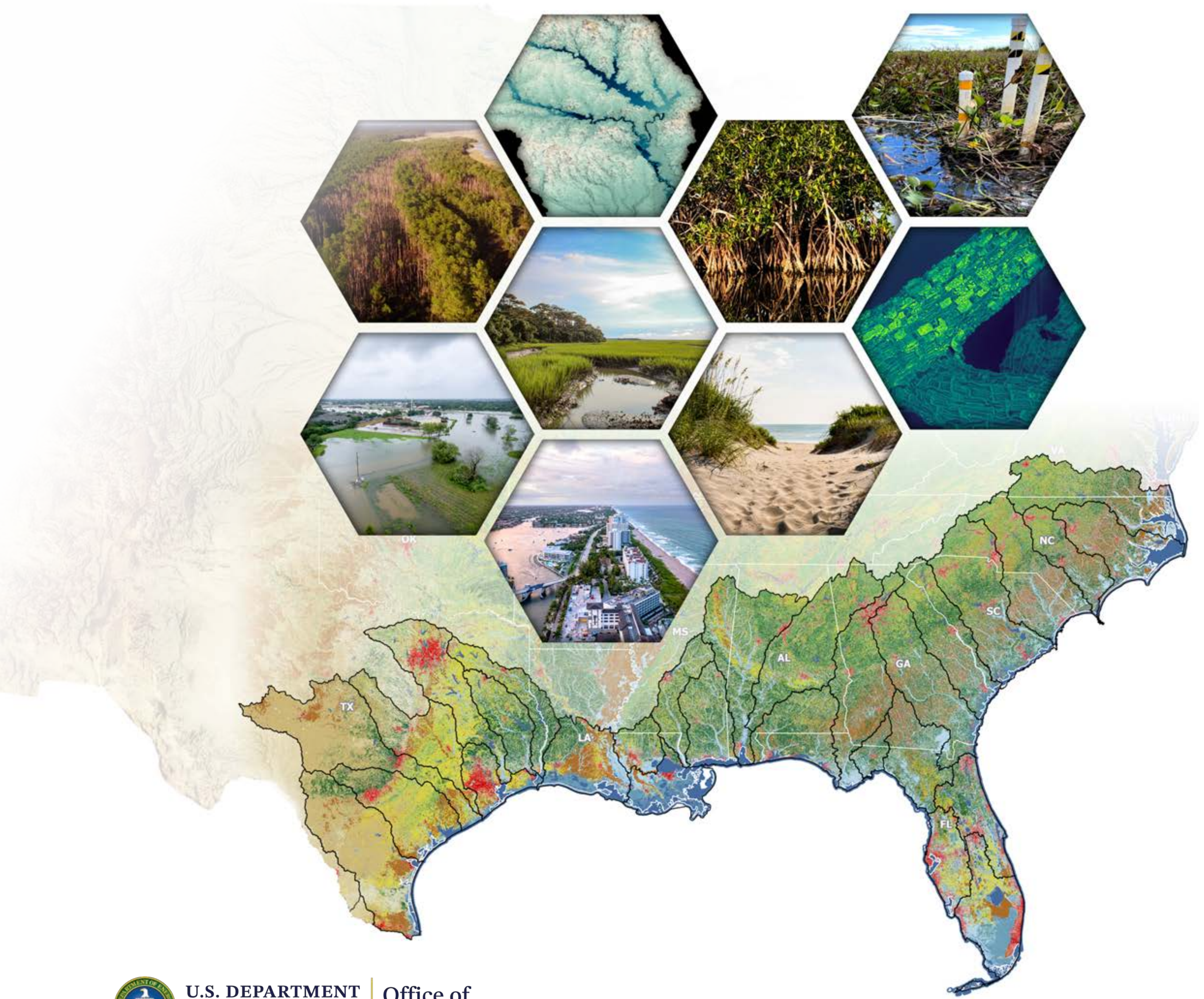
DOE/SC-2026

Critical Knowledge Gaps for Coastal Systems

Research Priorities for Coastal Regions of the Southeastern United States

Workshop Report



U.S. DEPARTMENT of ENERGY | Office of Science
Biological and Environmental Research Program

Critical Knowledge Gaps for Coastal Systems

Research Priorities for the U.S. South Atlantic and Gulf of Mexico

Workshop

March 26–27, 2024
Gaithersburg, Maryland

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Office of Science
Biological and Environmental Research Program

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The Biological and Environmental Research (BER) program supports transformative science and scientific user facilities examining complex biological, Earth, and environmental systems. BER research seeks to understand the fundamental biological, biogeochemical, and physical principles needed to predict a continuum of processes occurring across scales, from molecules and genomes at the smallest scales to ecosystems and the Earth system at the largest scales. This research—conducted at U.S. Department of Energy national laboratories—is contributing to a future of energyand infrastructure security, independence, and prosperity for all Americans.

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April 2026

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Executive Summary

Critical and Highly Vulnerable Coastal Systems

Coastal watersheds and shorelines are home to 52% of the U.S. population and provide trillions of dollars of economic and ecosystem services each year. However, these regions are subject to increasing frequency and intensity of compounding hazards that generate substantial damages. Sea level rise is increasing flooding and salinization of low-lying areas; periodic storm surges push ocean water farther inland and increase salinity in freshwater resources. Changing weather patterns, water management, and land cover all affect water and sediment flow to the coast in ways that exacerbate extreme flooding and drought. These impacts eventually drive systems past tipping points and lead to rapid and often irreversible transformation.

Degradation of coastal systems reduces their capacity to provide natural resources, support the nation's energy production and distribution, and buffer communities and infrastructure against storms. The economic costs associated with impacts to these coastal systems are substantial. Coastlines are hit with multiple billion-dollar disasters each year, and federal spending for coastal disaster response is projected to increase 70% by 2050 due to increased development, flooding, and storm damage.

The coastal region of the southeastern United States is critically important to the nation's energy security but exceptionally vulnerable to these pressures. This report defines the southeastern U.S. coastal zone as extending south along the Atlantic Ocean from the Virginia–North Carolina border and west along the Gulf Coast to the Rio Grande.

The eight states in this region contain a quarter of the U.S. population and substantial energy infrastructure, including (1) the Strategic Petroleum Reserve, (2) more than 80% of existing or proposed liquefied natural gas terminals, (3) more than 50% of U.S. oil-refining capacity, and (4) 10 commercial nuclear power facilities. Indeed, 35% of the nation's energy production and consumption derive from states along the southeastern coast. Southeastern coastal systems also support numerous shipping ports, resource-based industries (e.g., forestry, fisheries, and agriculture), and tourism.

Ecosystems in this region exist along gradients of salinity (freshwater to saline) and inundation (infrequent to consistent) and are shaped by both marine influences and processes throughout watersheds that drain into the coastal plain. The low relief that defines the coastal plain facilitates extensive flooding in response to sea level rise, extreme tides, storm surges, and heavy rainfall. In addition, the southeastern United States is frequently and increasingly impacted by (1) heat waves, hurricanes, tornadoes, and drought; (2) fires (both wildfires and prescribed burns); (3) invasive species proliferation; and (4) land-use pressures from dense human populations and associated energy and transportation infrastructure.

Research Focus in the Southeastern United States

Although all coastal systems share fundamental and conceptual similarities, knowledge transferability from other coastal regions to the southeastern United States is challenged by the region's distinct and highly diverse physical, ecological, hydrological, and climatic features. The Southeast has vast flat plains that experience large gradients in temperature and precipitation, generating substantial ecosystem heterogeneity and making the region a hot spot for biodiversity, with more than 1,800 endemic species. Moreover, southeastern coastal systems experience high frequency and intensity of compounding disturbances that push them toward uncertain trajectories. The properties of these heterogeneous systems and their interactions with each other and with regional and global change result in challenges that are unique from those of other U.S. coastal regions.

The relative lack of historical model development and evaluation focused on southeastern coastal systems means that Earth system models (ESMs), including the U.S. Department of Energy (DOE)–supported Energy Exascale Earth System Model (E3SM), may not accurately represent key processes and vulnerabilities in the region. Advancing predictive understanding of the Earth system therefore requires specific understanding of the foundational attributes and processes of southeastern coastal systems, their vulnerabilities, and their response to individual and compounding stressors. Failure to address gaps in knowledge and modeling capability will prevent adequate assessment of risk to energy systems.

The need to improve predictive understanding of critical coastal systems in the southeastern United States aligns with research priorities of DOE's Biological and Environmental Research (BER) program. Within BER, the Earth and Environmental Systems Sciences Division (EESSD) strategically supports basic research to address key uncertainties and enhance multiscale representation and predictability of the Earth system. EESSD has a long history of using large-scale, long-term field studies, model development, and advanced analytical and computational capabilities to provide the fundamental science needed to tackle DOE mission–relevant scientific and energy challenges. Southeastern coastal systems present a unique opportunity to engage DOE capabilities and collaborate with regional and interagency partners to address Earth system understanding across a hierarchy of scales, targeting a crosscut of EESSD strategic science priorities in a region important to the nation's energy security.

Recent BER efforts are improving fundamental understanding and predictability of coastal systems, generating novel scientific insights, and stimulating advances in model development. While ongoing funding for research is currently focused on other U.S. coastal regions, a dedicated focus on the southeastern coast is warranted to capture the region's unique hot and humid climate, flat landscape, highly diverse and spatially heterogeneous ecosystems, and perturbation from frequent and intensifying disturbances (e.g., hurricanes). Moreover, the dynamic processes and land–water interactions inherent to coastal systems are not yet represented in ESMs. These challenges preclude adequate predictive understanding of coastal systems and their feedbacks among land, ocean, and atmospheric systems at local-to-global scales.

To identify research needs and opportunities for improving predictive understanding of coastal systems in the southeastern United States, EESSD's Environmental System Science program held a workshop in March 2024 on Critical Knowledge Gaps for Coastal Systems: Research Priorities for the U.S. South Atlantic and Gulf of Mexico. The workshop brought together a community of researchers from diverse disciplines to identify (1) major vulnerabilities of southeastern coastal systems; (2) critical gaps in knowledge, data, and modeling that limit predictive understanding of these systems; and (3) key science priorities for the region.

Vulnerability Driven by Compounding Disturbances

Southeastern coastal systems are uniquely challenged by the convergence of several overlapping stressors and disturbances that occur at high frequency and magnitude and can push systems toward tipping points. For example, sea level rise is a critical stressor that drives inland migration of coastlines and coastal ecosystems by increasing flooding frequency, submerging land, raising groundwater tables, and increasing salinization of surface and groundwater. Even minor changes in sea level rise impact large areas of the flat coastal plain, where low relief is compounded by ground subsidence associated with land development, belowground resource extraction, and reduced sediment loads from rivers. Consequently, uplands and freshwater wetlands on the southeastern coast are converting to saline wetlands and open water more than any other region in the country, leading to rapid ecosystem transition and land-cover loss. Continued submergence of coastlines across the region over the next few decades will flood beachfront properties and shrink natural buffer areas that mitigate the effects of hurricanes and storm surges on coastal and inland communities.

The southeastern United States also experiences frequent, high-intensity hurricanes and tropical storms. Ten hurricanes (five at Category 3 or higher) made landfall in this region between 2020 and 2023. These storms bring high winds and heavy rain that (1) uproot, flatten, or defoliate vegetation; (2) generate pulses of saltwater intrusion into freshwater resources; and (3) cause deposition, erosion, and sediment redistribution. Episodic seawater flooding from storm surge and extreme tides exacerbates chronic salinization from sea level rise and groundwater extraction. Since 2000, high tides alone have increased flooding frequency by 400 to 1,000% along the South Atlantic and Gulf coasts. Seaward flooding is compounded by heavy precipitation events over land that generate large freshwater flows toward the coast.

The southeastern United States is also vulnerable to rising air temperatures and thermal extremes. For example, mangroves are migrating northward at the expense of tidal marshes as freeze events decrease in frequency and intensity. This vegetation shift affects ecosystem structure and function by affecting nutrient and carbon cycling, marsh elevation, coastal protection, and coastal food webs. Extreme heat and drought events alter freshwater flows to the coast and drive ecosystem transitions that have cascading effects on ecological function.

In addition, nearly every southeastern coastal system has been modified to support increasing population density and associated resource requirements. Rivers are extensively dammed for hydroelectric power generation, recreation, and flood control; dredged to support navigation; and constrained by levees to prevent flooding. Land subsidence contributes to saltwater intrusion. Developed areas and shrublands have greatly expanded over the last few decades with comparable decreases in forests, agriculture, and wetlands. These changing patterns of land use and land cover modify water, sediment, and nutrient delivery to the coast. Moreover, coastlines have been directly altered to support residential and commercial developments and infrastructure meant to preserve beaches. These alterations have the potential to constrain ecosystem migration, influence ecosystem function, and drive state changes to different ecosystems, potentially reducing their capacity to provide services (e.g., water filtration, erosion control, and carbon storage) and economic benefits (e.g., tourism, fishing, and storm mitigation).

Key Knowledge, Data, and Modeling Gaps

Predictive understanding of the function and trajectory of southeastern coastal systems is limited by interconnected gaps in knowledge, data, and modeling. These critical gaps include uncertainties in the distribution and connectivity of coastal systems, biogeochemical processes underlying ecosystem function, and response to compounding stressors and disturbances. Dedicated efforts are needed to address these key gaps by using model-informed experiments and observations to improve quantification and predictive understanding of system attributes and process interactions.

Distribution and Connectivity of Coastal Systems

Drivers and Consequences of Shifting Ecosystem Distributions

The southeastern coastal plain hosts diverse and unique ecosystems that are gaining, losing, or shifting geographic areas under pressure from sea level rise, intensifying weather extremes, land cover change, and other disturbances. The extent of these ecosystem changes is poorly described, and the magnitude of ecosystem area losses and gains over time is unknown. These gaps challenge efforts to accurately assess current states and predict future trajectories. Accompanying the need to characterize current ecosystem ranges at finer spatial resolution is the need to anticipate their changing distributions within the region. Identifying the current and future ranges of diverse ecosystems is critical for understanding how their distributions are shaped by environmental drivers and defining their contributions to local ecosystem services and globally relevant processes (e.g., carbon storage and biogeochemical fluxes).

Processes Controlling Land-Surface Elevation

Land-surface elevation relative to mean sea level and tidal ranges determines ecosystem exposure to flooding and salinization. Current predictions of land-surface elevation changes rely on empirical relationships that cannot adequately capture underlying processes (e.g., sediment transport and deposition, groundwater extraction, organic matter accumulation, and belowground productivity such as root growth). These processes are highly variable across the region because of pronounced differences in vegetation and sediment dynamics. Furthermore, humans routinely modify land-surface elevation by building structures that affect water and sediment flow to the coastline. Process-based understanding and model representation of factors driving vertical accretion or collapse of the land surface and their response to diverse environmental drivers are needed to predict interactions of sea level rise with land-surface elevation, vegetation, and coastal hydrology at scales necessary for Earth system predictability and hazard mitigation.

Spatial Heterogeneity in Lateral Exchange

Coastal boundary dynamics (i.e., land–water exchange) are not explicitly represented in current ESMs. Their inclusion is difficult because of their spatial heterogeneity relative to the typical ESM grid size, the need to represent lateral exchange, and active modification of boundaries by human activities and sea level rise. Lateral fluxes of water, sediment, solutes, and other biotic and abiotic constituents from uplands into coastal plains, between terrestrial and aquatic compartments, and through coastal systems to the ocean are difficult to measure and poorly quantified. When flux data are available, they often represent large areas, limiting attribution to any one system or component. There is a pressing need to better characterize lateral flow through watersheds and between land and open water, particularly in response to compounding sea level rise, extreme precipitation events, and hurricanes and tropical storms. Moreover, the ability to represent exchange among grid cells and between land and ocean models remains a key challenge. Novel approaches and methods to capture the high spatial heterogeneity of the southeastern coastal plain and to measure and model lateral fluxes need to be developed to fully capture how an intensifying hydrologic cycle impacts flooding and biogeochemical cycling in coastal systems.

Biogeochemical Processes Underlying Ecosystem Function

Dynamic Carbon Storage and Fluxes

Southeastern coastal systems (e.g., mangroves and salt marshes) have exceptional potential to remove carbon from the atmosphere and store it in plant biomass and soil organic matter that increases land-surface elevation. Carbon storage is enhanced in depositional and saturated environments such as wetlands, where organic matter is buried under anoxic conditions that slow decomposition. Wetlands comprise more than 20% of the southeastern region. Accurate and verifiable quantification of plant biomass and soil carbon stocks across these coastal watersheds is still lacking, as is an understanding of coupled interactions between carbon and other biogeochemical cycles in response to disturbances. Furthermore, freshwater wetlands emit more than 50% of global methane, a potent gas produced under anoxic conditions. Methane production decreases with increasing salinity but increases with warming and saturation, and methane release to the atmosphere is modulated by vegetation, wind, and inundation. These complexities generate uncertain trajectories in methane dynamics across the southeastern coast where increasing temperatures, pervasive flooding, salinization, and changes in land cover and land use are driving shifts in the extent and function of different wetland types.

Biogeochemical Processes Across Gradients

Oxidation–reduction (i.e., redox) electron–transfer reactions provide the energy needed for biogeochemical processes but depend on the availability of electron donors and acceptors. Coastal systems possess gradients of water saturation and salinity that create high spatial and temporal variability in reactants. As a result, coastal biogeochemistry is often dominated or influenced by spatial or temporal pulses of high activity (e.g., hot spots and hot moments). Redox conditions in soil and sediment have typically been assessed at discrete times and locations, resulting in uncertainty as to how these processes vary across heterogeneous environmental conditions caused by complex, intersecting gradients and disturbances. It is unclear how redox gradients vary spatially across soil pore networks and as a function of hydrologic flow paths, soil bulk density, and plant root structures unique to the diverse soil types and ecosystems that exist across southeastern coasts. More complete quantification of redox variability and biogeochemical reactions is needed to constrain organic matter accumulation, nutrient cycling, and sulfide toxicity and their responses to various stressors and disturbances.

Plant–Microbe–Soil Interactions

The composition and function of microbial communities change in response to saturation, salinity, and shifts in plant communities that alter belowground carbon allocation and nutrient uptake. Expected shifts in plant communities and introduction of tropical species to southeastern coastal regions will have unknown effects on rhizosphere and soil microorganisms and their interactions with the soil matrix. Furthermore, plant and microbial communities may exhibit asynchronous responses to changing environmental conditions that are not well constrained. Investigating interactions among plants, microbial communities, and their soil environment in response to environmental drivers is necessary to determine impacts on carbon storage, nutrient cycling, and biogeochemical fluxes.

Response to Compounding Stressors and Disturbances

The southeastern United States is experiencing pronounced sea level rise and saltwater intrusion that occur within the context of previous modifications to the landscape and concurrently with a variety of other disturbances that compound their effects on coastal systems. Uncertainty emerges from the interactions of multiple stressors and disturbances that occur at variable frequencies and generate unexpected effects on ecosystem structural losses and recovery potential. Coastal ecosystem structure and function and associated biogeochemical processes need to be understood within the context of a range of environmental conditions that drive the trajectory of ecosystem state changes. Novel approaches are needed to evaluate interactions among various compounding stressors and disturbances within the context of antecedent conditions.

In particular, human modifications to the southeastern coast are widespread and substantially impact natural processes, necessitating consideration of how human activities fit within the broader understanding and representation of these systems. Land use and land cover are changing rapidly in the southeastern United States, due largely to declining forest cover from increased development. In addition, human water use and flood mitigation efforts have significantly modified surface and subsurface hydrology. Research efforts need to consider current and future human-related changes to the landscape, which will add stressors to these already altered systems as populations grow and the built landscape displaces natural coastal ecosystem features and functions.

Science Priorities and Research Opportunities

The diverse and dynamic nature of coastal systems in the southeastern United States provides a unique and transformative opportunity to advance predictive understanding of coastal systems globally by refining representation of key processes across distinct environmental settings and compounding disturbances. Two-way interactions between modeling and experiments (a ModEx approach) are key to advancing predictive understanding of these systems. Access to high-performance computing, along with flexible and adaptive mesh capabilities, is enabling more dynamic, realistic, and location-specific model representation of coastal systems. These capabilities in turn can deliver vital information to local decision-makers and characterize critical feedbacks to the whole Earth system.

Ongoing advances in autonomous field instrumentation enable continuous observations of environmental parameters that can inform models in real time, while model outputs and uncertainty quantification assist development of laboratory- to field-scale investigations of critical knowledge gaps. Molecular-scale measurements available through multiple DOE user facilities (e.g., synchrotron light sources, neutron sources, the DOE Joint Genome Institute, and the Environmental Molecular Sciences Laboratory) support mechanistic understanding of multiscale observations. Artificial intelligence and machine learning (AI/ML) approaches can be used to extract patterns from increasingly complex datasets and facilitate development of a process-based, integrated modeling framework. Workshop participants identified key science priorities for southeastern coastal systems that would take advantage of these capabilities to address critical gaps.

Understand Coastal Responses to Compounding Disturbances

Although the effects of compounding stressors and disturbances on coastal systems can be difficult to discern from observations alone, the development of big data and AI/ML approaches presents a new opportunity to identify complex patterns through analysis of complementary, high-resolution datasets. These approaches require substantial data synthesis efforts to align disparate datasets collected across multiple agencies and at different spatial and temporal scales. In addition to synthesizing historical and real-time data streams, ecosystem-scale experiments targeting natural and manipulated gradients will be instrumental in understanding how different systems respond to diverse stressors and disturbances. Aggregating and synthesizing historical and near-real-time data through collaborative efforts across disciplines, agencies, and stakeholders are critical to identify remaining data and knowledge gaps, advance model development, and ultimately enable science-based decisions.

Describe Biotic Shifts and Associated Biogeochemical Processes

Across the diverse and spatially heterogeneous southeastern coast, there is a need to define current ecosystem distribution and function and observe long-term trajectories of ecosystem transitions. This knowledge would enable predictive understanding of sequential state changes associated with a combination of environmental drivers, including sea level rise. Shifting vegetation and microbial communities associated with these state changes feed back to biogeochemical processes including carbon and nutrient storage, transformation, and fluxes. Direct field-scale manipulation would enable comprehensive assessment of how ecosystems as a whole respond to key variables affecting coastal systems. Improved representation of these processes in predictive models will inform experiments targeting key uncertainties and enable exploration of how ecosystem transition or loss will propagate to ecosystem function (e.g., genomic indicators of microbial structure and function, biogeochemical reactions, carbon and nutrient cycling, and hydrologic cycling).

Examine Coastal Dynamics in a Watershed Context

An integrated perspective is needed to understand how coastal dynamics are shaped by watershed processes, particularly in understudied watersheds that drain to the oceans. Water, sediment, and solute transport from uplands to the coast affects the structure and function of coastal systems but is modified by changes in land use and land cover and weather extremes that include heavy precipitation and drought. Observation and modeling efforts should emphasize connectivity between and among upland and wetland ecosystems, including interactions among climatic and anthropogenic drivers, shifting vegetation distributions, lateral transport of water and carbon, vertical accretion and surface elevation, and belowground geochemical and microbial processes.

Build an Integrated Multiscale Modeling Framework

Aligned with these priorities, there is a specific need to advance model frameworks capable of representing processes and integrating observations across scales to tackle fundamental questions in coastal science. The intersection of heterogeneous southeastern coastal systems with diverse disturbances presents a unique opportunity to capture a range of processes relevant to coastal systems more broadly. Several existing model frameworks represent physical and biogeochemical processes at resolutions ranging from the pore scale to tens of kilometers. However, true multiscale integration requires bridging gaps in scale and process specificity across modeling approaches. Important knowledge gaps must be addressed to update representation of processes specific to southeastern coasts and integrate knowledge transfer among these models to accurately capture coastal system complexities and feedbacks.

Path Forward

Coastal systems in the southeastern United States provide substantial economic and environmental value to the nation but are uniquely vulnerable to compounding stressors and disturbances. Predictive understanding is needed to evaluate the full range of how these diverse coastal systems function and respond to ongoing environmental pressures in order to identify impacts on coastal populations, critical energy infrastructure, and industries. Current understanding and representation are limited by crosscutting gaps in knowledge, data, and modeling, driven in part by the complexity of coastal systems.

Developing and integrating high-performance computing, process-based modeling, AI/ML, autonomous sensors, remote sensing, and molecular-scale techniques present an opportunity to advance predictive understanding of highly diverse southeastern coastal systems and their interactions with global processes. Dedicated efforts using two-way model–experiment integration (i.e., ModEx) can refine scientific understanding and provide predictive capabilities needed to enable science-based decisions. Research focused on southeastern coastal systems presents an opportunity for BER to advance science priorities, engage and facilitate interagency collaboration, and provide tools and insights needed to address energy security and other DOE mission–relevant challenges.

Chapter 1

Research Focus on Southeastern U.S. Coasts

Coastal systems provide substantial ecosystem services that contribute three-quarters of the world's total economic value (Martínez et al. 2007). In the United States, coastal watersheds and shorelines are home to approximately half the population and provide trillions of dollars of economic and ecosystem services each year (NOAA 2013, 2025a).

However, coastal systems are experiencing several compounding challenges that threaten the nation's energy security by damaging infrastructure, natural resources, and communities (Risky Business Project 2014; Desmet et al. 2018; Ward et al. 2020; O'Donnell et al. 2024). Flooding, salinization, and extreme weather destroy property, degrade freshwater resources, and lead to population displacement (see Fig. 1.1, p. 2).

The economic costs associated with impacts to coastal systems are substantial. Coastlines are hit with multiple billion-dollar disasters each year (NOAA NCEI 2025). Federal spending for coastal disaster response is projected to increase 70% by 2050 due to increased development, flooding, and storm damage (U.S. CBO 2024). The impacts of these disasters are exacerbated by ongoing stressors to coastal ecosystems (e.g., rising sea levels, nutrient pollution, invasive species, and reduced sediment loads).

Coastal systems in the southeastern United States are acutely susceptible to these hazards (USGCRP 2018). Disasters along the Gulf Coast alone have generated $365 billion in property damage (62% of U.S. disaster losses) since 2005. Every coastal county has experienced multiple federally declared disasters during that time (ASU CEHMHS 2025; FEMA 2025; Rumbach et al. 2025).

In this report, the coastal region of the southeastern United States refers to the coastal plains that extend south from the Virginia–North Carolina border along the South Atlantic and west along the Gulf Coast to the Rio Grande. These systems include (1) coastal watersheds that drain into shorelines and directly impact processes

Key Points

- Coastal regions of the southeastern United States support extensive infrastructure critical to the nation's energy security.
- Energy production and distribution in the region rely on robust natural ecosystems to supply resources and mitigate hazards.
- Addressing critical knowledge gaps in ecosystem structure and function will provide information needed to strengthen resilience against environmental pressures.

