PROJECT SUMMARY

Overview:

Since 2000, the Florida Coastal Everglades Long Term Ecological Research (FCE LTER) program has been revealing how the accelerating rate of sea-level rise interacts with climate variability and freshwater management to shape gradients of coastal ecosystem production, the movement of energy through food webs, and the value of ecosystem services to growing human populations. FCE long-term data, experiments, and models have shown rapid-paced changes associated with sea-level rise, extreme events, and freshwater flow diversion, threatening the persistence of vegetated habitat, dependent food webs, significant below-ground carbon stocks, and associated ecosystem services. Everglades restoration is increasing seasonal freshwater pulses while a 2017 hurricane delivered a storm surge pulse to the FCE, offering an unprecedented landscape-scale test of the overarching question: Will increased pulses of fresh and marine water and their associated resources maintain vegetated coastal ecosystems supporting highly connected food webs and valued ecosystem services as sea-level rise accelerates? The FCE IV conceptual framework integrates theoretical concepts of 'ecosystem development' and 'pulse dynamics' to understand how social-ecological responses to increasing climate variability and extremes depend on the magnitude, timing, and duration of these 'pulses' and their interaction with other persistent changes ('presses'). Four hierarchical research questions ask: (1) how the climate drivers of hydrologic presses and pulses are changing, (2) how governance of freshwater restoration reflects changing values of ecosystem services, (3) how ecological landscapes serve as endogenous filters that feed back to the climate system, and (4) how ecosystem structural and functional responses influence long-term ecosystem trajectories. These questions will be addressed through continued long-term and new data collection along two transects with contrasting hydrologic presses and pulses, human dimensions research, a new ecosystem vulnerability experiment, process and landscape-scale modeling and scenarios approaches, and a large suite of collaborative projects sponsored by leveraged funding.

Intellectual Merit:

The proposed research expands understanding of disturbance ecology by integrating theories of pulsed dynamics and ecosystem development. Social-ecological systems are linked by disturbance, disturbance may change system vulnerability to other environmental drivers, and feedbacks among ecosystems and disturbance drivers can influence trajectories of ecosystem development. The proposed research predicts that freshwater restoration will reduce the effects of sea-level rise on saltwater intrusion (a hydrologic press), and that fresh and marine hydrologic pulses will control resource distribution and long-term trajectories of coastal ecosystems and services. Freshwater restoration provides a landscape-scale test of how social-ecological systems are coupled in coastal regions exposed to accelerated sea-level rise and extreme events. Synthesis efforts will use data from national and international research networks aimed at understanding how chronic presses and increasing pulses determine ecosystem trajectories, addressing one of the most pressing challenges in contemporary ecology.

Broader Impacts:

FCE will continue to be based at FIU, engaging students from one of the largest minority-majority-serving institutions in the U.S. (>58,000 students, >90% underrepresented). FCE is addressing the Big Idea of NSF INCLUDES and contributing to broadening participation of underrepresented communities in STEM fields with guidance from the NSF Strategic Plan (FY 2018-2022). FCE scientists train and mentor all levels of early career scientists. The FCE Graduate Student Organization is large, active, and diverse, and will continue to be a central emphasis of science and education. Education & Outreach programming will provide mentoring to K-12 students and teachers through a new participatory science program using the global Tea Bag Index, expanded classroom use of the FCE children's book, integration of undergraduate researchers into a new Research Experience for Undergraduates site, and engagement of artists in distributed exhibits showcasing Everglades-inspired artwork. Communications will be through a monthly newsletter, press releases, social media, research blogs, public events, and exhibits. By co-developing research with scientists from non-government organizations and government agencies at local to global scales, the FCE epitomizes the process of convergence science in the field of ecology.

I. INTRODUCTION *[Note: Italicized citations are FCE products]*

A. Overview

Human-induced climate change is increasing climate variability and extreme events, producing rapid and often unpredictable changes in ecosystems and societies (Harris et al. 2018). Social-ecological responses to increasing climate variability and extremes depend not only on the magnitude, timing, and duration of these 'pulses' but also on their interaction with other ongoing, persistent changes ('presses,' - Box 1 lists key terms). Understanding social-ecological responses to changing drivers and feedbacks at different spatiotemporal scales is a grand challenge in ecology that requires long-term research (*Gaiser et al. 2020*). **The Florida Coastal Everglades (FCE, Fig. 1) is a model social-ecological system to address how the accelerating rate of sea-level rise interacts with climate variability and freshwater management to shape gradients of coastal ecosystem production, the movement of energy through food webs, and the value of ecosystem services to growing human populations.** We have shown how low-gradient, karstic coastal ecosystems are exceptionally exposed and highly sensitive to even small changes in sea-level rise, climate-driven hydrologic variability and extremes (i.e., hurricanes, floods, droughts), and freshwater distribution (*Gaiser et al. 2015a*). Climate conditions over the last several thousand years allowed for slow development of freshwater marshes, mangrove forests, and seagrass meadows that provide critical services such as carbon sequestration and burial, freshwater aquifer recharge, and valuable recreational fisheries. However, accelerating rates of sea-level rise and decades of diverting fresh water away from coastal ecosystems have accelerated rates of saltwater intrusion, leading to declining ecosystem states, abrupt transitions from vegetated to open water habitat ('peat collapse' - *Wilson et al. 2019a*), and reduced ecosystem service values (*Sklar et al. 2019a*).

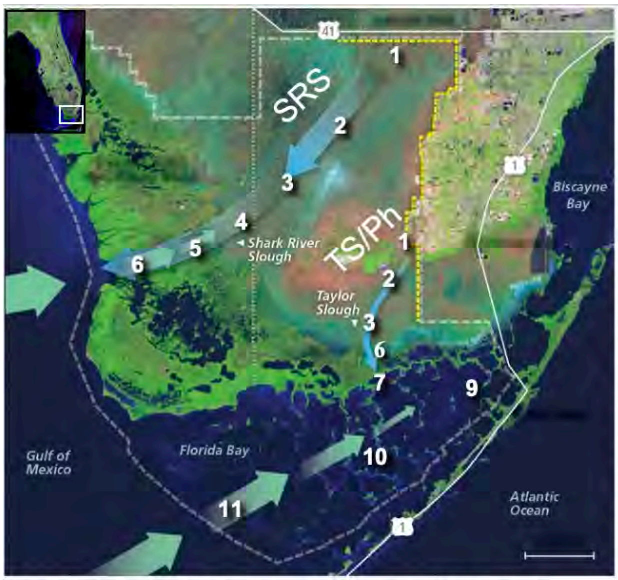


FIGURE 1. THE FCE RESEARCH DOMAIN in the State of Florida (inset) showing research sites (*numbered*) along Shark River Slough (SRS) and Taylor Slough/Panhandle (TS/Ph) in Everglades National Park (*dotted white line*). Biophysical studies focus on changes in ecosystem structure and processes determined by the relative influence of fresh (*blue arrows*) and marine (*green arrows*) water supplies. Freshwater supplies to SRS and TS/Ph are increasing due to restoration of inflows via bridges along the northern FCE boundary and delivery projects along the eastern boundary, respectively (indicated *by yellow dashed line*). Social-ecological studies focus on interactions between cultural and economic values of ecosystems as they change, and the governance of freshwater restoration.

BOX 1. KEY TERMS IN THIS PROPOSAL:

Press: Extensive and directional change (*Collins et al. 2011*). *In the FCE,* the critical hydrologic press is saltwater intrusion, measured by increasing salinity in the marsh-mangrove ecotone and decreasing upstream relative to downstream water levels (*Dessu et al. 2018*). The press of saltwater intrusion reflects this balance of increasing sea-level rise and freshwater inputs (Figs. 6a, b).

Pulse: Pulses can be cyclical (i.e., daily, seasonal) or abrupt, typically measured as the magnitude of change relative to its duration (Jentsch & White 2019). *In the FCE,* freshwater restoration and climate change are increasing:

- ***Freshwater pulses*** - driven by increasing magnitude and variability in rainfall (including from tropical storms) and freshwater restoration; measured by amplitudes of water level relative to flooding duration.
- ***Marine pulses*** **-** driven by tides and hurricane storm surges; measured by tidal and surge (water level) amplitude and lateral extent relative to duration.

Both pulses mobilize resources including phosphorus that limits production, sediment (from marine storm surges) that builds elevation, and organisms that support food webs.

Hydrologic Connectivity: Water-mediated transfer of matter, energy, and/or organisms (Pringle 2001). *In the FCE,* hydrologic connectivity is measured by inundation extent at several spatiotemporal scales, and ecological signals of marine and freshwater source connectivity (e.g., dissolved organic carbon, salinity, animal movement).

Ecosystem Development: A developing ecosystem is one where carbon dioxide sequestration exceeds loss over annual-to-decadal timescales, and carbon stores accumulate (Odum 1969). *In the FCE,* carbon is stored in both inorganic (calcium carbonate, marl soils) and organic soils (peat).

For the past 20 years, the FCE LTER program has been a transdisciplinary hub for scientists, managers, and educators working toward a **collective goal of understanding, informing, and managing the fate of coastal ecosystems facing climate change** (*Childers et al. 2019*). While long-term data, experiments, and models have shown rapid-paced changes associated with saltwater intrusion, Everglades restoration projects implemented over the last 5 years are increasing seasonal freshwater pulses to the FCE. We are well-positioned to test the effects of these interventions with 15+ years of pre-restoration research characterizing two transects that differ in connectivity to marine and freshwater supplies. The FCE also experienced a major hurricane (Irma) in 2017 that delivered a ~3 m storm surge containing a large-scale mineral sediment deposition (<10 cm) enriched in the limiting nutrient, phosphorus (P). Storm surge subsidies fuel mangrove forest recovery from storms, allowing them to keep pace with sea-level rise by building peat soils that increase soil elevation (*Breithaupt et al. 2020*; *Castañeda-Moya et al. 2020*). Periods of hydrologic connectivity also allow marine consumers to transport nutrients upstream where they may further fuel production (*Matich et al. 2017*). Here, we build on the theories of pulse dynamics (Jentsch & White 2019) and ecosystem development (Odum 1969) to predict that freshwater restoration will reduce the rate of saltwater intrusion (a hydrologic press) and that fresh and marine hydrologic pulses will control resource distribution and long-term trajectories of coastal ecosystems and services (*Kominoski et al. 2018*). Feedbacks that influence whether ecosystems develop or decline – including soil accretion on the press of saltwater intrusion, ecosystem service values on freshwater governance, and evapotranspiration on regional rainfall – occur across multiple spatial scales and over years to decades ideally captured by long-term research.

FCE IV will build on the groundbreaking results from FCE I-III to address the overarching question: **Will increased pulses of fresh and marine water and their associated resources maintain vegetated coastal ecosystems supporting highly connected food webs and valued ecosystem services as sea-level rise accelerates?** While FCE is increasingly hydrologically pulsed at multiple spatiotemporal scales (Box 1), our primary focus is on the effects of increasing pulses of restored fresh and storm-driven marine water expected to generate the largest near-term signals of change (*Kominoski et al. 2020*). Continued long-term data collection, manipulative studies, and models are required to test how increases in freshwater pulses through Everglades restoration and increasing marine pulses due to climate change will reverse declining ecosystem trends detected in FCE I-III. We will empirically test how social-ecological systems are coupled in coastal regions exposed to accelerated sea-level rise and extreme events, thereby addressing one of the most pressing challenges in contemporary ecology.

