11% of the US land area in the Coastal Plain is cultivated and about 55,850 hectares (138,000 acres) of this farmland is within 0.9 m (3 ft) of projected sea level rise (USDA 2008, NOAA 2017). 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.

Very few crops can grow in sustained 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., 2019). 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., 2019). 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 region 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 in terms of 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.

Call to Action

To answer this complex question collaboration across disciplines with an eye towards social and economic equity are needed. Land owners, 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 land owners and managers. Collaborations across state-lines will enable researchers, farmers, and land managers to learn how different groups are dealing with SWISLR. It 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). It may also help improve land management and water quality policies going forward.

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

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

SWISLR represents extreme stress to many plants, leading to two coordinated changes, expansions inland of the ranges of more salt-tolerant species and inland retreat of less 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 (Anderson et al., 2022; Bernhardt, 2022; Osland et al., 2022; Taillie et al., 2019a; Ury et al., 2021b; Weston, 2014; White et al., 2022). Since pollinators, herbivores, and 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 forests to marsh can be associated with substantial losses of both aboveground and belowground carbon stocks (Smart et al., 2020; Smith and Kirwan, 2021), due to direct changes in soil chemistry and hydrology (Ardón et al., 2018; Ury et al., 2021a) and plant mediated feedbacks (Lerdau and Slobodkin, 2002). The increased abundance of standing dead trees (snags) can affect 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, Tulley et al. 2019).

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 to what extent 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 that can 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 in order to develop and use a standard sampling and measurement method. Along with identifying the patterns of ecosystem response, and building mechanistic models, a synthesis of methods used in ecosystem science should be created and analyzed to identify the best-practices for future research. All three of these 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?

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 has been found to influence exposure and social vulnerability, with historically red-lined neighborhoods seeing increased risk of flooding, and agriculturally ditched landscapes being more vulnerable to SWISLR impacts (Bhattachan et al., 2018; Katz, 2021). Adaptation to impacts and risk is not distributed equally across the coastal plain due to the (typically) high costs of adaptation options available, often leaving low income and rural communities with high exposure to SWISLR (Gittman et al., 2015; Schlosberg, 2007). Understanding both how coastal communities are impacted, and how communities are responding to impacts, 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 historic 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.

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. In order 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 should 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, from do-nothing to restoration to retreat.

4. CONCLUSIONS:

Under all realistic climate change scenarios the extent and duration of SWISLR into Coastal Plain systems will increase significantly. 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, we need to transform the way both scholars and stakeholders 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, worldwide, transform in response to, 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. Better understanding of SWISLR 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 on making it easy for any interested individual to discover and learn from research and management activities. Facilitating and sharing diverse knowledge when confronting SWISLR will help cross boundaries associated with current SWISLR research and management efforts.

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