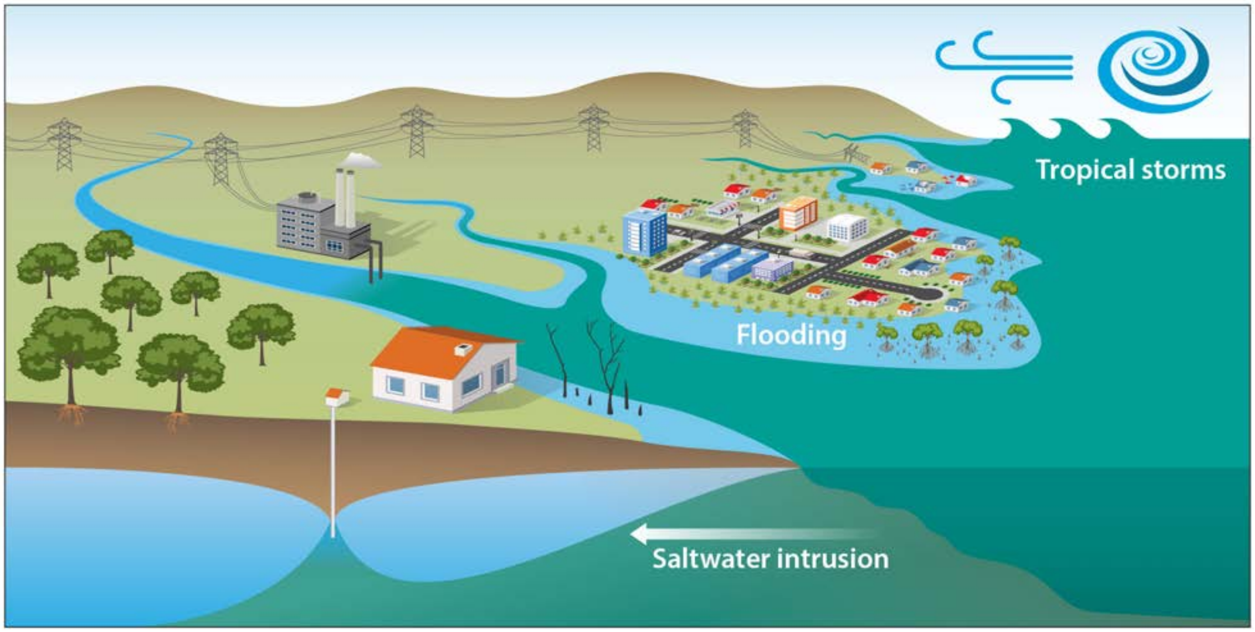


Fig. 1.1. Prominent Hazards to Communities and Infrastructure in Coastal Regions of the Southeastern United States. Flooding and saltwater intrusion associated with sea level rise are stressors, which impose continuous pressure on a system, whereas tropical storms are disturbances, which temporarily alter ecosystem structure.

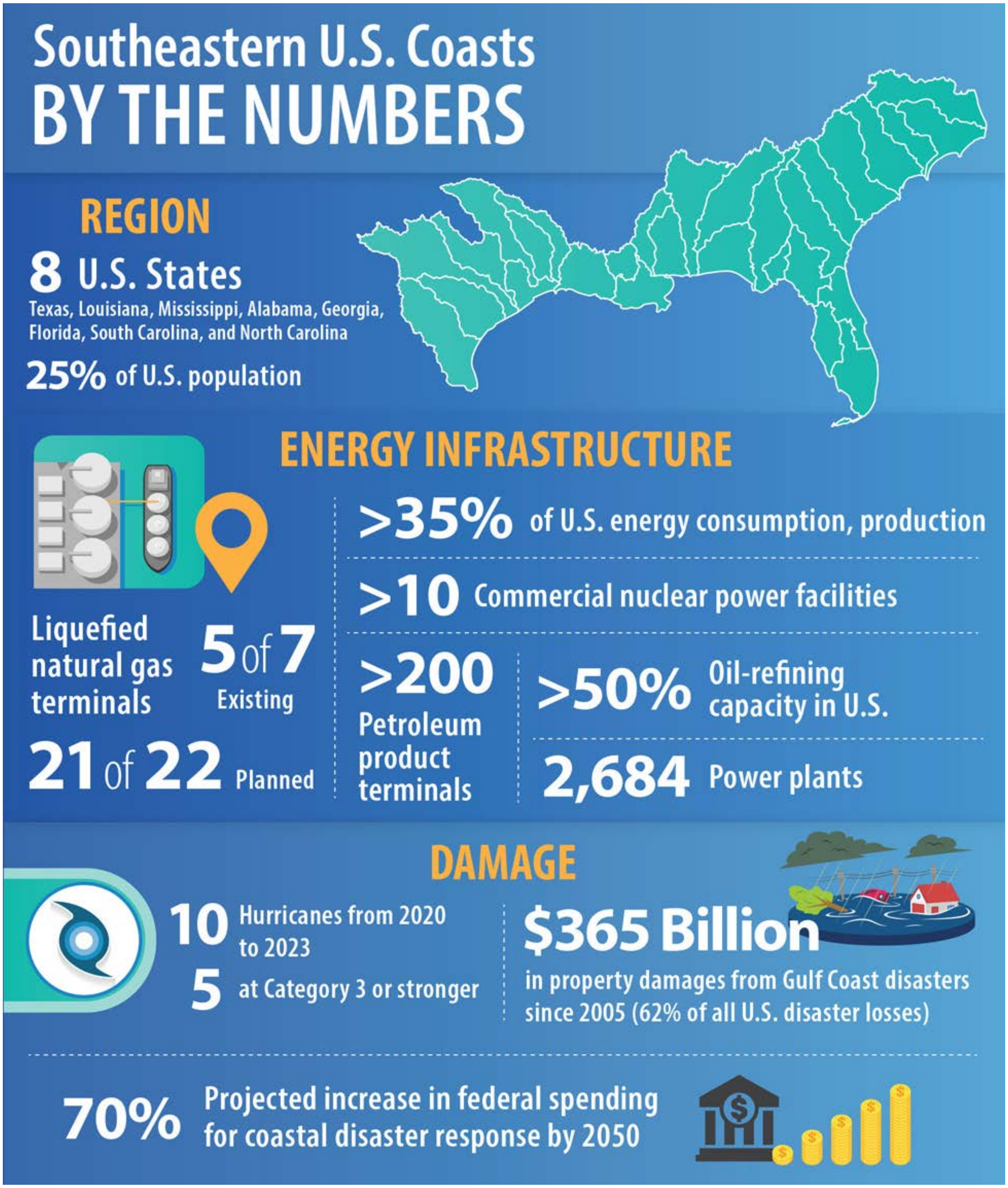
happening at the coast (NOAA 2025b) and (2) coastal shorelines that are directly adjacent to open water and experience the brunt of coastal hazards.

1.1 Significance of Southeastern U.S. Coastal Systems

The eight states that make up this region contain a quarter of the U.S. population and support substantial energy, industry, and commercial infrastructure (NOAA 2013; U.S. Census Bureau 2024). Their critical importance to the nation's energy security is underscored by their contributions to energy production (see Fig. 1.2, p. 3). The coastal plain also contains heavy mineral sands (i.e., placer deposits) enriched in critical minerals essential to energy operations (e.g., rare earth elements, thorium, titanium, and zirconium; Shah et al. 2017; Van Gosen et al. 2019).

Southeastern coastal systems directly support the nation's economy by providing land and water resources and buffering communities and infrastructure against storm damage, flooding, and saltwater intrusion. These systems are critical interfaces exchanging water, solutes, and sediment between continents and the ocean. For example, many coastal systems mediate globally significant nutrient and gas fluxes (Mcleod et al. 2011; Siikamäki et al. 2013; Rogers et al. 2023). Nutrient storage and transformation in coastal systems regulate nutrient export from rivers into open waters (Bouwman et al. 2013) and can mitigate formation of harmful algal blooms that are dangerous to people and aquatic life.

Low elevation gradients along coastal plains in the southeastern United States make coastal systems particularly vulnerable to flooding and saltwater intrusion (see Fig. 1.3, p. 4; USGCRP 2018). More of this region's freshwater wetlands and uplands are predicted to convert into saline wetlands than in any other U.S. location (Osland et al. 2022a). Even more land is being converted to open water as changing sea levels, ground subsidence, waterway management, and sediment depletion drown coastal wetlands. Louisiana, for example, has lost more than 5,000 km^2 of coastal land



Southeastern U.S. Coasts
BY THE NUMBERS

REGION

8 U.S. States
Texas, Louisiana, Mississippi, Alabama, Georgia, Florida, South Carolina, and North Carolina

25% of U.S. population

ENERGY INFRASTRUCTURE

Liquefied natural gas terminals
5 of **7** Existing
21 of **22** Planned

>35% of U.S. energy consumption, production

>10 Commercial nuclear power facilities

>200 Petroleum product terminals

>50% Oil-refining capacity in U.S.

2,684 Power plants

DAMAGE

10 Hurricanes from 2020 to 2023
5 at Category 3 or stronger

$365 Billion in property damages from Gulf Coast disasters since 2005 (62% of all U.S. disaster losses)

70% Projected increase in federal spending for coastal disaster response by 2050

Fig. 1.2. Southeast U.S. Coasts Key for Energy, Vulnerable to Disturbance. The eight states that comprise the southeastern U.S. coastal zone contain significant energy infrastructure (U.S. EIA 2025a, 2025b) and experience a high magnitude and frequency of disasters.

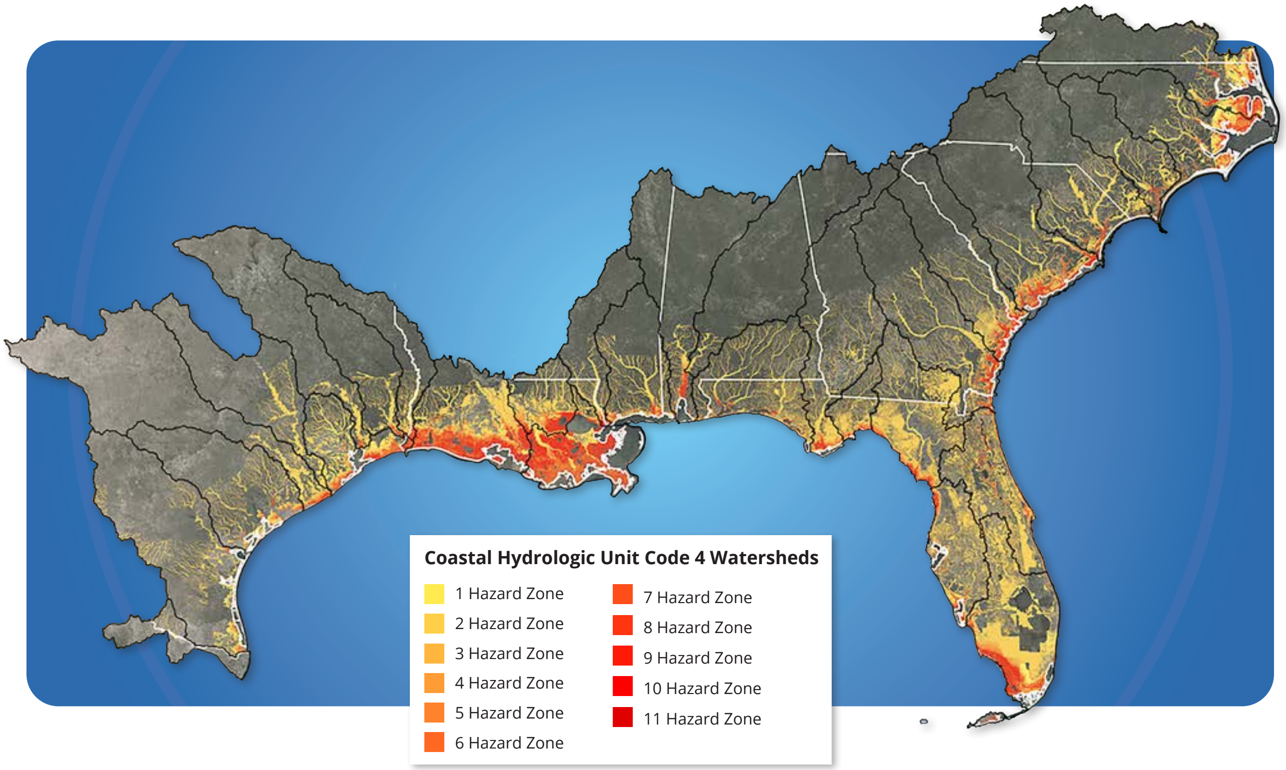


Fig. 1.3. Coastal Flood Exposure in the Southeastern United States. Areas prone to flooding are highlighted according to hazard level; darker colors indicate more flood hazards for a given location. Flooding hazards may arise from one or more causes, including (1) high-tide flooding; (2) high risk (1%) and moderate risk (0.2%) annual flooding probability, as designated by the Federal Emergency Management Agency; (3) storm surges for Category 1–3 hurricanes; (4) projected scenarios of 1-, 2-, or 3-foot increases in sea level; and (5) tsunami run-up zones. Watersheds draining into the coast are outlined in black. [Map courtesy Chris DeRolph, Oak Ridge National Laboratory. Data used for the map were obtained from coast.noaa.gov/floodexposure.]

since 1932 (CPRA 2023). Continued submergence of coastlines across the southeastern United States over the next few decades will increase flooding and shrink natural buffer areas that mitigate the effects of hurricanes and storm surges on inland communities.

Effects of sea level rise and saltwater intrusion are compounded by frequent disturbances including hurricanes and tropical storms, freshwater flooding from heavy precipitation, drought, fire, invasive species, changes in land use and land cover, extreme temperatures, and decreased sediment supply (Ward et al. 2020).

Drought lowers groundwater tables and increases the extent to which seawater can intrude inland, increasing plant mortality and salinization of water resources (McKee et al. 2004; Desantis et al. 2007; Lovelock et al. 2017). Land subsidence and storm surges associated with hurricanes push saltwater even further inland and contribute to plant mortality and the formation of "ghost forests" (Kirwan and Gedan 2019). Increasing temperatures facilitate the northward migration of tropical species such as mangroves, where they are susceptible to periodic extreme freeze events that damage and kill vegetation (Osland et al. 2020a). Invasive species take advantage of weakened vegetation to proliferate and spread, further altering ecosystem processes (Gandhi and Herms 2010). These effects are widespread and ongoing, motivating focused attention on the southeastern United States to advance scientific understanding of how coastal systems function now and into the future and how they interact with the larger Earth system.

1.2 Workshop Objectives

Given the economic importance of southeastern coastal systems, the Environmental System Science program within the U.S. Department of Energy's (DOE) Biological and Environmental Research (BER) program hosted the Critical Knowledge Gaps for Coastal Systems: Research Priorities for the U.S. South Atlantic and Gulf of Mexico workshop in March 2024 (see Appendix A: Workshop Agenda, p. 56) The workshop's objective was to obtain input from the research community on major knowledge, data, and modeling gaps and corresponding science priorities relevant to predictively understanding southeastern coastal systems (see Appendix B: Workshop Discussion Questions, p. 59). This workshop complemented a recent BER report on *Optimizing DOE Opportunities to Research Land–Atmosphere Interactions in the U.S. Southeast* (U.S. DOE 2024) and built on concepts outlined in another BER report, *Research Priorities to Incorporate Terrestrial–Aquatic Interfaces in Earth System Models* (U.S. DOE 2017).

Experts in biogeochemistry, hydrology, ecology, geomorphology, microbiology, modeling, and research coordination attended the workshop, representing institutions including DOE national laboratories, academic institutions, and other federal agencies (see Appendix C: Workshop Participants, p. 60). Several attendees were leaders or participants in collaborative research efforts including the National Science Foundation (NSF)–supported Long-Term Ecological Research, Research Coordination, and Critical Zone Collaborative networks and the National Oceanic and Atmospheric Administration's National Estuarine Research Reserve System and Sea Grant.

The workshop included plenaries on coastal systems and their vulnerabilities, current capabilities for modeling Earth systems, and coordinated research activities in the southeastern coastal region. Participants discussed unique characteristics of the southeastern United States (see Ch. 2, p. 7); the episodic, chronic, and compounding disturbances and stressors that most affect southeastern coastal systems (see Ch. 3, p. 19); the major knowledge, data, and modeling gaps that limit predictive understanding of these systems (see Ch. 4, p. 33); and science priorities and research opportunities for the region (see Ch. 5, p. 47).

Chapter 2

Coastal Systems of the Southeastern United States

The southeastern United States contains highly diverse and heterogeneous coastal systems with a wide variety of vegetation, soils, and hydrology. This chapter describes the major landforms and ecosystem types within these systems and key ecological and hydro-biogeochemical processes.

Key Points

- Coastal systems in the southeastern United States are characterized by low elevation gradients that facilitate extensive flooding and generate high spatiotemporal heterogeneity in inundation and salinity.
- These coastal systems have unique human dimensions, including extensive coastal-based industries and growing populations.
- The structure and function of coastal ecosystems are shaped by interconnected hydro-biogeochemical processes that link ecosystems across a terrestrial-to-marine continuum.

2.1 Overview of the Coastal Continuum

The southeastern United States is hot and humid with frequent extreme events, including hurricanes and other storms that bring intense rainfall. The low relief that characterizes the coastal plain results in a large lateral extent of persistent flooding and saltwater intrusion due to ongoing increases in sea level and periodic flooding associated with tides, rainfall, and storm surge.

Inundation and salinity gradients generated from freshwater and saltwater flooding shape the distribution of tidal and nontidal ecosystems on a continuum from uplands to the ocean. These ecosystems range from upland forests and freshwater (palustrine) wetlands in the interior portion of the coastal region to mangroves and saltmarshes (estuarine wetlands) along the coastline (see Fig. 2.1, p. 8). In areas subject to tides, tidal variability ranges from microtidal (less than 2 m) in states along the Gulf Coast to mesotidal (2 to 4 m) along the Atlantic Coast.

Southeastern coastal systems also have unique human dimensions, including (1) growing, concentrated populations and their associated infrastructure; (2) economies driven by proximity to the coast, such as fisheries, oil and gas production, and tourism; and (3) water resource demands driven by large populations and extensive industry.

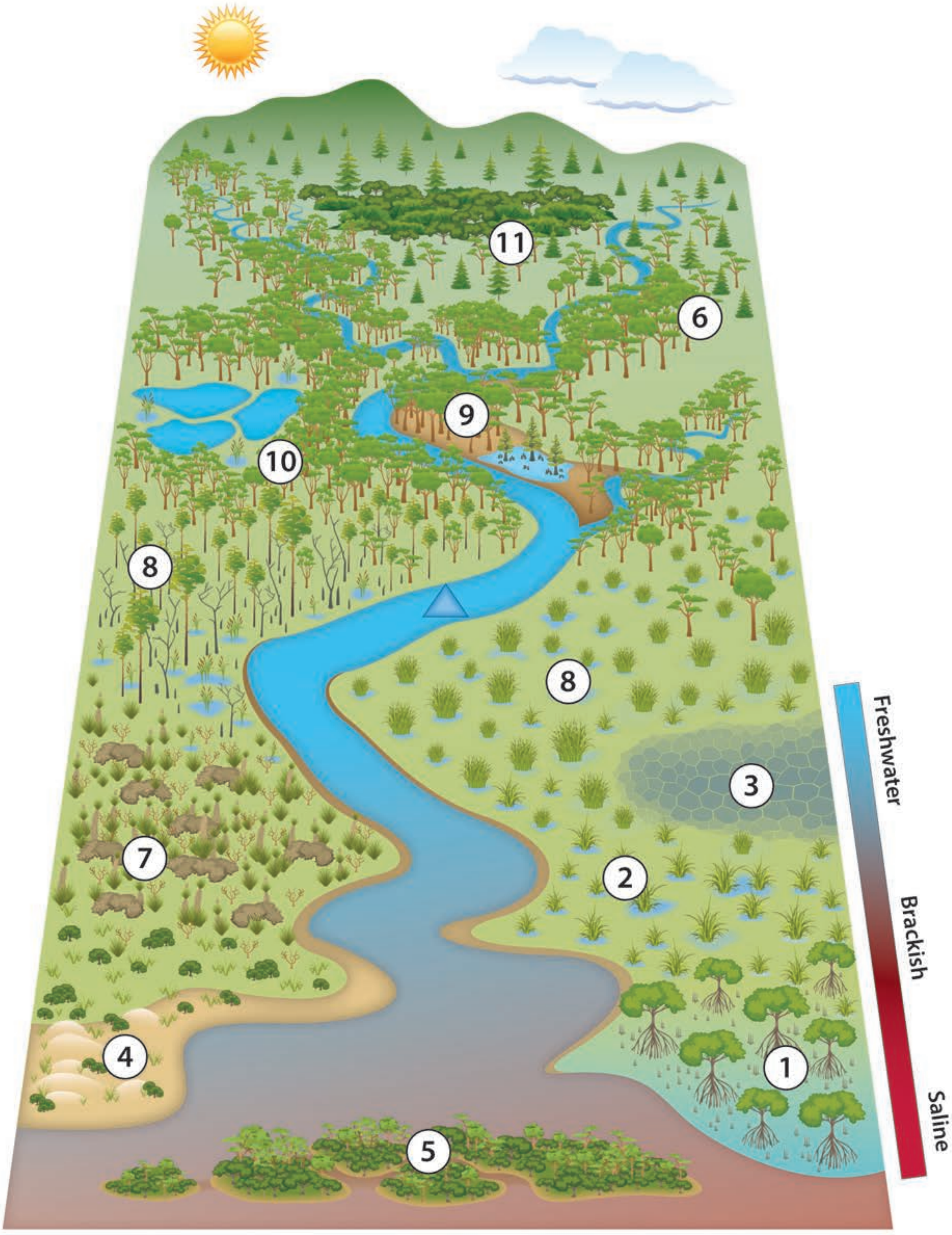


Fig. 2.1. Coastal Ecosystems in the Southeastern United States. Conceptual distribution of coastal ecosystems including **(1)** mangroves, **(2)** saltmarshes, **(3)** saltflats, **(4)** coastal sand dunes, **(5)** maritime forests, **(6)** upland forests, **(7)** scrub and shrublands, **(8)** tidal freshwater marshes and forested wetlands, **(9)** bottomland hardwoods, **(10)** nontidal wetlands, and **(11)** pocosins. The water shows a salinity gradient from saline (red) to freshwater (blue). The triangle represents the head of tide (i.e., the upstream limit of water affected by the tide).

Table 2.1: Land Cover Along the South Atlantic and Gulf Coasts

Land Cover Class	Area in 2021 (km^2)	Percent of Total Coastal Area	Area Change from 2010 to 2021 (km^2)	Percent Change in Area
Developed	53,800	7.4	2,845	5.6
Cultivated	80,003	10.9	-74	-0.1
Pasture/Hay	71,013	9.7	-1,874	-2.6
Grassland/Herbaceous	33,263	4.5	3,531	11.9
Deciduous/Evergreen Forest	162,529	22.2	-5,925	-3.5
Scrub/Shrub	78,783	10.8	1,493	1.9
Palustrine Wetlands*	159,439	21.8	143	0.1
Estuarine Wetlands*	17,975	2.5	-94	-0.5
Open Water	67,992	9.3	274	0.4
Other†	6,730	0.9	-321	-4.6

Land cover by area and class in 2021 and the accompanying change in area from 2010 to 2021. [Data from the National Oceanic and Atmospheric Administration’s Coastal Change Analysis Program (NOAA 2025c)]

** Palustrine and estuarine wetland classes include forested, shrub, and emergent wetland subclasses.*

† Other includes unconsolidated shore, bare land, and palustrine and estuarine aquatic beds.

In some cases, the land area of a given ecosystem (see Table 2.1, this page) will fragment and shrink as environmental and human-related pressures constrain available land area. For example, urban development can limit the landward transgression of salt-adapted ecosystems if trends in sea level continue, leading to a “coastal squeeze” that drives habitat loss.

2.2 Major Landforms and Ecosystem Types

Coastal plains of the southeastern United States form on top of terrestrial sediments eroded from the continental interior and on marine carbonates deposited under shallow oceans. Landforms in this region include flat and rolling plains, mineral-rich river deltas, tidal embayments and estuaries, and karstic carbonate systems (Dürr et al. 2011; Wiken et al. 2011; Worthington et al. 2020). The soils that develop across these landscapes reflect interactions between the underlying lithology and other soil-forming factors. Upland soils are dominated by highly weathered Ultisols in the east that grade into more fertile Alfisols and Vertisols west of the Mississippi River (West et al. 2017; U.S. NRCS 2022). Spodosols develop on acidic, sandy substrates throughout Florida, while Histosols (i.e., peat) occur in flooded landscapes along the Louisiana coast and south of Lake Okeechobee in Florida (West et al. 2017; U.S. NRCS 2022).

Accumulation of coastal sediments eroded from metamorphic and igneous rock has also generated heavy mineral sands (i.e., monazite–xenotime-bearing placer deposits) across the southeastern coastal plain (Shah et al. 2017). These deposits have primarily been targeted for titanium extraction but also represent a potential domestic source of thorium (used in molten salt reactors) and rare earth elements that are broadly critical for advanced technologies (Van Gosen and Ellefsen 2018; Van Gosen et al. 2019).

The coastal ecosystems described in this chapter (see p. 10 p. 10–p. 15) develop on these landforms

[Courtesy John Dreyer, Getty Images]

Mangroves

- Saltwater-adapted tree communities that fringe tropical and subtropical coastlines around the world
- Encroach into saltmarshes in response to (1) milder winter temperatures and (2) decreased frequency of freeze events
- Limited growth when low winter temperatures and the number of days below freezing exceed ecophysiological thresholds for cold tolerance
- Protect coastlines from tropical storms
- Provide raw materials and habitat for fisheries

[Courtesy Adobe Stock]

Saltmarshes

- Saline and brackish wetlands that are flooded and drained by tides
- Dominant coastal ecosystem in the southeastern United States
- Characterized by peat and graminoid vegetation cover
- Reduce wave energy
- Stabilize coastlines against erosion
- Improve water quality by filtering contaminants
- Support industries such as fishing and tourism
- In the last few decades, an estimated 50% of global saltmarshes have been degraded or lost

as a function of environmental gradients (Ewel et al. 1998; Twilley et al. 2022). These diverse ecosystems do not exist in isolation but form a continuum linked by regional climate and weather patterns, surface and subsurface hydrology, nutrient exchange, and sediment transport. The most marine endmembers of the coastal ecosystem continuum are characterized by saline, hydric (i.e., saturated) conditions. At the most terrestrial endmember, salinity reduces to zero and hydrological differences dictate mesic versus xeric conditions.