B. Evolution of FCE Research and Conceptual Framework

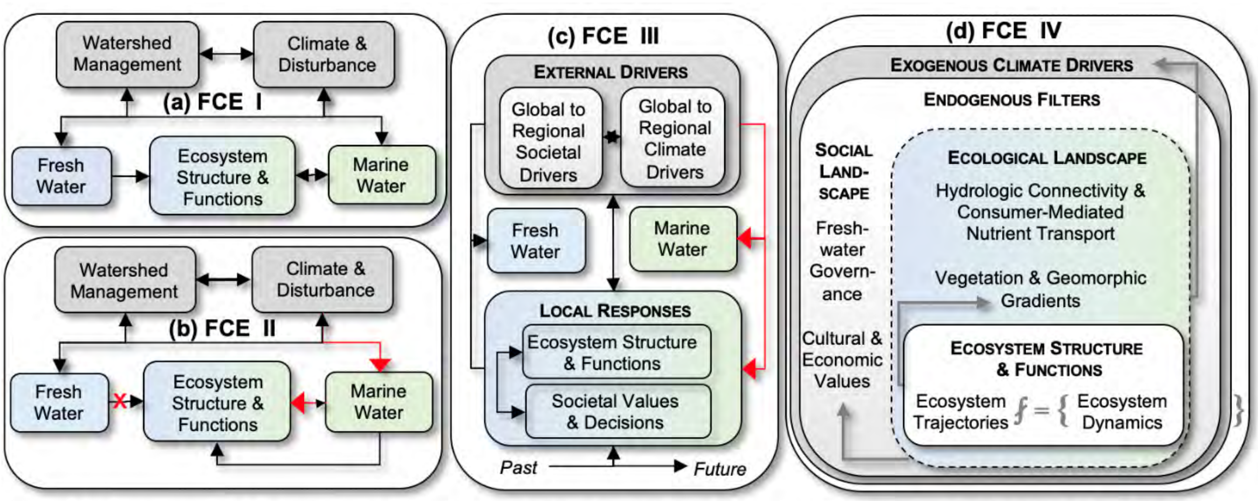


Figure 2. Evolution of Conceptual Frameworks Guiding FCE LTER Research From FCE I (2000)-FCE IV (2024).

The FCE program was launched in 2000 to determine the origins, dynamics, and fate of coastal productivity in highly oligotrophic, karstic ecosystems that occupy 15-20% of Earth's land surface (Ford & Williams 2007). During **FCE I** (2000-2006), we established research sites along two drainages, Shark River Slough (SRS) and Taylor Slough/Panhandle (TS/Ph) in Everglades National Park (Fig. 1) to study how ecosystem structure and functions (*blue*-*green box*, Fig. 2a, including biogeochemistry, primary production, organic matter quality, and food webs) reflect a shifting balance of *fresh* and *marine* water supplies driven by water management and climate changes (*gray boxes*). Fresh water with very low total P (<10 ug TP L^{-1}) is delivered to the FCE through canals primarily during the subtropical wet season (June-November, when the FCE receives 70% of its rainfall). Our gradient design demonstrated the "**upside-down" biogeochemical nature of karstic oligotrophic coastal ecosystems** (relative to deltaic, riverine estuaries), whereby marine water supplies the limiting nutrient (P) (*Childers et al. 2006a*). Our two transects differ in their connectivity to upstream freshwater and downstream marine water sources that are reflected in their productivity and soil types. Nutrient concentrations and net ecosystem productivity are higher along the organic (peat) soil gradient of SRS that is tidally connected to the Gulf of Mexico than the mineral (marl) soil gradient of tidally-restricted TS/Ph (*Chambers & Pederson 2006;* Fig. 3). Freshwater oligotrophic marshes of SRS are flooded for >9 mo y^{-1} and are dominated by sawgrass (*Cladium jamaicense*) and productive microbial (periphyton) mats (*Ewe et al. 2006*). A marsh-mangrove ecotone occurs where freshwater meets marine, transitioning to a tidal, riverine mangrove forest of *Rhizophora mangle, Laguncularia racemosa, Avicennia germinans,* and *Conocarpus erectus,* which is **among the most productive ecosystems in the world** (*Rovai et al. 2018*). Freshwater marshes of TS/Ph are flooded for <9 mo y^{-1}. Frequent drying drives organic matter oxidation, and extensive, thick, calcareous periphyton mats that precipitate calcium carbonate soils and sequester phosphorus (*Gaiser et al. 2014*). These highly oligotrophic marshes transition to low-stature (scrub) red mangrove (*R. mangle*) forests whose productivity is fueled by P from marine groundwater discharge through limestone bedrock (*Price et al. 2006*). This drainage meets the Gulf of Mexico after first passing through the seagrass meadows of Florida Bay that sequester marine P supplies (*Herbert & Fourqurean 2009*).

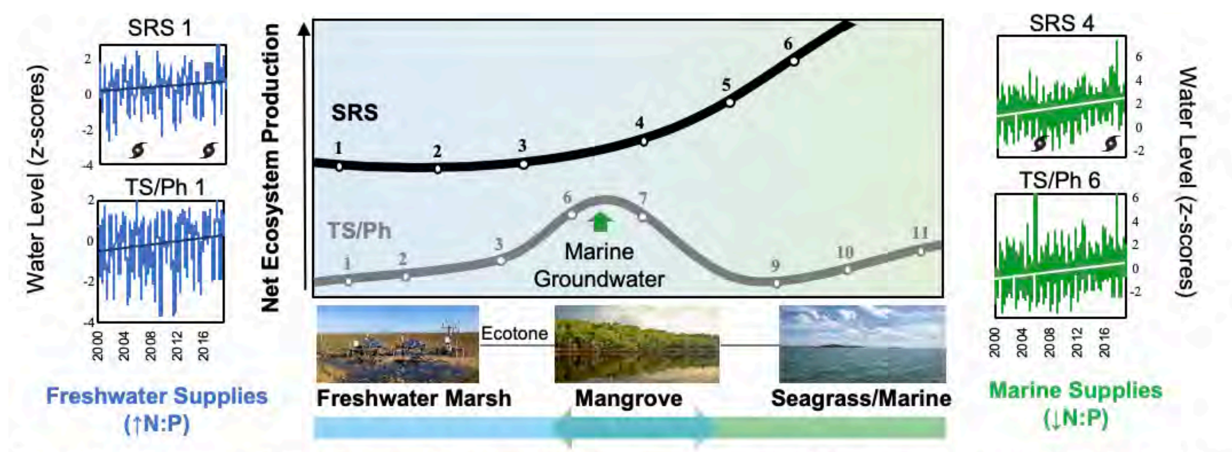


FIGURE 3. GRADIENTS OF NET ECOSYSTEM PRODUCTION differ between the two FCE drainages due to contrasting fresh (left, in *blue*) and marine (right, in *green*) water supplies of phosphorus (P) relative to nitrogen (N). Numbers refer to FCE sites (Fig. 1). **SRS** receives freshwater from inflow structures during the wet season, and marine water from daily tidal pulses and occasional hurricane-driven storm surges. It is a more productive, yet still oligotrophic, drainage where productivity increases toward the coast. TS/Ph is a smaller drainage with smaller seasonal freshwater inputs, and weak tidal pulses. It is a less-productive, oligotrophic drainage where productivity peaks in the ecotone where marine groundwater delivers P in the dry season. Water levels for marsh (SRS 1 and TS/Ph 1) and mangrove (SRS 4 and TS/Ph 6) sites are increasing due to increased rainfall and restored seasonal inflow pulses and the press of sea-level rise.

In **FCE II** (2007-2012), we predicted that freshwater restoration would generate a strong ecosystem signal in this low-gradient landscape, shifting productivity gradients coastward. Instead, restoration was delayed (*red x*, Fig. 2b) due to political conflicts among stakeholders (*Ogden 2008*), allowing us to quantify high variability in hydrology, primary producers, biogeochemistry, organic matter fluxes, and food web structure. These data improve our ability to detect effects of restoration as it is implemented (*Trexler &*

Goss 2009; Briceño & Boyer 2010). We documented **rapid rates of interior migration of marine-derived salt and P** (*red arrows*, Fig. 2b), **particularly from dry-season groundwater discharge** (*bottom arrow*, Fig. 2b) (*Saha et al. 2012*) **and punctuated by hurricanes** (*Castañeda-Moya et al. 2010*).

In **FCE III** (2013-2018, described in detail below), we formalized our human dimensions research to **better understand the interactions of societal values and decisions** with coastal ecosystem functions and services (Fig. 2c). Accelerating sea-level rise (3× faster than prior decade) and continued restoration delays increased the extent of saltwater intrusion (Dessu et al. 2018). Elevated salinities were associated with declines in sawgrass production in the marsh-mangrove ecotone (*Troxler et al. 2014*)*,* collapse of below-ground biomass and rapid elevation loss (*Charles et al. 2019*)*,* die-off of seagrasses (Hall et al. 2016), and altered marsh-estuary trophic linkages (*Matich et al. 2017*). Our findings suggest that **persistence of vegetated coastal ecosystems and their services relies on pulses from freshwater restoration and marine subsidies** that offset the press of sea-level rise on saltwater intrusion.

Over the last 18 months, we reflected on our findings and feedback from the 2018 NSF LTER renewal panel to develop a new conceptual framework to guide **FCE IV** (2021-2024) and future research (Fig. 2d, expanded version in Fig 5). Our framework depicts long-term (decadal to multi-decadal) ecosystem development trajectories as a function of shorter-term (daily to yearly) ecological structural and functional responses to interacting, hierarchical scales of social-ecological drivers of hydrologic presses and pulses. Below we describe this framework in detail (*Section I.D*), after reflecting on our theoretical motivations.

C. Theoretical Rationale

A recent review of disturbance in social-ecological systems (*Gaiser et al. 2020*) outlined three grand challenges that long-term ecological research is well-suited to address: (1) social and ecological systems are inextricably linked by disturbance, (2) disturbance may change system vulnerability to other environmental drivers, and (3) feedbacks between ecosystems and disturbance drivers can be significant. Addressing these three challenges through multi-decadal transdisciplinary research that captures interactions among disturbance events, ecosystem states, and water management decisions across multiple scales should profoundly advance our understanding of the social-ecological feedbacks to disturbance processes underlying long-term change (Grimm et al. 2017). The FCE program offers insight into all three challenges by having: (1) social and biophysical research with a transdisciplinary team studying their interactions, (2) a disturbance-prone and sensitive ecosystem with multi-decadal data preceding a landscape-scale manipulation (i.e., freshwater restoration), and (3) the ability to measure feedbacks between a climate press and ecosystem state (i.e., sea-level rise and elevation change) and social systems (i.e., freshwater restoration and ecosystem service provisioning).

Disturbance and Ecosystem Trajectories: Odum (1969) predicted that fundamental patterns and processes change across multiple levels of ecological organization as ecosystems undergo succession and develop carbon stores following disturbance. *Kominoski et al. (2018)* reviewed how evidence from long-term ecological research has informed ecosystem development theory, showing that a change in disturbance regime can alter the trajectory of carbon gains or losses at any development stage (*hourglass symbols,* Fig. 4a). Trajectory changes occur when self-stabilizing feedbacks become outweighed by destabilizing ones and may be accompanied by a state transition (Ratajczak et al. 2018). In coastal ecosystems, maintenance of net autotrophy as vegetation zones move inland with shifting resource and salinity gradients facilitates the development of vast belowground stores of carbon (*Macreadie et al. 2019*). However, interactions between biotic processes (vegetation growth, trophic dynamics) and changing abiotic stressors (e.g., salinity, water depths, and inundation duration) may lead to nonlinear responses characterized by abrupt and unpredictable degradation of vegetated habitat to open-water states (*Frankovich et al. 2012;* McGlathery et al. 2013). Forecasting whether coastal ecosystems continue to develop or transition to another vegetated state (e.g., freshwater marshes to mangroves) or to slowly or abruptly decline to open water requires an understanding of interactions among climate (i.e., sea-level rise, storms) and social (water management) drivers of saltwater intrusion, other potentially interacting disturbances (e.g., hurricanes), and ecosystem responses occurring across spatiotemporal scales.

