SE CASC Coastal Resilience Working Group

July 31, 2021

Part I. Report Summary

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Introduction

The southeastern United States (SEUS) has experienced multiple stresses in climate, land use and sea level rise in the past century and this is expected to continue through the rest of this century (USGRP, 2018). These multiple stresses have affected and will continue to affect the ability of ecosystems to provide people with essential goods and services (Pan et al., 2015; Tian et al., 2012). The Fourth US National Climate Assessment (USGRP, 2018) indicates that the SEUS is vulnerable to the adverse impacts of climate change, and is already experiencing increased impacts of persistent extreme weather events. Rapid environmental changes may create greater stress on water resources and ecosystems. For example: higher-than-average sea level rise rate (> 3 mm/yr) is projected in part of the Gulf of Mexico Coast regions (Gleick et al., 2013; Hammar-Klose and Thieler, 2001; Vermeera and Rahmstorf, 2009), extreme climatic events (droughts, hurricanes) would occur more frequently and cause significant stress and shortfalls on water resources (Karl et al., 2009; Li et al., 2011; Oki and Kanae, 2006; Rauscher et al., 2011).

It is within this context that great emphasis is being placed by governments, stakeholders, and researchers on fostering resilient communities and resilient systems (National Academy of Sciences, 2012). Resilience to climate change and other natural hazards has been defined as the ability of communities to prepare for, absorb, recover from, and successfully adapt to actual or potential adverse events (National Academy of Sciences, 2012; Cutter et al., 2013). To address the complexity of adequately depicting risk and resilience to climate-related hazards, and to improve predictability, there is a critical need for methodological advancements that integrate multiple layers of information. Of significance is gaining a better understanding of the drivers of resilience that occur within coastal ecosystems for an improved understanding of how natural, social and built systems interact to create differential impacts and recovery potential. In the absence of such advancements, disparities in the resilience of communities will remain uncertain, and decision-making efforts to reduce climate-related coastal impacts may be misguided and fail.

The Coastal Resilience Working Group (WG) of the Southeast Climate Adaptation Science Center (SE CASC) aims to understand the needs, gaps, and opportunities for coastal resilience in the region through developing a network of researchers leveraging existing efforts and stakeholder connections. It is composed of key researchers identified from each of the SE CASC consortium universities (Auburn University, Duke University, North Carolina State University, University of Florida-Gainesville, University of South Carolina, and University of Tennessee-Knoxville) and includes United State Geological Survey (USGS) researchers (see Table 1). The WG held semi-monthly meetings since January 2020 with 10-12 researchers participating in each meeting where common interests and areas of expertise were shared. Through these meetings, areas of greatest opportunity and needs that were aligned with the USGS SE CASC mission were identified: Coastal Modeling, Coastal Restoration and Ecosystem Management, Climate and Coastal Hazard Modeling, and Policy and Communication. Two of these themes, Coastal/Climate Modeling and Coastal Restoration/Management, were selected for more robust exploration and literature review for potential areas of continued investigation by the working group. A synopsis of these thrust areas are included as weblinks in this report: Part II: Land-Ocean Continuum Modeling and Part III: Watershed Modification Effects on Coastal Ecosystems. An additional task was completed by the working group where the Southeast Coastal Resilience Organization Database was developed to assist those interested in coastal resilience in the southeastern United States to quickly find others doing related work. The list includes organizations involved in research, advocacy, stewardship, education, and funding. Anyone can add new organizations to the database, and users can explore the full list of organizations, search for certain types of organizations, and view summaries of the roles, types, and geographic scopes of organizations in the database. The WG culminated the year's activities with a session at the Carolinas Coastal Resilience Conference in April 2021 to reach out to additional partners in order to expand the group and to receive feedback. This session included 25 attendees from multiple universities, federal and state agencies and non-governmental organizations, many of whom indicated their interest in collaborating with the group and attending future events.

Table 1. List of 2020-2021 Coastal Resilience WG Participants, Roles, and Areas of Expertise.

Participant	Affiliation	Role	Expertise
Leadership			
Karen McNeal	Auburn University	CASC Co-Lead	Climate Communication and Co-Production Assessment
Lydia Olander	Duke University	CASC Co-Lead	Metrics for tracking and reporting on social and economic benefits of coastal restoration
Wendy Graham	University of Florida-Gainesville	CASC Co-Lead	Director, Water Resource Institute
Mary Watzin	North Carolina State University	CASC Co-Lead	Coastal Resilience and Sustainability Initiative at NC State
Cari Furiness	North Carolina State University	CASC Co-Lead	NC State SE CASC Program Manager
Mike Allen	University of Florida	Coastal Restoration Co-Lead	Population dynamics and ecology of fishes
Hanqin Tian	Auburn University	Coastal/Climate Modeling Co-Lead	Ecosystem modeling under climate change
Brad Murray	Duke University	Coastal/Climate Modeling Co-Lead	Downscaling of climate forecasts for coastal conditions (waves and wind) for the Carolinas
Participants			
Latif Kalin	Auburn University	Presenter	Land-use change, watershed and wetlands modeling
Kelly Dunning	Auburn University	Presenter	Coastal policy making for recovery of infrastructure

Francis O'Donnell	Auburn University	Presenter	Saltwater intrusion modeling and coastal planning
Brian Silliman	Duke University	Presenter	Role of species interactions in coastal restoration
Katie Warnell	Duke University	Data Base Developer	Modeling salt marsh migration, blue carbon and coastal protection for states
Christine Angelini	University of Florida	Presenter	Center for coastal solutions at the University of Florida; integration of ecology and restoration engineering
David Kaplan	University of Florida	Presenter	Hydrological, ecological and human drivers of coastal change
Katy Serafin	University of Florida	Presenter	Flooding and erosion hazards in a changing climate
Maitane Olabarrieta	University of Florida	Presenter	Improving coastal hazard forecasts; simulating total water levels during tropical cyclones
Holden Harris	University of Florida	Presenter	Population dynamics and ecology of fishes
Scott Alford	University of Florida	Participant	Population dynamics and ecology of fishes
Karen Schlatter	University of Florida	Participant	Research Coordinator, Water Resources Institute
Gavin Smith	North Carolina State University	Presenter	Disaster response and resilience, relocation policies
Casey Dietrich	North Carolina State University	Presenter	Shoreline engineering and management
Dave Eggleston	North Carolina State University	Presenter	Coastal Ecosystems and oyster management
Roy He	North Carolina State University	Presenter	Coupled air-sea climate modeling and prediction
James Cronin	USGS	Presenter	Strategic habitat conservation for the Gulf Coast
Mitch Eaton	USGS	Presenter	Adapting coastal systems with climate uncertainty: correlated risks in spatial planning
Mike Osland	USGS	Presenter	Climate change and sea-level rise effects on coastal wetlands
Simeon Yurek	USGS	Presenter	Spatial conservation planning, optimal decision making for coastal resilience

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Part II. Research priority: System-based modeling of the Land-Ocean Continuum (LOC)

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Introduction

Coastal ecosystems and landscapes are experiencing increased climate stressors including frequent floods, powerful storm surges, intense hurricanes and rising sea levels, and these stressors are likely to escalate in the coming years. In addition, the increasing human population along the coast, with resulting land use change and urbanization, imposes multiple additional stresses (including altered freshwater discharge, elevated nutrient loads and altered sediment export, increased water temperatures, etc) which pose threats to the resilience and health of coastal ecosystems and communities. From both scientific and management perspectives, it is essential to develop a systems modeling framework that incorporates terrestrial, coastal and aquatic processes and drivers along the Land-Ocean Continuum (LOC) to improve our understanding and forecasting ability, as well as to facilitate coastal resilience and adaptation to multiple stresses.