Coastal systems in the southeastern United States are particularly susceptible to multiple compounding stressors and disturbances (see Ch. 3, p. 19) that can push them toward compositional and functional tipping points. As such, the distribution of ecosystem types, their hydro-biogeochemical functions, and their interactions with regional and global Earth systems are expected to shift over time.

Disturbances many kilometers inland may propagate through this continuum and affect ecosystem integrity along the coastline. For example, Hurricane Helene moderately impacted the Gulf Coast directly but brought extreme rainfall and landslides to the headwaters of several coastal watersheds hundreds of miles inland. The water, sediment, and solutes mobilized by inland events flow through watersheds and

[Courtesy Adobe Stock]

Upland Forests

- Forests shifting from deciduous trees in the interior to evergreen near the coast
- Fire-adapted and subject to frequent prescribed burns to prevent encroachment of understory or invasive species
- Include several endemic pine (e.g., longleaf, slash, and sand), oak (e.g., live oak), and other tree species
- Pine woodlands and savannas have shrunk and fragmented under multiple pressures
- Extensively used for forestry, particularly loblolly pine; in the last 50 years, forestry has expanded and replaced agriculture throughout the region

[Courtesy NC Wetlands]

Tidal Freshwater Marshes and Forested Wetlands

- Marshes and forested wetlands that occur in lower coastal plains subject to tides
- Develop where salinity is less than 0.5 parts per thousand
- Negatively impacted by episodic and chronic exposure to even low-level salinity caused by storm surges, droughts, or strong tides
- Provide erosion and flood control
- Support fisheries and recreation
- Filter excess nutrients from surface water

are transformed by interactions along their flow paths before reaching estuaries along the coast.

2.3 Key Ecological and Hydro-Biogeochemical Processes

Coastal ecosystems are shaped by processes that occur throughout their contributing watersheds and propagate toward the coast. These interconnected ecological and hydro-biogeochemical processes determine ecosystem function and response to changing environmental conditions.

Processes Controlling Land-Surface Elevation

Mean sea level rise refers to global average increases in ocean elevation. Relative sea level rise, which ultimately determines exposure to flooding and salinization, is the change in ocean elevation relative to the land-surface elevation at a given location.

Changes in land-surface elevation over time reflect the balance between vertical accretion and subsidence. Vertical accretion is the rate of upward land growth resulting from sediment deposition, organic matter accumulation, and belowground productivity (i.e., root growth). Subsidence refers to decreases in elevation


[Courtesy Adobe Stock]

Saltflats

- Short-lived variants of mangroves and saltmarshes featuring bare, cracked earth
- Occur in dry periods with high evapotranspiration, sandy soils, and concentrated salinity
- Sparsely colonized by extremely salt-tolerant vegetation (e.g., *Salicornia* spp., *Batis maritima*, and *Conocarpus erectus*)
- Present along the Atlantic and Gulf coasts, but increasingly more expansive along the Texas coastline as rainfall decreases


[Courtesy Adobe Stock]

Coastal Scrub and Shrublands

- Arid, nutrient-poor ecosystems prone to fire that are dominated by shrubs suited to those conditions
- Present in Florida, southwestern Louisiana, and along the western Gulf Coastal Plain in Texas
- Many existing coastal shrublands have been converted to croplands
- Shrublands that have not been cultivated provide important grazing habitats for livestock

resulting from sediment compaction, organic matter decomposition, and withdrawal of subsurface fluids.

Land loss occurs when water persistently inundates the land surface, for example, when rising water levels outpace increases in elevation. An ecosystem's buffer against rising water levels is called elevation capital, or the distance between the land surface and the minimum elevation at which vegetation can survive.

Vertical accretion is highly variable across the southeastern United States due to pronounced differences in vegetation and sediment dynamics. River systems in the region deliver suspended sediments to the coast where they subsidize vertical accretion. The high mineral content of suspended sediments is especially important for maintaining elevation in wetland ecosystems where relative rates of sea level rise exceed accrual of organic material (Edmonds et al. 2023).

Although European colonization initially led to widespread erosion that increased sediment loads to the coast, substantial human modification of riverine systems in the form of dams and channelization has reduced water flow throughout watersheds and contributed to recent declines in fluvial sediment transport (Syvitski and Milliman 2007; McCarney-Castle 2010). For example, the Mississippi River has been heavily dammed and channelized through the construction of levees that hydrologically isolate the river from its surrounding floodplain, reducing the sediment subsidies available to increase or maintain the elevation of neighboring wetlands.

Reduced sediment loads are perhaps most notable in larger, heavily modified river systems of the southeastern United States—the Mississippi, Mobile–Tensaw, Apalachicola–Flint, and Savannah rivers. However,


[Courtesy Sarah Toner, U.S. Fish and Wildlife Service]

Pocosins

- Shrub-dominated isolated wetlands that occur in low-lying, poorly drained shallow basins along elevated portions of the Atlantic Coastal Plain (Schafale and Evans 2015; NOAA 2024)
- Formed by the accumulation of dense organic matter in saturated, sandy soils over thousands of years
- Remove excess nutrients from water that flows into estuaries
- Spatial extent has been drastically reduced by drainage and conversion to other land uses


[Courtesy Adobe Stock]

Nontidal Wetlands

- Seasonally or permanently flooded depressions outside the tidal influence
- Prevalent and productive freshwater ecosystems
- Support high biological diversity
- Recharge groundwater
- Nontidal wetlands lacking “continuous surface connection” to navigable waters are vulnerable to drainage and development (Gold 2024)

smaller riverine systems in the region have also experienced significant declines in suspended sediment delivery (Weston 2014). Land-use change in watersheds can impact sediment delivery. For example, agricultural, urban development, and deforestation activities readily mobilize sediments, affecting riverine suspended sediment concentrations (Howarth et al. 1991; De Boer 1997; Saenger et al. 2008).

The balance between root production and turnover (i.e., loss) is an important control on soil organic matter content that in turn affects land elevation (Rogers et al. 2019; Saintilan et al. 2020, 2023; Cahoon et al. 2021). In coastal wetlands with low sediment inputs, surface elevation increases when rates of organic matter accumulation and belowground biomass production are greater than rates of decomposition or loss. Although flooding and high salinity slow decomposition and allow organic matter to accumulate (Baustian et al. 2012; Ganju et al. 2024), these factors can stress plants and decrease their productivity, leading to elevation loss (Morris et al. 2016; Morris and Sundberg 2024). Therefore, land-surface elevation’s ability to keep pace with rising sea level critically depends on how plant production and organic matter decomposition respond to environmental changes.

Plant Traits Across Coastal Environmental Gradients

The tolerance of different plant species for flooding, salinity, and nutrient availability determines their distribution within and among coastal ecosystems (see Fig. 2.1, p. 8; LaFond-Hudson and Sulman 2023). Plant traits vary across environmental gradients and affect ecosystem processes. For example, in freshwater

[Courtesy U.S. National Park Service]

Coastal Sand Dunes

- Mounds or ridges of accumulated sand that develop along coastlines
- Size depends on sediment size, wind, vegetation cover, tidal action, erosion, and tropical cyclones
- Vegetation enhances dune growth by decreasing wind speed and stabilizing deposited sediments
- Protect built infrastructure by dissipating energy from storm events (e.g., tropical cyclones)
- Tamaulipan lomas, found along the Texas coastline, are clay dunes formed from windblown sediments that rise above a tidal flat and support dense shrublands or grasslands

[Courtesy Adobe Stock]

Bottomland Hardwood Forests

- Deciduous and evergreen hardwood forests that develop in floodplains and line river corridors that drain into estuaries
- Inundation is controlled by proximity to the river, localized leveeing, drainage, and year-round river output modulated by year-to-year variability and upstream damming
- Remove sediments and nutrients from rivers, thus decreasing eutrophication in estuaries
- Support the forestry industry through forest regrowth and harvest

wetlands with greater nutrient availability, plants tend to allocate more resources to growth of aboveground shoots than to belowground roots (i.e., reduced root-to-shoot ratios) because plants need less extensive root networks to acquire nutrients (Song et al. 2019; Morris and Sundberg 2024).

In contrast, when nutrients are less abundant, wetland plants allocate more resources to root production (i.e., higher root-to-shoot ratios) as a foraging strategy to optimize nutrient uptake (Chapin et al. 1986; Vitousek and Farrington 1997; Song et al. 2019). Increasing salinity can also shift biomass allocation from shoots to roots to enhance plant water uptake. Differences in biomass allocation in turn affect photosynthesis, transpiration, and soil stability.

Vegetation also drives complex feedbacks with hydrology that affect the fate and transport of sediments, nutrients, and other waterborne materials. Differences in plant structures individually and collectively alter the rate, volume, and residence time of water flow by modifying transpiration and physically impeding water flow across a landscape. For example, sediment deposition in floodplain marshes is greatest where medium-high vegetation structure slows water movement but declines where high vegetation confines water and sediment to the river channel (Nardin et al. 2014).

By affecting solute and sediment transport, interactions between vegetation and hydrology affect rates of organic matter burial, nutrient transport, and soil accretion. In coastal mangrove forests, the large root


[Courtesy Adobe Stock]

Maritime Forests

- Pine- and oak-dominated forests that occupy extensive regions of barrier islands (i.e., elongated sand deposits that form parallel to the coast)
- Rely heavily on rainwater to saturate their porous, sandy soils
- Often have embedded mangroves or saltmarshes in areas exposed to higher salinity
- Stabilize shorelines
- Provide habitat for diverse wildlife
- Serve as a natural defense against wind and wave energy

volume that anchors mangroves against wind and waves also increases belowground woody biomass contributions to soil accretion and carbon burial (Comeaux et al. 2012; Doughty et al. 2016; Feher et al. 2020). Mangrove root structures also buffer built infrastructure from hurricane-induced storm surge and wave energy (see Ch. 3: Coastal Vulnerabilities to Stressors and Disturbances, p. 19; Twilley et al. 2016).

Carbon Dynamics

A key feature of many coastal ecosystems is their ability to sequester large amounts of carbon from the atmosphere and store it in plant biomass and soil carbon, yielding high carbon flux and storage per unit of land area relative to other landscapes.

Storage and Sequestration

Mangroves, saltmarshes, and tidal freshwater wetlands are some of the most carbon-dense ecosystems on Earth (Adame et al. 2024). Studies have reasonably mapped soil and biomass carbon stocks and sequestration rates across mangroves and saltmarshes in the southeastern United States (Simard et al. 2019; Rovai et al. 2018, 2021; Maxwell et al. 2023a, 2023b; Woltz et al. 2023; Holmquist et al. 2024). However, fewer data are available for tidal freshwater wetlands, which have only recently been recognized as “blue carbon” ecosystems (see Ch. 4: Critical Gaps in Knowledge, Data Availability, and Model Representation, p. 33; Adame et al. 2024).

Carbon storage is enhanced in depositional and saturated environments such as the wetlands that comprise more than 20% of land area in the southeastern coastal region (see Table 2.1, p. 9). In wetlands, organic matter is buried under anoxic conditions that slow decomposition. When oxygen gas (O_2) is depleted from soils and sediments, microorganisms perform anaerobic metabolisms that use nitrate, ferric iron, and sulfate as terminal electron acceptors. These metabolisms yield less energy than aerobic decomposition and result in accumulation of belowground carbon.

Low-relief landforms in the southeastern coastal plains support extensive wetland soils that develop anoxic conditions under nearly persistent saturation. Along the Gulf Coast, ground subsidence and low tidal ranges contribute to persistently waterlogged soils. Organic matter association with minerals may enhance carbon storage in soils but varies with sediment type and composition (Shields et al. 2016; Mirabito and Chambers 2023; Bianchi et al. 2024).

Lateral Exchange

Lateral export of organic and inorganic carbon species from coastal systems to the ocean represents a large but relatively unconstrained carbon flux. Tidal export of carbon species, particularly inorganic carbon, has only recently been recognized as a key mechanism for long-term carbon sequestration in coastal waters, yet it may account for 25 to 40% of mangrove and saltmarsh carbon budgets (Bogard et al. 2020; Reithmaier et al. 2023).

Comparisons of net lateral tidal carbon exchange across coastal systems are not yet feasible due to data scarcity (Santos et al. 2019; Reithmaier et al. 2023), thus presenting a critical knowledge gap for understanding the magnitude, transport, and fate of coastal carbon within the Earth system. To date, vertical and lateral carbon flux data are restricted to a few sites that do not capture the diversity of coastal systems in the southeastern United States (see Ch. 4: Critical Gaps in Knowledge, Data Availability, and Model Representation, p. 33).

Methane Dynamics

Coastal systems also present uncertainties in globally relevant methane (CH_4) emissions. Methane that is produced in soils and sediments is released to the atmosphere by ebullition and passive diffusion and through plant-mediated transport (Le Mer and Roger 2001; Wang et al. 2024).

Freshwater wetlands are responsible for approximately half of global methane emissions (Bridgham et al. 2013) and are pervasive along the southeastern U.S. coast. Methanogenesis is a microbial metabolic pathway that produces methane during decomposition of organic matter under anoxic and highly reducing conditions when other microbial respiration pathways are substrate limited.

Marine-influenced coastal systems are generally considered to be low contributors to the global atmospheric pool of methane because sulfate from seawater supports more energetically favorable sulfate reduction pathways instead of methanogenesis (Poffenbarger et al. 2011; Steinmuller et al. 2019, 2020). However, methane production and consumption are high in freshwater-dominated coastal systems, such as deltas (Roberts et al. 2015; Wang et al. 2021) and may also be high in saltmarsh systems dominated by methanogenic pathways that are not inhibited by sulfate (Capooci et al. 2024).

In addition to microbial community and substrate controls, methane production is influenced by several environmental factors—generally decreasing with increased salinity but increasing with warming and saturation. Methane is also consumed and oxidized to carbon dioxide through microbial methanotrophic pathways, typically in oxic unsaturated soil layers.

In brackish and saline systems where daily tides continuously replenish soils with sulfate-rich water that suppresses methanogenesis (Kroeger et al. 2017), freshwater inputs from rain or flooding can stimulate methane production and release (Seyfried et al. 2023). These competing pathways and environmental complexities generate uncertain trajectories in methane fluxes across the southeastern United States where ecosystems are experiencing increasing temperatures, pervasive flooding, salinization, and changes in land cover and use.

Biogeochemical Reactions and Microbial Processes

Coastal systems frequently exhibit pulses of high biogeochemical activity (e.g., hot spots and hot moments) driven by high spatial and temporal variability in oxidation–reduction (redox) electron–transfer reactions. Redox conditions measured in soil and sediment represent the relative abundance of redox-active species and vary with inundation, salinity, and other environmental drivers (see Fig. 2.2, p. 17). For example, oxidizing conditions that support aerobic decomposition occur in drained soils where oxygen gas can diffuse into pore spaces, but reducing conditions prevail in flooded soils where oxygen gas is depleted more quickly than it can be replenished. Salinity introduces high concentrations of sulfate that are respired by microorganisms in the absence of oxygen gas.

Redox conditions have typically been assessed at discrete times and locations, resulting in uncertainty

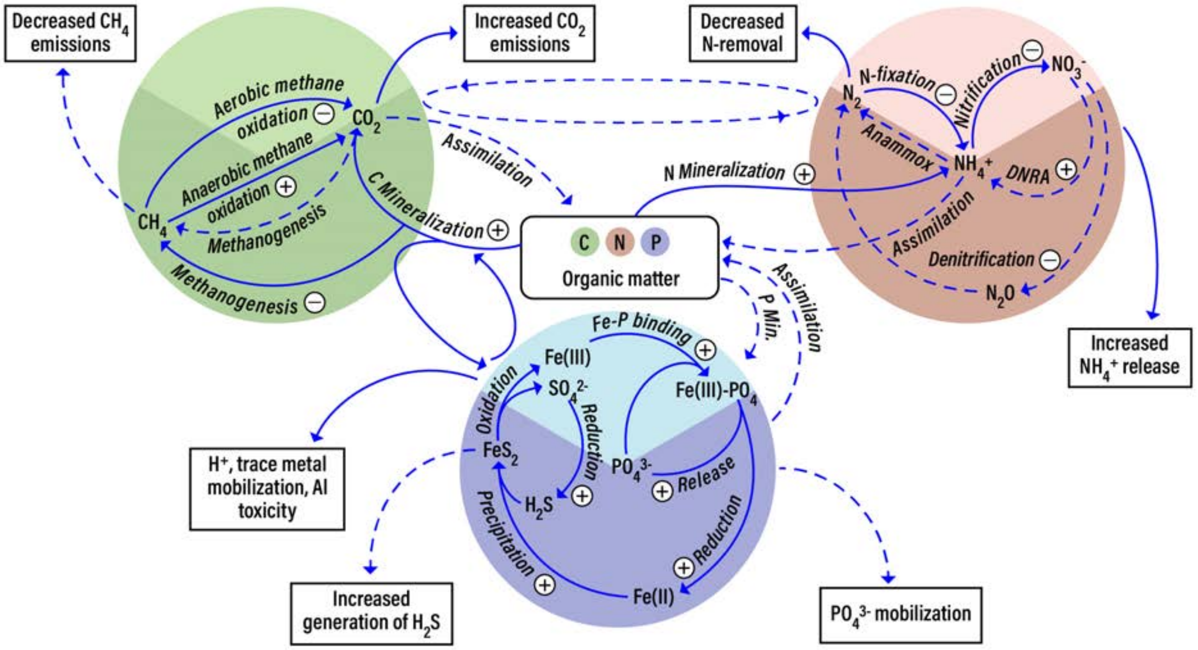


Fig. 2.2. Interconnected Effects of Sea Level Rise and Saltwater Intrusion on Biogeochemical Reactions Associated with Element Cycling. Carbon (C), nitrogen (N), and iron–phosphorus–sulfur (Fe–P–S) cycling are predicted to change in freshwater wetlands with sea level rise. Arrows indicate predicted increases and decreases in response to saltwater intrusion. Carbon dioxide (CO_2), methane (CH_4), and sulfide (H_2S) fluxes will alter accordingly. [Adapted from Herbert, E. R., et al. 2015. "A Global Perspective on Wetland Salinization: Ecological Consequences of a Growing Threat to Freshwater Wetlands," *Ecosphere* **6**(10), 1–43. DOI:10.1890/ES14-00534.1 under a Creative Commons Attribution 3.0 Unported License (CC BY 3.0).]

around how redox processes vary continuously over space and time in response to complex, intersecting gradients. For example, redox conditions and their associated biogeochemical reactions vary with water-level fluctuations and depend on the availability of geochemical reactants. Roots and microorganisms affect redox reactions by taking up water and solutes, exuding organic compounds, and modifying soil properties (Zhang and Furman 2021). Soil particle size and organic matter content influence the redox response of soils and sediments to water fluctuations by regulating water flow and residence time within different-sized pore spaces (LaCroix et al. 2023).

In addition, lateral exchange of water between soils and tidal channels can introduce reactants and flush out reaction products (Fettrow et al. 2023). Plants and microbes introduce additional temporal variability (e.g., phenology and temperature response). For example, roots of some wetland plants develop aerenchyma (i.e., soft tissue with air spaces) that allows efficient seasonal transport of oxygen from the atmosphere into the roots to facilitate root respiration (Colmer 2003). Oxygen transport through aerenchyma can alter belowground redox dynamics by leaking O_2 out of the roots into the surrounding soil (Noyce et al. 2023). Thus, interconnected changes in vegetation, hydrology, and sedimentation propagate to belowground biogeochemical reactions that affect ecosystem productivity and feed back to the Earth system.

Nutrient Cycling

Soil redox conditions shape biogeochemical processes for carbon, nutrients, and other elements that influence ecosystem function. Nitrate reduction under anoxic conditions results in the gaseous loss of nitrogen (N) as nitrous oxide (N_2O) or N_2, which has the dual effect of removing excess nutrients from systems receiving nutrient-rich runoff while emitting a potent trace gas (N_2O; Ye et al. 1994). Plant uptake converts bioavailable nitrogen [i.e., ammonium (NH_4^+), nitrate (NO_3^-), and phosphorus [i.e., phosphate (PO_4^{3-})] into organic forms that remove excess nitrogen and phosphorus from continental runoff while providing long-term nutrient storage in soils (Howard-Williams 1985).

In coastal systems flooded by sulfate-rich seawater, sulfate reduction is an important microbial metabolic process and is coupled with organic matter decomposition. Sulfide is a product of sulfate reduction that can accumulate in porewaters and potentially lead to plant stress or mortality (Koch and Mendelssohn 1989), particularly in freshwater ecosystems that have low sulfide tolerance (LaFond-Hudson and Sulman 2023). Precipitation reactions with iron and other metals under flooded conditions can decrease porewater sulfide and its stress on plants, but metal–sulfide accumulation can lead to soil acidification and plant dieback under drought conditions (McKee et al. 2004).

Iron cycling is another redox-sensitive process with important implications for coastal ecosystems, particularly those that receive iron-rich sediments from terrestrial runoff (Shields et al. 2016; Yu et al. 2021; Ma et al. 2025). Iron oxyhydroxides form under oxidizing conditions that occur above the water table or on the surfaces of aerenchymatous roots that introduce oxygen into saturated soils. These minerals strongly bind organic matter, phosphate, and a suite of other constituents, potentially limiting their accessibility to plants and microorganisms. Reductive dissolution of iron oxyhydroxides (e.g., via anaerobic microbial respiration or sulfide attack under anoxic conditions) releases dissolved ferrous iron and sorbed constituents into solution. As such, iron cycling can exert significant control over soil carbon storage, anaerobic respiration pathways, nutrient solubility, and sulfide toxicity to plants in iron-rich coastal systems (Schoepfer et al. 2014; Yu et al. 2021).

Structure and Function of Microbial Communities

Microbial communities mediate most biogeochemical processes. The composition and function of microbial communities change in response to fluctuating environmental conditions or more persistent shifts in saturation, salinity, and plant community composition (Jackson and Vallaire 2009; Morrissey et al. 2014; Barreto et al. 2018; Zhang et al. 2021). Salinity strongly controls microbial community composition and the abundance of different functional genes related to carbon- and nitrogen-cycling pathways (Zhang et al. 2021).

The rooting structures of different vegetation types further shape soil microbial communities and their metabolic pathways by regulating the flow of oxygen and organic exudates into the subsurface (McKee et al. 1988; Holmer et al. 2002; Barreto et al. 2018), potentially altering belowground biogeochemical processes as dominant plant species shift across the landscape. However, the patterns and mechanisms of such shifts are poorly understood, and plant and microbial communities may exhibit asynchronous responses to changing environmental conditions. For example, plant biomass allocation can exhibit nonlinear responses to temperature changes due to decoupled warming effects on plant nitrogen demand and microbial production of plant-available nitrogen (Noyce et al. 2019). Additionally, saltwater intrusion may promote rapid microbial sulfate reduction that leads to sulfide toxicity for plants with low sulfide tolerance (Lamers et al. 2013; LaFond-Hudson and Sulman 2023).

Chapter 3

Coastal Vulnerabilities to Stressors and Disturbances

The location of coastal systems at the land–sea interface makes them vulnerable to stressors and disturbances from marine, atmospheric, and terrestrial realms (see Fig. 3.1, p. 20). While these overlapping factors affect coastal systems worldwide, southeastern U.S. coasts experience a high magnitude and high frequency of episodic, chronic, and compounding stressors and disturbances.

In this report, disturbances are defined as events that temporarily alter ecosystem processes (Borics et al. 2013). Stressors are continuous factors imposed on an ecosystem (see Appendix D: Glossary, p. 61).

This chapter highlights the unique and generalizable disturbances and stressors that may perturb southeastern coastal systems and evaluates the role of compounding disturbances and stressors in shaping coastal system structure and function.

3.1 Impacts of Stressors and Disturbances

Disturbances (e.g., storm surge) temporarily alter ecosystem processes or attributes (e.g., primary productivity) but occur infrequently enough to allow the system to recover to its previous state, except in the case of extreme disturbances that push the system over a certain impact threshold (i.e., a tipping point; Ward et al. 2020).

Frequently occurring disturbances (e.g., several hurricanes striking the same land area repeatedly) or continuous stressors [e.g., sea level rise (SLR)] can permanently shift the trajectory of the ecosystem, eventually leading to an ecosystem state change. Stressors and disturbances can compound one another—for example, SLR exacerbates storm flooding—and magnify their individual impact on the health, function, and future resilience of coastal ecosystems. The unique confluence of the inherent complexity of coastal systems with compounding disturbances and stressors challenges predictive understanding of how these systems will function or undergo state changes in response to shifts in the Earth system.

Key Points

- Coastal ecosystems of the southeastern United States experience a uniquely high frequency and magnitude of overlapping stressors and disturbances.
- Compounding stressors and disturbances can result in nonlinear responses that push ecosystems past tipping points.
- Ecosystem state changes impact the ability of coastal systems to provide natural resources and mitigate coastal hazards.
- Antecedent conditions can shape ecosystem response to new stressors or disturbance events.