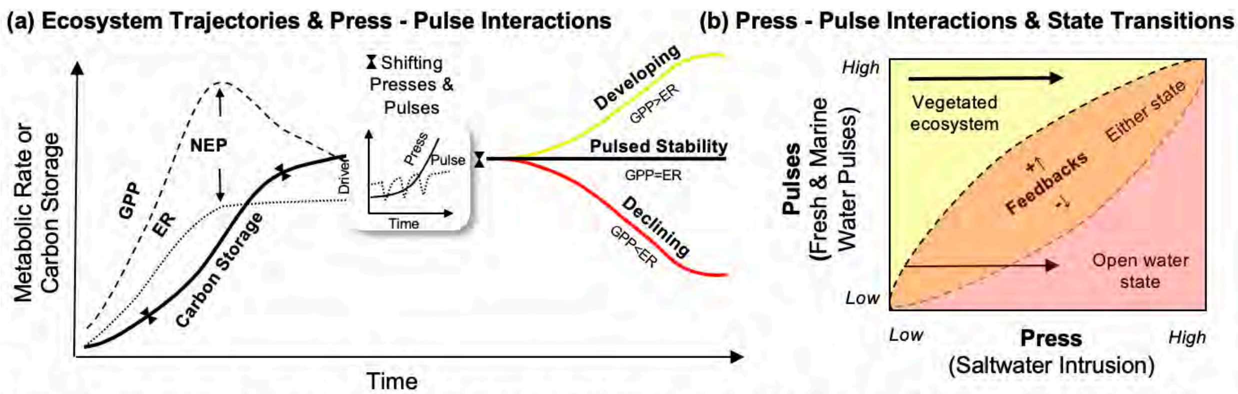


FIGURE 4. ECOSYSTEM DEVELOPMENT TRAJECTORIES AND PRESS-PULSE INTERACTIONS. (a) As ecosystems develop, the balance of gross primary production (GPP) and ecosystem respiration (ER) determines net ecosystem production (NEP) and carbon storage. A shift in ecosystem presses and pulses may occur at any time (⧗). Interactions between the presses and pulses, and ecosystem feedbacks to them, will determine whether an ecosystem continues to develop (*yellow line*), stabilizes (*black line*), or declines (*red line*) (*Kominoski et al. 2018*). (b) In coastal ecosystems, whether habitats remain vegetated and in a carbon accreting state (*yellow area at high pulse, low press*), or decline (losing stored carbon and transitioning to an open water state) (*red area at low pulse/high press*) will be determined by whether critical thresholds (*dotted lines*, influenced by ecological feedbacks) are crossed (after Ratajczak et al. 2018). Arrows show example trajectories. With the same magnitude of saltwater intrusion, the highly pulsed system (*thick line at top*) remains in a vegetated state while the less pulsed system (*thin line at bottom*) is more likely to transition to open water.

Pulse Dynamics and Social-Ecological Changes: We propose to test whether hydrologic pulses, a ubiquitous feature of aquatic ecosystems (Junk et al. 1989; Poff et al. 1997) and regulator of coastal wetland functions (Odum et al. 1995), maintain vegetated wetlands that support carbon accumulation in coastal ecosystems facing sea-level rise. The theory of pulse dynamics recently summarized by Jentsch & White (2019) emphasizes the need for an inclusive paradigm to understand how diverse ecosystems respond to pulses. This theory integrates decades of discoveries and theoretical advancements suggesting that pulses will change resource ratios, availability, and storage, including the stoichiometric requirements and resource accumulation rates of organisms in food webs. Ecological responses to these resource changes are determined by: (1) rates of energy flux, (2) landscape patterns that regulate resource flows, and (3) species distribution patterns. Coastal ecosystems are ideal for testing these predictions because they are strongly regulated by both tidal marine and freshwater pulsing that may maintain them in a continuous state of development (Odum et al. 1995). Marine and freshwater pulses may relax resource limitation and distribute biota into osmotically suitable habitat, maintaining critical ecosystem services including aquifer recharge, carbon sequestration, and recreational fisheries. On the other hand, if freshwater flows are insufficient to counteract the effect of sea-level rise on saltwater intrusion, osmotic stress may overwhelm the physiological capacity of species to persist (Elliott & Quintino 2007). Formulating these competing hypotheses about species tradeoffs in response to disturbance allows us to address questions about the consequences of these tradeoffs to the provisioning of ecosystem services and water governance (Palmer & Ruhl 2015; Henry et al. 2019).

D. Conceptual Framework

Our new conceptual framework (Fig. 5) motivates four questions (below) that we will address through our detailed research plan (*Section III.A*), containing short-term (4 year) goals that support longer-term (decadal) objectives. Climate variability and change (*outer gray box*) are the exogenous drivers of hydrologic presses and pulses, which are constrained by endogenous filters and responses (*lighter inner gray box*) in social-ecological landscapes (separated by a deliberately permeable – dashed – boundary). On the social landscape, shifting cultural and economic values influence governance decisions that control freshwater distribution to the FCE. On the ecological landscape (*blue-green box*), vegetation and geomorphic gradients determine the propagation of hydrologic presses and pulses through coastal ecosystems (*small white graphs*), and the ability of consumers to mediate nutrient transport across freshwater marsh, mangrove forest, and marine seagrass ecosystems (*inset photos*). Dynamics in each of these ecosystems reflect these interacting scales of drivers operating on shorter temporal scales (days, years), and of response lags that matter to longer-term (decadal) ecosystem trajectories (*Rastetter et al. 2020*). Ecosystem dynamics – the variability in structure and functions of vegetation, consumer, and detrital/microbial communities and fluxes of carbon – interact with changes in abiotic resources and stressors resulting from hydrologic presses and pulses to determine ecosystem trajectories and carbon stocks. Three key feedbacks (*gray arrows*) determining social-ecological vulnerability to the press of sea-level rise are between: (1) elevation change and saltwater intrusion, (2) ecosystem services and the governance of freshwater pulses, and (3) evapotranspiration and regional rainfall.

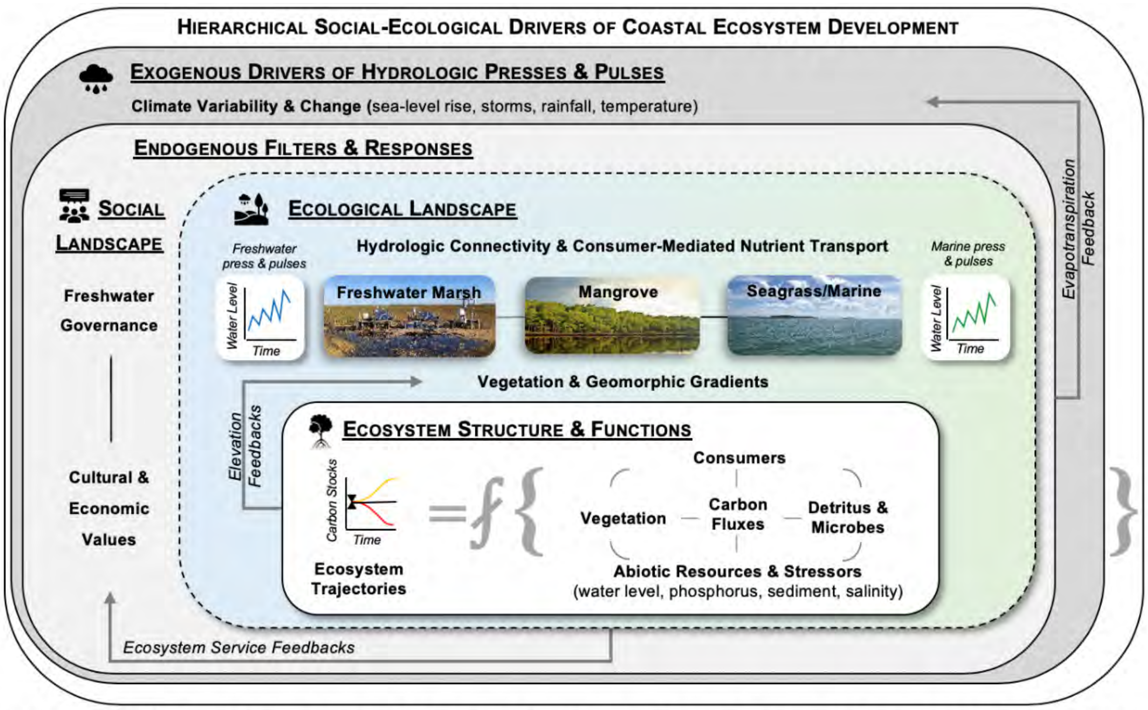


FIGURE 5. THE FCE CONCEPTUAL FRAMEWORK DEPICTING HIERARCHICAL SOCIAL-ECOLOGICAL DRIVERS OF COASTAL ECOSYSTEM DEVELOPMENT trajectories as a function (*ƒ*) of ECOSYSTEM STRUCTURE & FUNCTIONS (center white box), ENDOGENOUS FILTERS & RESPONSES on the SOCIAL AND ECOLOGICAL LANDSCAPES (*blue-green box* separated by permeable – dashed - boundary), and EXOGENOUS DRIVERS OF HYDROLOGIC PRESSES & PULSES (*outer gray box*). The FCE program addresses four questions across these nested scales to reveal whether increased hydrologic pulses of both *fresh* and *marine* water supplies (*lines in small white graphs*) will maintain coastal ecosystems in a developing (carbon accumulating) trajectory (*yellow line*) as sea level rises. We hypothesize that developing trajectories will be maintained by positive feedbacks (*gray arrows*) of soil elevation gains relative to sea-level rise, ecosystem services to freshwater governance, and increased evapotranspiration to regional hydroclimate.

QUESTION 1 [EXOGENOUS DRIVERS OF HYDROLOGIC PRESSES & PULSES]: How will global climate change alter regional climate variability and extremes – the exogenous drivers of hydrologic pulses and presses? This question addresses a key uncertainty about the likelihood of extreme climate events (Stott 2016) by linking global and regional (land-ocean-atmospheric feedbacks) climate forcings, the exogenous drivers of FCE hydrologic pulses. FCE research has identified signals of directional change in global and regional climate drivers in our rainfall data. Analysis of over 100 years of precipitation data found an overall increasing trend in wet season and annual precipitation and a reduction in wet season duration (Abiy et al. 2019a*;* Fig. 6a), also noted by Irazzary-Ortiz et al. (2013) in 32 long-term Florida precipitation datasets. Recently implemented restoration projects, including >4 km bridges along the northern boundary of SRS (Fig. 6e) and water storage and delivery structures along the eastern boundary of TS/Ph, have increased the influence of these rainfall pulses on wet-season water levels in the FCE (*Dessu et al. 2018*; Fig. 3). In addition, we anticipate that the predicted increase in tropical storm rainfall (Patricola & Wehner 2018) will further increase pulses of wet-season inflows. These climate and management-driven increases in freshwater pulses coincide with extended tidal marine pulsing associated with the press of sea-level rise (also highest in the wet season *Dessu et al. 2018;*

Ensign & Noe 2018; Fig. 6c), and increased storm surge amplitudes (Fig. 6d) resulting from higher tropical storm intensity (Walsh et al. 2016; Fig. 6b). These exogenous drivers are expected to deliver more water to the FCE (Fig. 6f), especially in the wet season (Fig. 6c), increasing hydrologic connectivity and generating a potential regional landscape feedback to the hydroclimate via evapotranspiration (*Lagomasino et al. 2015*).

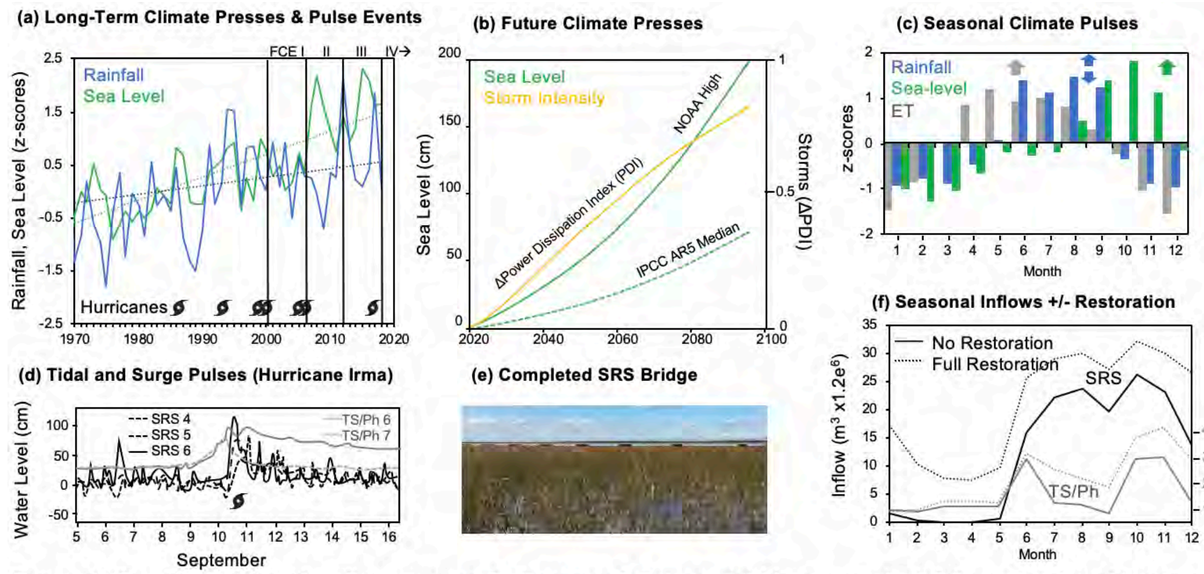


Figure 6. Climate Drivers And Projections Of Presses & Pulses. (a) Mean annual rainfall, sea level, and hurricanes (🌀) over the past 50 years; (b) projections for sea-level and storm intensity; (c) seasonality in mean rainfall, sea-level, and evapotranspiration (ET) (arrows indicate direction of projected change); (d) changes in water level in SRS and TS/Ph with passage of Hurricane Irma (Sept 2017); (e) a completed SRS bridge - one of many projects restoring freshwater pulses to FCE; (f) modeled monthly inflows to 1.5 km^2 subregions of SRS and TS/Ph for a year with average rainfall (1982) using the Everglades Landscape Model without (base) and with full restoration (*note scale difference for TS/Ph on right y-axis*).