Price and Rosenfeld (2012) noted 27 products or services desired to meet stakeholder needs in the areas of coastal, beach, and nearshore hazards; water quality; marine operations; ecosystems and fisheries; and long-term climate change. Two-thirds of these products and services require results from models. The Price and Rosenfeld (2012) synthesis study identified, as a core requirement across all regions, the development of modeling capabilities be developed to deliver analyses and forecasts, on appropriate time and space scales, for land use and land change, ocean circulation, waves, inundation, water quality, and ecosystems.

Need for Coupled Modeling

Terrestrial, intertidal, and aquatic ecosystems react coherently to multiple stresses, and thus assessment of coastal resilience requires a Land-Ocean Continuum (LOC) modeling framework which fully couples the physical and biogeochemical processes of terrestrial and freshwater and coastal landscapes and ecosystems. Originally, this concept arose in the context of full carbon accounting inland system (Regnier et al. 2013; Tian et al. 2015), which calls for a consideration of both vertical and lateral carbon fluxes along the land-ocean continuum (Figure 1 and 2). In addition, researchers have come to realize that changes in water and sediment delivery rates, arising from terrestrial land-use and water management changes, can strongly affect the expansion or loss of intertidal habitats and ecosystems, including tidal marshes (e.g. Kirwan and Murray, 2011; Braswell and Heffernan, 2019). An expansion of the LOC research scope to include the regional nitrogen and phosphorus cycles and fluxes of sediment and biological material (e.g. cyanobacterial blooms) in the coastal region, highlighting the importance of integrating terrestrial and aquatic components as a whole system, is required.

Current modeling tools lack the ability to represent the synergistic effects between land, aquatic, intertidal and nearshore systems. For example, land models simulate the carbon, nitrogen, and water dynamics within the land, but do not explicitly address the leaked fluxes of carbon, nutrients, biological materials, and sediment to the inland waters. River models and coastal models, which allow simulations of water flow, water quality, and landscape/habitat change can not well address the changes in inputs arriving from land models in the context of anthropogenic impacts. Although most watershed models have both land and riverine components, the model structure of the land components in these models are simplistic, hampering their ability to forecast complex ecosystem response to global environmental change. Therefore, the current practice of linking terrestrial and coastal models through boundary conditions is not sufficient; instead, more closely coupled or integrated models that reproduced complex feedbacks and interactions are urgently needed.

System-based modeling of the LOC is one of the most promising future research topics to advance our understanding and prediction of coastal resilence. One of the critical components is to better represent the coupling of terrestrial and coastal processes, in ways that explicitly consider plant phenology, bio-physics, soil biogeochemistry, land-atmospheric interactions, and riverine fluxes of water, carbon, nutrient, biological materials, and sediment. In addition, extensive water extraction and allocation substantially changes the water cycle and associated nutrient cycles which can result in a reversal of mass exchange from the aquatic system to the land ecosystem. The scientific community needs to work on fully coupling land, river, lake, coastal wetland, estuarine, and nearshore processes, to understand the overall system holistically.

Need for Synergistic Modeling and Observation System Advances

To facilitate the development of LOC models, monitoring and measuring systems require significant improvements. Since most of the observations of inland waters are located near the river outlet, the net exports of water flow, carbon, and nutrient are relatively well constrained, but less information is available for estimating mass losses such as carbon and nutrient loading, sedimentation, and degassing, within coastal environments (estuaries, bays and intertidal wetlands), but upstream of the river outlet. To better understand these lateral fluxes of water, carbon nutrients and sediments at the LOC, we need a better monitoring system that combines advanced *in-situ* and remote sensors to reduce the uncertainty of the associated key variables. For instance, the water surface area of ephemeral streams and wetlands requires a high spatial and temporal resolution remote sensing datasets. Also, identifying the sources of carbon, nutrient and sediment loading to the LOC requires continuous *in-situ* sensor measurements and *in-situ* experiments to support the development and parameterization of empirically grounded LOC models.

Advances in modeling capabilities can drive improvements in observational capabilities, as well as the reverse. A principal goal of system-based modeling of the LOC can be summarized as enhancing the values of observations through model-based synthesis and data assimilation to provide robust and reliable past, present, and forecasted LOC conditions to underpin science-based climate change solutions. A second, equally important goal is to apply models to observing system design and operation to help optimize the observational suite and thereby further enhance model-based outputs. Guided by these principal goals, we list below a number of priorities areas that should be pursued in as part of a concerted community effort to advance modeling technologies, sustain continuous improvement in model skills, and development of new and enhanced model-based products to better address climate change challenges and societal needs in coastal resilience and sustainability:

(1) Model coupling, emphasising improvements to terrestrial and marine state realism through coupling technique developments applicable to land surface, rivers, ocean circulation, waves, atmosphere, ecosystem, and other components.

(2) Data assimilation (DA), including research and development on DA methods, and DA-system inter-comparison frameworks emphasising use of the full suite of terrestrial and marine observations, including ecological data.

(3) Nearshore processes, linking land-ocean continuum analyses with models of groundwater flow, wetlands, estuaries, surf zone dynamics, coastal geomorphology and sediment transport, discharge and plume dispersion, pathogens, harmful algae, and biogeochemistry.

(4) Data sharing and model skill assessment, including development of a pan-regional model-data portal built on standardised web services, and comprehensive tools and benchmarks for interoperability, modeling metrics, and skill assessment.

(5) Modeling for observing system design, evaluation, and operation, using observing system simulations, network gap analysis, sensitivity analysis to implement and evaluate an effective and efficient Land-Ocean Continuum observing system.

(6) Ensemble prediction, developing probabilistic prediction methods for terrestrial, aquatic and marine states, extreme events (e.g., tropical cyclones, flooding, and erosion), and delivering quantitative uncertainty estimates for models and products.