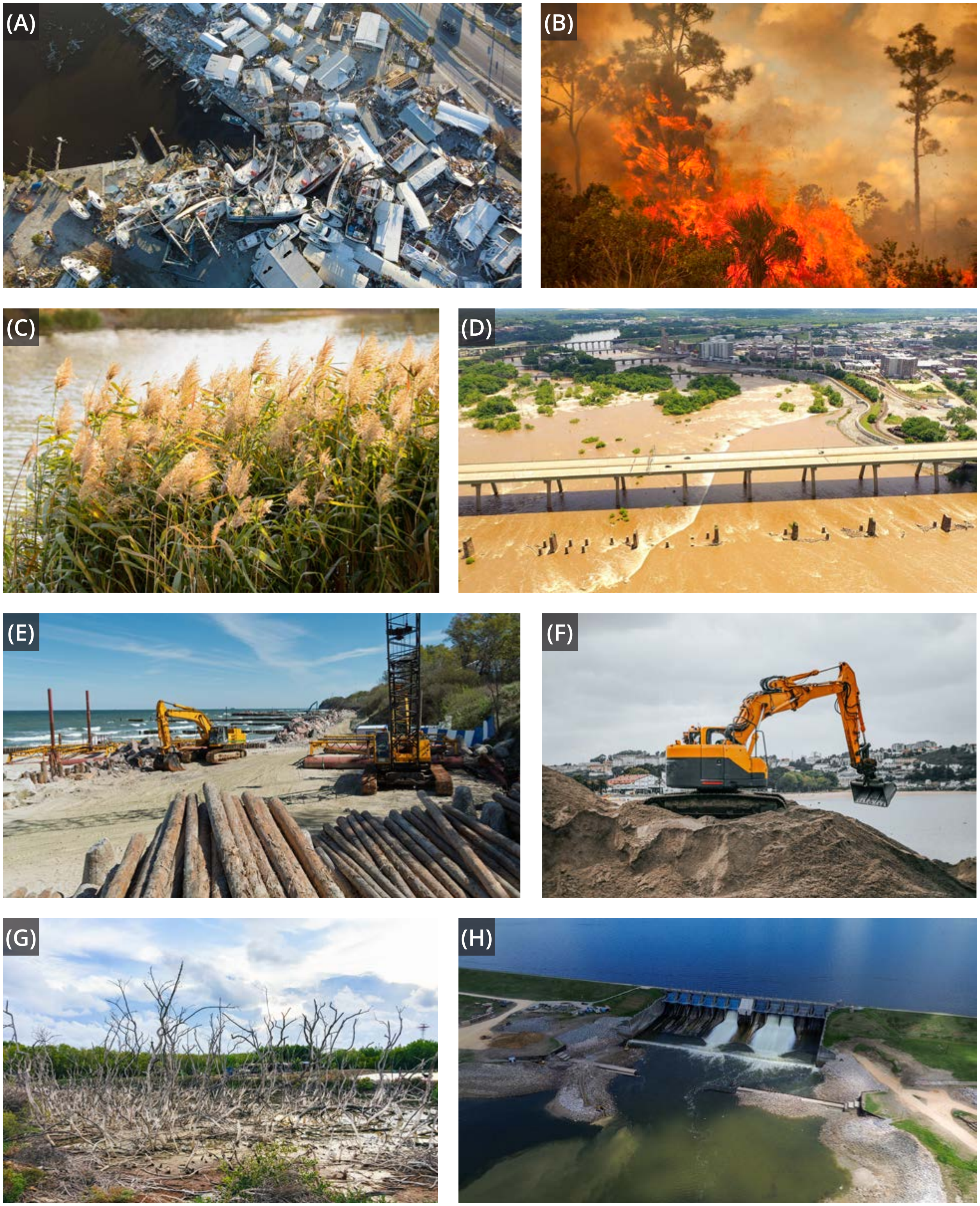


Fig. 3.1. Prominent Stressors and Disturbances in Southeastern Coastal Systems. (A) Damage from tropical storms, **(B)** fire, **(C)** invasive species (e.g., *Phragmites*), **(D)** flooding, **(E)** land-use change, **(F)** coastal engineering, **(G)** saltwater intrusion, and **(H)** hydrologic management. [(A), (C), (E), and (G) courtesy Adobe Stock; (B), (D), (F), and (H) courtesy Getty Images]

Table 3.1: Projected Coastal Ecosystem State Change and Associated Changes in Areal Annual Carbon Dioxide Equivalents in the Conterminous United States by 2100

Current Ecosystem State	Future Ecosystem State	Projected Land Area Change (km^2)	Projected CO_2-eq Change ($Mg\ CO_2eq\ km^{-2}\ y^{-1}$)
Upland herbaceous	Fresh tidal marsh	1,876	+1,301 (**)
Upland forest	Fresh tidal marsh	291	+1,809 (**)
Freshwater marsh	Saline tidal marsh	15,150	-650 (**)
Freshwater forest	Saline tidal marsh	11,184	-142 (**)
Upland herbaceous	Saline tidal marsh	10,463	+651 (**)
Upland forest	Saline tidal marsh	1,537	+1,159 (**)
Saline wetland	Water (seagrass)	4,618	-98 (*)
Saline wetland	Water (sediment)	13,854	-36 (*)

Projected changes in land area and carbon dioxide equivalent [megagrams (Mg) of CO_2-eq per km^2 (km^{-2}) per year (yr^{-1})] are for a scenario where sea level rises by 1.2 to 1.5 meters by 2100, an intermediate-high scenario consistent with a low-intermediate scenario for sea level rise by 2150.

Data from Osland et al. 2022a and Kirwan et al. 2023. Ecosystem types as defined in Osland et al. 2022a. Saline wetlands include both tidal marshes and tidal (i.e., mangrove) forests. Herbaceous includes upland agricultural crops, pasture, and grassland. No distinction is made between tidal and nontidal coastal wetlands.

***95% confidence interval that the actual value is within 100% of the estimate*

**95% confidence interval that the actual value is within or greater than 100% of the estimate*

Ecosystem state changes impact the ability of coastal systems to provide natural resources and mitigate coastal hazards. Marsh migration and coastal deforestation are particularly prominent state changes along the southeastern coastline (see Table 3.1, this page) driven by compounding effects of rising sea levels and extreme events.

Ecosystem migration has system-level impacts. For example, mangrove encroachment into brackish and saltmarshes has been accelerating along southeastern U.S. coasts with unclear consequences for soil organic matter, ecosystem carbon uptake and release, and resilience to storms and changes in relative sea level (Osland et al. 2022b; Kirwan et al. 2023). Recent evidence has shown that encroaching mangroves can increase organic matter density in soil and biomass (Simpson et al. 2019) and enhance storm surge protection potential (Menéndez et al. 2020). However, if vertical accretion cannot match the pace of rising sea level, inundation can result in peat collapse and the conversion of land to open water (Morris et al. 2023). Loss of mangroves and saltmarshes exposes adjacent brackish, oligohaline, and tidal freshwater systems to excess salinity that propagates effects of saltwater intrusion.

3.2 Marine Stressors and Disturbances

Sea Level Rise

The projected global increase in sea level is perhaps the most significant marine stressor on coastal environments. Averaged across the globe, sea levels have risen at a rate of around 1.5 mm per year since 1900 (Church and White 2011) and accelerated to over 3 mm per year more recently (Nerem et al. 2018; Dangendorf et al. 2019).

The South Atlantic and Gulf coasts have experienced substantially higher rates of SLR than the global average. Since 2010, tide gauge records for the region reveal a SLR rate of more than 10 mm per year, which has led to high-tide (i.e., nuisance) flooding in many areas not historically inundated (Dangendorf et al. 2023).

Relative SLR along the South Atlantic and Gulf coasts is exacerbated by decreasing ground elevation associated with subsidence (see Fig. 3.2, this page; Kolker et al. 2011; Ohenhen et al. 2024). A key factor driving subsidence along the Gulf Coast is downward movement of the continental plate due to the weight of river-derived sediments (Ivins et al. 2007). Subsurface fluid extraction (e.g., water, oil, and gas) and draining of wetlands also result in subsidence as soils become more compressed (McCall 2018).

The rapid rates of SLR experienced along the southeastern coast are virtually irreversible, requiring thousands of years to recover (Ehlert and Zickfeld 2018). This means SLR will be a continuous stressor on coastal systems for generations to come, regardless of human interventions.

Rising sea levels are projected to increase flooding frequency and saltwater intrusion in inland systems, affecting the frequency and duration of plant exposure to inundation and salinity. Without barriers, a primary outcome of these collective changes is inland migration of coastal wetlands (see Fig. 3.3, p. 23; Kirwan and Geden 2019; Osland et al. 2022a).

Marsh migration occurs as SLR submerges land and converts wetlands along the coastline to open water while creating favorable conditions for marshes further inland as non-wetland plants die off. As uplands transition to wetlands, changes in biogeochemical processes and carbon storage also occur (Smith and Kirwan 2021; Smith et al. 2023). Marsh migration occurs at the expense of other ecosystems but can be constrained by the built environment and land developments that occupy potential migration pathways.

Impacts of increased flooding and groundwater salinization on ecosystem migration and function are particularly critical to understand in the southeastern United States given the projected near-term impacts of SLR on coastal cities and communities (Ohenhen et al. 2024).

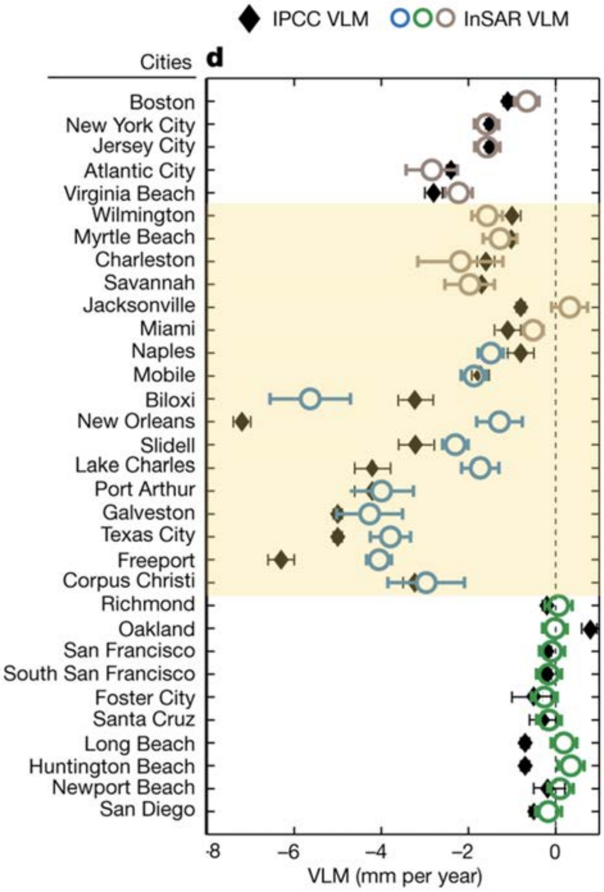


Fig. 3.2. Annual Rates of Vertical Land Motion in U.S. Cities Along the Atlantic, Gulf, and Pacific Coasts. The yellow shaded area encompasses cities on southeastern U.S. coasts, highlighting elevated rates of negative vertical land motion (VLM) in this region. VLM is the increase (positive VLM) or decrease (negative VLM) of ground elevation due to subsidence or uplift. Diamonds mark VLM derived from tide-gauge stations using the Intergovernmental Panel on Climate Change (IPCC) database. Colored circles mark VLM measured with interferometric synthetic aperture radar (InSAR). [Modified under a Creative Commons Attribution 4.0 International License (CC BY 4.0) from Ohenhen, L. O., et al. 2024. “Disappearing Cities on US Coasts,” *Nature* **627**, 108–15. DOI:10.1038/s41586-024-07038-3.]

Flooding

Episodic seawater flooding, usually driven by storm surge or extreme tides, is a major disturbance compounding the effects of chronic saltwater intrusion and soil salinization.

High-tide flooding has increased in frequency over the last several decades; South Atlantic and Gulf coasts

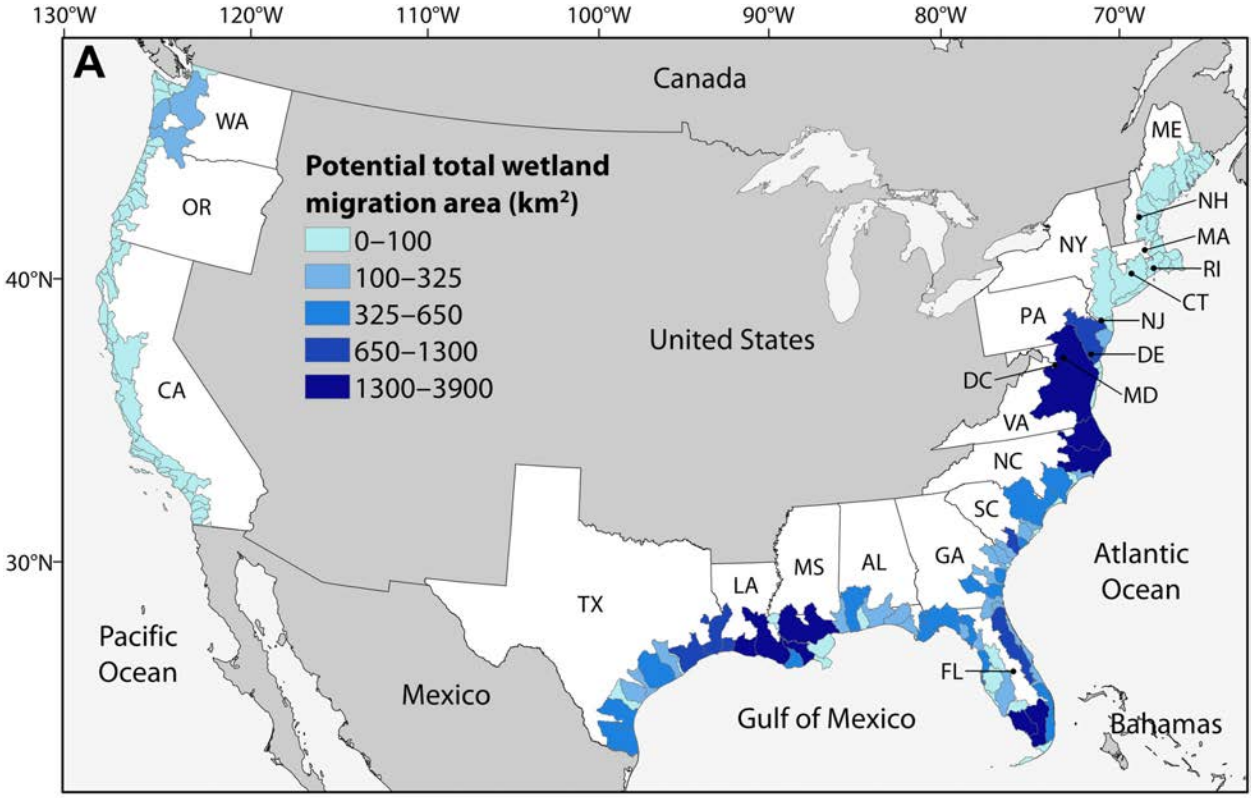


Fig. 3.3. Coastal Wetlands Migration. Projected landward migration of wetlands located within estuarine drainage areas across the conterminous United States by the year 2100 in response to 1.5-m global mean sea level rise (an intermediate-high scenario). Wetland migration refers to changes in the geographic distribution and areal coverage of wetlands. Six states within the Southeast (i.e., Louisiana, Florida, North Carolina, Texas, South Carolina, and Georgia) are expected to experience more wetland migration than any other states along U.S. coastlines. [Recreated under a Creative Commons Attribution 4.0 International License (CC BY 4.0) from Osland, M. J., et al. 2022. "Migration and Transformation of Coastal Wetlands in Response to Rising Seas," *Science Advances* **8**(26), eabo5174. DOI:10.1126/sciadv.abo5174.]

experience both greater frequency and acceleration of high-tide flooding relative to other U.S. coastlines (Sweet et al. 2018). For example, Charleston, S.C., averaged less than one day of high-tide flooding per year between 2000 and 2004 but averaged 12.8 days per year between 2019 and 2023 (Sweet et al. 2018).

The southeastern United States is also the region most vulnerable to storm surge from both tropical and extratropical (i.e., midlatitude) cyclones (Nederhoff et al. 2024). Storms can drive profound changes in biogeochemical fluxes and stocks over short time periods, such as those that occurred during Hurricane Harvey. Pre-storm conditions may return within days (Patrick et al. 2020), assuming permanent shifts in ecosystem structure and function do not occur. Other impacts of tropical cyclones (e.g., wind and rain) are discussed in the Extreme Weather section (see p. 25).

Salinization

Persistent salinization (associated with saltwater intrusion) and periodic salinization (associated with storm surges) cause die-off of freshwater forests and facilitate conversion to scrub–shrub and marsh systems (White et al. 2022). Excessive flooding and sulfate inputs associated with saltwater intrusion also increase porewater sulfide, which is toxic to wetland plant communities and leads to reduced plant productivity or even mortality (Koch and Mendelssohn 1989). Increases in flooding associated with changing sea levels and watershed runoff can further decrease oxygen transport into soils and increase stress on plant roots that require oxygen for respiration. In places where the living root network holds together organic soils, oxygen-limited soil conditions that develop during flooding can lead to plant mortality and increase carbon loss by marsh collapse (Chambers et al. 2019).

Ocean Warming and Acidification

Warming of the world's oceans will affect coastal habitats beyond the impacts of SLR, though the response of coastal ecosystems to warming surface waters remains poorly quantified (Valiela et al. 2023), particularly in the southeastern United States.

Gulf waters have warmed at a rate of around 0.19°C per decade over the last 50 years—roughly double the rate of warming in the global ocean (Wang et al. 2023)—whereas water temperatures along the South Atlantic Coast have in some cases cooled (Lima and Wethey 2012). Coastal systems will experience both top-down and bottom-up warming—from the top down via atmospheric temperature increases and from the bottom up (e.g., soil column) via warming water temperatures.

Experimental studies in the mid-Atlantic have explored the impact of such whole-system warming on wetland productivity, which can greatly alter plant productivity and both elemental and nutrient cycling (e.g., increased methane fluxes; Noyce and Megonigal 2021). For example, moderate above- and belowground warming has been shown to increase resilience of marsh systems in the mid-Atlantic by enhancing root growth, belowground carbon accumulation, and elevation gain, whereas higher temperatures (more than 1.7°C above ambient) cause elevation loss and increased carbon decomposition (Smith et al. 2022).

Ocean acidification has resulted in around a 0.1 decrease in global ocean pH during the 21st century (Orr et al. 2005). Similar levels of acidification have been observed in coastal systems of the southeastern United States that receive seawater inputs (Osborne et al. 2022). Ecosystem response to acidification may vary among systems with different underlying lithology. Karstic carbonate dominates the Florida landscape and extends along much of the South Atlantic (Doctor et al. 2020). Acidification could speed up karst weathering, but the topic has not garnered much attention outside of populated areas with high risk of infrastructure loss (Morton 2003). Many other coastal wetlands naturally experience high variability in subsurface pH over the course of both seasons and tidal cycles; they may be relatively resistant to acidifying conditions (Baumann et al. 2014) compared to surface water habitats that support calcifying organisms.

3.3 Atmospheric Stressors and Disturbance

Atmospheric stressors and disturbances related to temperature, precipitation, and extreme weather events are critical but poorly understood drivers of ecosystem processes in the coastal region of the southeastern United States.

Temperature

Changing temperature patterns, including increases in annual average air temperature and temperature variability (i.e., thermal extremes), are superimposed on a broad range of temperature regimes spanning from subtropical in southern Florida to highly seasonal further north.

Annual average air temperatures in the Southeast have steadily increased since the 1970s; the last decade is the hottest on record (Vose et al. 2017). Increased annual average temperature stems from higher daily minimum temperatures and warmer spring and fall temperatures (Vose et al. 2017; Carter et al. 2018). For example, the freeze-free period was nearly 2 weeks longer in the 2010s than any previous decade (IPCC 2023).

The minimum temperature and number of freezing days play important roles in mediating vegetation distributions. The southeastern coastal plain falls along a unique ecological position where the northern range of tropical coastal wetland species (e.g., mangroves) intersects the southern range of temperate coastal wetland species (e.g., saltmarsh grasses). Mangroves are freeze sensitive, and thus the severity of low winter temperatures dictates the northern limit of mangrove survival. The poleward migration of mangroves into formerly saltmarsh environments has been attributed to the long-term trend of increasing minimum temperatures and decreasing number of freeze days (Osland et al. 2020b).

The southeastern coastal region is also subject to infrequent but potentially devastating thermal extremes (i.e., heat waves and deep freeze events). According to recent Earth system models, the number and intensity of heat waves is projected to increase, whereas the number of extreme cold events is projected to decrease (Vose et al. 2017). While increased heat waves may not directly affect mangroves, infrequent but extreme freeze events can cause widespread mangrove die-off (Cohen et al. 2018) and limit the northern expansion of black mangroves (Osland et al. 2020a).

Precipitation

The frequency and intensity of extreme precipitation events are increasing in the Southeast (Easterling et al. 2017). Since the 1990s, the number of extreme rainfall events has reached historic highs (Kunkel et al. 2010). Extreme rainfall events can result in coastal and inland flooding that threatens human life, energy infrastructure, and ecosystems.

Freshwater flooding effects on coastal systems vary. The influx of freshwater can flush ecosystem porewater and eliminate hypersaline conditions that stress vegetation (Cahoon 2006). Conversely, the prolonged saturated conditions resulting from extreme flooding can cause hydrologic stress on vegetation, leading to mortality and changes in ecosystem structure that depend on flood duration (Gabler et al. 2017; Stagg et al. 2020, 2021).

Precipitation events also have contrasting effects on ecosystem topography. Heavy rain can mobilize and transport sediment to coastal systems, which may prove an important source of sediment for vertical land accretion and corresponding resilience to changing sea levels (Cahoon 2015). However, extreme rain may also erode sediment from coastal wetlands into the nearshore ocean (Cahoon 2006).

Conversely, drought is caused by a prolonged lack of precipitation. Drought frequency and intensity are projected to increase in the future (Wehner et al. 2017; IPCC 2023). Drought drives widespread hydrologic changes including surface water and groundwater drawdown, reduced river flows, and decreased soil moisture. In coastal systems, drought has been linked to marsh dieback due to decreased freshwater inflows that result in elevated salinity from evapoconcentration and acidification from sulfide oxidation (McKee et al. 2004; Silliman et al. 2005; Hughes et al. 2012; McDowell et al. 2022). Drought also drives saltwater intrusion into surface and subsurface water reservoirs, affecting groundwate r-dependent ecosystems and freshwater resources (Whitehead et al. 2009; Michael et al. 2017; Tully et al. 2019).

Extreme Weather

High winds associated with hurricanes and tropical storms present another atmospheric disturbance to coastal systems. Nearly all tropical storms hitting the United States either directly or indirectly impact a southeastern coastline. For example, all 10 hurricanes (five at Category 3 or higher) that made landfall in the United States between 2020 and 2023 hit a southeastern coastline (NOAA 2025d).

Tropical storm trends are variable, but models point to long-term increases in storm-associated wind speeds (Kossin et al. 2017). While coastal vegetation is often touted as coastal protection from storms and may minimize wind damage to infrastructure (Farber 1987), high winds can also be detrimental to vegetation through defoliation, stem breakage, or windthrow (Doyle et al. 1995; Morton and Barras 2011; Taillie et al. 2020). High winds and waves that flatten plants can also cause significant deposition, erosion, and sediment redistribution that can alter ecosystem structure and function depending on the resilience of specific plant communities (Platt et al. 2014).

3.4 Terrestrial Stressors and Disturbances

Terrestrial stressors and disturbances occur throughout watersheds that drain into coastal environments.

Alteration of freshwater hydrology, development and urbanization, fire (i.e., natural wildfire and prescribed burning), invasive species, agriculture (e.g., ranching), and other landscape changes are prevalent in the southeastern coastal regions.

These factors influence the fate and transport of water and waterborne materials (e.g., sediments and solutes) from headwaters to the coast, with impacts on coastal ecosystems. For example, nitrogen loading from agricultural runoff increases overall saltmarsh productivity but reduces root-to-shoot ratios (Morris and Sundberg 2024), reducing soil shear strength and increasing marsh susceptibility to forces such as storm surge (Pennings et al. 2021; Jafari et al. 2024).

Freshwater Use and Flow

The delivery of freshwater from watershed uplands to coastal systems impacts their salinity along with the delivery of nutrients and sediments. High riverine and groundwater discharge can freshen coastal ecosystems and alter salinity gradients by pushing saltwater further seaward. Freshwater also carries sediment and nutrients derived from continental runoff and delivers them to coastal systems where they can be transformed, stored, and/or exported into the ocean. Decreases in salinity and increases in sediment and nutrient loading associated with riverine inputs have complex and uncertain effects on ecosystem structure and function. Plant productivity can increase in response to lower salinity and higher nutrient availability, facilitating sediment deposition and increased ground elevation, but vegetation can correspondingly become less tolerant to periodic pulses of high salinity (Elsey-Quirk et al. 2019).

Conversely, low freshwater discharge to coastal ecosystems during drought facilitates saltwater intrusion and leads to salinization of freshwater resources used by plants, municipalities, and industry. Saltwater intrusion up the Mississippi River during low river discharge is a long-term reoccurring issue that has necessitated construction of underwater sills to prevent upstream migration of the saltwater wedge (Soileau et al. 1990; Fagerburg and Alexander 1994). Saltwater intrusion into coastal ecosystems during drought can lead to extensive plant mortality that is exacerbated by longer-term increases in flooding (Elsey-Quirk et al. 2024).

Watershed hydrologic cycles are heavily influenced by weather and other longer-term environmental drivers and events, from local hurricanes that are projected to increase in severity and frequency, to regional droughts, and to global water cycles such as those associated with the El Niño–Southern Oscillation. Hurricane Helene is one example of a major disaster that had moderate direct impacts along the Gulf Coast but brought extreme rainfall and landslides to the headwaters of several coastal watersheds, leading to flooding and sediment deposition downstream.

Direct alterations to watershed hydrology include water use for agriculture, recreation, energy, and drinking and construction of engineered structures such as impoundments, levees, and channels. These water withdrawals and redistribution efforts have significant impacts to southeastern coasts. For example, the hydrology, water budget, and flow regime in South Florida have been drastically altered by engineered channelization for flood protection and land development, diverting water away from historic flow paths. These alterations have reduced natural freshwater flow to Florida Bay, exacerbated episodic droughts, and contributed to ecological degradation in extensive coastal ecosystems.

Land Use and Land Cover

Land-use and land-cover change (LULCC) in the Southeast occurs at higher rates than in many other regions of the country (Homer et al. 2020). Commercial forestry of softwoods (e.g., loblolly pine) is a prominent land use in the region and is associated with regular forest harvest and regrowth (Napton et al. 2010). Forestry has increased in importance and led to afforestation of agricultural lands over the last several decades (Napton et al. 2010).