Question 2 [Endogenous Filters & Responses – Social Landscape]: How will shifting cultural and economic values of changing ecosystem functions and services influence governance of freshwater restoration? This question examines how changes in ecosystem structure and functions are linked to cultural and economic values of ecosystem services that influence water governance, a critical endogenous driver of freshwater pulses to the FCE. Water governance refers to the networks of social actors whose interactions shape water management decision-making processes, thereby determining the institutions and infrastructure systems that mediate interactions between social and ecological systems (Bakker 2010; Lave 2012; Grove 2018). In South Florida, the rate and quantity of freshwater released into the Everglades reflects governance dynamics that attempt to align desires for flood control with emergent cultural and economic values of Everglades ecosystem services (Sklar et al. 2005). Ecosystem services provided by developing ecosystems in the FCE include gains in elevation 'capital' that reduces saltwater intrusion (Cahoon et al. 2019), carbon dioxide (CO_2) sequestration and storage (*Jerath et al. 2016*), recharge to an aquifer supplying 9 million people with freshwater (*Price et al. 2019*), and maintenance of a \$446M y^{-1} Florida Bay fishery (Stainback et al. 2019). The conversion of the Everglades to hard infrastructure in the 1940's, designed to reduce flood pulses and store water for agricultural and urban expansion, began compromising these services (Grunwald 2007; Cloern et al. 2016). Efforts to recover historic seasonal freshwater pulses have provoked backlashes from stakeholders dependent on flood mediation (*Price et al. 2019*). Although social conflicts determine the pace, scale, and scope of pulse restoration, adaptive management efforts are beginning to transform how governance networks incorporate scientific knowledge and local stakeholder concerns into water management decision-making processes (*Sklar et al. 2019b*; *Ogden et al. 2019*). Understanding these shifting governance dynamics thus requires understanding how water pulses, and the ecosystem functions they support, intersect with the evolving nature and scope of cultural and economic valuation of ecosystem services.

QUESTION 3 [ENDOGENOUS FILTERS & RESPONSES – ECOLOGICAL LANDSCAPE]: How does geomorphology (elevation, soil depth) influence hydrologic connectivity to fresh and marine water pulses to determine the succession of vegetation and transport of nutrients by consumers? This question addresses how changes in ecosystem structure and functions interact with the expression of presses and pulses across the landscape as controlled by endogenous geomorphologic gradients. We build on pulse dynamics theory, and particularly on how hydrologic connectivity across the landscape determines energy fluxes and how these energy fluxes in-turn control ecological responses to pulse events (Jentsch & White 2019). In flowing water ecosystems, hydrologic pulsing determines hydrological connectivity and thus the transport of water, matter, and organisms (Junk et al. 1989; Pringle 2001). In shallow, slow-flowing ecosystems like the Everglades, geomorphology – a function of bedrock geology and soil accumulation – influences the propagation of pulses across the landscape, and its expression in hydrologic connectivity (Larsen 2019). Hydrologic connectivity is expected to increase (particularly in the wet season) as more fresh water is delivered and sea level continues to rise (Fig. 6c). We anticipate that greater wet-season hydrologic connectivity will lessen constraints on animal movement (due to higher water levels and increased flooded habitat), increasing scales of trophic coupling and consumer-mediated transport of nutrients in the landscape (Nelson et al. 2019). How seasonal pulses of hydrologic connectivity influence coastal wetland geomorphology through ecological feedbacks to soil elevation determines the exposure and sensitivity of coastal wetlands to saltwater intrusion (*Tully et al. 2019*; *Kominoski et al. 2019*). This differential exposure and sensitivity to changing hydrologic pulses across the landscape may be an important determinant of trajectories at the ecosystem scale (Newman et al. 2017).

QUESTION 4 [ECOSYSTEM STRUCTURE & FUNCTIONS]: How will increased pulses of fresh and marine water and their associated resources change ecosystem structure and functions that control ecosystem development trajectories in coastal ecosystems facing the press of accelerating sea-level rise? This question examines how short-term (daily to seasonal) dynamics of resources and stressors (e.g., P, sediment, water level, and salinity) – driven by pulses of restored freshwater and marine storm-surge – regulate seasonal to annual dynamics of vegetation, detritus and microbes, consumers, and ecosystem fluxes of carbon that influence longer-term (decadal to multi-decadal) ecosystem development trajectories. We will build on theory of how changes in resource ratios and availability driven by pulses (Jentsch & White 2019) increase nutrient retention, stimulating net primary production in highly oligotrophic ecosystems. Increased nutrient retention by producers should increase quality for consumers and decomposers (Hunter 2016), greening food webs, and increasing trophic efficiency (Rooney & McCann 2012). We will test how increased internal and external P loading resulting from increasing freshwater and marine pulses alter the stoichiometric requirements, physiological states, and resource accumulation rates of organisms (Sterner & Elser 2002; Iwasaki & Noda 2018) to offset the stress of the press of increasing salt exposure (*Wilson et al. 2019a*). Increasing pulses of fresh water that meet federally mandated P limits (<10 ugL-1) should increase P loads that will attenuate downstream in this highly oligotrophic landscape (*Gaiser et al. 2006a*). Periodic exposure of coastal ecosystems to marine pulses will not only relax P limitation but may also deliver and/or favor salt-adapted species upstream (*Jiang et al. 2014*), facilitating inland movement of mangroves that build carbon stocks and elevation, and decreasing vulnerability of soils to collapse. Alternatively, we may find that resource pulses are insufficient to offset the stress of saltwater intrusion, the outcomes of which depend on the osmoregulatory capacity of organisms (Velasco et al. 2019).

E. Response to Prior Review

The FCE LTER program was placed on probation in summer 2018. Here we summarize the major reviewer/panel criticisms and how we have addressed them (→):

- *Conceptual Framework:* The panel was unclear about how the conceptual framework motivated integration of the described work plan. → We developed a new integrative conceptual framework (Fig. 5) to guide the FCE program that is anchored in theory and guided by long-term discoveries (described in *Section II.A*). This framework motivates four hierarchical questions about driver-response interactions and three critical feedbacks that will be addressed through nested hypothesis-led working groups.

- *Press-Pulse Regime:* The panel wanted more evidence of the status and trends of presses and pulses. → We define presses and pulses (Box 1), provide evidence of increasing hydrologic presses and pulses and their drivers (Figs. 3, 6a,c,d), document their impacts on long-term dynamics of ecosystem structure and functions (Figs. 7- 13), and show future projections (Figs. 6b,f, 14). We clarify theoretically-motivated expectations of how ecological changes resulting from amplified pulses may elicit biophysical and social-ecological feedbacks to determine the rate of saltwater intrusion, our long-term press.
- *Integration of Water Management:* The panel agreed that the inclusion of water management is a critical component of FCE research but thought it could be better integrated. → Our conceptual framework depicts the social landscape of FCE as both a critical endogenous driver of presses and pulses and also vulnerable to resultant changes in ecosystem functions and services via feedbacks. FCE studies have always addressed the social and ecological drivers of water management change, and they are now explicit in our conceptual framework, data collection, and modeling plans.
- *Trophic Dynamics:* The panel thought we could do more to amplify our work on trophic dynamics. → Over the last 18 months we conducted a comprehensive assessment of coastal food webs to start a new line of theory-motivated inquiry on spatial food webs and long-term data collection on trophic metrics (Fig. 16), depicted in the diagram requested by our mid-term review (Fig. 10). We also describe how we will evaluate the cultural and economic services, including those provided by food webs (e.g., recreational fisheries, indications of restoration progress) that are directly related to freshwater restoration.
- *Broader Impacts:* The panel wanted a more in-depth description of our approach to education and human resources development. → Our education plan has been modified to highlight new activities that integrate with our research plan we include a *Diversity and Inclusion Plan* (see *Project Management Plan*), an element we had not previously explained despite our highly diverse membership.
- *Generalizability:* The panel was impressed by our publication volume but was concerned about whether FCE science is reaching a broader audience. → We redesigned our program to improve our ability to inform and transform social-ecological studies of ecosystems undergoing rapid environmental change, grounding it in theory advanced through LTER collaborations (*Kominoski et al. 2018; Gaiser et al. 2020*). We achieve broader, generalizable intellectual merit through expanded synthesis activities and continue strong international collaborations that will ensure our results continue to be relevant to other coastal ecosystems nationally and globally, and that have been a hallmark of the FCE program.

II. RESULTS OF PRIOR SUPPORT

A. Intellectual Merit

During FCE III and the first 18 months of FCE IV (2013-2020), we produced 419 works that acknowledge FCE, consisting of 321 journal articles, 2 books, 38 book chapters, 5 thematic issues of journals, and 53 dissertations and theses, culminating in 825 published works during the life of the program. Over the last 6 years, 11 publications were in broad, high-impact journals (impact factor >10, e.g., *Science, Nature, PNAS*). Extramural funding leveraged for FCE research averaged 7 times the NSF base. We developed and continued 176 data packages that are searchable by LTER core area, fully compatible with the LTER Network Information System, and discoverable on the LTER Environmental Data Initiative (EDI) data portal and DataOne (see *Data Management Plan* for details). Here, we summarize results of this research that exemplify advancements to our ecological understanding and lay the groundwork for this proposal.

FCE III and early FCE IV research was organized around four goals to reveal the social-ecological drivers and consequences of a shifting balance of fresh and marine water supplies to coastal ecosystems (Fig. 2c): (1) **Water** - assessing how climate change, particularly accelerating sea-level rise, interacts with political conflicts over freshwater distribution; (2) **Ecosystem Dynamics** - determining how the balance of fresh and marine water supplies control ecosystem structure and functions through the dynamics of **biogeochemistry**, **organic matter**, **primary producers**, **consumers**, and the rates and pathways of **carbon** sequestration; (3) **Legacies** - characterizing spatiotemporal patterns of ecosystem sensitivity to, and legacies of, past climate variability and land/water-use change, and; (4) **Scenarios** - modeling how future policy scenarios of freshwater distribution may reduce vulnerability to rapid climate change.

1. Water: *By coupling long-term hydrologic and social science studies, FCE research has quantified the rates and pathways of accelerated saltwater intrusion in coastal wetlands, while also identifying successful pathways toward resolving restoration conflicts and achieving optimal scenarios for water quantity, flow, and quality.* Studies of the drivers of climate variability continue to underscore the importance of global-atmospheric interactions beyond the FCE boundaries. The rapid rise in sea level (*Haigh et al. 2014*; Fig. 6a) is due to a weakening of the Gulf Stream (Mitchum et al. 2017). Sea level is highest in the wet season (Fig. 6c) causing surface water salinities to rise at the marsh-mangrove ecotone, faster in TS/Ph than SRS due to its lower elevation (*Dessu et al. 2018*). Wet-season rainfall increased by 29 cm between 1995-2016, attributed to the warm phase of the Atlantic Multidecadal Oscillation (*Abiy et al. 2019b*; Fig. 6a). Freshwater inflows currently only account for 9-19% of annual water budgets (*Sandoval et al. 2016*), but new upstream infrastructure (bridges, retention structures) is increasing water levels in freshwater marshes (Fig. 3). This infrastructure resolves some of the conflicts among restoration stakeholders attempting to meet hydrologic goals while maintaining water quality (*Ogden et al. 2019*) – both required to maintain iconic properties of the oligotrophic, P-limited Everglades (*Gaiser et al. 2015a; Price et al. 2019*). Agricultural best management practices are reducing water use (*Yoder 2019*), required to meet the demands of a growing population (*Onsted & Roy Chowdhury 2014; Aldwaik et al. 2015*). Wetland treatment is now allowing P inflows to meet the mandated maximum of 10 µg TP L^{-1} (*Rivera-Monroy et al. 2019a*). The 2017 authorization of a 300 million m^3 reservoir and 26 km^2 of treatment wetlands to store and clean water will provide more seasonal freshwater pulses to the FCE, reducing saltwater intrusion into the marsh-mangrove ecotone (*Dessu et al. 2018*) and the region's freshwater supply, the Biscayne Aquifer (*Blanco et al. 2013*).