Need for Downscaling of Coastal Climate Forcing From Global Forecasts

In addition, if models are to be useful for forecasting changes in the LOC, downscaled forecasts of coastal climate scenarios will be needed as input. The downscaled forecasts will need to include not only temperature and precipitation statistics, but also the climatology of other variables that drive events and changes in coastal systems, especially involving wind, waves, and water levels. Downscaling from global climate model forecasts to regional and local coastal specific variables is a relatively new endeavor, presenting valuable opportunities.

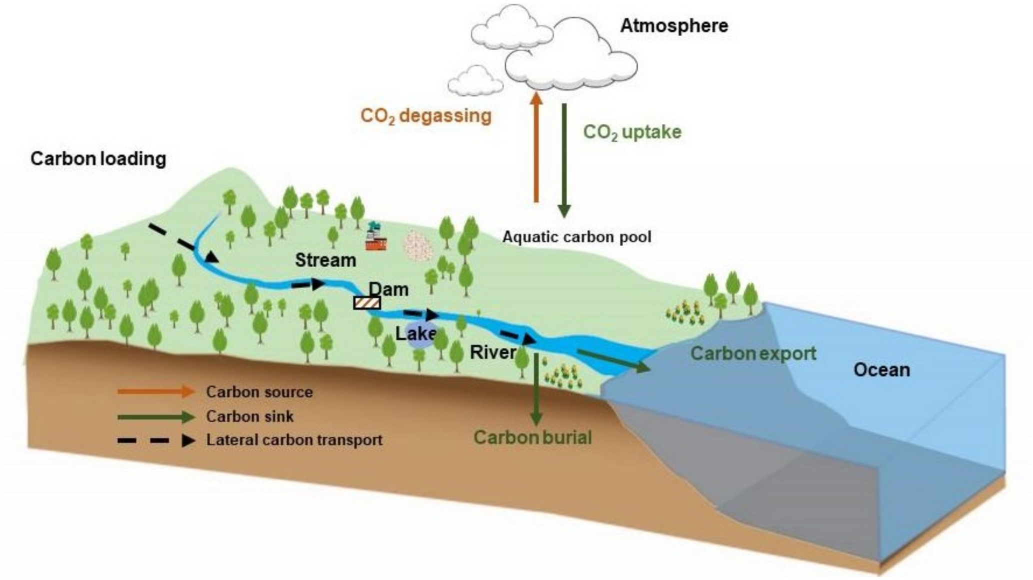

Figure 1. Schematic of the Land-Ocean Continuum (LOC) with special emphasis on vertical and lateral carbon fluxes along the LOC.

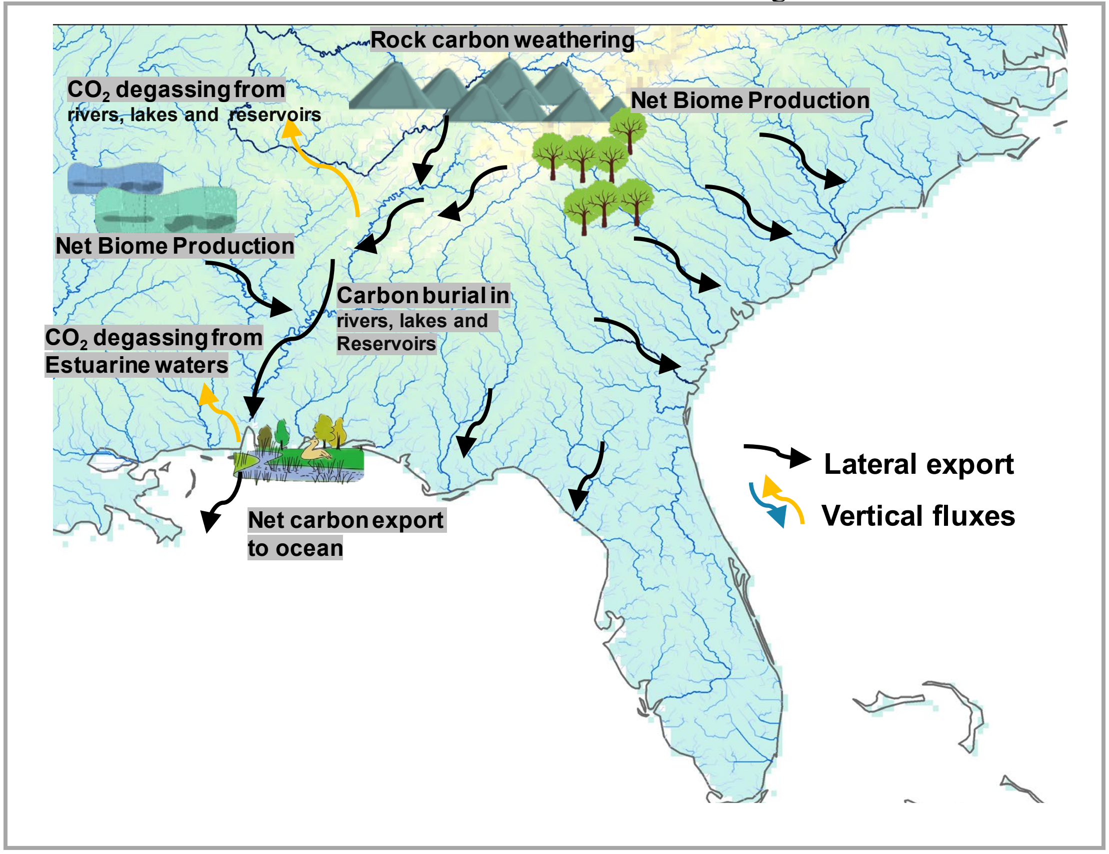

Figure 2. Spatial diagram for vertical and lateral carbon cycling at the Land-Ocean Continuum (LOC) over the southeastern United States

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Part III. Watershed Modification Effects on Coastal Ecosystems: A Synthesis from Selected Gulf of Mexico Estuaries

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Introduction

As urbanization and agriculture continues to expand to meet the needs of growing human populations, so do their effects on water resources (Broussard et al. 2009). Freshwater inputs into estuarine systems drive estuarine environmental conditions (e.g., salinity and turbidity), habitat availability, sedimentation, eutrophication, or pollution (Alber 2002). These environmental drivers the ecological processes for coastal fisheries and natural-resource dependent economies (de Mutsert et al. 2012). Climate change is expected to directly affect estuarine environmental conditions and freshwater flow rates into estuaries via changes precipitation, evaporation and evapotranspiration rates (Hernández-Bedolla et al. 2017). Further expected impacts from a changing climate include sea level rise, which will bring saline waters into estuaries [citations], and increased frequency and intensity of hurricanes. These cause direct physical damages to foundation species (e.g., oyster reefs and seagrasses) and can heighten pollutant and nutrient loads due from terrestrial runoff (Edmiston et al. 2008). Effective management to sustain coastal ecosystems will require understanding the potential for compounded impacts from land/water use and climate change on freshwater quality and quantity.