Although forest expansion increases carbon uptake and storage in biomass, sequestration rates could decline as forests age and are replaced by developed land (Zhao et al. 2013). In addition to LULCC, deforestation associated with rising sea levels and storms has led to net

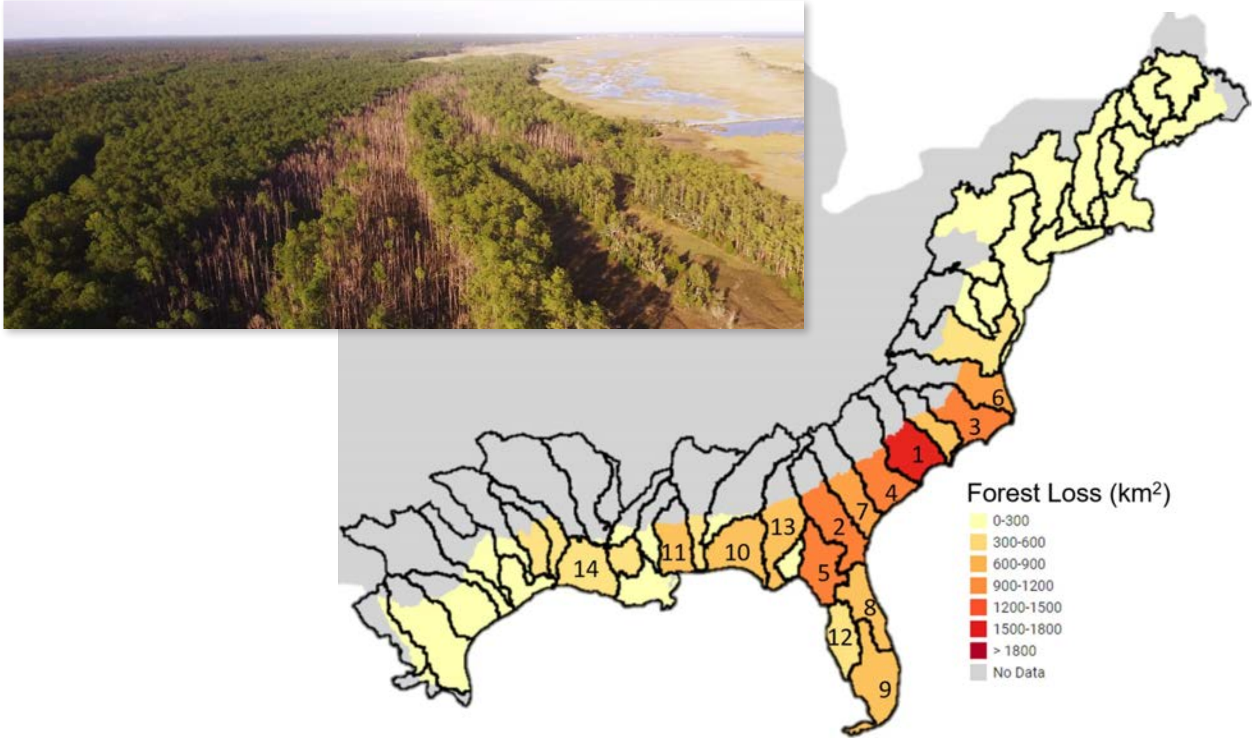


Fig. 3.4. Forest Loss in the Coastal Plain. Forest loss in South Carolina driven by compounding effects of hurricane damage and insect pests **(left)**. Map of forest loss in coastal watersheds (subregional size associated with four-digit Hydrologic Unit Codes) along the Atlantic and Gulf coasts **(right)**. [Photograph courtesy Tom O'Halloran, Clemson University. Map reprinted with permission from Springer Nature from White, E. E., et al. 2022. "Climate Change Driving Widespread Loss of Forested Wetlands Throughout the American Coastal Plain," *Ecosystems* **25**, 812–27. DOI:10.1007/s10021-021-00686-w. Copyright © 2021, The Author(s), under exclusive license to Springer Science Business Media, LLC, part of Springer Nature.]

forest loss in the coastal plain (see Fig. 3.4, this page; White et al. 2022). Deforestation resulting from urban development or other disturbance can destabilize soils, leading to erosion and sediment transport, and alter stream solutes by decreasing nutrient uptake by plants (Nagy et al. 2011; Chambers et al. 2016).

Land Development

The Southeast is also experiencing high rates of urbanization and expansion of developed land (Homer et al. 2020) driven by substantial population growth (U.S. Census Bureau 2023). Land development associated with (sub)urban expansion leads to increases in impervious surface areas, surface and subsurface flow through concrete channels and pipes, and local air temperatures (e.g., "heat island" effect). Expansion also introduces distributed and point sources for contaminants (e.g., sewer pipes, fertilizer, roads, and other infrastructure), among other changes.

Development may also lead to widespread wetland drainage and construction on nontidal wetlands that have variable state-level protections (Gold 2024), as well as other environments such as dunes, barrier islands, and hardwood hammocks. These landscape alterations alter the quantity and composition of material flowing through watersheds toward the coast and can degrade coastal ecosystems by distorting delivery of water, sediment, nutrients, and toxicants.

The effects of altered watershed-scale material transport to the coast are compounded by direct modifications to the coastline. Development along coastlines can lead to erosion and contribute to land degradation and loss (Morton 2003). Vegetation such as mangroves and saltmarshes can stabilize sediment and mitigate the effects of intense seaward storms, but their removal increases vulnerability of coastal environments to storm surge and wind damage. Engineered features associated with shoreline hardening (e.g., seawalls and bulkheads) disrupt sand and sediment exchange along coastlines and can limit inland marsh migration with SLR and increase erosion on adjacent beaches.

Fire

While fire impacts nearly every terrestrial ecosystem, the large extent and high frequency of its occurrence throughout the Southeast is unique, giving rise to a range of fire-adapted traits and processes in the region. Prescribed burning is a common management approach in forests and coastal wetlands for preventing wildfires, combating invasive species, and maintaining important habitats.

The Southeast accounts for the majority of all federally prescribed burns in the United States even though federally managed lands in the Southeast are less extensive than in the West (Mitchell et al. 2014; Melvin 2020; Cummins et al. 2023). Additional prescribed burns occur on private land used for recreation and hunting (Cummins et al. 2023). The total prescribed burn area in the Southeast can even exceed areas burned by wildfires in the rest of the United States (Mitchell et al. 2014).

These prescribed burns tend to be highly concentrated, particularly in counties within coastal watersheds of Florida, Georgia, and Alabama, and reoccur on time intervals that vary by ecosystem type. Although the majority of burned area in the Southeast results from prescribed fires, the region also experiences the highest number of wildfires in the United States (Brey et al. 2018). These wildfires are small relative to those in the West, but they are widely dispersed and typically ignited by humans, not lightning (Mitchener and Parker 2013; Brey et al. 2018). Drought induced by long-term changes in the environment is likely to increase the frequency and severity of wildfires while making it more difficult to implement prescribed burns. Increases in wildfire severity and burn area can impact ecosystem carbon stocks and pose substantial risk to human communities (Mitchell et al. 2014).

Alterations in fire regimes are broadly important to southeastern U.S. coastal systems given that fire suppression and decreases in prescribed burns (1) lead to mesophication of forested ecosystems (i.e., increase in dominance of species preferring wetter conditions; Nowacki and Abrams 2008); (2) enable proliferation of invasive species such as *Phragmites* (e.g., common reed), *Fallopia* (e.g., Japanese knotweed), and *Vitex* (e.g., beach vitex) that frequently colonize areas of high disturbance; and (3) result in an overall decrease in biodiversity in fire-adapted systems (Mitchell et al. 2014). Few studies have focused on mesophication of fire-adapted forests and the interaction of this process with other stressors in the Southeast. Reduced fire frequency can result in a change of understory species composition instead of overgrowth of existing species (Nowacki and Abrams 2008), which can lead to full structural change of the ecosystem.

3.5 Compounding Effects of Multiple Stressors and Disturbances

Although marine, atmospheric, and terrestrial stressors and disturbances (see Fig. 3.5, p. 29) affect coastal systems individually, the coincident timing of events or pressures may catalyze additional, nonlinear ecosystem shifts that can push the system beyond tipping points that limit or prevent recovery. These compounding effects are not unique to the southeastern coast; however, this region is more vulnerable to certain overlapping stressors and disturbances than other U.S. coastal regions.

Antecedent conditions are particularly important for mediating ecosystem response to new stressors or disturbance events (see Fig. 3.6, p. 30). Ecosystems that have already been stressed to some extent prior to a disturbance are more likely to transition to a new ecosystem state, whereas less-stressed ecosystems are likely to resist or recover from the disturbance (Johnstone et al. 2016).

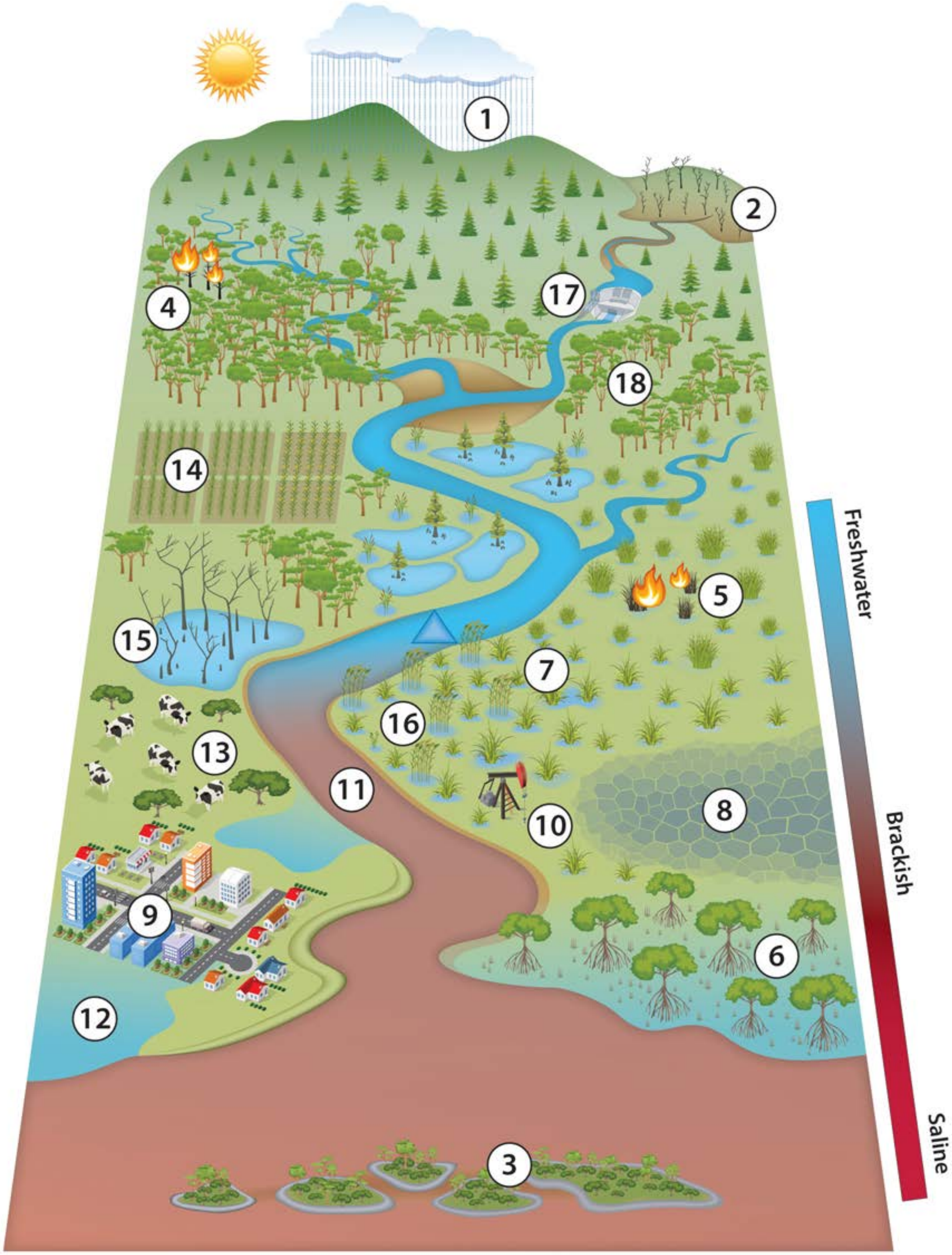


Fig. 3.5. Stressors and Disturbances in Southeastern U.S. Coastal Systems. This conceptual representation of stressors, disturbances, and their effects on coastal ecosystems includes **(1)** extreme precipitation, **(2)** drought, **(3)** shoreline hardening, **(4)** prescribed burns and **(5)** wildfires, **(6)** mangrove migration, **(7)** saltmarsh migration, **(8)** saltflat expansion, **(9)** urban development, **(10)** resource extraction, **(11)** saltwater intrusion, **(12)** flooding, **(13)** ranching, **(14)** agriculture, **(15)** salinization and ghost forests, **(16)** invasive species such as *Phragmites*, **(17)** impoundments, and **(18)** (de)forestation. The water shows a salinity gradient from saline (red) to freshwater (blue). In a disturbed coastal system, saline water has migrated farther upstream. The triangle represents the head of tide (i.e., the upstream limit of water affected by tide).

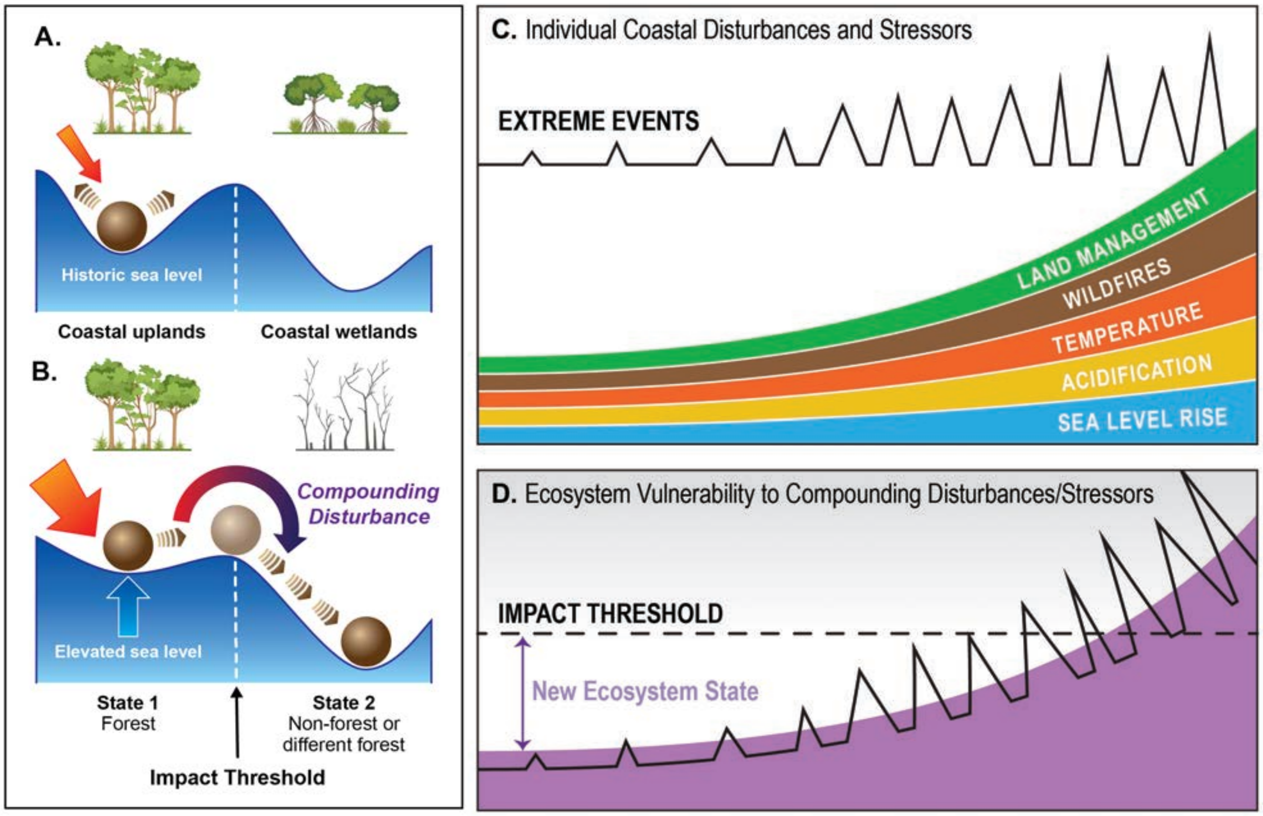


Fig. 3.6. Compounding Stressors and Disturbances Push Ecosystems to Tipping Points. (A) Ecosystems can experience stress and disturbances that do not push the system past an impact threshold that triggers a change in ecosystem state (e.g., conversion to marsh). **(B)** However, the compounding effect of various disturbances and stressors make a system more susceptible to state change, pushing the system over the impact threshold. **(C, D)** In line with the impact threshold concept, the cumulative effects of terrestrial, atmospheric, and marine stressors and disturbances increase the likelihood that an extreme event will result in ecosystem state change. [Left panel: Adapted with permission from John Wiley & Sons, Inc., from Johnstone, J. F., et al. 2016. "Changing Disturbance Regimes, Ecological Memory, and Forest Resilience," *Frontiers in Ecology and the Environment* **14**(7), 369–78. DOI:10.1002/fee.1311. © The Ecological Society of America. Right panel adapted under a Creative Commons Attribution 4.0 International License (CC BY 4.0) from Ward, N. D., et al. 2020. "Representing the Function and Sensitivity of Coastal Interfaces in Earth System Models," *Nature Communications* **11**, 2458. DOI:10.1038/s41467-020-16236-2.]

Aquifer salinization and forested wetland loss are two consequences of compounding stressors and disturbances that are important to southeastern coastal systems. Compounding disturbances such as these can both directly and indirectly impact coastal biogeochemistry. For example, carbon stored either above ground (e.g., vegetation) or below ground in soils can be rapidly lost as ecosystem structure changes. However, this disturbance-related carbon loss is not necessarily permanent. Additional stored carbon can be replaced by surviving ecosystems (e.g., a wetland replacing a forest) in less than a decade (Smith et al. 2023).

Example 1: Drought and Storm Surge Impact on Aquifer Salinization

Droughts are caused by a deficit in precipitation. Reduced aquifer recharge during drought periods lowers groundwater tables, surface water levels, and river discharge rates. Reduced freshwater availability due to drought poses a serious threat to vegetation and can cause plant stress and mortality in both fresh and saline ecosystems. When droughts coincide with storm surges or high-water events, threats to ecosystems and aquifers are amplified.

Storm surges drive overland saltwater flooding and saltwater intrusion (Cantelon et al. 2022), introducing saltwater into freshwater environments. Following a flooding event, saltwater infiltrates vertically into the subsurface, particularly through topographic depressions (Yu et al. 2016). The magnitude of saltwater infiltration is, in part, impacted by the depth of the unsaturated zone (i.e., the space between the groundwater table and the ground surface that can accommodate water). When drought lowers groundwater levels, there is more space for saltwater to infiltrate into the subsurface, increasing the volume of saltwater in the unconfined aquifer and decreasing water quality. Compounding effects of drought and storm surge can increase the extent and duration of saltwater intrusion and amplify ecosystem degradation, particularly in groundwater-dependent ecosystems. Given the sensitivity of coastal vegetation to saltwater, concurrent drought and storm surge events may catalyze vegetation die-off (Elsey-Quirk et al. 2024).

Notably, saltwater intrusion is also happening on longer timescales due to sea level change, which alters the hydraulic balance between land and sea. Even without surge events, droughts accelerate shifts in this balance and have the potential to enhance salinization of coastal aquifers and ecosystems. However, more work needs to be done to better understand the ecosystem ramifications of compounding atmospheric and marine stressors.

Example 2: Forested Wetland Loss After Repeated Stress and Disturbances

Along the North American Coastal Plain, rising sea level, frequency of tropical storm landfalls, and topography (slope and elevation) are the main drivers of coastal wetland deforestation (see Fig. 3.4, p. 27; White et al. 2022).

Coastal forest species are generally adapted to withstand some amount of variability in groundwater salinity and flooding associated with storms or extreme tides (Conner 1994). Deforestation occurs when vegetation can no longer recover from the combined effects of either (1) a stressor (e.g., SLR) and an extreme disturbance or (2) multiple extreme disturbances (Fagherazzi et al. 2019).

While mature trees may be capable of surviving one or several disturbances, the niche where juvenile trees can regenerate (Jackson et al. 2009) moves inland as a result of the combined effects of SLR and storm frequency (Fagherazzi et al. 2019). Mortality in mature trees occurs as coastal forests are increasingly exposed to salinity and hypoxic soil conditions associated with flooding (McDowell et al. 2022), ultimately leading to deforestation if regeneration cannot keep pace with loss.

The coastal region of the southeastern United States has among the most reported observations of coastal forest mortality in the world, rivaled only by the mid-Atlantic (McDowell et al. 2022), suggesting the Southeast is an ideal region to study this globally important phenomenon to further understand how compounding disturbances alter both ecosystem state and function.

Chapter 4

Critical Gaps in Knowledge, Data Availability, and Model Representation

Predictive understanding of the function and trajectory of southeastern coastal systems is limited by critical knowledge gaps in the (1) distribution and connectivity of coastal systems, (2) biogeochemical processes underlying ecosystem function, and (3) response to compounding stressors and disturbances (see Fig. 4.1, p. 34). Addressing these knowledge gaps—along with interconnected challenges in data and modeling—is key to predicting the occurrence and severity of coastal flooding, estimating the conversion of land to open water, establishing resources needed to support coastal economies, and buffering coastal communities and infrastructure against damage. Efforts to overcome these gaps will generate information and tools that can help develop solutions to these challenges.

Dedicated efforts to incorporate two-way interactions between modeling and experiments (a ModEx approach) can help address key gaps. Combining artificial intelligence and machine learning (AI/ML) with physics-based models and model-informed experiments and observations can improve quantification and predictive understanding of system attributes and process interactions, which in turn support multiscale modeling developments.

Key Points

- Stressors, disturbances, and hydro-biogeochemical processes interact to influence coastal ecosystems.
- Knowledge gaps in coastal systems are interconnected because the features of coastal systems are interconnected.
- Interactions among processes and their compounding effects are not well understood or well represented in models.

4.1 Distribution and Connectivity of Coastal Systems

Drivers and Consequences of Shifting Ecosystem Distributions

The southeastern coastal plain is a patchwork of ecosystem types, some unique to the region (e.g., mangroves) and some with greater areal coverage than in other regions across the continental United States (e.g., bottomland hardwood forests and saltmarshes). These ecosystems play different roles in global biogeochemical cycles and respond differently to regional stresses, such as current and projected changes in sea level, evolving patterns of storm frequency and intensity, and human-related pressures (Kirwan et al. 2025).

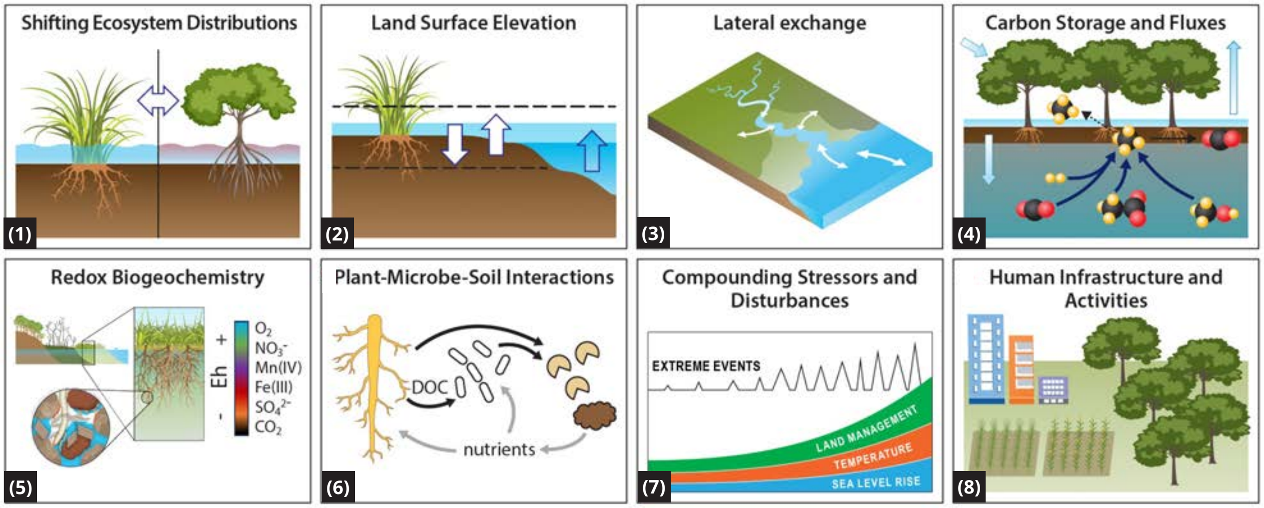


Fig. 4.1. Critical Gaps Limiting Predictive Understanding of Coastal Systems. Knowledge, data, and modeling gaps emerge in **(1)** drivers and consequences of shifting ecosystem distributions, **(2)** processes controlling land-surface elevation, **(3)** spatial heterogeneity in lateral exchange, **(4)** dynamic carbon storage and fluxes, **(5)** biogeochemical reduction–oxidation (electron–transfer) processes across gradients, **(6)** plant–microbe–soil interactions, **(7)** effects of legacy and compounding stressors and disturbances, and **(8)** impacts of human infrastructure and activities.

Key Research Questions

- How do vegetation and associated microbial communities respond to compounding stressors and disturbances, including inundation and salinity?
- What are the tipping points that cause ecosystems to collapse and/or be replaced by a different ecosystem?
- What are the possible trajectories of ecosystem transitions?

As a result of these stresses, the southeastern coastal plain is undergoing a geographic redistribution of ecosystems. Individual ecosystem types are gaining, losing, or shifting their position on the landscape (Kirwan and Gedan 2019). Ultimately, the coastline is receding as terrestrial ecosystems convert to wetlands and wetlands become submerged and transition to open water (see Fig. 4.2, p. 35).

These changes are driven by species-specific tolerances to temperature, salinity, and inundation that influence interspecific competition, vulnerability to other stressors (e.g., pest infestation), direct mortality, and the ability to maintain land-surface elevation relative to sea level (Spivak et al. 2019). Understanding how ecosystem distribution and function respond to environmental drivers will (1) improve predictions of land loss, flooding, storm damage, and saltwater intrusion and (2) inform solutions for addressing habitat preservation and water quality.

Anticipating changes in the distribution of species and related ecosystem functions requires greater knowledge of (1) how plant and microbial communities respond to changes in salinity, inundation, and other stressors and disturbances and (2) the timescales over which ecosystem transitions occur.