2. Ecosystem Dynamics: *Saltwater intrusion is increasing salinity and P in the marsh-mangrove ecotone, reducing sawgrass production but increasing connectivity of marine and freshwater food webs. Freshwater marshes exposed to salt can experience abrupt losses of vegetation and stored carbon – a pattern that may be reversed with freshwater restoration.* Variability in the magnitude of fresh and marine water delivery along the FCE gradients drives dynamics of water **biogeochemistry** (*Davis et al. 2018; Kominoski et al. 2020*). During the dry season and extended droughts, TP is concentrated in marsh surface water (*Davis et al. 2018*). Where marshes dry completely, organic matter mineralization drives P release after reflooding (*Sola et al. 2018*). Downstream, wet-season surface water TP and DOC concentrations vary with the extent of tidal and storm-driven marine supplies (Figs. 7, 8), while in the dry season, groundwater intrusion through limestone mobilizes P to the root zone (*Flower et al. 2017a,b*). These marine pulses leave legacies in soils and water that influence long-term plant and microbial productivity and composition (*Mckay et al. 2017*; *Castañeda-Moya et al. 2020; Kominoski et al. 2020*). We have been at the forefront of advancing methodologies for tracing the sources and fate of DOC in aquatic ecosystems (*Jaffé et al. 2014*), showing that most DOC in tidal rivers is freshwater-derived and is decreasing over time with the loss of upstream carbon sources due to decades of drying and oxidation (*Cawley et al. 2013; Regier et al. 2016).* Only ~10% of the mangrove-derived carbon is transported by tidal drainages in organic (mainly particulate) form (*Regier & Jaffé 2016; Chen & Jaffé 2016*), while the rest is transported downstream as dissolved inorganic carbon (*Troxler et al. 2015*).

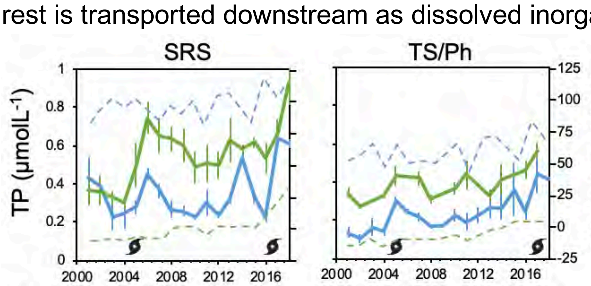
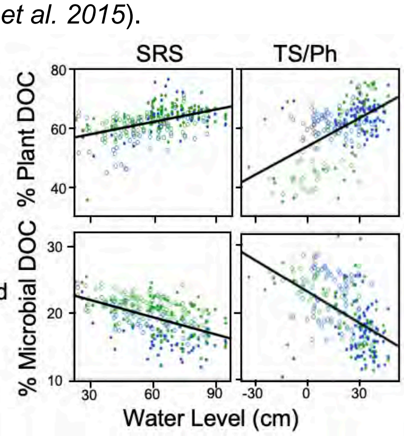


FIGURE 7. PULSE EVENTS AND TOTAL PHOSPHORUS (TP) LEGACIES. Annual mean (+/- standard error) of water TP (*lines*) and water depth (*dashed lines*) in *mangrove* estuaries and *freshwater* marshes, showing resource legacies of storm surge (🌀) pulses in 2005 and 2017, especially in tidal SRS.

FIGURE 8. DISSOLVED ORGANIC CARBON (DOC) from plant and microbial sources in the *mangrove* estuary and *freshwater* marsh in wet (filled circles) and dry (open circles) seasons (2004-2014).



Our studies of **primary producers** have quantified how spatiotemporal variability in marine and freshwater supplies control patterns and trends in composition, distribution, biomass, and net primary productivity of coastal vegetation (*Herbert & Fourqurean 2009; Troxler et al. 2014; Danielson et al. 2017; Marazzi et al. 2019*). In freshwater marshes, sawgrass productivity is equal to that of periphyton mats formed by cyanobacteria and diatoms (*Marazzi & Gaiser 2018*), which are abruptly lost upon exposure to TP exceeding 10 µg L^{-1} (*Gaiser et al. 2015b*). Where freshwater restoration is increasing wet-season water depth, we are observing dominance transitions from sawgrass to a deeper-water slough species (*Eleocharis cellulosa*). In the marsh-mangrove ecotone, rapid declines in periphyton biomass and sawgrass productivity are occurring where salinity exceeds 5-10 and 10-20 ppt, respectively (Fig. 9; *Troxler et al. 2014; Mazzei & Gaiser 2018).* Declines in sawgrass productivity are less pronounced where plant roots can access P desorbed or dissolved from saltwater-exposed carbonate sediments or rock (*Liu et al. 2014; Flower et al. 2017b*). Mangrove forests are also stimulated by P but stressed by salt, such that every 10 ppt increase in salinity results in a 5% decline in production (*Barr et al. 2013; Castañeda-Moya et al. 2013*). The seagrass meadows of Florida Bay are also highly sensitive to salinity extremes. Following a multi-decadal recovery from a 1980 seagrass die-off (Fourqurean & Roblee 1999), the extended drought and high temperatures of 2015 and 2016 caused another massive die-off of seagrass meadows in Florida Bay (*Hall et al. 2016*), due to anoxia and sulfide toxicity (*Arias-Ortiz et al. 2017*).

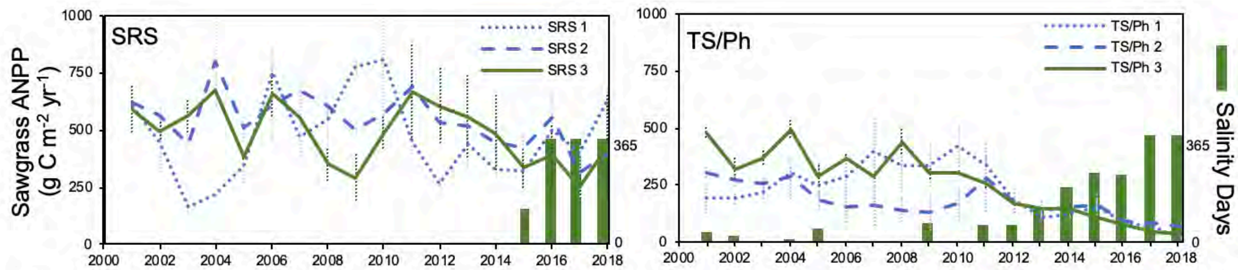


FIGURE 9. FRESHWATER MARSH PRODUCTIVITY. Long-term trends in the number of days with measurable salinity at SRS 3 and TS/Ph 3 (*green bars*), and trends in mean (± standard error) of sawgrass (*Cladium jamaicense*) Annual Net Primary Productivity (ANPP) at freshwater SRS and TS/Ph sites (*blue lines*), with significant negative relationship to salinity days at SRS 3 and TS/Ph 3 (*green lines*) [recent declines at TS/Ph 1 and 2 are related to water level increases from freshwater restoration].

Our research on **consumers** has shown how salinity, P availability, and inundation change the role of detritus in food webs, the strength of trophic interactions, and the spatial scale of consumer-mediated habitat linkages (Figs. 10, 11). In freshwater marshes, periphyton mats are the primary source of carbon for consumers (*Williams & Trexler 2006; Belicka et al. 2012*). The degree of P limitation is negatively correlated with edibility of the autotrophic bacteria in periphyton, which is positively correlated with mesoconsumer density and biomass (macroinvertebrates and small fishes; *Sargeant et al. 2011; Trexler et al. 2015*). At the coast, top and mesoconsumers (sharks, alligators, piscivorous fishes) show a strong reliance on marsh prey production, which is regulated by the severity of marsh drying (*Boucek & Rehage 2013; Boucek et al. 2016a*). This prey subsidy is a strong driver of consumer distribution, as consumers

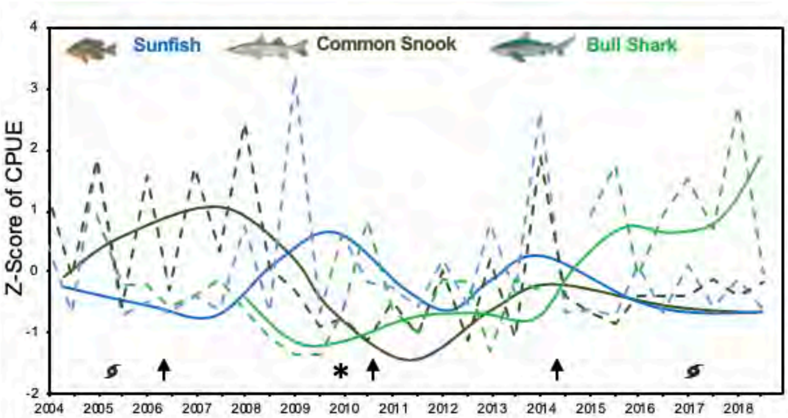


FIGURE 11. SEASONAL CATCH PER UNIT EFFORT (CPUE) of dominant large estuarine consumers (Common Snook and Bull Sharks) and their freshwater prey (*Lepomis* sunfishes) which pulse into SRS, with LOESS curves (a locally estimated regression approach) overlaid to illustrate long-term trends. Values are averaged across wet (Jun-Dec) and dry (Jan-May) seasons. Hurricanes (🌀), droughts (↑), and cold snaps (*) are determinants of both prey and consumer abundance.