The purpose of this white paper is to evaluate examples of landscape-level processes in estuaries and develop a framework to conceptualize and consider management challenges across

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broad spatial scales. This white paper will be revised for publication in a peer-reviewed journal by fall of 2021, and we hope the draft will solicit friendly review comments from the partners in the Climate Adaptation Science Center. We conducted four case study examples of northern Gulf of Mexico (GoM) estuaries and their watersheds to identify both their unique characteristics and the common drivers relevant to maintaining healthy estuaries. One more case study for Galveston Bay is also planned. From these, we developed a conceptual model to generalize the pathways for how climate, land use, and water management affect estuarine food webs. Our model updates previous conceptual frameworks with contemporary research. Gentile et al. (2001) developed a risk-based model of ecosystem management for South Florida's regional and coastal ecosystems to scenario-test linkages between societal actions, environmental stressors, and social-ecological effects. Soon after, Alber (2002) developed a generalized conceptual framework for estuarine freshwater provisioning management in which the quantity, quality, and timing of water input drove physical estuarine conditions that determined, production and living resources. This model updated by Palmer et al. (2011) with case studies of different estuarine systems (bays, lagoons, or tidal rivers) to more explicitly considered the downstream effects on the integrity, diversity, functionality, and sustainability of an estuary's living resources. Compared to previous models, we more specifically consider drivers of water availability between broad climatic forcing and local human use and management, consider eco-environmental feedback pathways, and specifically define the affected estuarine living marine resources.

Case Studies

Our case studies are organized into three basic parts: i) general estuary characteristics, ii) threats to the system and its resources, and iii) management and restoration efforts to address these. We then synthesize these threats into a conceptual model to describe linkages and feedbacks.

Mississippi River Basin

The Mississippi River basin (MRB) is the largest watershed in North America and third largest in the world (Milliman and Meade 1983). It drains approximately 3.3 million km^2 of land (40% of the continental United States) and provides the GoM with ~81% of its freshwater input through joint discharge through the Balize Delta and Atchafalaya River (Aulenbach et al. 2007).

Sediment deposition by the MR created Louisiana's Deltaic Plain (i.e., the Mississippi River Delta), stretching from the west side of Vermillion Bay in central Louisiana (eastern edge of the Chenier Plain) to the eastern side of the state. Southeastern Louisiana is comprised of extensive marshes (Sasser et al. 2014) that support rich coastal ecosystems, including economically important fish and invertebrate species (Hollweg et al. 2020, Baker et al. 2020). Louisiana's commercial landings are dominated by estuarine-dependent species (e.g., penaeid shrimps [Family Penaeidae], Gulf menhaden *Brevoortia patronus*, and blue crab *Callinectes sapidus*), which are some of the most valuable fisheries in the United States (NMFS 2018).

Increased MRB nutrient loads, primarily nitrogen but also phosphorus and silica, associated with changes in land use across the MRB have created one of the world's largest areas of hypoxic water, the GoM dead zone (Rabalais et al. 2002, Turner and Rabalais 2003). The MRB experienced heavy deforestation throughout the 1800s, with much of the cleared land being converted to farmland in the U.S. Midwest throughout the 1900s (Turner and Rabalais 2003). Spatial expansion of farmland in the last century has been relatively modest (11.5% increase), but industrial farming practices have decreased crop diversity, with a notable focus on corn production in the U.S. Midwest (Broussard and Turner 2009). This has contributed to higher nitrogen loads within the MRB that are subsequently inputted into the GoM (Turner and Rabalais 2003, Broussard and Turner 2009), leading to unprecedented phytoplankton productivity. Decaying organic matter in bottom waters from these blooms depletes dissolved oxygen levels and leads to massive areas inviable to many species, creating "dead zones" (Rabalais et al. 2002).

Alteration of coastal Louisiana's hydrology has reduced sedimentation in its delta and contributed to large-scale erosion and loss of wetlands. The U.S. Army Corps of Engineers (USACE) and Mississippi River and Tributaries Project began construction of levees along the MR in Louisiana after the 1920s to reduce flooding risk to residents of south Louisiana, including the city of New Orleans, and to minimize sedimentation of shipping channels (Kemp et al. 2014). Confining the MR to its current path restricts sediment delivery to other parts of the delta and inhibits land accretion processes derived from natural changes in the river's path. Extensive canal dredging, largely for the oil and gas industry from 1950-1980, has also contributed to sediment disturbance and land loss (Turner 1997). Reduction in sediment delivery and sediment destabilization combined with natural forms of land loss (e.g., subsidence and rising sea levels) is driving rapid wetland loss; peak land loss rates in the 1970's was ~83.5 km^2 per year and the current rate of loss is 28 km^2 per year (Couvillion et al. 2017).

State and federal entities are working to manage and mitigate this wetland loss threatening coastal resources. In 1990, congress passed the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA; Boesch et al. 1994) to fund large-scale restoration of coastal Louisiana and the Coastal Restoration and Protection Authority's (CRPA) Master Plan (coastal.la.gov). The current iteration of this initiative invests $50 billion to projects for 2017 to 2022 designed to maintain Louisiana's coast (CRPA 2017). Half of the budget of Louisiana's 2017 Master Plan is dedicated to risk reduction that includes maintaining structures such as levees (CRPA 2017). The other half is dedicated to restoration, primarily in the form of marsh creation ($17.8 billion) and sediment diversions from the MR ($5.1 billion; CRPA 2017). The Environmental Protection Agency (EPA) created the Mississippi River/Gulf of Mexico Hypoxia Task Force (HTF) to research and monitor the GoM dead zone and create plans to reduce nitrogen and phosphorus inputs into the MRB through state and federal programs (EPA 2017). These efforts represent large-scale collaborations of up-stream and down-stream stakeholders along the MRB using management within the watershed to address coastal issues.

Though these efforts are intended to resolve major issues facing coastal Louisiana, there are multiple initiatives, and their implementation requires balance of diverse interests. Management of nutrients released from agriculture in the MRB requires federal incentives to buffer potential loss of profits incurred by farms to employ reduced fertilizer use and higher crop diversity (EPA 2017). River diversions used to reduce flooding risk along the MR alter environmental conditions (e.g., salinity, turbidity, and inundation) and introduce sediment to eroding wetlands. Intense or prolonged environmental changes redistribute organisms, altering food webs and resulting in winners and losers among species and fisheries (de Mutsert et al. 2012). Similar to conflicts of interest derived from nutrient management along the MRB, management of discharge at the mouth of the MR has resulted in interstate conflicts due to losses of natural resources. For example, mortality to oyster stocks occurred in the Mississippi Sound after opening of the Bonnet Carré Spillway (Posadas et al. 2017), and changes in water flow characteristics has strong implications for fish recruitment. These large-scale projects clearly require integrated approaches to balance objectives and potential costs across spatial and temporal scales of efforts.