Determining the current distribution of different ecosystem types is an important first step toward

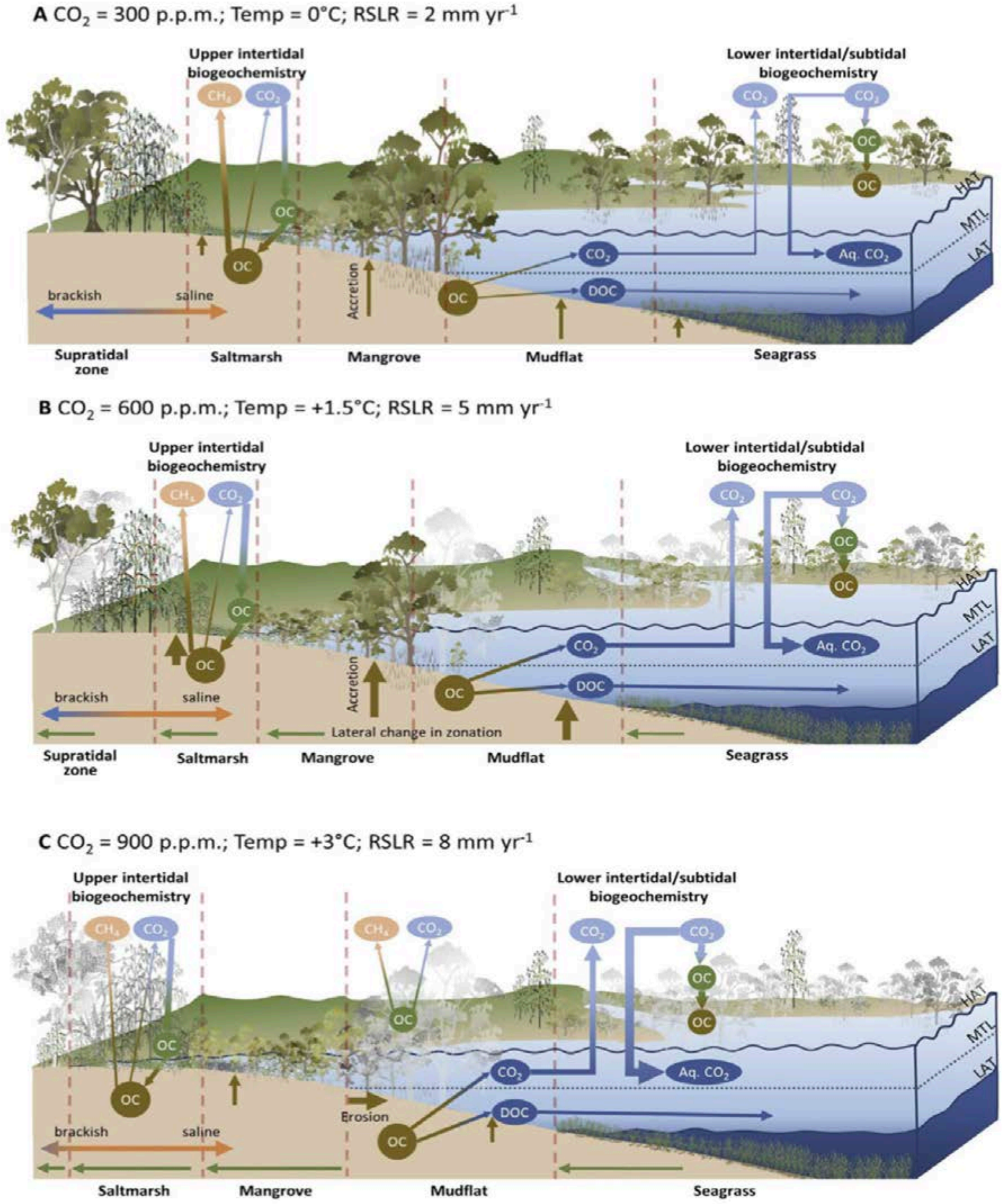


Fig. 4.2. Interacting Effects of Carbon Dioxide, Warming, and Relative Sea Level Rise. Predicted shifts in coastal vegetation and associated biogeochemical cycling of carbon vary under baseline, mid-level, and high-level emission scenarios. Under **(A)** the baseline scenario, carbon is fixed by *in situ* vegetation and contributes to soil carbon accumulation. Under **(B)** the mid-level emissions scenario, elevated atmospheric carbon dioxide strengthens organic carbon sequestration. Saline intrusion reduces methane emissions on the landward edge. Under **(C)** the high emissions scenario, coastal systems reach a tipping point where relative sea level rise exceeds vertical accretion, leading to vegetation mortality and shoreline retreat. [Recreated under a Creative Commons Attribution 4.0 International License (CC BY 4.0) from Rogers, K., et al. 2023. "The Present, Past and Future of Blue Carbon," *Cambridge Prisms: Coastal Futures* **1**, e30. DOI:10.10.1017/cft.2023.17.]

understanding drivers and consequences of future ecosystem change. Several ecosystems are underrepresented in global or regional land-cover maps (e.g., bottomland hardwood forest and tidal freshwater forested wetland). Spatial heterogeneity in ecosystem types and properties is a key challenge associated with generating these maps at scales needed for adequate coastal representation in global budgets and Earth system models (ESMs).

Some historical data exist on ecosystem distribution, but these datasets have limited use in predictive modeling because they often have coarse resolution and may have few measurements on drivers of change (e.g., soil properties and inundation extent and frequency).

Independent studies have examined the effects of changing environmental drivers (e.g., freezing, salinity, and inundation) on plant species composition and ecosystem function, but few attempts have been made to collate the information and evaluate complex interactions among drivers. Furthermore, only limited data are available on microbial community shifts in both composition and activity in response to perturbation. The mechanisms underlying ecosystem transitions and the timescales over which transitions occur need to be clarified to project the future functions of coastal ecosystems and their feedbacks to the atmosphere and oceans.

Data and Modeling Needs

Data on the function and structure of coastal ecosystems (e.g., photosynthesis, canopy structure and traits, and microbial communities and traits) are essential for model simulations of terrestrial carbon and water cycles but currently lacking. Additionally, spatially explicit datasets capturing key information on soil properties, including surface–subsurface salinity gradients, hydraulic parameters (e.g., soil water potential), and soil thermal and redox gradients are required to understand ecosystem distribution relative to environmental drivers. Spatially resolved datasets of these properties are also important for identifying key drivers of coastal gas fluxes (e.g., methane and nitrous oxide) and ecosystem transitions. Synthesizing and harmonizing existing but disparate data into model-ready datasets is a critical need to enable broader use and advances in predictive modeling capabilities (Wilkinson et al. 2016).

Modeling capabilities need to improve to advance predictive understanding of the processes driving shifting ecosystem distributions. Specific improvements include (1) developing plant functional types representative of coastal ecosystems (e.g., bottomland hardwood forest, tidal freshwater wetlands, mangroves, and graminoid and succulent saltmarsh); (2) including vegetation dynamics within modeling frameworks; (3) representing plant effects on gas transport [e.g., through air space tissue (i.e., aerenchyma)]; and (4) representing solute and sediment transport and their feedbacks on vegetation and biogeochemical processes. These model capabilities can also inform experiments targeting new knowledge generation.

Processes Controlling Land-Surface Elevation

Land-surface elevation relative to sea level and tidal ranges determines ecosystem exposure to flooding and salinity. Therefore, it is critical to develop a predictive understanding of land-surface elevation based on the interconnected processes driving elevation change: (1) fluxes of sediment, carbon, and nutrients through coastal systems; (2) organic matter accumulation or removal through decomposition; (3) the interaction of organic matter with minerals; and (4) net plant belowground productivity (Langley et al. 2009; Spivak et al. 2019). Particularly needed are efforts to understand the mechanisms driving peat collapse—the loss in structural integrity of highly organic soils and the subsequent decrease in land-surface elevation over several months to years (Chambers et al. 2019). Understanding of these factors' responses to diverse stressors and disturbances is needed to predict future states of coastal systems.

In addition to natural processes, humans routinely modify elevation by building structures that affect the flow of water and sediment. While models predicting inundation sometimes include levees and other structures, a better large-scale understanding of how human infrastructure affects sediment transport

Key Research Questions

- How do natural and human-relevant disturbances contribute to sediment accumulation, loss, and redistribution across coastal ecosystems?
- What are the drivers and consequences of peat collapse in coastal organic soils?
- What processes determine where and to what extent elevation change will keep pace with projected increases in sea level?

and deposition is needed. Interactions among water and sediment flow processes ultimately determine land-surface elevation change and how resilient ecosystem and biogeochemical processes are to future sea levels.

Data and Modeling Needs

Efforts to characterize and model the processes affecting elevation change are limited by the difficulty in accurately quantifying land-surface elevation across the low-gradient southeastern coastal plain.

The high spatiotemporal heterogeneity of sediment redistribution caused by moderate to extreme storm events contributes to data sparsity and poses additional challenges in model representation.

Frequently updated digital elevation models with centimeter-scale resolution are necessary to evaluate changes in land-surface elevation and enable assimilation into models. In addition, base data layers [e.g., maps of subsidence rate, relative rates of sea level rise (SLR), and microtopography] are needed for both direct model input and for upscaling processes from local to regional scales. To further develop a fundamental understanding of controls on land-surface elevation and to parameterize models, additional data are needed on heterogeneity in water residence time, subsurface properties (e.g., soil types and hydraulic parameters), and surface–subsurface salinity gradients.

Spatial Heterogeneity in Lateral Exchange

Coastal boundaries are not explicitly represented in current ESMs because of challenges in representing lateral fluxes of water, sediment, and solutes within and between diverse ecosystems such as those present in the southeastern United States. Lateral exchange is very poorly understood, partly because these fluxes are difficult to accurately quantify.

Material can be mobilized from watershed uplands and transported into the coastal plains, exchanged between terrestrial and aquatic components, transformed during storage or transport, and exported from coastal ecosystems into the atmosphere or ocean. Interactions among ecosystem properties (e.g., soil and vegetation) and storage, transport, and export of materials need to be characterized.

The southeastern United States experiences unique hydrologic drivers that influence lateral exchange. For example, low elevation gradients allow flooding to redistribute water across large areas. In addition, wind drives hydrologic redistribution in microtidal areas along the Gulf Coast, interacting with river stage, sea level, and tides to influence inundation depth and extent. Better understanding of how these hydrologic drivers interact with ecosystem properties to regulate lateral fluxes is needed to predict, for example, land-elevation change and flooding, saltwater intrusion and

Key Research Questions

- To what extent are coastal ecosystems shaped by upland processes in their contributing watersheds?
- How are sediment, solutes, and gases transported laterally between ecosystems and exchanged between terrestrial and aquatic ecosystems, both inland freshwater and marine?
- How are transported materials transformed along their flow paths?

salinization of soil and water resources, and contaminant transport during flooding (e.g., dispersal of sewage, industrial chemicals, and agricultural runoff).

Data and Modeling Needs

In contrast to available carbon stock data, both vertical (e.g., burial and soil gas emissions) and lateral (e.g., total alkalinity and dissolved and particulate carbon) carbon fluxes in coastal wetlands have been widely overlooked (Reithmaier et al. 2023; Rosentreter et al. 2023).

Measuring and modeling these fluxes requires improved understanding of surface and subsurface water flows, which itself requires high-resolution spatiotemporal measurements of subsurface properties and atmospheric drivers (e.g., precipitation, temperature, relative humidity, and winds). To fully characterize lateral fluxes, water flow estimates need to be coupled with understanding of biogeochemical processes driving carbon dynamics, a critical knowledge gap discussed in the next section (see Section 4.2: Biogeochemical Processes Underlying Ecosystem Function, this page).

Quantifying lateral fluxes is challenging because of their high level of heterogeneity in space and time. For example, carbon fluxes in mangrove ecosystems (e.g., soil organic carbon sequestration, litterfall, and fine root productivity) differ among coastal systems (Breithaupt and Steinmuller 2022; Arnaud et al. 2023; Adame et al. 2024), emphasizing the need to obtain flux parameters across a range of environmental conditions. Fluxes are also difficult and expensive to measure. Available flux data often represent large areas, limiting the ability to attribute them to any one ecosystem type or component. Inexpensive mass balance estimation techniques do exist, but their accuracy in determining lateral fluxes is not known. New methods to measure and model lateral fluxes of water, solutes, and sediments would enable more accurate datasets and better model representation and insight into underlying processes. For example, fluxes of dissolved organic carbon and dissolved inorganic carbon need to be quantified across terrestrial–aquatic interfaces.

In addition to challenges obtaining accurate flux data, predictions about water and solute flow across a range of scales are limited by a rudimentary representation of coastal boundary conditions within models.

Limited observations of lateral transport and simplified approximations of the coastal boundary slow the development of a mechanistic understanding of interactions among fluvial, pluvial, and marine fluxes. Appropriate representations of inland boundaries and flow propagation through river networks are needed to accurately represent the coastal interface. However, ESMs, such as DOE's Energy Exascale Earth System Model (E3SM), do not explicitly represent the subgrid connectivity necessary to capture exchanges along both inland and coastal boundaries. Recent developments have started to represent the effects of subgrid macrotopographic features on water flow (Jan et al. 2018). However, these advances are still not refined enough to capture coastal connectivity and redistribution of water, sediment, and nutrients at the fine scales required to evaluate biogeochemical transformations.

4.2 Biogeochemical Processes Underlying Ecosystem Function

Dynamic Carbon Storage and Fluxes

Associated with an improved understanding of ecosystem distribution, connectivity, and transition is the need to quantify the current and future effects of various ecosystems on globally relevant processes, such as carbon storage. The southeastern coastal plain contains highly productive ecosystems that benefit from abundant water and nutrients paired with warm temperatures and long growing seasons (Feagin et al. 2020). In coastal wetlands, high plant productivity is complemented by comparatively slow rates of decomposition as a result of oxygen limitation and the accompanying lower energetic potentials.

Carbon storage is further enhanced in depositional environments where minerals interact with soil organic matter, further reducing carbon's accessibility to degradation (Spivak et al. 2019). Conversely, mortality caused by invasive pests, fire, inundation, drought, and saltwater intrusion reduces photosynthetic carbon uptake and decreases carbon stock (Li et al. 2022).

Key Research Questions

- What are the magnitudes of key functions (e.g., carbon storage and fluxes) associated with major ecosystems?
- How do key functions change with ecosystem disturbance and transitions?
- How do aboveground and belowground processes interact to control carbon dynamics across environmental gradients relevant to the southeastern United States?
- How do methane fluxes and methanogenesis pathways vary across environmental gradients and respond to shifting drivers?

Many coastal ecosystems store a large amount of carbon in plant biomass and soils but also emit high quantities of methane, a potent gas produced under the anoxic conditions typical of wetlands. Methane production is influenced by environmental conditions (e.g., temperature, pH, oxygen availability, and water elevation) and can be limited by substrate competition with microorganisms performing more energy-yielding metabolisms (e.g., sulfate and iron reduction; Arias-Ortiz et al. 2024). Methane fluxes to the atmosphere are modulated by additional factors including consumption by methanotrophs in oxidizing surface layers, ebullition, and plant-mediated transport (Villa et al. 2020). The complexity of the processes responsible for methane production, consumption, and fluxes has challenged attempts to upscale methane cycling across broad regions. Links between methane production and fluxes and ecosystem types remain unclear.

Data and Modeling Needs

Accurate and verifiable quantification of plant and soil carbon stocks and exchange rates across coastal systems is still lacking, as is an understanding of how these carbon stocks interact with other biogeochemical cycles and respond to disturbance. Overall, effects of increasing salinity and inundation on processes controlling net carbon balances need to be understood at scales spanning saline to freshwater zones (Kirwan et al. 2023). Efforts to quantify carbon budgets and their controlling processes are needed to predict changes in land-surface elevation and associated vulnerability of ecosystems to flooding and saltwater intrusion.

Generating predictive understanding of carbon and methane storage requires improving quantification of key parameters across the southeastern coastal plain. For example, data on vertical and lateral carbon fluxes are needed to estimate carbon storage; that information is both spatially and temporally scarce across different coastal systems in the southeastern United States (Reithmaier et al. 2023; Rosentreter et al. 2023).

Although carbon flux measurements are indispensable to estimating carbon uptake and long-term removal, determining key ecological and geomorphic controls on carbon dynamics is still necessary (Kirwan et al. 2023). Incomplete understanding of these controls limits both the upscaling of process-based understanding to regional scales and incorporating these processes into ESMs. While carbon stocks and fluxes have been relatively better described in tidal saline wetlands, whether the general trends described in such systems apply to other tidally influenced upstream ecosystems has not been tested. Additionally, soil properties—including surface–subsurface salinity gradients, hydraulic parameters (e.g., soil water potential), and soil thermal and redox gradients—remain poorly characterized at the regional scale. These properties drive coastal cycling of important compounds (e.g., methane) and coastal ecosystem changes (e.g., formation of ghost forests), but spatially explicit datasets are still lacking.

Oxidation–Reduction (Electron–Transfer) Reactions Across Gradients

Coastal systems exist across gradients of saturation that create high spatial and temporal variability in soil oxidation–reduction (redox) conditions that affect

Key Research Questions

- How do biogeochemical parameters (e.g., soil and solute composition and gas fluxes) reflect redox patterns at scales that range from soil pores to landscapes?
- How are biogeochemical parameters shaped by, and how do they influence, interactions among vegetation, microbial communities, water flow, and sediment?
- How does variable saturation result in ecosystem processes that differ from those in relatively stable redox systems?

plant mortality, gas releases, and nutrient and contaminant solubility.

While saturation in upland soils is typically limited to heavy rain events or isolated in small pores, wetlands flood and drain regularly in response to storm events, tides, and seasonal variability in riverine inputs. Variable inundation leads to dynamic redox conditions as oxygen is depleted during flooded periods and reintroduced as soils drain (Machado-Silva et al. 2024). SLR and saltwater intrusion increase inundation and alter water chemistry, potentially driving long-term shifts in redox conditions that feed back to the entire affected system (see Fig. 4.3, p. 41; Herbert et al. 2015).

Additional geomorphic, hydrologic, and biological processes generate complex, interconnected effects on redox reactions that are not well resolved. Recent utilization of continuous sensors is improving understanding of how redox conditions in soils and sediment vary with hydrologic forcings (Wallace et al. 2019; Grande et al. 2022; Guimond et al. 2025) and in response to plant-mediated gas exchange (Noyce et al. 2023). However, the biogeochemical and hydrological processes underlying redox variability and connections to specific chemical reactions remain opaque. It is also necessary to investigate the complex, sometimes cryptic chemical reactions [e.g., via reactive oxygen species (Zhao et al. 2022)] that occur under a range of redox regimes and influence nutrient cycling and organic matter decomposition.

Data and Modeling Needs

Better information is needed on how redox gradients vary at different spatiotemporal scales, e.g., across soil pore networks and as a function of hydrologic flow paths, soil bulk density, and plant root structures. Evaluating redox potential and associated environmental parameters at a high spatiotemporal resolution is necessary to understand how redox biogeochemistry varies with soil properties and in response to drivers and disturbances.

Current methods to sample and analyze soil solutes cannot adequately capture the temporal variability associated with tides, necessitating new approaches for analyzing solutes at high temporal resolution, comparable to methods currently used for surface water.

ESMs currently represent redox conditions as binary—either oxic (unsaturated) or anoxic (saturated). However, rates of organic matter decomposition and carbon cycling are regulated by a full range of microbial metabolisms that overlap in space and time. Furthermore, redox conditions indirectly regulate nutrient and carbon bioavailability by promoting the formation or dissolution of minerals that bind and remove solutes from solution (e.g., sorption of organic matter and phosphate to iron oxides). Binary representations of redox conditions do not account for the gradient of biogeochemical reactions that occur along a "redox ladder," where oxygen and other terminal electron acceptors are progressively depleted.

Recent advances coupling the reactive transport model PFLOTRAN with E3SM provide a mechanism for incorporating redox processes into landscape-scale simulations (Sulman et al. 2024). However, additional development of critical biogeochemical processes (e.g., mineral dissolution and precipitation, sorption processes, and complex sulfur cycling) and vegetation dynamics [e.g., radial oxygen loss from plant roots (O'Meara et al. 2024)] is needed to be truly representative. A more complete understanding of

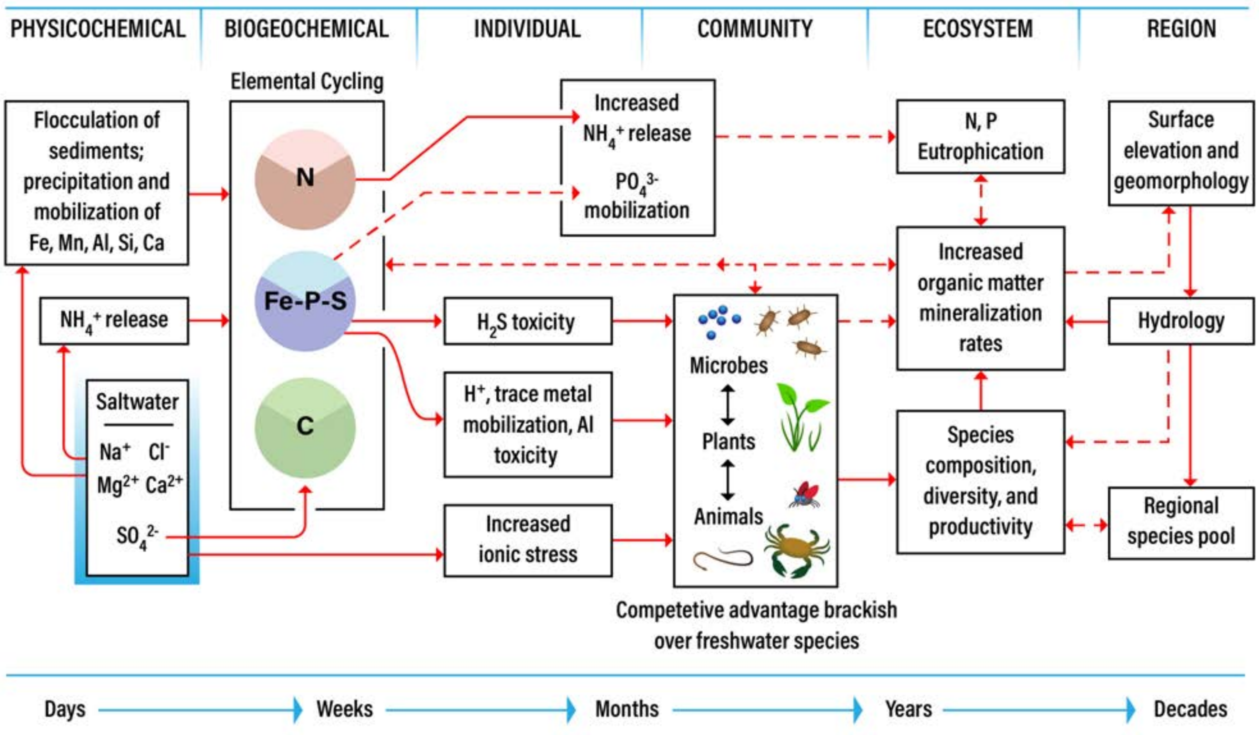


Fig. 4.3. Interconnected Effects of Flooding and Saltwater Intrusion on Biogeochemical Processes. Predicted ecosystem effects of inundation and salinization span physicochemical changes; the abiotic environment; and plant, microbe, and animal species. Solid arrows indicate pathways with a high level of scientific consensus on the direction and magnitude of change. Dashed arrows indicate pathways with limited data availability or scientific consensus. Iron (Fe), manganese (Mn), aluminum (Al), silicon (Si), calcium (Ca), sodium (Na), magnesium (Mg), chlorine (Cl), sulfate (SO_4^{2-}) , sulfide (H_2S) , ammonium (NH_4^+), and phosphate (PO_4^{3-}) are represented. Details of element cycling for carbon, nitrogen, and iron–phosphorous–sulfur (Fe–P–S) systems are provided in Fig. 2.2 (see p. 17). [Adapted from Herbert, E. R., et al. 2015. "A Global Perspective on Wetland Salinization: Ecological Consequences of a Growing Threat to Freshwater Wetlands," *Ecosphere* **6**(10), 1–43. DOI:10.1890/ES14-00534.1 under a Creative Commons Attribution 3.0 Unported License (CC BY 3.0)].

redox variability and redox-sensitive biogeochemical processes—complemented by model development—will enhance model integration of these processes and their response to environmental perturbation.

Plant–Microbe–Soil Interactions

Stressors and disturbances to coastal systems drive changes in plant and microbial community composition and function, which together regulate biogeochemical processes but may be decoupled (Yu et al. 2024). For example, microbial function (e.g., gene expression and protein production) is expected to respond to environmental change more quickly than community structure (e.g., community composition and gene abundance), but the recoverability and resilience of community structure and timescales of adaptation are unknown.

Plant and microbial communities are highly interactive, with plants influencing microbial community composition (Li et al. 2024). Despite their close relationship, plant and microbial communities may exhibit asynchronous responses to changing abiotic conditions that alter the landscape of biotic interactions. For example, microbial communities may respond to changing environmental conditions within one week to one month while plants exhibit a response time of greater than two years (Dang et al. 2018). Investigating

Key Research Questions

- How do microbial communities and functions differ across inundation and salinity gradients?
- What are the timescales over which plant and microbial communities respond to changing environmental conditions?
- How do asynchronous responses of plants and microbial communities to environmental change affect ecosystem function?
- How can information on microbial community structure and function be meaningfully incorporated into current or future model frameworks?

how interactions among plants, microbial communities, and their soil environment change in response to perturbation is necessary to elucidate impacts on ecosystem redistribution and nutrient storage and cycling.

Data and Modeling Needs

To further advance understanding of the role plant–soil–microbe interactions play in controlling biogeochemistry, more data are needed on how microbial community dynamics respond to (1) changes in environmental conditions (e.g., redox, salinity, and pH) and (2) plant community composition and activity. In particular, mechanisms determining the resilience and recoverability of plants and microbes to disturbances are understudied. Knowledge of disturbance effects on biogeochemical cycling and plant–microbe interactions is also insufficient. Understanding these mechanisms requires spatially explicit information on temperature, redox, and salinity gradients in soils in addition to temporally and spatially resolved data on microbial community structure and function and plant species distribution and activity.

Leveraging new knowledge to improve predictive models requires parallel model development. Current microbial models include both trait-based and metabolism-based models (Marschmann et al. 2024; Rubinstein et al. 2024). State-of-the-science model development is focused on improving model scalability and integrating trait- and metabolism-based models into ongoing multiscale modeling efforts. Additional needed improvements include capturing the effects of (1) biotic interactions within and across domains, (2) dominant versus rare metabolisms, and (3) spatial and temporal dynamics in microbial communities. Using neural networks, including long short-term memory, to develop and evaluate surrogate models is a promising strategy to reduce computational costs and improve representation of microbial processes in large-scale models.

4.3 Ecosystem Response to Compounding Stressors and Disturbances

Effects of Legacy and Compounding Stressors and Disturbances

Flooding and saltwater intrusion are the major stressors for coastal regions, particularly in the southeastern United States (Osland et al. 2022a, 2024). These chronic stressors occur within the context of previous modifications to landscapes and are concurrent with a variety of other stressors and disturbances that may compound their effects. Many disturbances are increasing in intensity and frequency (e.g., drought, hurricanes, and biotic agents; Hoffman et al. 2024). As described throughout this report, stressors and disturbances have complex and interconnected feedbacks to vegetation structure and processes, microbial community composition and function, hydrology, land-surface elevation, and biogeochemical cycles but are typically studied in isolation. Uncertainty emerges when multiple stressors and disturbances that occur at variable frequencies interact, generating unexpected effects on ecosystem structure and recovery potential.

Data and Modeling Needs

Gaps in data synthesis, ecosystem-scale experimentation, and model representation limit understanding of

Key Research Questions

- How do legacy effects of past disturbances influence ecosystem resiliency and response to subsequent disturbances?
- How do different combinations of compounding stressors and disturbances drive ecosystem response and transitions?
- How do the magnitude and frequency of compounding disturbances influence ecosystem trajectory?

varied ecosystem response to compounding stressors and disturbances. Addressing these gaps is challenged by diversity in the type, magnitude, and frequency of stressors and disturbances and in the antecedent conditions present within an affected system.