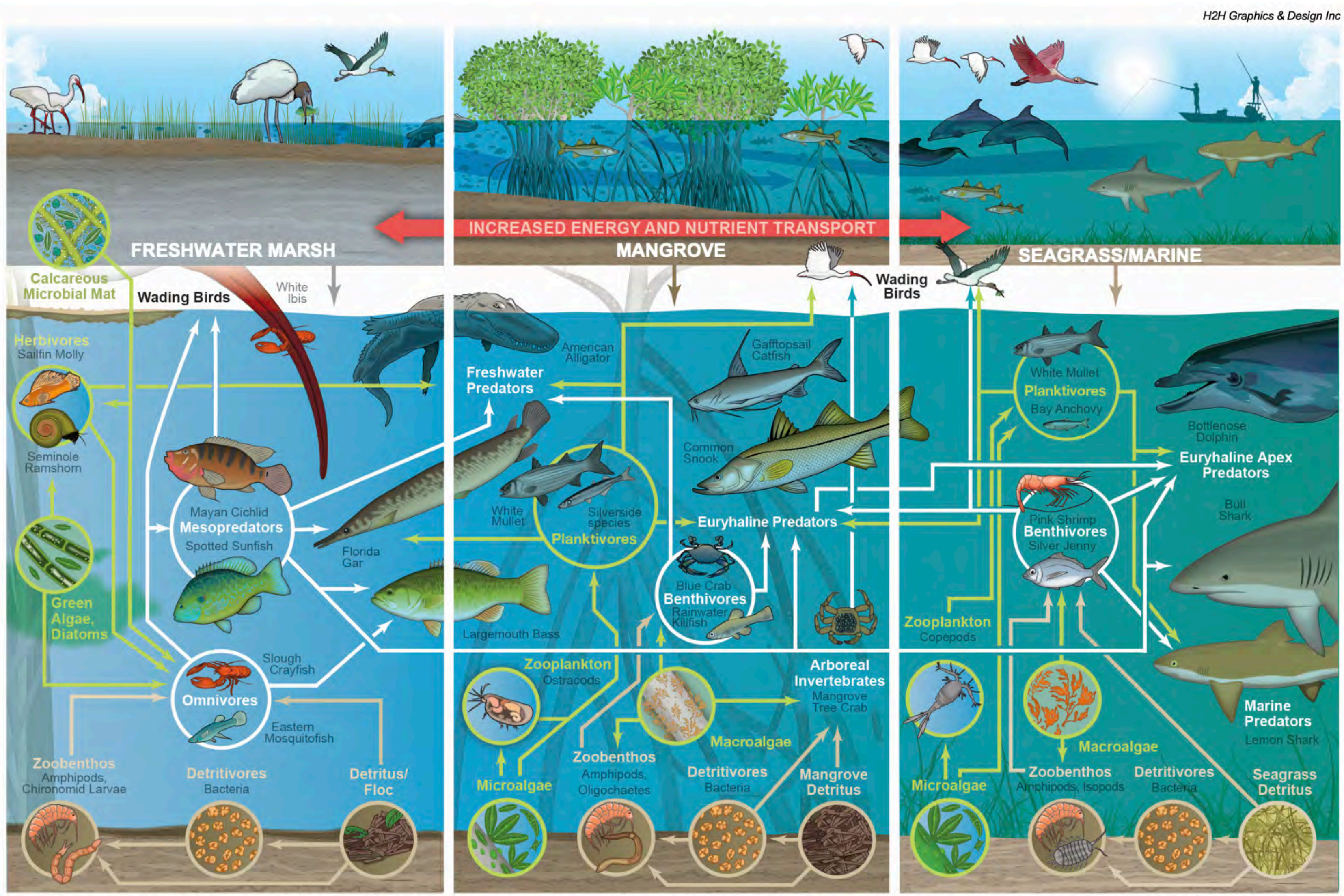


FIGURE 10. DIAGRAM OF THE FLORIDA COASTAL EVERGLADES FOOD WEB illustrating numerically dominant species in the major functional groups and the key basal resources across freshwater marsh, mangrove and seagrass/marine food webs. The influence of increased freshwater and marine pulses are expected to alleviate P limitation and increase production and energy flux through higher quality algal-based trophic pathways (green arrows) relative to lower-quality detrital pathways (brown arrows - consumers that rely on both pathways are shown with white arrows); increasing trophic efficiency, secondary production, and trophic coupling across habitats via increased movement of mobile consumers.

move from marine to freshwater marsh ecosystems tracking seasonally-displaced marsh prey (*Matich & Heithaus 2014; Griffin et al. 2018*), partitioning resources and space differently among individuals and taxa (*Rosenblatt et al. 2015: Matich et al. 2017*). Along with freshwater marsh prey pulses, extreme events (cold spells, hurricanes, droughts) drive long-term prey and consumer abundances (*Boucek & Rehage 2014, Boucek et al. 2016b*) and movements (*Boucek et al. 2017; Strickland et al. 2019; Massie et al. 2019*; Fig. 11). Consumers inhabiting areas with no access to marsh subsidies rely on marine epiphytic production (*Eggenberger et al. 2019*).

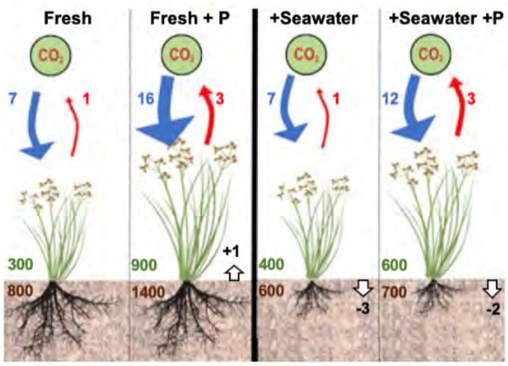


FIGURE 12. FRESHWATER MARSH RESPONSE TO SALTWATER INTRUSION from manipulations of phosphorus (+ 15 μmol P d^{-1}) and seawater (9 ppt NaCl). Responses include changes in carbon dioxide flux (*blue and red arrows*, μmol CO_2 m^2 s^{-1}), biomass of above and belowground vegetation (*green and brown numbers*, respectively, in g m^{-2}, respectively) and soil elevation gain or loss (*arrows*, in cm).

The shifting balance of fresh and marine water supplies drives spatiotemporal variability in net ecosystem **carbon** balance along a freshwater-marine gradient through its influence on P, salinity, and duration of inundation (*Troxler et al. 2013*). Our experiments have shown a reduction in sawgrass root production with salt exposure that shifts peat marshes from carbon sinks to sources (*Wilson et al. 2018a; Servais et al. 2019a*), resulting in losses of soil elevation and carbon stocks (*Charles et al. 2019*) – analogous to the spatially patchy and abrupt collapse of peat soils observed on the FCE landscape and elsewhere (*Tully et al. 2019*). However, our subsidy-stress experiments, designed to decouple the influences of P and salinity, suggest that plants exposed to saltwater can increase CO_2 uptake in the presence of increased P (Fig. 12). Long-term data from our freshwater marsh eddy flux towers illustrate how seasonal inundation duration determines whether marshes are a carbon source or sink, controlled mainly by ecosystem respiration (*Malone et al. 2013; Zhao et al. 2019*). The formation and dissolution of carbonate minerals that comprise the inorganic fraction of FCE soils have implications for the net ecosystem carbon balance (*Howard et al. 2018*) – which we can now assess at our new seagrass-dominated eddy flux site. Additionally, our cross-site research has underscored the potential regulatory role of top consumers in regulating coastal carbon stocks (*Atwood et al. 2015*).

3. Legacies: *The FCE paired transect design has enabled robust documentation of how disturbance legacies determine ecosystem trajectories and suggest that vulnerability to saltwater intrusion in coastal wetlands may be reduced by freshwater and marine pulses.* Our paleoecological research shows that tidal and storm-driven marine P subsidies have fueled the long-term inland migration of mangroves, offsetting negative effects of saltwater intrusion on organic carbon burial over the last century (*Breithaupt et al. 2012*). Interestingly, Florida Bay shows high rates of net primary productivity, but burial rates of autochthonous inorganic mineral carbon are 4-10× higher than burial rates of organic carbon (*Howard et al. 2018*). The pace of interior-ward movement of SRS mangroves over the last century is linked to the historic rate of sea-level rise (*Yao & Liu 2017*; Fig. 13), but decadal accretion rates (-1.5-4.7 mm y^{-1}) of TS/Ph scrub mangroves are much lower than the current local sea-level rise rate (9

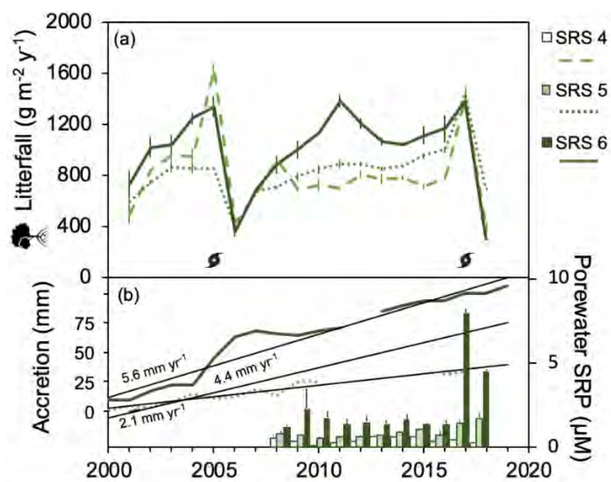


FIGURE 13. MANGROVE PRODUCTION AND ACCRETION REFLECT STORM-SURGE RESOURCE PULSES FROM HURRICANES WILMA (2005) AND IRMA (2017). (a) Annual mean litterfall (with standard errors) show defoliation and rapid regrowth, fueled by pulses of (b) porewater soluble reactive phosphorus (SRP - *bars with standard errors*) from P-rich sediments delivered from the Gulf of Mexico that also increased accretion rates (black *lines with slope of linear regression*).

mm y^{-1}). Sites with the highest accretion rates (SRS mouth) contained 5 cm of inorganic carbon from Hurricane Wilma (Oct. 2005) and 4 cm from Hurricane Irma (Sept. 2017) equivalent to 50 and 40 years of organic carbon accretion, respectively (*Breithaupt et al. 2019a*). These mineral storm deposits contained double the P content of mangrove peat soils (*Castañeda-Moya et al. 2020;* Fig. 13), which is gradually sequestered into plant biomass and leached out of soils and pulsed upstream with tides (*Davis et al. 2019; Kominoski et al. 2020;* Fig. 7). This P subsidy induced rapid (<5 years) forest recovery in areas where canopy defoliation was >90% (*Danielson et al. 2017*). As leaf turnover recovered over time, foliar residence time decreased to pre-Wilma values – a relationship that could be used as a proxy of canopy recovery and resilience in studies across mangrove ecotypes and coastal settings (*Rivera-Monroy et al. 2019b*). We also documented the role that landscape configuration plays in the response of seagrass meadows to both direct (erosion and burial) and indirect (changes in water quality) impacts from hurricanes (*Wilson et al. 2019b*).

4. Scenarios: *Taking advantage of episodic "natural" disturbances and experiments, we are parameterizing models to evaluate the limits of primary producers to the stressor of saltwater intrusion, constructing new models for relating drivers to responses, evaluating ecosystem resilience and recovery trajectories to disturbances, and informing scenarios that are helping us to project the future of the FCE.* We modeled ecosystem responses to sea-level rise (0.5 m) interacting with climate change (+1.5 ºC, +7% evapotranspiration, and ±10% rainfall), predicting that mangrove forests would migrate up to 15 km inland and freshwater habitat area would decrease by more than 25% by 2060 (*Flower et al. 2017c*). Increased rainfall provided significant benefits to the salinity regime (Fig. 14), providing a more gradual adjustment for at-risk flora and fauna – a benefit that, when coupled with freshwater restoration, increase the capacity for mangrove establishment and forest development to the interior (*Flower et al. 2019*). This work has allowed key stakeholders to recognize that coastal ecosystems contain large stores of carbon in vegetation and soils of significant value ($2-3.4 billion in social cost of mangrove wetlands; *Jerath et al. 2016; Wetzel et al. 2017*) that are at risk of being released to the atmosphere with excessive salinity, extreme drought, and nutrient enrichment (*Fourqurean et al. 2012a,b; Breithaupt et al. 2014; Suárez-Abelanda et al. 2014*).

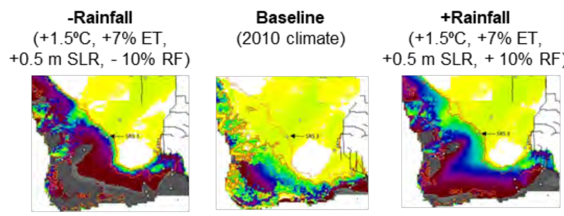


FIGURE 14. EVERGLADES LANDSCAPE MODEL (ELM) SIMULATIONS of daily mean surface water salinity for three climate scenarios of temperature (°C), evapotranspiration (ET), and sea-level rise (SLR), and rainfall (+/-RF).