Apalachicola Bay

Apalachicola Bay is a wide and shallow estuary (mean depth 2.6 m) approximately 63,000 ha confined hydrologically from the Gulf of Mexico by a network of narrow east-west oriented barrier islands. Hardbottom in the estuary consist of extensive oyster reefs that are predominantly subtidal and that spatially cover 1,600–4,000 ha (Grizzle et al., 2018, 2019). Water quality conditions in the estuary are considered excellent due to the low population density of the Florida coastal Big Bend region (Havens et al., 2013; zu Ermgassen et al., 2013; Grizzle et al., 2019). Approximately 90% of the estuary's freshwater is delivered by the Apalachicola River, Florida's the largest river in terms of flow, which discharges freshwater at rates ranging from approximately 550–1,800 m^3s^{-1}. Over 80% of this water in the Apalachicola River drains from the upstream Chattahoochee and Flint watersheds. Collectively, the Apalachicola-Chattahoochee-Flint (ACF) basin is one of the largest watersheds in the United States and encompass >50,000 km^2 of land. The human population in the ACF basin is over 7 million with the majority of this concentrated in the metropolitan area of Atlanta, Georgia (Camp et al., 2015). The basin also includes large areas of intensive agriculture that use irrigated water from its groundwater.

The case study of Apalachicola Bay is unfortunately notable due to the sudden and catastrophic collapse of its 150+ year old oyster fishery in 2012. Before this oyster populations here were demonstrably healthy and robust (Beck et al., 2011; zu Ermgassen et al., 2013). The fishery supported approximately 2,500 jobs (Havens et al., 2013) and its annual landings comprised approximately 90% of oyster landings in the state and 10% of oyster landings in the country (Pine et al., 2015). A suite of post-hoc investigations has not identified a primary driver for the collapse, but rather collectively describes complex interactions of environmental and anthropogenic drivers. A stock assessment of the oyster fishery concluded that it was not being overfished in the traditional sense where spawning stock biomass was reduced to levels that reduce subsequent recruitment (Pine et al., 2015), but the assessment suggested harvest may have contributed to the removal of shell substrate needed for larval settlement (Pine et al., 2015). Studies of collapsed oyster populations in the Chesapeake Bay indicate that degradation of the geometry of oyster reefs caused by harvest will contribute to a recruitment failure (Wilberg et al., 2013; Colden and Lipcius, 2015; Colden et al., 2017). Considerable attention and scrutiny has been paid to altered environmental conditions in the bay and hydrology of the ACF. In 2012, the ACF basin had been experiencing a multi-year drought and the resulting low river flow led to increased salinity in Apalachicola Bay for a multiyear period (Havens et al., 2013; Camp et al., 2015; Fisch and Pine, 2016). High estuarine salinity levels (generally >25 psu) reduce oyster feeding and growth (Livingston et al., 2000; Wang et al., 2008; Ehrich and Harris, 2015) and concomitantly increase mortality rates in oysters from disease (La Peyre et al., 2009; Petes et al., 2012) and predation (Garland and Kimbro, 2015; Kimbro et al., 2017, 2020; Pusack et al., 2019).

The relative degree to which water withdrawals contributed to these reductions in freshwater discharge and the Apalachicola Bay oyster collapse exemplifies the potential for upstream-vs-downstream stakeholder conflict. Water rights disputes between Florida, Alabama, and Georgia concerning the ACF basin date back to the 1980s (Grizzle et al., 2019). In 2013 the state of Florida filed an injunction against Georgia and requested relief damages with the argument that Georgia's inequitable water consumption had and continues to damage the ecology and economy of Apalachicola Bay (Lancaster, 2017). Following the eight-year legal dispute the U.S. Supreme Court ruled unanimously to dismiss the case (United States Supreme Court 2021). Justice Amy Coney Barrett stated in the court opinion that Florida did not meet the burden of proof that Georgia's water was the cause of harm but, also, "we emphasize that Georgia has an obligation to make reasonable use of [ACF] Basin waters in order to help conserve that increasingly scarce resource" (United States Supreme Court 2021).

The Apalachicola Bay oyster fishery has not recovered nor demonstrated signs that recovery is imminent. Oyster landings in 2019 were less than 10,000 kg and represent a 99% decline compared to the 5-year average of landings prior to the collapse, compelling the Florida Fish and Wildlife Conservation Commission (FWC) to declare a five-year moratorium on oyster harvest until at least December 2025 (Norberg and Estes, 2020). The FWC is concurrently beginning restoration efforts with $20 million of support from the National Fish and Wildlife Foundation's (NFWF) Gulf Environmental Benefits Fund, with $17 million of the NFWF grant dedicated towards deploying reef material for recruitment. Reef construction expected to begin in 2022 (Norberg and Estes, 2020). The precipitation-hydrological model forecast by Neupane et al. (2019) predicts that flow rates, on average, will remain relatively stable in the Apalachicola River over the next 30–50 years even under the RCP8.5 climate scenario.

Suwannee River Estuary

The Suwannee River is one of the largest undammed rivers in the Eastern United States, flowing 450 km and draining approximately 25,000 km^2 of north central Florida and south central Georgia (Garrett and Conover, 1984). Its lower watershed has strongly coupled surface water and groundwater with spring flow from the Floridian aquafer (Cohen, 2008; Mitra et al., 2014). The river mouth drains into the Suwannee Sound between Horseshoe Point and Cedar Key. Brackish waters in the estuary extend up to tens of kilometers offshore due to the relatively high riverine input, low topography, and low wave energy (Radabaugh et al., 2021). This region of Florida's "Nature Coast" are characterized by extensive sea grass meadows, intertidal oyster reefs, salt marshes, and black mangroves, and the region is recognized for its significance to conservation (Williams et al., 1999; Beck and Odaya, 2001; Southwick Associates, 2015). The coastline and watershed are relatively undeveloped with lower human population densities compared most coastal communities in the USA. Jobs in natural resources (e.g., fishing, forestry, farming, or tourism) also contribute a substantial portion to the Nature Coast economy with 13% of the jobs here directly dependent on natural resources compared to 1% of jobs in Florida overall (Southwick Associates 2015).