There is a need to synthesize historical observations of ecosystem response to varied disturbances within the context of antecedent conditions. These observations could include disturbance parameters (e.g., rainfall, wind speed, water level, and salinity) as well as pre- and post-disturbance ecosystem properties (e.g., plant mortality, ground elevation, and soil and water composition).

Novel ecosystem-scale experiments are needed to study changes to affected ecosystems in near real time to capture a broad suite of parameters and improve understanding of how compounding disturbances translate to ecosystem change. Integrating knowledge obtained from past observations with novel studies that employ the ModEx approach can generate new knowledge about how interactions between drivers and local ecosystems may either stabilize landscapes or amplify impacts of future SLR and saltwater intrusion.

Representation of disturbance dynamics in large-scale models (e.g., ESMs) is currently limited to land-cover change and fire and excludes specialized disturbance impacts in the coastal zone. Model representation of land-cover change is connected to how human land use has shifted over time or is projected to shift in the future (e.g., conversion of forest to agriculture, abandonment of older farmlands, and urban and suburban development). Representation of fire includes the intentional use of fire in forested areas as well as wildfire factors (e.g., fuel loads and lightning) and human-related factors (e.g., nearness to population centers and economic activity) that influence ignition sources and fire management potential.

ESMs do not currently integrate land cover with SLR and coastal land area, although these interactions are paramount to representing flood dynamics on the southeastern coastal plain. Efforts to close this gap are in the early stages; no global-scale models have included these processes in their Coupled Model Intercomparison Project–class simulations. Work is also underway to represent the transport of sediment in river networks, which is critical for predicting ground elevation in the coastal zone and could help capture flood impacts.

Higher spatial resolutions are needed to enable better modeling of tropical storms. Expanding representation of storm impacts in the coastal zone beyond precipitation and wind speed is also needed. Most land models do not represent how wind speed, direction, and duration affect vegetation or infrastructure. Ocean waves are represented in some ESMs, but impacts of wave height and energy on water levels and erosion in coastal zones are not yet included.

Impacts of Human Infrastructure and Activities

Land use and land cover are changing rapidly in watersheds that drain into southeast coastlines due to urbanization, cultivation, and (de)forestation (Hoffman et al. 2024). These changes affect vegetation distribution; carbon storage; surface and subsurface water flow; sediment transport and deposition; and carbon, nutrient, and contaminant loading into stream networks.

Surface and subsurface hydrology have been substantially modified to mitigate flooding and accommodate

Key Research Questions

- How will human-relevant influences throughout contributing watersheds influence the structure and function of coastal ecosystems?
- How will infrastructure and resource use associated with dense and increasing coastal populations influence water and sediment redistribution in coastal ecosystems?
- What are the broader ecosystem effects of new coastal infrastructure meant to combat increasing intensity and frequency of hurricanes and flooding?

human water use. For example, water is managed and rerouted through infrastructure like dams, water channels, and impervious surfaces. Sediments are removed and redistributed via dredging, beach nourishment, and building development. These modifications can substantially increase the spatial extent of SLR and saltwater intrusion.

Given that human modifications of coastal regions are widespread and entangled with natural processes, it is necessary to consider how human activities fit within the broader understanding and representation of coastal ecosystems. Research efforts need to evaluate human-relevant changes to the landscape, including increasing freshwater salinization, decreasing water availability within contributing watersheds, and more extensive land development—all of which will become increasingly pressing if the human population in coastal areas increases.

Data and Modeling Needs

Southeastern coastal systems are characterized by unique and diverse human dynamics and infrastructure, posing a unique challenge for integrating human impacts within modeling frameworks. To support investigation into human impacts on coastal systems, models need to better incorporate a broad range of infrastructure, which can affect the spatial distribution and flow of freshwater and saline water. For example, the spatial distribution of infrastructure such as channels, levees, and canal gates across the region is still unclear, and thus the spatial extent of saltwater intrusion is likely much larger than the immediate oceanfront. The level of detail in infrastructure data varies and could be improved with a regional-scale data hub.

4.4 Critical Gaps in Integrating Multiscale Model Frameworks

Advances in integration of model frameworks are needed to represent processes and integrate observations across scales to tackle fundamental questions in coastal science. The diverse coastal systems and disturbances present in the southeastern United States present a unique opportunity to capture a range of processes relevant to coastal systems more broadly.

Several existing modeling frameworks represent physical and biogeochemical processes at resolutions ranging from pore-scales to tens of kilometers within modeling domains that include individual patches and hillslopes and the globe (see sidebar: Example Modeling Capabilities, p. 45). However, progress is needed to bridge the gaps in scale and process specificity across model approaches to enable true multiscale integration.

Models at finer spatial scales (e.g., AquaMEND and PFLOTRAN) represent microbial and geochemical reactions in mechanistic detail. Models at intermediate scales (e.g., PFLOTRAN and Advanced Terrestrial Simulator) resolve 3D and multiphase flow and reactive transport. Models at larger spatial scales (e.g., E3SM and Functionally Assembled Terrestrial Ecosystem Simulator) represent forest cohort demography, system interactions, and lateral connectivity while supplying coordinated boundary conditions and integrated effects of lateral process connections to models at fine scales. Even though this modeling ecosystem is highly flexible, the needed modeling capabilities described for each knowledge gap must be addressed at scale to accurately capture the complexities and feedback mechanisms encountered in coastal systems.

Example Modeling Capabilities

AquaMEND

github.com/jianqiuz/AquaMEND_salinity_module

AquaMEND is a modeling framework that combines microbial-explicit and aqueous-explicit geochemical models to better represent decomposition, salinity, pH, and soil organic carbon availability (Zheng et al. 2025). AquaMEND's capacity to simulate interactions between abiotic and biotic mechanisms offers a versatile tool for studying and predicting the effects of soil salinization on belowground carbon cycling.

PFLOTRAN: A massively Parallel reactive FLOw and TRANsport model for describing surface and subsurface processes

pflotran.org

PFLOTRAN is an open-source, state-of-the-art multiphase flow and reactive transport simulator designed to leverage high-performance computing infrastructure for subsurface Earth systems applications. Its code has been used to simulate the migration of contaminants in groundwater and *in situ* leaching of mineral ore deposits.

PFLOTRAN provides flexible biogeochemical modeling capability by allowing incorporation of system-specific reaction networks through its sandbox (Hammond et al. 2014). PFLOTRAN has been coupled to the E3SM Land Model to resolve redox reactions and nutrient cycling in the rooting zone and is linked to the Advanced Terrestrial Simulator as a biogeochemistry engine in the subsurface. PFLOTRAN code is available on bitbucket (bitbucket.org/pflotran).

Advanced Terrestrial Simulator (ATS)

github.com/amanzi/ats

Developed by DOE national laboratories, ATS is an integrated hydrology and reactive transport model that can simulate response variables such as evapotranspiration, ponded water depth, soil moisture, and geochemical concentrations. ATS can represent both surface and subsurface processes and solve problems from the watershed to river basin scale. The ATS code is based on a multiphysics framework, which combines with a powerful mesh infrastructure to enable strong coupling of processes. ATS offers unique capabilities in thermal integrated hydrology, such as freeze–thaw processes, and can model evapotranspiration, plant dynamics, ice in frozen soils, and deformation. Geochemistry support is provided through the Alquimia interface library (github.com/LBL-EESA/alquimia-dev) to link with geochemistry engines from PFLOTRAN or CrunchFlow. ATS has been deployed in coastal and land–water interface settings.

Energy Exascale Earth System Model (E3SM)

e3sm.org

E3SM is an ongoing, state-of-the-science modeling, simulation, and prediction project supported by DOE and designed for exascale computing. This fully coupled model simulates aspects of Earth system variability and projects decadal changes that will critically impact the U.S. energy sector in the future. Biogeochemistry, cryosphere systems, and the water cycle are the key scientific drivers for E3SM's development, along with a need to address uncertainty in model projections. E3SM features atmosphere, ocean, sea ice, land

Continued on p. 46

Continued from p. 45

ice, land, and river components at low and high resolutions (100 and 25 km). The E3SM team plans to release Version 4 in 2028.

Although some low-resolution configurations can be done on a laptop, E3SM runs best on high-performance computing systems. Users can access E3SM through a supported machine at a DOE laboratory. E3SM's source code is available at GitHub (github.com/E3SM-Project/E3SM), and E3SM data is available through the Earth System Grid Federation.

Energy Exascale Earth System Model Land Model (ELM)

docs.e3sm.org/E3SM/ELM

Within DOE's E3SM framework, ELM simulates the exchanges between terrestrial land surfaces and other Earth system components, facilitating understanding of hydrologic cycles, biogeophysics, and terrestrial ecosystem dynamics. The advent of state-of-the-art datasets and exascale computers has made kilometer-scale resolution feasible. ELM has been applied to multiple projects within BER to simulate boreal peatlands, Arctic tundra, and other ecosystems of interest. This model can represent soil hydrology, snow processes, microbial function, plant hydraulics, and land management practices. The ELM code is available on GitHub (github.com/E3SM-Project/E3SM).

Functionally Assembled Terrestrial Ecosystem Simulator (FATES)

eesm.science.energy.gov/technical-highlights/fates-e3sm-functionally-assembled-terrestrial-ecosystem-simulator

FATES is a next-generation numerical terrestrial ecosystem model that simulates and predicts growth, death, and regeneration of plants and subsequent tree size distributions. When coupled with an Earth system model, FATES allows representation of potential ecosystem responses to changes in resource availability (e.g., water, light, and nutrients) and atmospheric composition—and how ecosystem change alters Earth system dynamics.

This vegetation demography model is an external module implemented in ELM as ELM-FATES, a pairing that enables studies of forest disturbance from storms. The FATES code is available on GitHub (github.com/NGEET/fates).

Chapter 5

Science Priorities and Research Opportunities

5.1 Advancing Coastal System Understanding and Prediction

Coastal regions of the southeastern United States possess unique, diverse systems that are highly vulnerable to saltwater intrusion, freshwater and saline flooding, and increasing frequency and severity of extreme events. These drivers initiate change in coastal systems, often at multiple scales simultaneously and with unclear consequences. Anticipating ongoing changes in the structure and function of southeastern U.S. coastal systems is key to protecting population centers and energy resources in the region.

Understanding the processes that shape southeastern U.S. coastal systems and developing associated tools to address knowledge gaps will generate the predictive capabilities needed to assess risk, inform decision-making, and develop solutions to ongoing challenges. This chapter highlights four science priorities that will advance these goals:

1. **Understand coastal responses to compounding disturbances.** Flooding from coastal and inland storms, extreme events, ongoing changes in sea level, and other compounding stressors and disturbances will affect ecosystem distributions and their associated hydro-biogeochemical functions.
2. **Describe biotic shifts and associated biogeochemical processes.** Understanding interdependent interactions among vegetation, geomorphology, hydrology, biogeochemistry, and microbiology is essential for predicting how key ecosystem functions will respond to compounding stressors and disturbances within given antecedent conditions.
3. **Examine coastal dynamics in a watershed context.** The structure and function of coastal systems must be understood within a watershed context, given that inland processes (e.g., changes in land use and land cover, sediment transport, and surface and

Key Points

Priority: Understand coastal responses to compounding disturbances

Opportunities:
- Use long-term monitoring to capture ecological responses to extreme events
- Design experiments targeting compounding stressors and disturbances

Priority: Describe biotic shifts and associated biogeochemical processes

Opportunities:
- Investigate shifting vegetation and microbial communities
- Define interactions between shifting biota and biogeochemical processes

Priority: Examine coastal dynamics in a watershed context

Opportunities:
- Evaluate effects of watershed processes on coastal systems
- Define ecosystem distributions in all watersheds draining to the South Atlantic and Gulf coasts

Priority: Build an integrated multiscale modeling framework

Opportunities:
- Couple large-scale models to enable process representation
- Leverage existing models to enhance model integration
- Construct digital twins for specific coastal zones

subsurface hydrology) produce impacts that propagate toward the coasts.

4. **Build an integrated multiscale modeling framework.** Connecting models within a single, integrated framework can enhance process representation and better account for feedback mechanisms across scales.

Multiple research opportunities exist within each identified science priority. Investigating these opportunities within a model–experiment (ModEx) framework allows researchers to examine process connections from encompassing watersheds to the coastal zone, providing actionable insights that inform land management and energy security. Ultimately, capitalizing on these research opportunities will advance understanding of coastal systems and in doing so, establish the multiscale, predictive modeling capabilities needed to meet DOE mission–relevant challenges and ensure energy security.

The short-term research opportunities identified in this report are not comprehensive. Instead, they serve as examples for working within an integrated conceptual framework that can accommodate larger efforts as resources allow.

5.2 Crosscutting Approach To Research Opportunities

Integrating model, data, and experiments through a ModEx approach is key to advancing predictive understanding of how the structure and function of coastal systems will respond to drivers of change within the context of landscape modulators such as development, forestry, urbanization, and agriculture (see Fig. 5.1, p. 49). Observation and modeling efforts should emphasize connectivity between and among watershed, upland, and wetland ecosystems, including (1) interactions among environmental and human-related drivers, (2) shifting vegetation distributions, (3) lateral transport of water and its dissolved and particulate loads, (4) vertical accretion and surface elevation, and (5) belowground geochemical and microbial processes.

Readily available, accessible, standardized, and aggregated historical data are needed to inform, test, and improve predictive models. However, meeting this need will require overcoming remaining challenges in data sharing, locating, and searching, along with inconsistencies in data formats and quality. Multidisciplinary and multiagency coordinated efforts to improve metadata standards and build a centralized, standardized, and accessible data portal could significantly alleviate these challenges, enabling more seamless and comprehensive data synthesis and use across study sites and regions.

Efforts are needed to integrate existing data into relevant predictive models and to strengthen the flow of information from models to experiments through multiscale modeling. Model–data integration through parameterization, data assimilation, and parameter estimation is important for reducing uncertainty. Increasingly needed, however, is the use of multiscale models to (1) pose testable hypotheses and (2) design experiments and associated data collection that will target knowledge gaps and improve process understanding for coastal systems. Manipulation experiments that test model-generated hypotheses can (1) improve understanding of how coastal system respond to drivers of change and (2) increase capabilities for predicting response to projected change. Existing managed systems such as coastal restoration projects may serve as living laboratories to evaluate model performance and test new hypotheses.

Developing new mechanistic understanding and representation of coastal systems requires (1) high-resolution field observations using continuous environmental sensors and remote sensing capabilities and (2) AI/ML-assisted analysis of harmonized datasets. Combining intensive and extensive sampling designs can improve both detailed, system-level understanding and knowledge transfer across heterogeneous ecosystems and environmental drivers.

Complementing field observations with existing experimental and analytical approaches can elucidate underlying mechanisms difficult to infer from observation alone. Existing approaches include direct field-scale ecosystem manipulation, *in situ* mesocosms, laboratory experiments, and molecular-scale genomic and geochemical capabilities available at DOE user facilities.

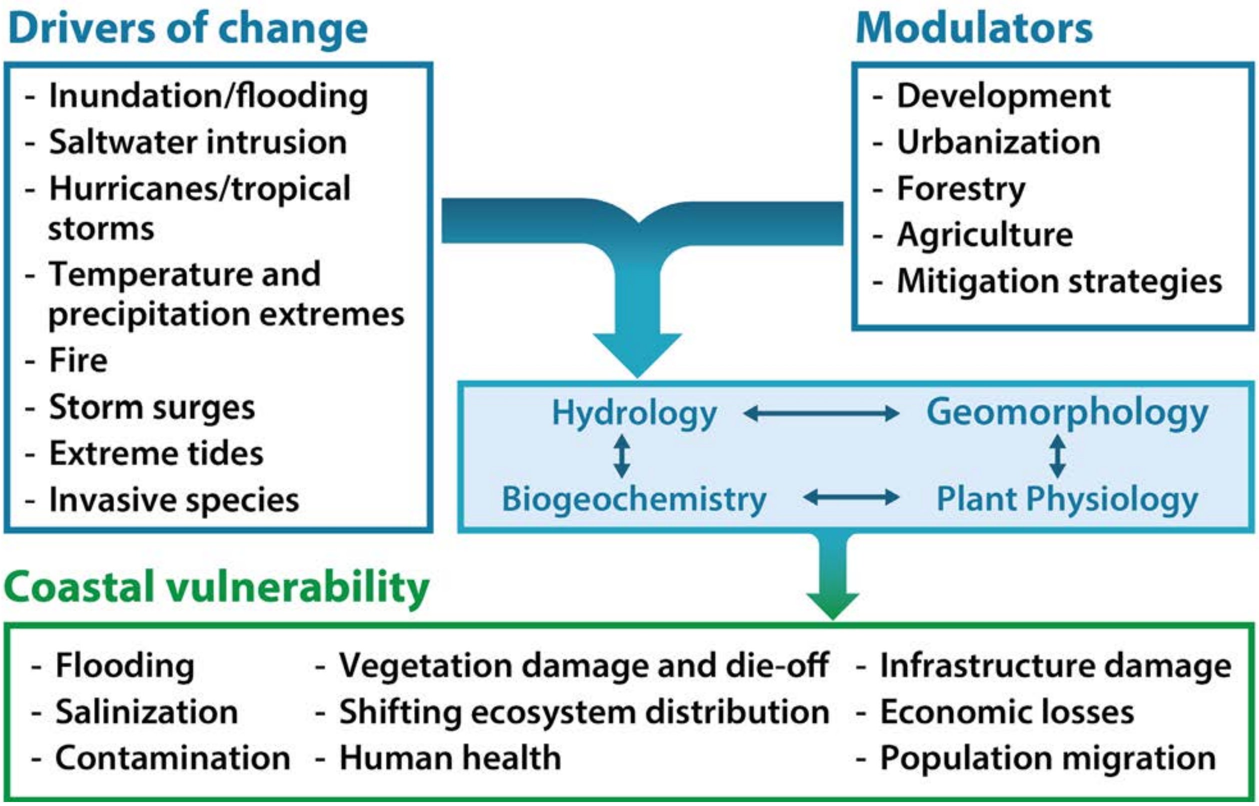


Fig. 5.1. Interacting Factors Influencing Southeastern U.S. Coastal System Vulnerability. These systems are exposed to multiple drivers of change that in turn are modulated by human activity across scales ranging up to entire watersheds. The resulting changes are reflected in all aspects of a coastal system, including its hydrology, geomorphology, biogeochemistry, and vegetation responses. These interactions result in an array of coastal vulnerabilities.

5.3 Science Priority: Understand Coastal Responses to Compounding Disturbances

Coastal hazards and disturbances are projected to increase in magnitude and frequency throughout the southeastern United States, exacerbating the vulnerability of coastal communities to hurricanes and tropical storms, flooding, saltwater intrusion, freezing, fires, and droughts. Elucidating the effects of compounding stressors and disturbances on coastal systems is therefore critical for assessing risk to coastal communities and infrastructure and developing solutions to prevent and reduce damage.

Research Opportunity: Use Long-Term Monitoring To Capture Ecological Responses to Extreme Events

An opportunity exists to synthesize and evaluate historical datasets acquired by long-term monitoring programs. These datasets capture baseline conditions and can be used as a reference point to identify effects of ongoing disturbances to coastal systems. Long-term datasets also provide a unique opportunity to capture ecological responses to past disturbance because they include not only event data but also pre- and post-disturbance data, which are difficult to acquire through short-term sampling due to the random nature of these events. Evaluating historical responses of coastal systems to extreme events across a broad range of environmental conditions can establish driver–response relationships that can be incorporated into predictive models.

Existing data provided by long-term ecological monitoring capabilities, state-specific coastal resources, and remote-sensing sources offer a robust foundation for synthesis and gap analyses. Current resources include but are not limited to the (1) National Science Foundation's Long-Term Ecological Research (LTER) Network, (2) National Oceanic and Atmospheric Administration's National Estuarine Research Reserve System, (3) Coastal Carbon Research Coordination Network, (4) AmeriFlux Network, (5) Louisiana's Coastwide Reference Monitoring System, and (6) NASA's Delta-X and MERRA-2 campaigns (see Appendix E: Long-Term Coastal Monitoring Programs in the Southeastern United States, p. 62).

Research Opportunity: Design Experiments Targeting Compounding Stressors and Disturbances

In addition to synthesizing historical and ongoing data streams, experiments are needed to understand how systems that span natural and manipulated gradients respond to diverse stressors and disturbances. Predictive models can be used to guide experimental design—including when, where, and what to collect—to best understand certain driver–response behaviors, ultimately leading to better model parameterization and process representation with reduced uncertainties.

Field-scale manipulation experiments like those pioneered by DOE (e.g., the Spruce and Peatland Responses Under Changing Environments and Free Air Carbon Dioxide Enrichment experiments) can target ecosystem-scale stressor and disturbance scenarios. For example, the manipulative TEMPEST (Temperate Ecosystem Manipulation to Probe Effects of Storm Treatments) experiment in the mid-Atlantic is designed to understand how freshwater and saltwater floods may alter soil biogeochemical cycles and vegetation in a deciduous coastal forest. Another example is the TRACE (Tropical Responses to Altered Climate) experiment in Puerto Rico that investigates independent and compounding effects of warming and hurricane disturbance on biogeochemical processes in tropical forests.

Leveraging existing restoration projects and manipulation studies as experimental sites or model testbeds can be a cost-effective approach to gathering new data and testing hypotheses. For instance, opportunities to study ecosystem responses to large-scale interventions are possible with efforts such as the Mississippi River and Everglades restoration projects and existing LTER manipulations, including the Seawater Addition Long-Term Experiment (SALTEx), which is focused on salinization of a tidal freshwater marsh.

5.4 Science Priority: Describe Biotic Shifts and Associated Biogeochemical Processes

Sea level is projected to rise across southeastern U.S. coastal systems. This shift is a defining feature of these systems, more so than in terrestrial ecosystems where specific directional changes (i.e., increases or decreases) in abiotic drivers (e.g., temperature and precipitation) are less certain. The expected rise in sea level presents a high-priority opportunity to combine observation, experiments, and modeling across a broad, spatially distributed range to examine effects of flooding and saltwater intrusion on coastal ecosystems.

Research Opportunity: Investigate Shifting Vegetation and Microbial Communities

Efforts are needed to identify the complex drivers and mechanisms determining how vegetation and associated microbial communities shift in response to flooding and saltwater intrusion. Opportunities exist to observe and model sequential state changes, such as large-scale shifts in vegetation communities (e.g., forest-to-marsh transitions), associated with sea level rise. Observational studies lasting at least 10 years are needed to characterize these responses across existing and evolving salinity gradients. These studies can investigate ecosystem state changes as they occur relative to more stable ecosystems and probe the complex yet sequential mechanisms that underpin tipping points to state changes.

For example, the extensive formation of ghost forests along the eastern U.S. coast is highly heterogeneous. New very-high-resolution remote sensing data and ML techniques could provide understanding of how ghost forests develop in response to (1) environmental drivers (e.g., elevation, salinity, and drought frequency); (2) biological drivers (e.g., insect outbreaks); and (3) human modifications to the landscape (e.g., ditching). The relative importance of these drivers is still unclear at the regional scale.

To align with observations, novel plant functional types (PFTs) should be included within models such as the E3SM Land Model (ELM) and Functionally Assembled Terrestrial Ecosystem Simulator (FATES). Seasonally inundated bottomland hardwood forests, tidal freshwater wetlands, mangroves, and graminoid and succulent saltmarshes are key ecosystems of the southeastern United States not yet represented in models. Including these new PFTs in models would enable hindcasting (i.e., using existing datasets for model evaluation and iterative improvement) of vegetation change (e.g., recent transitions to ghost forest or mangrove expansion). Improved models can then be used to forecast vegetation changes under various coastal stressors and compounding disturbances.

Research Opportunity: Define Interactions Between Shifting Biota and Biogeochemical Processes

Experiments and observations are needed to establish two-way interactions between shifting biological communities and biogeochemical processes. Concurrently, ecosystem models need to integrate vegetation and soil biogeochemistry components to enhance process representation. For example, carbon allocation to leaves, stems, and roots depends on nutrient uptake from soils, which in turn depends on litter and soil organic matter turnover and trophic interactions within soil microbial communities. Furthermore, ground elevation relative to sea level determines plant survival and is in turn influenced by litter inputs, decomposition, and plant-mediated sediment deposition. Improved representation of these processes could enable full coupling between vegetation communities and reactive transport codes to predict coastal system dynamics under changing environmental conditions.

5.5 Science Priority: Examine Coastal Dynamics in a Watershed Context

Ecosystem transitions and landscape change occur in response to complex drivers that operate throughout coastal watersheds, not just at the coastline. Building a system view that evaluates not only coastal systems but also their encompassing watersheds is paramount to obtaining predictive understanding of coastal systems.

Research Opportunity: Evaluate Effects of Watershed Processes on Coastal Systems

A pressing need exists to develop predictive understanding of how the water, sediment, and nutrients delivered from watersheds into coastal systems regulate their elevation relative to sea level. This understanding must incorporate watershed hydrology with interactions among sediment deposition, plant traits, and organic matter accrual and decomposition at the coast. It is also necessary to consider the frequent tropical storms that make landfall along the South Atlantic and Gulf coasts and generate episodic disturbance from high winds, heavy rain, and storm surge. Representation of watershed hydrology must consider urban development and widespread agriculture and forestry, together with extensive damming, dredging, and other hydrologic manipulations, that have significantly altered sediment, organic matter, and nutrient inputs to the coastal plain.

Distributed watershed modeling capabilities, such as the Advanced Terrestrial Simulator (ATS), incorporate process-based model representation and afford the spatial resolution needed for coastal systems. Using ATS, it is feasible, though challenging, to examine two-way interactions during disturbance events extending, for example, from estuaries into bottomland wetland systems of the southeastern coastal plain. Framing compounding and episodic events in the context of broader watershed-scale simulations provides more reasonable boundary conditions at the upland extent of coastal systems. This improved accuracy is needed to define baseline conditions for surface and subsurface hydrology, salinity distributions, redox states, and geomorphological conditions for sediment dynamics.

Research Opportunity: Define Ecosystem Distributions in All Watersheds Draining to the South Atlantic and Gulf Coasts

Determining how natural and modified gradients control vegetation distribution supports predictive understanding of long-term biotic shifts and more rapid effects of disturbance events. A necessary first step in evaluating future change is to generate hydrobiogeographic descriptions of all the subregional watersheds (i.e., Hydrologic Unit Code 4) draining to the South Atlantic and Gulf coasts. This near-term opportunity can begin by synthesizing the best-available (e.g., 30 m) land cover, elevation, and hydrographic data.

These synthesis efforts can leverage continued releases of high-resolution (e.g., 1 m) land-cover data for coastal regions of the United States, although current data is limited to canopy, impervious surface, and water features (NOAA 2025c).