In summary, the Everglades is a complex social-ecological system with emergent properties resulting from a long history of conflicts over water use, reduced freshwater inflows, and increased sea-level rise and storms (*Gaiser et al. 2015a; Childers et al. 2019*). Saltwater intrusion has caused abrupt release of CO_2 from marshes to the atmosphere via collapse of peat soils. In the absence of sufficient fresh water, catastrophic losses of soil elevation will hinder the landward migration of mangroves by reducing seedling establishment in deeper, sulfide-rich water (*Chambers et al. 2016; Troxler et al. 2019*). A consequence of soil elevation loss is reduced social-ecological resilience to sea-level rise and decreased ecosystem service values. *Freshwater restoration now provides a manipulation at an unprecedented scale to determine whether the return of freshwater pulses interacts with increasing marine resource pulsing to reverse these trends, and preserve core ecological features of coastal wetland ecosystems that enhance their ability to persist as sea-level rise accelerates.*

Ten Most Significant Publications (2014-2020) **denotes graduate and **undergraduate student author*

Boucek, R. & J.S. Rehage. 2014. Climate extremes drive changes in functional community structure. Global Change Biology 20:1821-1831. DOI:10.1111/gcb.12574*

Castañeda-Moya, E., V.H. Rivera-Monroy, R.M. Chambers, X. Zhao, L. Lamb-Wotton, A. Gorsky, E.E. Gaiser, T.G. Troxler, J.S. Kominoski, & M. Hiatt. 2020. Hurricanes fertilize coastal wetlands in the Gulf of Mexico: The case of Florida Everglades mangrove forests, USA. Proceedings of the National Academy of Sciences. DOI:10.1073/pnas.1908597117*

Childers, D.L., E.E. Gaiser & L.A. Ogden. 2019. The Coastal Everglades: The Dynamics of Social-Ecological Transformation in the South Florida Landscape. Oxford University Press.
Gaiser, E.E., D.M. Bell, M.C.N. Castorani, D.L. Childers, P.M. Groffman, R.C. Jackson, J.S. Kominoski, D.P.C. Peters, S.T.A. Pickett, J. Ripplinger, & J.C. Zinnert. 2020. Long term ecological research and evolving frameworks of disturbance ecology. BioScience 70:141-156. DOI:10.1093/biosci/biz162
Haigh, I.D., T. Wahl, E.J. Rohling, R.M. Price, C.B. Pattiaratchi, F.M. Calafat & S. Dangendorf. 2014. Timescales for detecting a significant acceleration in sea level rise. Nature Communications 5:3635. DOI:10.1038/ncomms4635
Howard, J., J.C. Creed, M.V.P. Aguiar & J.W. Fourqurean. 2018.* CO_2 *released by carbonate sediment production in some coastal areas may offset the benefits of seagrass "Blue Carbon" storage. Limnology and Oceanography 63:160-172. DOI:10.1002/lno.10621*
Kominoski, J., E.E. Gaiser, E. Castaneda-Moya, S. Davis, S. Dessu, P. Julian, D.Y. Lee, L. Marazzi, V. Rivera-Monroy, A. Sola**, U. Stingl, S. Stumpf, D. Surratt, R. Travieso, & T. Trexler. 2020. Disturbance legacies increase and synchronize nutrient concentrations and bacterial productivity in coastal ecosystems. Ecology. DOI:10.1002/ecy.2988.*
Matich, P., J.S. Ault, R. Boucek, D.E. Bryan, K.R. Gastrich, C.L. Harvey, M.R. Heithaus, J.J. Kiszka, V.A. Paz*, J.S. Rehage & A.E. Rosenblatt*. 2017. Ecological niche partitioning within a large predator guild in a nutrient-limited estuary. Limnology and Oceanography 62:934-953. DOI:10.1002/lno.10477*
Rovai, A., R.R. Twilley, E. Castañeda-Moya, P. Riul, M. Cifuentes-Jara, M. Manrow-Villalobos, P. Horta, J.C. Simonassi, A.L. Fonseca & P. Pagliosa. 2018. Global controls on carbon storage in mangrove soils. Nature Climate Change 8:534-538. DOI:10.1038/s41558-018-0162-5*
Wilson, B. J., S. Servais*, S.P. Charles*, V. Mazzei*, E. Gaiser, J.S. Kominoski, J.H. Richards, & T.G. Troxler. 2019. Phosphorus alleviation of salinity stress: effects of saltwater intrusion on an Everglades freshwater peat marsh. Ecology 100:e02672. DOI:10.1002/ecy.2672*

B. Broader Impacts

Education Programs: FCE has a very active education and outreach program that promotes the professional development of the majority-minority populations of FIU and our K-12 schools. Our Schoolyard program focuses primarily on Miami-Dade County Public Schools by engaging a diverse population of pre-/professional-service teachers in Science, Technology, Engineering, and Math (STEM) disciplines, and our community partners to increase Everglades literacy. Since 2013, our scientists have mentored 179 K-12 students and 4 teachers in our Research Experience Program. Teachers generate Data Nuggets available online and in use within and outside the State of Florida. We provided professional development to 114 teachers from 70 schools, delivered 73 K-12 presentations, and high school students have presented 17 posters receiving 42 awards (26 local, 12 state, 1 national, and 3 international). Our children's book has been placed in 488 K-8 schools and 50 public libraries, and our *Predator Tracker* and *Alligators of Shark River* apps are used globally. Since 2013, 247 undergraduates from 26 universities in 9 U.S. states and 3 other countries have worked with FCE researchers. This program was formalized in 2019 through an NSF Research Experiences for Undergraduates (REU) site grant at FIU focused on coastal ecosystems. FCE graduate students have always been very active participants in the FCE and LTER Network (see *Romolini et al. 2013*). They co-produce science as a result of mentoring by both academic and agency scientists, and are engaged in all aspects of the FCE program, including writing proposals and leading authorship of 53% of our publications, mentoring undergraduate and high school students, and engaging in public participatory science projects.

Broadening Participation: FCE is based in Miami at FIU, the nation's largest majority-minority-serving (64% Hispanic; n = 37,272) and the fourth largest U.S. university (n = 58,063). FCE excels at serving this community by introducing students to ecological science and the effects of human activities in the Earth's biosphere. We focus on recruitment of underrepresented groups into our research experience programs, resulting in a majority of FCE undergraduate students identifying as underrepresented groups (49% Hispanic; 4% non-Hispanic Black, and 65% female). Similarly, a total of 66% of the 179 students and 165 teachers working with FCE scientists are from underrepresented groups (60% Hispanic).

Dissemination: Since 2013, 92 FCE researchers have participated in over 700 media events that include 32 local, national and international news agencies. Our findings have been shared with the public through Miami's Frost Science Museum, the Ft. Lauderdale Museum of Discovery and Science, coverage in 51 television/radio segments (including episodes of *Changing Sea, Shark Week,* and *Ocean Mysteries*), our *Diatom of the Month* blog that is now managed internationally, and over 337 outreach events and more than 189 public presentations. Our collaboration with the *Tropical Botanic Artists* has led to 24 art exhibitions with over 80 paintings displayed at 14 venues across South Florida and three national exhibits. During the *COP21 Paris Talks* in 2015, FCE Artist in Residence, Xavier Cortada launched the first annual exhibit at *Art Basel Miami* consisting of discussions addressing sea-level rise, global climate change, and biodiversity loss and featuring works created at FCE, HJ Andrews, and Hubbard Brook LTERs. FCE scientists also express data through music with three compositions available on YouTube.

Benefits to Society: FCE is dedicated to the continued co-production of knowledge as a direct conduit of FCE findings to resource managers, decision-makers, and other stakeholders (*Gaiser et al. 2019*). In collaboration with the Everglades Foundation, we have provided over 138 briefings and 72 tours to local, state, national and international lawmakers, non-governmental organizations, and community partners. FCE scientists have testified to the U.S. House of Representatives and the European Union Parliament, counseled the Intergovernmental Panel on Climate Change and the National Academy of Science Independent Review of Everglades Research, and discussed the relevance of findings to resource decisions with former President Barack Obama, former Senator Robert Graham, the Florida Congressional Delegation and their staffs, and former White House Science Advisor Dr. John Holdren. We also engage with decision makers to translate science into restoration policy (i.e., *Wetzel et al. 2017*).

Synthesis, Cross-Site, and LTER Network-Level Activities: Collaborations within and outside of FCE generate synthesis products, including our contribution to the Oxford University Press LTER book series: "*The Coastal Everglades: The Dynamics of Social-Ecological Transformations in the South Florida Landscape*" (*Childers et al. 2019*), chapters in other synthesis books (DeLaune et al. 2013; Entry et al. 2015; Batzer & Boix 2016; Willig & Walker 2016), and cross-site syntheses of ecosystem development and disturbance theory (*Kominoski et al. 2018; Gaiser et al. 2020*). We continue to mobilize cross-LTER site comparisons, including studies of global black carbon distribution (*Khan et al. 2017*), sea-level rise vulnerability (*Tully et al. 2019*), roles of apex predator movements (*Rosenblatt et al. 2013; Boucek & Morley 2019*), changes in seagrass carbon stocks (*Christiaen et al. 2014; Arias-Ortiz et al. 2017*), global mangrove biogeochemistry and productivity across geomorphological settings (*Twilley et al. 2019; Ribeiro et al. 2019*), and drivers of mangrove resilience (*Farfán et al. 2014; Roy Chowdhury et al. 2017*). Our international collaborations remain a strong pillar for synthesis and include comparative works on subtropical wetlands (*Gaiser et al. 2015a; Marazzi et al. 2017; Rivera-Monroy et al. 2017*), the role of wetlands in the global carbon cycle (*Barr et al. 2014*), and global information exchange (*Vanderbilt & Gaiser 2017; Vanderbilt et al. 2017*). FCE researchers are active in LTER Network leadership including serving on 7 committees (contributing heavily to Information Management– see *Wheeler et al. 2017*).

Supplemental Support: Supplemental support in 2015 enhanced our research infrastructure, including updating our data servers, meteorological and flux towers, aquatic sensors, and acoustic consumer tracking arrays. We also used supplemental funds in 2016 and 2019 to enhance our research experience program for high school students and teachers (described above), and a 2017 equipment supplement replace instruments on our eddy flux towers and acoustic tracking devices lost during Hurricane Irma.

III. Proposed Research - Intellectual Merit

A. Research Platform and Design

We will use a combination of: (1) continued long-term and new biophysical data collection and remote sensing along our two transects and mixed-methods human dimensions research, (2) a new ecosystem vulnerability experiment, (3) data-driven process and landscape-scale modeling approaches, and (4) numerous projects sponsored by leveraged funding to address our four hierarchical research questions.

1. **Long-term data:** We will continue to collect data in seven LTER core areas (Box 2) to address hypotheses described below. These data are obtained from our biophysical platform along our two transects and include meteorological measurements, assessments of vegetation community structure and production, collections to determine the quality, metabolism, composition, and movement of dissolved and particulate detritus and microbes (including periphyton mats), and the composition, stoichiometry, stable isotope composition across food webs, and the movement of aquatic consumers. Carbon fluxes will be measured by our extensive flux network containing towers in each ecosystem type along both transects. Data on ***Abiotic Resources & Stressors*** supporting all hypotheses include assessments of water total organic carbon, total dissolved solids, TP, and total nitrogen at 3- to 5-day intervals, sensor-based measurements of water level, temperature, dissolved oxygen, and salinity, and monthly surface water samples of dissolved carbon and inorganic nutrients. Abiotic data will be used to determine the amplitude and duration of water column salinity, sediment, and P pulses in relation to daily, seasonal, and event-driven variability in water levels, seasonal freshwater inflows, storm surge pulses, and tides – long-term observations to be used in enhancing our process-based hydro-ecological models. Notable new biophysical collections will include: (1) measurements of surface water temperature, alkalinity, and pH at all sites to determine net calcification rates, (2) porewater salinity sensors in the marsh-mangrove ecotone to understand variability in saltwater intrusion, (3) an expanded suite of soil surface elevation tables and shallow sediment cores to track long-term accretion and carbon burial rates, (4) comprehensive stable-isotope and fatty acid assessments of food webs, and (4) expanded use of remote sensing tools to quantify landscape-scale vegetation and geomorphological change. Our social-ecological research will continue to generate data in the form of interview transcripts and modeled economic ecosystem service values.

Box 2. Summary of Core Variables Measured in FCE Long-Term Studies listed by working group and hypothesis ($H_{1\text{-}4}$) and indicating LTER core research areas of primary production (PP), population dynamics and trophic structure (PS), organic matter accumulation or utilization (OM), inorganic inputs and movements of nutrients through the ecosystem (IM), patterns and frequency of disturbances (DP), land use and land cover change (LU), and human-environment interactions (HE) (see *Supplemental Documents: List of FCE Datasets* for more detail).