Forecasted changes in land-use, human population, and climate are expected to alter the region's interlinked hydrology, ecology, and economy. Human population growth is predicted to increase 30–75% by 2040 (Smith and Rayer, 2014). Large areas of cordgrass *Spartina alternifloa* have converted to mangroves, primarily *Avicennia germinans* (Stevens et al., 2006; Scheffel et al., 2017; Langston and Kaplan, 2020) and populations of common snook *Centropoums undecimalus*, a large and piscivorous fish, have recently established populations in the region (Purtlebaugh et al., 2020). The greatest threat to the Nature Coast system will be how water provisioning from the Suwannee River will impact the estuary's hydrology and salinity (Kaplan et al., 2016), and the cascading impacts this will have on regional coastal resources. Despite having relatively low anthropogenic disturbances, oyster reefs in the Suwanee River estuary have declined 66% between 1982 and 2011, with the greatest reef loss (88%) occurring on offshore oyster bars (Seavey et al., 2011). Research on this from the last decade support Seavey et al.'s

(2011) hypothesis that a cascading loss of offshore barrier oyster reefs reduced freshwater detention and protection of wave action, which led to a further collapse of reefs (Fisch and Pine, 2016; Frederick et al., 2016; Kaplan et al., 2016; Moore et al., 2020). The combination of lower salinity and projected warmer summer temperatures are further expected to increase oyster mortality (Rybovich et al., 2016; Southworth et al., 2017; Thomas et al., 2018). Phytoplankton levels are also affected by river discharge (Bledsoe and Phlips, 2000) which, in turn, affect primary production and food web dynamics (Sinnickson et al., 2021a) as well as the Cedar Key hard clam aquaculture industry worth roughly $40M (Adams et al., 2014). Under the RCP8.5 IPCC climate and precipitation scenario, mean annual streamflow in the Suwannee River during the 2080s will be 13% lower than it is currently and summer streamflow will be 25% lower compared to present day (Neupane et al., 2019). Water withdrawal in the Suwannee River Management District for agriculture has increased 5-fold between 1980 and 2010 (Marella, 2014), and land-use changes in the region from converting forestry to agriculture or urban development will require higher water withdrawals in the future.

Current work on these issues includes long-term monitoring programs, large-scale reef restoration, and integrative modelling. Long-term data exists for river flow (available: waterdata.usgs.gov/02323500), water quality (T. Frazer, unpublished), fisheries independent monitoring (Florida Wildlife Conservation Commission [FWCC]), and oysters (Frederick et al., 2016; Radabaugh et al., 2021). Oyster reef restoration efforts in the estuary began following Seavey et al. (2011). In 2018, large-scale restoration of the Lone Cabbage Reef (LCR) was completed (Frederick et al., 2016; Moore et al., 2020) and reef monitoring has been conducted as part of the LCR project since 2011 (available: github.com/LCRoysterproject). The scale of the LCR reef reconstruction (5-km long, 8-years, $7 million) represents an attempt to restore historic hydrological regimes (Kaplan et al., 2016). Recent integrative modeling research has been initiated to understand and forecast the ecological and economic impacts of land-use and climate change on the Suwanee River estuary's coastal food webs and fisheries.

South Florida

South Florida was originally a mosaic of wetland landscapes covering 36,000 km^2 that drained from the Kissimmee River into Lake Okeechobee and through the Everglades before emptying into both the GoM (from Ten Thousand Islands to Florida Bay) and the Atlantic Ocean

(Biscayne Bay). Marsh, forest, grassland, and swamp habitats are interconnected by slow sheet flow throughout the system, creating extensive habitat that supports the area's unique and diverse ecosystem. Endemic species include numerous wading birds, Florida panther, and the only crocodile species in the U.S. The Everglades is one of the largest wetlands in the U.S. and holds international significance as a World heritage Site (nps.gov/ever). On the coast, extensive mangrove forests and seagrass beds support estuarine ecosystems that have created some of the most iconic coastal recreational fisheries in the U.S.

Extensive hydrological modification has been made to South Florida to meet the needs of the region's growing population and agricultural industry. Efforts to drain and develop South Florida began in 1800s with the federal Swamplands Act enacted in 1850 to make civic infrastructure possible (Light and Water 1994). A large-scale network of canals, including the two canals to hydrologically connect Lake Okeechobee east to the Atlantic Ocean through the St. Lucie Canal and west to the GOM through the Caloosahatchee Waterway, were constructed to drain more of the region, allow homes and navigable shipping canals, and protect from flooding. In 1948, U.S. Congress passed legislation to create the Central and Southern Florida Project, the largest civil works project at that time, allowing the USACE and Central and Southern Florida Flood Control District (predecessor of the South Florida Water Management District, SFWMD) to construct three large Water Conservation Areas (current cumulative area: ~3,500 km^2) between Lake Okeechobee and the Everglades for water management and flood protection, continuing drainage and disruption of natural sheet flow. This initiative also created the Everglades Agricultural Area south of Lake Okeechobee, facilitating agriculture in the region that has become a major industry for Florida. Agriculture production here is dominated by sugar cane (highest production in the U.S. from Florida) along with citrus (44% of U.S. production from Florida), and cattle (18th largest in the U.S.) (FDACS 2019). The region has become heavily urbanized with populations expanding in Miami-Dade, Broward, Palm Beach, and Monroe counties beginning in the 1950s (Light and Walter 1994); more than 40% of Florida's human population now the region (CERP 2020). Approximately one third of South Florida's wetlands have been drained, including approximately half of the Everglades, reducing freshwater flow in the system by ~70% (SFERTF 2020).

Anthropogenic landscape alterations caused large-scale damage to South Florida's coastal ecosystems. Expulsion of nutrient loaded water from Lake Okeechobee through the Caloosahatchee and St. Lucie Rivers contributes to more frequent and larger harmful algal blooms (HABs) on both Florida's Gulf and Atlantic Coasts (Heil and Muni-Morgan 2021). These blooms can cause severe ecological damage, creating fish and marine mammal kills, and pose human health risks through exposure to toxins released by organisms causing the blooms either directly or through accumulation in seafood. Reduction in freshwater inflow into Florida Bay has contributed to mass die-off of seagrasses (Hall et al. 2021) and sponges (Butler and Dolan 2017) within the bay. Both serve as foundation species, facilitating ecosystem function by improving water quality, being key components in nutrient cycling, and providing habitat for numerous marine species. Coastal development has led to loss of South Florida mangrove forests that provide habitat for numerous estuarine species and shoreline stabilization. South Florida now has the highest concentration of invasive species in the U.S., including plants (e.g., Brazilian pepper *Schinus terebinthifolia*) and predators (Burmese pythons *Python bivittatus*), that have caused landscape-scale modification to the system and declines in native species (SFERTF 2020).