Additional very-high-resolution remote sensing and hyperspectral remote sensing capabilities can support mapping of ecosystem distributions and quantification of key ecosystem properties. Quantifying vegetation distribution within the context of landscape features and other contextual information can help identify environmental drivers of ecosystem distribution and evaluate associated biogeochemical processes. This information would provide a consistent point of reference for more detailed studies in individual watersheds or along smaller coastline segments. If this mapping effort had extensive geographic coverage, it would lay a foundation for connecting land and nearshore ocean processes in Earth system models (ESMs) that span global-to-hyper resolutions through improved representation of the coastal zone and the watershed-scale factors driving coastal ecosystem processes.

5.6 Science Priority: Build an Integrated Multiscale Modeling Framework

An integrated modeling framework that represents underlying processes and their interactions across multiple interconnected scales is needed to capture the complex dynamics of southeastern coastal systems. Bringing together fine, intermediate, and large scales into a multiscale modeling framework enables each model to capture unique processes that then inform process representation at other scales (see Fig. 5.2, p. 53).

Fine-scale models feature the most detailed representations of biogeochemical and microbial processes and interactions among vegetation, microbial communities, and the physical environment. Representing these processes in mechanistic detail provides a foundation for parameterizing those processes within models operating at larger spatial scales.

Models at intermediate scales can resolve 3D multiphase flow and transport in the connected surface and subsurface systems, serving as a bridge between fine- and large-scale models. These models can be used to understand and represent the interactions of multiple vegetation types and microbial communities in a more generalized physical and hydrologic context. This scale captures the ecosystem dynamics of plant communities as they evolve under the compound stressors and disturbances that are actively reshaping coastal systems. For example, salinity induces changes in trace gas fluxes both directly, via changing reaction kinetics within microbial communities, and indirectly, via mortality-induced shifts in vegetation communities and associated belowground processes.

Models at the largest spatial scales represent system interactions and lateral connectivity while supplying coordinated boundary conditions and integrated effects of lateral process connections to models at fine scales. This scale is needed to represent how watershed

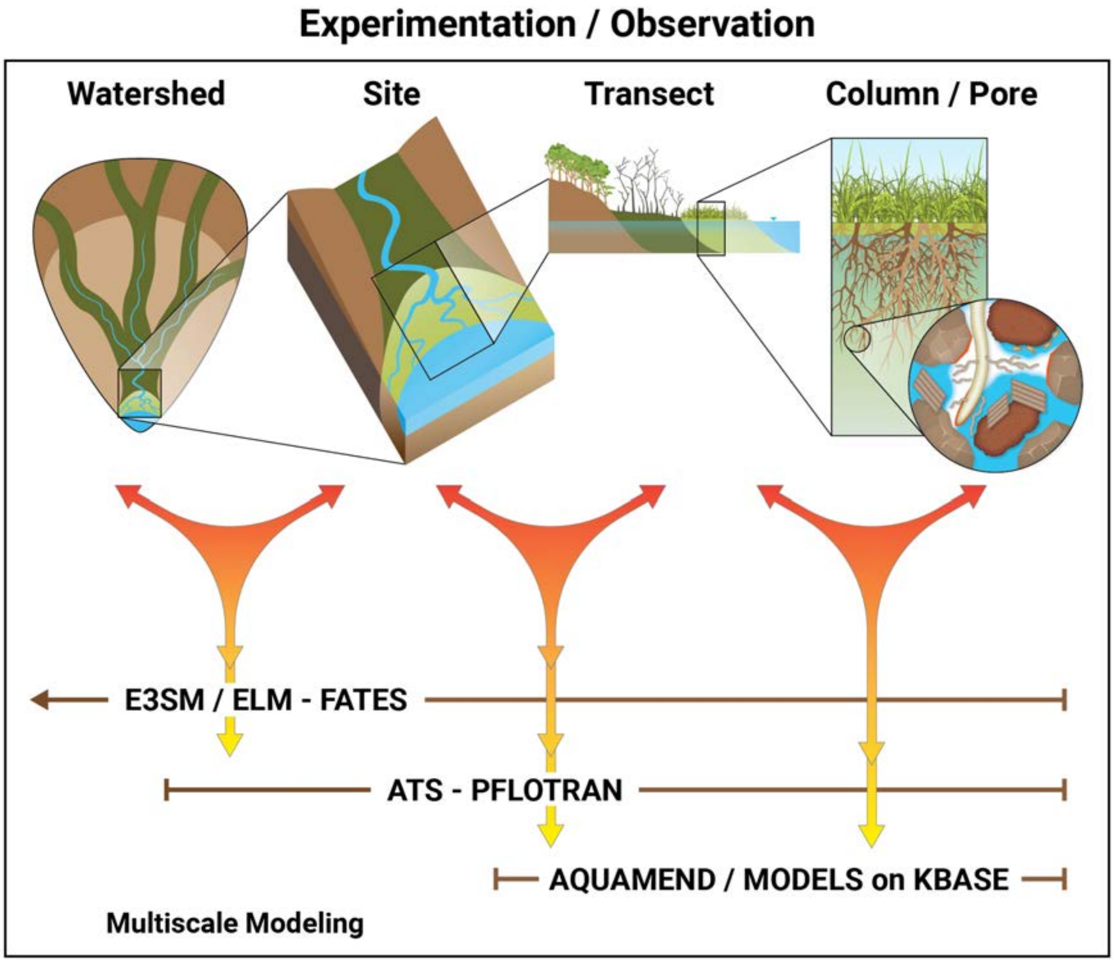


Fig. 5.2. Multiscale Modeling Framework for Systems-Level Understanding of Coastal Processes and Vulnerabilities. This understanding requires experimentation and observation efforts across multiple spatial scales, spanning entire watersheds, sites within watersheds, transects within those sites, and column- and pore-scale studies along those transects. An integrated system of multiscale models can take advantage of observations and experimental knowledge gained across this scaling hierarchy, resulting in comprehensive predictive understanding of the current system and its likely future trajectories.

processes regulate conditions within coastal systems and how inland and seaward disturbances propagate through watersheds to the coast.

Research Opportunity: Couple Large-Scale Models To Enable Process Representation

Coupling large-scale models can enable representation of process interactions, providing a robust capability for studying feedback mechanisms at the watershed scale. This largest scale will form the basis for connecting coastal systems to ESMs, with research frontiers to be explored in the use of surrogate models, emulators, and AI/ML to improve performance at high spatial resolutions.

Research Opportunity: Leverage Existing Models To Enhance Model Integration

To leverage existing predictive capabilities, DOE can review the collection of models currently being used in the southeastern United States by different local and federal agencies. For example, Hydro-MEM (Hydro-dynamic Marsh Equilibrium Model) was developed to simulate coupled hydrodynamic and marsh accretion processes across a large estuarine system of the Apalachicola River in Florida. The predictive models outlined in the 2023 Louisiana Coastal Master Plan— including landscape models, storm surge and wave models, and risk assessment models— are additional modeling resources that can be leveraged to enhance the connection between mechanistic models and operational models. The Marsh Equilibrium Model and the Virginia Institute of Marine Science's shoreline management models have also been applied to states in the southeast coastal region.

Research Opportunity: Construct Digital Twins for Specific Coastal Zones

Integrating multiscale modeling, experiments, and observations can enable the construction of digital twins (i.e., a real-time interactive digital infrastructure that can provide immediate feedback and evaluation) for specific coastal zones. Digital twins are a cutting-edge approach using the most recent technological advances in AI, ML, and data infrastructures to synchronize observational and modeled data and identify and address knowledge gaps more efficiently. This technology could transform knowledge into actionable science for the region's decision-makers.

Chapter 6

Conclusion

Strategic focus on coastal systems of the southeastern United States is needed to secure energy resources and economic investments challenged by extreme weather and shifting landscapes. The diversity of ecosystems and compounding stressors and disturbances present in the region provide a significant opportunity to evaluate and address coastal challenges relevant not only to this region but across the United States and globally.

Advanced modeling capabilities can support decision-making for strategies needed to respond to ongoing coastal challenges. These predictive capabilities are limited by major uncertainties in the drivers and consequences of shifting ecosystem structure and function. Resolving knowledge gaps through experimental, observational, and computational research is therefore a significant research priority to improve model representation of southeastern coastal systems and their role in global processes.

Advances in both process-based understanding and model representation are constrained by difficulties obtaining accurate data on (1) land-surface elevation; (2) carbon stocks; (3) water, solute, and sediment fluxes; and (4) ecosystem area and distribution in this low-gradient, highly heterogeneous region. Where data do exist, compiling and synthesizing the data to build new knowledge is an ongoing challenge.

Tightly integrating model development with data synthesis, ecosystem-scale observations, and manipulative field and laboratory experiments is the key to accelerating predictive understanding and the development of an ambitious modeling framework.

In order to represent coastal systems and predict their future trajectories, current models need to develop sufficient representation of:

- Diverse plant functional types
- Lateral exchange
- Dynamic microtopography
- Microbial processes
- Redox reactions
- Disturbances
- Landscape modifications

Closing critical knowledge gaps on these topics can provide details needed to improve process representation; however, representation will remain incomplete if models do not account for the impact of processes happening at other scales. Establishing connectivity among models within a multiscale framework can benefit process representation by bringing together information currently siloed within different model systems.

Because of the unique features and vulnerabilities of southeastern coastal systems, integrating southeastern coastal processes and observations into multiscale models is vital to establishing the predictive understanding needed to protect ecosystem services, energy infrastructure, and communities in the southeastern United States.

Appendix A

Workshop Agenda

Day 1 – Tuesday, March 26

8:00 a.m.	**Breakfast**
8:30 a.m.	**Opening Plenary**
8:30–8:35 a.m.	Introduction and SC Statement of Commitment *Brian Benscoter, U.S. Department of Energy*
8:35–8:40 a.m.	Welcome from EESSD *Gary Geernaert, U.S. Department of Energy*
8:40–8:50 a.m.	DOE-ESS Charge and Workshop Objectives *Brian Benscoter, U.S. Department of Energy*
8:50–9:00 a.m.	Workshop Logistics *Elizabeth Herndon, Oak Ridge National Laboratory*
9:00–9:10 a.m.	***Introductions: Breakout Group A***
9:10 a.m.	**Session 1: Characterizing Southeastern Coastal Zones**
9:10–9:30 a.m.	Introduction to Different Ecosystems of the Southeastern U.S. and their Unique Properties and Challenges *Ken W. Krauss, Louisiana Universities Marine Consortium*
9:30–10:10 a.m.	Introduction to Models Being Used in DOE Research and their Gaps *Panel Moderator: Peter Thornton, Oak Ridge National Laboratory* **Short presentations:** • Bradley Christoffersen, The University of Texas–Rio Grande Valley • Ben Sulman, Oak Ridge National Laboratory • Xingyuan Chen, Pacific Northwest National Laboratory • Pamela Weisenhorn, Argonne National Laboratory • Joel Rowland, Los Alamos National Laboratory
10:10 a.m.	**Break**
10:30 a.m.	**Session 1 Breakouts** • Group A: Andre Rovai (moderator), Pamela Weisenhorn (notetaker) • Group B: Angelia Seyfferth (moderator), Xi Yang (notetaker) • Group C: John R. White (moderator), Jesus Gomez-Velez (notetaker)

12:00–12:15 p.m.	**Breakout Session 1 Reporting** (plenary room–5 minutes each group)
12:15 p.m.	**Lunch**
1:15 p.m.	**Session 2: Coastal Vulnerability** (plenary room)
1:15–1:25 p.m.	***Introductions: Breakout Group B***
1:25–1:45 p.m.	Observations of Recent Rapid Change at the Marsh-Forest Ecotone in South Carolina *Tom O'Halloran, Clemson University*
1:45–2:05 p.m.	Coastal Vulnerabilities to Sea-Level Rise and Saltwater Intrusion *Havalend E. Steinmuller, Louisiana Universities Marine Consortium*
2:05–2:25 p.m.	Data and Modeling Needs for Flood Hazards in the Gulf Coast *Clint Dawson, University of Texas*
2:25 p.m.	**Break**
2:45 p.m.	**Session 2 Breakouts** • Group A: Devon Eulie (moderator), Bradley Christoffersen (notetaker) • Group B: Nick Ward (moderator), Peter Thornton (notetaker) • Group C: Julia Guimond (moderator), Victoria M. Congdon (notetaker)
4:15–4:25 p.m.	***Introductions: Breakout Group C*** (plenary room)
4:25–4:40 p.m.	**Breakout Session 2 Reporting** (5 minutes each group)
4:40–5:30 p.m.	**Open Discussion** (co-chair moderated)
5:30 p.m.	**Adjourn Day 1**

Day 2 – Wednesday, March 27

8:00 a.m.	**Breakfast**
8:30 a.m.	**Announcements and Summaries** (plenary room) • SC Statement of Commitment • Summary of "Homework" Responses • Logistics for Day 2
8:50 a.m.	**Session 3: Critical Gaps in Data, Knowledge, and Modeling** Designing Experiments To Address Critical Knowledge Gaps
8:50–9:05 a.m.	Ongoing Research at LTER *Tiffany Troxler, Florida International University*
9:05–9:20 a.m.	TEMPEST *Nick Ward, Pacific Northwest National Laboratory*

9:20–9:35 a.m.	TRACE *Tana E. Wood, U.S. Forest Service*
9:35–9:50 a.m.	SPRUCE *Melanie Mayes, Oak Ridge National Laboratory*
9:50 a.m.	**Break**
10:10 a.m.	**Session 3: Breakouts** • Group A: Pamela Weisenhorn (moderator), Andre Rovai (notetaker) • Group B: Xi Yang (moderator), Angelia Seyfferth (notetaker) • Group C: Jesus Gomez-Velez (moderator), John R. White (notetaker)
11:40 a.m.–12:00 p.m.	**Breakout Session 3 Reporting** (plenary room–5 minutes each group)
12:00 p.m.	**Lunch**
1:00 p.m.	**Session 4: Prioritizing Research Opportunities and Collaboration (plenary room)**
1:00–1:20 p.m.	Research Coordination and Community Engagement *Brita Jessen, South Carolina Sea Grant Consortium*
1:20–2:00 p.m.	Existing and Legacy Research Efforts and Data in the Southeastern U.S. *Panel Moderator: Eric Ward, University of Maryland* **Short presentations panel:** • Holly Michael, University of Delaware • Victoria M. Congdon, University of Texas • Amanda Spivak, University of Georgia • Xi Yang, University of Virginia
2:00 p.m.	**Break**
2:20 p.m.	**Session 4: Breakouts** • Group A: Bradley Christoffersen (moderator), Devon Eulie (notetaker) • Group B: Peter Thornton (moderator), Nick Ward (notetaker) • Group C: Victoria M. Congdon (moderator), Julia Guimond (notetaker)
3:50–4:10 p.m.	**Breakout Session 4 Reporting** (plenary room–5 minutes each group)
4:10–5:00 p.m.	**Open Discussion and Concluding Remarks**
5:00 p.m.	**Workshop Adjourned**

Appendix B

Workshop Discussion Questions

Session 1

Characterizing Southeastern Coastal Zones

- What are the most important processes to consider when discussing the southeastern U.S.?
- What features and processes are unique but critical for southeastern United States coastal regions?
- Conversely, what features and processes of the southeastern U.S. are transferable to other coastal regions of the United States and worldwide?
- What processes outside of the "coastal zone" are important to consider when predicting key coastal processes?

Session 2

Coastal Vulnerability

- What are the episodic, compounding, and chronic disturbances that most affect ecosystem function of southeast coastal systems currently and into the future?
- What features or processes in coastal systems are most sensitive to disturbance?
- How do the direct impacts of disturbance propagate through coastal systems, and over what spatial and temporal scales?
- What is the ability to represent disturbance and/or its impacts (or not) in models, and at what spatial and temporal scales?

Session 3

Critical Gaps in Knowledge, Technology, Data, and Modeling

- What features within southeast coastal systems remain poorly constrained?
- What are the major uncertainties in drivers of change within SE coastal systems?
- What are the major knowledge and data gaps regarding how SE coastal systems function and respond to these drivers?
- In what ways do existing models not adequately represent the structure and function of SE coastal systems?
- Where do gaps in representation of SE coastal systems limit our ability to make predictions at continental to global scales?
- What technological advances are needed to support future efforts in the region?

Session 4

Prioritizing Research Opportunities and Collaboration

- What are opportunities for integrated observation, experimental, and modeling strategies (ModEx) that address key knowledge gaps in the SE coastal region?
- What are some ModEx-inspired opportunities for manipulation experiments?
- What prior and ongoing research efforts in the region are relevant for informing or to be leveraged by those strategies?
- What opportunities exist to promote multidisciplinary, multi-agency coordination?

Appendix C

Workshop Participants

Co-Organizers

Elizabeth Herndon, Oak Ridge National Laboratory*

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Ken W. Krauss, Louisiana Universities Marine Consortium*

Havalend E. Steinmuller, Louisiana Universities Marine Consortium*

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Holly Michael, University of Delaware

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Ashley Smyth, University of Florida

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Ben Sulman, Oak Ridge National Laboratory

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Susannah Tringe, Lawrence Berkeley National Laboratory

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Jorge Villa, University of Louisiana–Lafayette

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**Writing team*

Appendix D

Glossary

Brackish

slightly salty water with a salinity between 0.5 and 30 parts per thousand (ppt); this range covers the salinity levels of intracoastal bodies of water like estuaries, including oligohaline (0.5 to 5 ppt), mesohaline (5 to 18 ppt), and polyhaline (18 to 30 ppt) water bodies

Disturbance

an event that temporarily alters ecosystem processes

Elevation capital

the buffer created by sediment and organic matter buildup that maintains a wetland above a drowning threshold for vegetation

Estuary

a partly enclosed body of water with access to the open sea—such as a bay, salt marsh, or river delta—where tidal action mixes freshwater with saline ocean water

Freshwater

water that contains less than 0.5 parts per thousand of dissolved salts

Hydric

characterized by, relating to, or requiring an abundance of moisture

Mean (eustatic) sea level

the average height of the sea surface measured over an extended period for all conditions of tides, seasons, and storms

Mesic

characterized by, relating to, or requiring a moderate amount of moisture

Plant functional type

broad categories of plant species sharing similar properties and function within ecosystems

Redox reaction

chemical reaction where one substance loses electrons (oxidation) and another substance gains electrons (reduction)

Relative sea level rise

the change in the difference in elevation between the land and the sea surface at a specific time and location driven by a combination of eustatic sea level rise, land subsidence, or uplift

Saline

containing significant amounts of dissolved salts; water with a concentration of dissolved salts greater than 1,000 milligrams per liter (0.5 parts per thousand)

Sea level rise

changes in mean global sea level, often called eustatic sea level rise

Stressor

continuous factor imposed on an ecosystem

Subsidence

a reduction in land surface elevation as a result of soil compaction, shallow soil water loss, or pumping out of deep groundwater (contrast to "vertical accretion")

Tidal embayments

partly enclosed coastal bodies of water with a free connection to the open sea and with minimal input from rivers

Vertical accretion

accumulation of sediment and organic matter on the soil surface of a wetland that contributes to an increase in soil surface elevation (contrast to "subsidence")

Xeric

characterized by, relating to, or requiring only a small amount of moisture

Appendix E

Long-Term Coastal Monitoring Programs in the Southeastern United States

This list was gathered from workshop participants and is not intended to be exhaustive. All programs listed here are ongoing.

National Estuarine Research Reserve System

coast.noaa.gov/nerrs

Organizations: National Oceanic and Atmospheric Administration, state partners

Start: 1972

Region: Multiple sites (e.g., Sapelo Island in Georgia and Weeks Bay in Alabama)

Focus: Water quality, weather, habitat health

National Coastal Condition Assessment

epa.gov/national-aquatic-resource-surveys/ncca

Organization: Environmental Protection Agency

Start: 2010

Region: Entire southeast coastline

Focus: Water quality, sediment quality, benthic condition

Gulf of America Coastal Ocean Observing System

gcoos.org

Organizations: National Oceanic and Atmospheric Administration, partners

Start: 2005

Region: Gulf Coast states

Focus: Water quality, oceanographic data

Southeast Coastal Ocean Observing Regional Association

secoora.org

Organizations: National Oceanic and Atmospheric Administration, partners

Start: 2007

Region: North Carolina, Georgia, eastern coast of Florida

Focus: Water quality, oceanographic condition

National Mussel Watch Program

coastalscience.noaa.gov/science-areas/pollution/mussel-watch

Organization: NOAA

Start: 1986

Region: Along the southeastern coast

Focus: Chemical contaminants in bivalve tissues

Coastwide Reference Monitoring System

https://lacoast.gov/new/Default.aspx

Organizations: Louisiana Coastal Protection and Restoration Authority, partners

Start: 2003

Region: 390 monitoring locations across coastal Louisiana

Focus: Land change, hydrology (e.g., water level and salinity), vegetation composition and trends, vertical accretion and surface elevation trends, soil characteristics

Georgia Coastal Ecosystems Long-Term Ecological Research

gce-lter.marsci.uga.edu

Organizations: National Science Foundation, University of Georgia

Start: 2000

Region: Georgia coast

Focus: Long-term ecological research

National Water Level Observation Network

tidesandcurrents.noaa.gov/sltrends

Organization: National Oceanic and Atmospheric Administration

Start: 1850s

Region: Coastal tide gauges throughout Southeast

Focus: Sea level trends

Ocean Acidification Monitoring System

oceanacidification.noaa.gov

Organization: National Oceanic and Atmospheric Administration

Start: 2011

Region: Southeastern coastal waters

Focus: pH, carbonate chemistry

Flood Event Viewer

usgs.gov/tools/flood-event-viewer

Organization: United States Geological Survey

Start: 2017

Region: Southeastern coastal areas

Focus: Storm surge, flooding

Physical Oceanographic Real-Time System

tidesandcurrents.noaa.gov/ports.html

Organization: National Oceanic and Atmospheric Administration

Start: 1991

Region: Major ports throughout Southeast

Focus: Water levels, currents, meteorological data

Gulf Coast Ecosystem Restoration Council

restorethegulf.gov

Organization: RESTORE Council

Start: 2012

Region: Gulf Coast states

Focus: Ecosystem restoration

South Florida Ecosystem Restoration

evergladesrestoration.gov

Organizations: Federal and state agencies

Start: 1996

Region: South Florida

Focus: Comprehensive ecosystem monitoring

Harmful Algal Bloom Monitoring System

oceanservice.noaa.gov/hazards/hab

Organizations: National Oceanic and Atmospheric Administration, state agencies

Start: 1998

Region: Gulf Coast, Atlantic coast of Florida

Focus: Harmful algal bloom occurrence, toxin levels

National Coral Reef Monitoring Program

coris.noaa.gov/monitoring

Organizations: National Oceanic and Atmospheric Administration

Start: 2010

Region: Florida Keys, Flower Garden Banks National Marine Sanctuary (Texas/Louisiana)

Focus: Coral reef conditions

Coastal Carbon Research Coordination Network

serc.si.edu/coastalcarbon

Organization: National Oceanic and Atmospheric Administration, United States Geological Survey, National Science Foundation

Start: 2017

Region: Worldwide

Focus: Coastal wetland carbon science

AmeriFlux Network

ameriflux.lbl.gov

Organization: DOE Biological and Environmental Research program

Start: 1996

Region: North, Central, and South America

Focus: Ecosystem carbon dioxide, water, and energy fluxes

Florida Coastal Everglades Long-Term Ecological Research

fcelter.fiu.edu

Organizations: National Science Foundation, Florida International University

Start: 2000

Region: Florida Everglades

Focus: Long-term ecological research

Appendix F

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Appendix G

Acronyms and Abbreviations

AI	artificial intelligence
ATS	Advanced Terrestrial Simulator
BER	DOE Biological and Environmental Research program
DOE	U.S. Department of Energy
E3SM	Energy Exascale Earth System Model
EESSD	BER Earth and Environmental Systems Sciences Division
ELM	E3SM Land Model
ESM	Earth system model
FATES	Functionally Assembled Terrestrial Ecosystem Simulator
FEMA	Federal Emergency Management Agency
IPCC	Intergovernmental Panel on Climate Change
InSAR	interferometric synthetic aperture radar
LTER	Long-Term Ecological Research Network
LULCC	land-use and land-cover change
MEM	marsh elevation model
Mg CO_2eq	megagrams of carbon dioxide equivalent
ML	machine learning
ModEx	model–experiment
NOAA	National Oceanic and Atmospheric Administration
PFLOTRAN	massively Parallel reactive FLOw and TRANsport model for describing subsurface processes
PFT	plant functional type
redox	reduction–oxidation
SALTEx	Seawater Addition Long-Term Experiment
SLR	sea level rise
SPRUCE	Spruce and Peatland Responses Under Changing Environments
TEMPEST	Temperate Ecosystem Manipulation to Probe Effects of Storm Treatments
TRACE	Tropical Responses to Altered Climate
VLM	vertical land motion

Elements and Compounds

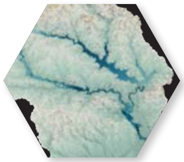
Al	aluminum
C	carbon
Ca	calcium
CH_4	methane
Cl	chlorine
CO_2	carbon dioxide
Fe	iron
H_2S	sulfide
Mg	magnesium
Mn	manganese
N	nitrogen
Na	sodium
N_2	dinitrogen gas
N_2O	nitrous oxide
NH_4^+	ammonium
NO_3^-	nitrate
O_2	oxygen gas
P	phosphorus
PO_4^{3-}	phosphate
S	sulfur
Si	silicon
SO_4^{2-}	sulfate

Appendix H

Cover Image Credits


Recent tree mortality at the forest-marsh ecotone in coastal South Carolina resulting from storm surge and subsequent beetle infestation. [Courtesy Tom O'Halloran, Clemson University]


Aerial view of Clear Lake in League City, Texas, during Hurricane Harvey. [Courtesy Adobe Stock]


Inundation pattern for a compound flooding event in the Neches River Basin of Southeast Texas as simulated by an integrated surface and subsurface hydrology model, the Advanced Terrestrial Simulator. [Courtesy Oak Ridge National Laboratory]

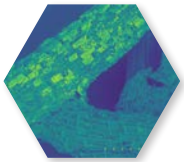

Marsh in South Carolina. [Courtesy Adobe Stock]


Aerial view of coastal Boca Raton, Fla. [Courtesy Adobe Stock]


Red mangroves on the shore of West Lake in Everglades National Park. [Courtesy Adobe Stock]


Cape Hatteras National Seashore, Outer Banks in North Carolina. [Courtesy Adobe Stock]


Shallow groundwater wells installed in a freshwater coastal delta in Louisiana. [Courtesy Oak Ridge National Laboratory]


False-color scanning electron microscopy image of a *Carex aquatilis* root encrusted with iron oxide minerals. [Courtesy Oak Ridge National Laboratory]


Map of land cover and watersheds in the southeastern coastal United States. [Courtesy Chris DeRolph, Oak Ridge National Laboratory]