Federal and state efforts have shifted to strategies that could potentially restore natural hydrologic processes in South Florida. The federal Water Resources Development Act (WRDA) of 1996 allocated financial resources to the restoration of South Florida's hydrology and ecosystems and created the South Florida Ecosystem Restoration Task Force (SFERTF). The SFERTF is a cooperation between seven federal (USACE, EPA, Department of Agriculture, National Oceanic and Atmospheric Administration, Department of Transportation), two tribal (Miccosukee Tribe of Indians of Florida and Seminole Tribe of Florida), and five state and local government (SFWMD, Florida Department of Environmental Protection, Miami-Dade County, City of Sanibel) entities to coordinate restoration efforts in South Florida. Further federal support to the SFERTF is provided by the U.S. Department of Interior's Office of Everglades Restoration Initiatives (OERI) by coordinating restoration and management efforts with the National Park Service (NPS), Fish and Wildlife Service (FWS), U.S. Geological Survey (USGS), and Bureau of Indian Affairs (BIA). The WRDA of 2000 enacted the Comprehensive Everglades Restoration Plan (CERP; largely led by USACE and SFWMD) to allocate $10.5 billion to restoration of South Florida hydrology and ecosystem health during the subsequent 35 years, making it the largest restoration plan in U.S. history (CERP 2020). These major restoration initiatives include hydrological restoration of sheet flow within the region, water supply planning to help combat saltwater intrusion and hypersalinity on the coast, water quality improvement within Lake Okeechobee and entering the Everglades, land acquisition, habitat conservation, control of invasive species, and flood protection (SFERTF 2020). The CERP is currently estimated at $23.158 billion with $1.3 billion spent during the last iteration (2015-2020, CERP 2020).

Conceptual model and synthesis

The social and ecological systems underpinning each of these GoM watershed-estuary case studies are unique. Their histories exemplify complex contemporary challenges for managing alterations in how estuaries are connected to upstream aquatic systems (via water) and concurrently affected by global changes. Lessons learned from these case studies show that in all cases there is a desire to restore and/or protect freshwater quantity and quality delivery to estuaries. The Mississippi River and South Florida case studies show a need for substantial hydrological modifications of the system in attempt to reset the flow dynamics to mimic pre-manipulation conditions. These also demonstrate attempts to restore large-scale hydro-ecological systems that have been fundamentally altered and demonstrates the complexities involved in multi-state, multi-agency cooperation. The "Water wars" following the Apalachicola Bay oyster collapse demonstrates up-versus-down-stream stakeholder conflicts in aquatic resources. The Suwannee River systems show arguably less alterations to flow dynamics, but the spatial and temporal characteristics of freshwater flow to both Apalachicola and Suwannee River estuaries are a key conservation and management need for natural resources (e.g., shellfish and finfish fisheries).

Qualitative models can help define the key components and connections in a complex, coupled human-natural system, and serve as communication tools to researchers, managers, stakeholders, and the general public. Despite clear and considerable differences between our case studies, they also demonstrate common pathways of how changes in upstream land-use and water provisioning affect downstream ecosystem functioning and resources. We generalize these into a conceptual model to describe these linkages, feedbacks, and impacts (Fig. 1). Water provisioning is affected by both local (water extraction, land-use changes) and non-local, climatic factors. These drivers can interact, for example, when drought both causes lower precipitation and increases water extraction. Collectively, upstream drivers determine the quantity, quality, and timing of water that is delivered into the estuary. This water provisioning affects environmental conditions and the ecology of foundation species (e.g., oysters, seagrasses, sponges, mangroves, marsh grasses). Importantly, ecological disturbances in changes can further feedback to alter the physical and chemical environment of the estuary. For example, environmental conditions that damage autogenic oyster populations cause deformation of the reefs that retain freshwater and maintain optimal environmental conditions. Allogenic feedbacks can also occur concomitantly as nutrient cycling is altered. For example, loss of mangroves and sponges reduce nutrient uptake, leading to higher turbidity and loss of seagrasses. Ultimately, declines in foundation species will deteriorate food webs and habitat for threatened species and affect their capacity to produce fisheries and ecosystem services.

From this model, review, and case studies, we discern and discuss the following key lessons.

Climate change impacts the system on multiple levels. Extreme droughts lead to more water extraction for agriculture and urban uses and reduce inflow, altering salinity dynamics in estuaries. There is a critical need to understand the relative strength, impact, and interactions between climate-driven precipitation and human water withdrawals. Increased frequency of droughts and floods are a consensus prediction of climate forecasts, and these stressors will be combined with changes in human water use via urbanization, changes in agricultural crops and practices, and water conservation strategies and implementation. Predicting the relative magnitude of climate versus human extraction on water will take interdisciplinary approaches including hydrology, meteorology, and economic aspects of watershed systems. Additionally, droughts often occur in the summertime and cooccur with extreme water temperatures, and this interaction of high temperature and salinities can harm and oyster and seagrass populations (Rybovich et al., 2016; Southworth et al., 2017; Thomas et al., 2018).

Concurrently, climate changes are driving poleward expansion of tropical cold-sensitive organisms (Pecl et al., 2017; Jacox et al., 2020; Osland et al., 2021). The northward expansion and establishment of mangroves is replacing of *Spartina* marsh grasses and altering biogeochemical and ecological processes (Saintilan et al., 2014; Scheffel et al., 2017; Osland et al., 2018; Langston and Kaplan, 2020). Fish assemblages throughout the region also changing due to tropicalization (Fodrie et al., 2010), including northward expansion of apex predators (Purtlebaugh et al., 2020) that are expected to affect coastal food webs and fisheries (Sinnickson et al., 2021b). Parallels may be observed in how the recent establishment of invasion of Red Lionfish (*Pterois volitans*) on GoM marine habitats has altered reef fish community structure and processes (Dahl et al., 2016; Chagaris et al., 2017, 2020), which has also developed as a novel fishery (Harris et al., 2020a, 2020b).

Alterations to freshwater quantity and salinity drives ecological changes. In estuaries, hyper-saline environments can drive intense "consumer fronts" capable of decimating foundation species and the ecosystems they support (Silliman et al., 2013). This co-occurrence of drought and run-away consumption has been in frequently observed in southeast coastal systems with large-scale die-offs in cordgrass salt marshes by periwinkle snails (Silliman et al., 2005) and oyster reefs by gastropods (Kimbro et al., 2017, 2020). Alteration in salinity regimes affects species distributions and food web structure in coastal ecosystems. Changes in spatial extent of salinity zones within estuaries (e.g., oligohaline, mesohaline, polyhaline) dictate habitat availability and quality. In environments within the physiological limits of a species, growth and survival may be impeded depending on energy needed to maintain individual physiological balance, food, shelter resources, and coexisting competitors and predators. These changes in growth and survival rates have population-level consequences that can affect ecological function and services, such as fisheries support.

Freshwater flow influences foundational species. Hydrological modifications impact foundation species, such as oysters, marshes, seagrasses, and mangroves. Foundation species modify environmental conditions at large spatial scales, allowing them to provide some level of support to nearly all organisms within an ecosystem. The sessile nature of foundation species makes them vulnerable to local environmental changes, especially if changes are intense or prolonged and exceed the limits of individual physiological tolerances. Given that many nearshore and intertidal foundation species play a role in sediment stabilization, redistribution, or loss of established expanses of foundation species can lead to further loss of habitat through changes in shoreline morphology and facilitation of other habitat forming species. Furthermore, changes in foundation species can alter the environment's landscape and hydrology, which in turn feedback into ecological functioning.

Large-scale problems require big restoration strategies. Our examples highlight that management agencies are increasingly using large-scale approaches to water management and restoration activities. Small-scale oyster restoration efforts may not restore the landscape and hydrology needed to maintain large spatial extent of brackish water (20-25 ppt salinity) that maintains optimum reefs. Oyster reef restoration efforts in the Suwannee River Estuary and Apalachicola Bay are thus being constructed on scales to try to potentially facilitate freshwater retention (Kaplan et al., 2016), with costs of eight and twenty million dollars, respectively. The efforts to restore historic hydrology regimes for the Mississippi River and Everglades are some of the largest environmental engineering and restoration projects ever initiated, costing tens of billions of dollars.

Understanding and forecasting requires integrative models. Simulations provide useful tools to establish management goals and examine possible effects of large-scale alterations (e.g., de Mutsert et al. 2012, Boesch 2006, Scavia et al. 2017). Examining a watershed-to-estuary continuum crosses scientific disciplines and requires end-to-end models that link hydrology, ecology, economics, and social processes, which can link or couple together. These will need to integrate an understanding of landscape-level hydrological processes under alternative climate and land-use scenarios, which inform time and spatially dynamic ecological models to estimate changes in biological production, habitat, energy transfer, and community composition. Linked hydrology-ecological models can then be used to assess the downstream economic impacts of scenarios in terms of ecosystem services, fisheries, aquaculture, and tourism. The inherent complexity and uncertainty of this modeling framework makes accurate forecasting unlikely and limits their tactical application by managers. Nevertheless, the integrative modeling can provide information for strategic planning and scenario gaming to explore solutions to alternative future states.

Integration of management systems is required. Differences between management priorities for the upstream use of water and the downstream needs of coastal systems drive current and pending resource conflicts [citations]. The watershed to estuary continuum crosses jurisdictional boundaries, and current management systems rarely are structured to consider the downstream impacts from upstream land-use and water management. Therefore, coordination is required at federal, state, and local levels (e.g., SFERTF, HTF, CWPPRA). Such collaborations require extensive assessment and monitoring to ensure that environmental initiatives are met and may require incentivization to encourage best management practices over more lucrative strategies (Bohlen et al. 2009). While each governing body has their own set of management objectives, there is not a framework for defining broader objectives or identifying tradeoffs in competing objectives. Higher level coordination, prioritization, and valuation of the services provided by freshwater resources, both on land and in the estuary is required to address this challenge. Collectively, the case studies and conceptual model presented herein indicate the need for integrated watershed-estuary management systems capable of making water management and land-use decisions (e.g., agricultural best practices) with consideration of downstream effects and ecosystem services.

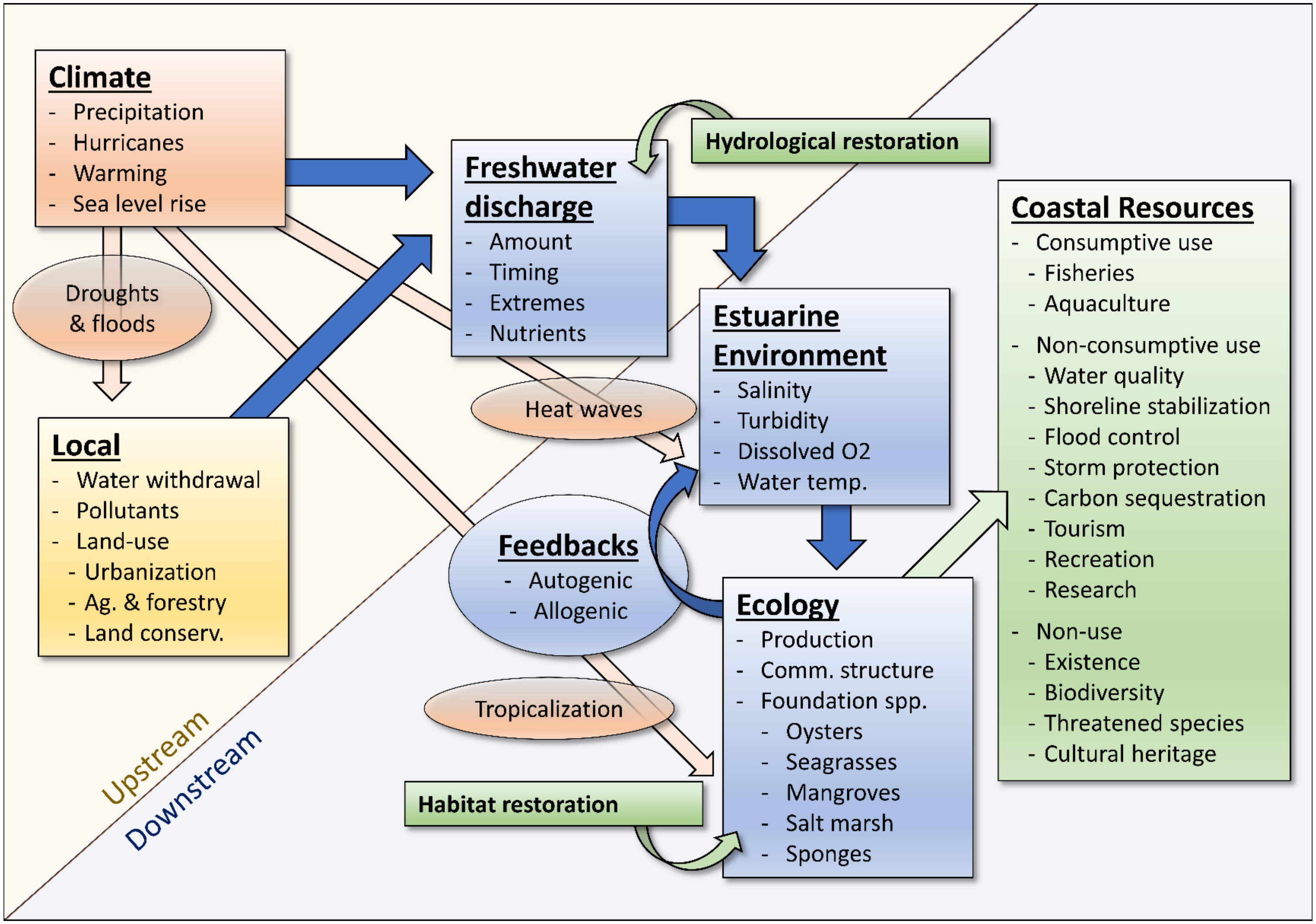

Figure 1 Conceptual schematic framework describe the pathways for how climate, land-use, water management ultimately affects estuarine living marine resources. Changes in freshwater quantity, quality, and timing drive physical environmental changes that alter estuary foundations, production, species composition, which in can cause feedbacks on the environment. considered in the context of concurrent climatic changes and restoration efforts.

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