Focal Area	Working Group (Hypothesis; Core Area)	Core Area Variable	Frequency – Location (Duration; p=present)
	Climate Variability & Change (H_1; DP)	Meteorology, model outputs, index values	Hourly, daily - distributed network within and outside FCE domain
	Cultural & Economic Values; Freshwater Governance (H_4; LU, HE)	Model economic outputs; Structured interviews	Annually
	Hydrologic Connectivity (H_{3a}; DP)	Water depth	Minute - SRS1-6, TS/Ph1-7 (2001-p)
		Groundwater temperature, dissolved oxygen, salinity, discharge, velocity	Minute – SRS1-3, TS/Ph 1-7 (2004-p) [select marsh sites for velocity]
		Groundwater nutrients, salinity	Biannually - SRS 4, 6; TS/Ph 3, 6, 7 (2000-p)
	Consumers, Consumer-Mediated Nutrient Transport (H_{2c}, H_{3b}; PP, OM)	Stable isotopes (C, N, S) of functional groups	Seasonally - SRS 3-6; TS/Ph 3, 7, 9-11 (2019-p)
		Consumer abundance and composition	Seasonally - SRS 2, 3, 4; TS/Ph 2, 3 (2004-p); TS/Ph 7, 9, 10, 11; SRS 6 (2020-p)
		Stoichiometry, fatty acids	Seasonally - SRS 2, 3; TS/Ph 3 (2016-p)
		Acoustic telemetry; radio telemetry	Continuous; Monthly - SRS 4-6 (2009-p) SRS 1-3 (2020-p)
	Vegetation & Geomorphic Gradients (H_{3c}; PP, LU)	Vegetation community (World View 2, 3); productivity (Sentinel 2, Landsat); structure and elevation (LiDAR); biomass (G-LiHT)	Biannual (2009-p); 5 d (2015-p), 16 d (1984-p); once per phase (2009, 2017, 2019), various (2015, 2017)
	Abiotic Resources & Stressors ($H_{1\text{-}4}$; IM)	Surface water salinity & dissolved nutrients; total organic carbon & nutrients	3-5 day; Monthly - All sites (2000-p)
	Vegetation (H_{2a}, H_{3c}; PP, PS)	Aboveground sawgrass, mangrove, seagrass biomass, productivity, composition; nutrients	Bimonthly; Annually - All sites (2000-p); Satellite sites (2020-p)
	Detritus & Microbes (H_{2b}; PS, OM)	DOM, POM characteristics	Monthly - All sites (2000-p)
		Soil, porewater nutrients and salinity	Annually - All sites (2000-p); Satellite sites (2020-p)
		Bacterial abundance, biomass, productivity	Monthly - All sites (2001-p)
		Litter decomposition rates	Periodic - All sites (2001-p)
		Microbial community composition	Quarterly - All sites (2019-p)
		Periphyton composition, biomass, palatability, nutrients; productivity	Quarterly; Annually - SRS 1-3; TS/Ph 1-3, 9-11 (2000-p)
		Plankton pigment concentrations	Monthly - All FCE sites (2000-p)
	Carbon Fluxes, Ecosystem Trajectories (H_{2d}, H_{2e}, PP, OM, DP)	Net ecosystem metabolism	Minute - SRS 2 (2009-p), SRS 6 (2004-p), TS/Ph 2 (2009-p), TS/Ph 7 (2017-p), TS/Ph 10 (2019-p)
		Soil elevation change	Annually - Mangrove sites (1999-p); Marsh sites (2020-p)

2. Experiments: The FCE program uses controlled experiments to reveal mechanisms underlying observed long-term changes as well as to parameterize and validate ecological models. For example, by coupling field chamber experiments with outdoor mesocosm experiments (*Wilson et al. 2018a,b; Charles et al. 2019; Sklar et al. 2019a;* Fig. 12), we identified mechanisms driving the potential for peat collapse in coastal ecosystems among those proposed by Chambers et al. (2019), and incorporated resultant functions into our ecosystem trajectory models (Q_4). Our new 'ecosystem vulnerability' experiment builds on the discovery that pulses of limiting nutrients (Fig. 7) may offset the osmotic stress of salinity on vegetation, reducing the potential for peat collapse. This experiment is designed to assess the capacity for P to offset osmotic stress on producers, consumers, and decomposers, and whether this subsidy-stress interaction is modulated by vegetation species traits. It thereby mechanistically addresses Q_4 while also generating functions for our ecosystem- and landscape-scale models (Q_3) that will be used to examine trajectories of carbon accumulation based on realistic scenarios of change in exogenous drivers. We outline the experiment here and provide detail as necessary by working group, below. The experiment will be conducted in a foot-accessible wetland adjacent to Everglades National Park where we have documented significant rates of saltwater and mangrove intrusion (Ross et al. 2000) but now the coastal wetland is receiving restored freshwater flows. We will establish forty 12.25m^2 experimental plots, ten each in two freshwater sawgrass marshes and two brackish wetlands of scrub red mangroves. Five replicate plots in each habitat type will receive a monthly pulse of P at 3× ambient concentration (using methods of *Daoust & Childers 2004*), and the other five plots will be control plots. Each plot will contain subplots where red mangroves are added or sawgrass removed, to determine whether assisted migration of species adapted to the primary press (saltwater intrusion) and capable of high net primary production in response to pulses (of P) will promote developing trajectories. In year 1, we will deploy continuous salinity and water level gauges to guide plot placement and set up experiments. We will begin treatments in year 2 and conduct quarterly collections of porewater chemistry (nutrients, ions), periphyton and plant composition (above- and below-ground production), consumer abundance, composition and stoichiometry, surface accretion using Feldspar markers, and leaf and soil decomposition through year 4, when we expect to be able to detect responses in soil accumulation (*Charles et al. 2019*).

3. Numerical Modeling: Our long-term spatiotemporal and experimental data drive a large suite of models that provide the context for social decisions that directly influence freshwater pulse restoration (Fig. 15). Syntheses afforded by our models range from regional water management (largely determined by social-ecological interactions) to ecological models of peat accumulation (largely determined by hydro-ecological interactions). Our modeling approach incorporates short-term feedbacks among plants, animals, soil, and water, to enable long-term predictions of where and why ecosystems develop (gain carbon stores) or decline (lose carbon stores). In FCE IV, we will reduce uncertainty in rainfall and evapotranspiration projections through advancements to climate downscaling (described in Q_1, below). Implications of these projections for current and future changes in the management of freshwater pulses will be explored using the regional water management models including the South Florida Water Management Model (SFWMM) and Regional Simulation Models (RSM) used in multi-agency evaluations of restoration outcomes (Obeysekera et al. 2015). These models provide the hydrologic boundary conditions for the Everglades Landscape Model (ELM), a regional-scale, integrated ecological assessment tool designed to help understand hydro-ecological dynamics over multi-decadal time scales (*Fitz et al. 2011*; Osborne et al. 2017) and to guide adaptive management of restoration (*Wetzel et al. 2017*). In simulating changes to habitat distributions, the ELM dynamically integrates surface and groundwater hydrology, P, salinity, soil accretion, and periphyton and vegetation succession. ELM has provided critical insight into knowledge gaps guiding hypotheses and data collection (*Flower et al. 2019*). We will also advance the Biscayne and Southern Everglades Coastal Transport (BISECT) model (Swain et al. 2019), which simulates surface-groundwater interactions on shorter time scales than ELM. In addition, we will use field data on Hurricane Irma's debris deposition and erosion distribution to validate our Coastal Estuarine and Storm Tide (CEST) model that predicts storm surge attenuation (*Zhang et al. 2012*, 2013). To explore how changes in hydrologically-driven changes in salinity, inundation, and nutrient supplies influence vegetation community transitions and soil elevation change, we will employ a spatially distributed freshwater marsh succession model (Pearlstine et al 2012), point-based soil-forest mangrove models (*Twilley & Rivera-Monroy 2009*), and a seagrass community model (*Madden 2013*). We will continue to develop our Everglades Peat Elevation Model (EvPEM) that includes functional responses of sawgrass aboveground and belowground productivity, decomposition and soil elevation change to salinity and inundation, and the Marsh Equilibrium Model (MEM; Morris et al. 2002) that we recently parameterized for mangroves, improving our understanding of plant-soil carbon dynamics.

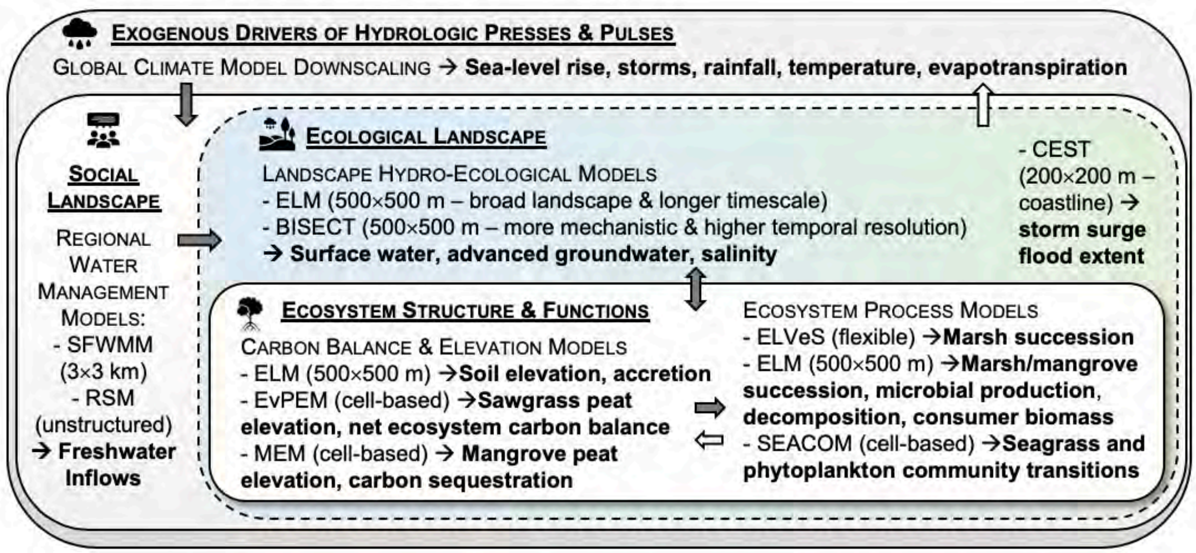


FIGURE 15. MODELING FRAMEWORK that maps to our conceptual framework (Fig. 5) and integrates FCE models across hierarchical scales. Regional downscaling of global climate models provides the exogenous press and pulse climate drivers to regional water management models that control endogenous freshwater pulses to the FCE. Climate and management models provide realistic scenarios of climate and management boundary conditions driving landscape hydro-ecological models. Ecosystem structure and function models are used to understand the consequences of shifting presses and pulses to dynamics freshwater marsh, mangrove, and seagrass ecosystems using functions informed by and validated with field and experimental data, improving mechanistic understanding and feed back to process functions in landscape hydro-ecological models. *Gray arrows* indicate direct connections between models, and *white arrows* represent indirect feedbacks through exchange of outputs.

4. Related Research Projects: We will balance long-term continuity with new efforts by continuing to leverage substantial support for both observational and experimental studies (including 58 leveraged projects continuing into FCE IV, see *Facilities, Equipment and Other Resources*). Our water quality, vegetation and consumer sampling along the TS/Ph transect share support from NSF, the U.S. Army Corps of Engineers, Department of Interior, and the South Florida Water Management District. Together with the US Geological Survey, these agency partners maintain a robust network of hydrologic, meteorological, and soil surface elevation monitoring stations throughout the Everglades, including long-term studies along the SRS and TS/Ph boundaries where new water delivery structures are being constructed and operated (*Bramburger et al. 2013; Kotun & Renshaw 2014; Sullivan et al. 2014*).

B. Detailed Research Plan

FCE IV research will address four hierarchical questions (**$Q_{1\text{-}4}$**) via hypothesis-led (**$H_{1\text{-}4}$**) working groups: **Q_1** – ***Climate Variability & Change***, **Q_2** – ***Cultural & Economic Values***, and ***Freshwater Governance***, **Q_3** – ***Hydrologic Connectivity***, ***Consumer-Mediated Nutrient Transport***, and ***Vegetation & Geomorphic Gradients***, and **Q_4** – ***Vegetation, Detritus & Microbes, Consumers, Carbon Fluxes***, and ***Ecosystem Trajectories***. Below we provide a justification for each hypothesis based on theoretically-guided expectations and long-term findings, and provide a detailed work plan.

Q_1: How will global climate change alter regional climate variability and extremes – the exogenous drivers of hydrologic pulses and presses? To address this question, we will use downscaled climate models to quantify feedbacks between the ocean, land, and atmosphere and generate boundary climate conditions for hydrological and ecological modeling efforts.

H_1 (<u>Climate Variability & Change</u>): Global climate change will increase climate variability and extremes in South Florida, and increasing evapotranspiration from the FCE will feedback to enhance wet-season rainfall. Uncertainty in future projections stem from South Florida's climate being driven by both remote modes of variability (i.e., teleconnections, *Moses et al. 2010*; Obeysekera et al. 2017) and by local variability and feedbacks associated with its land surface and neighboring water bodies (Blanchard & Lopez 1984; Nicholls et al. 1991). Using an intermediate greenhouse gas emission scenario, Kirtman et al. (2017) found that dry and wet season rainfall in South Florida will increase by the end of the century. Much of the FCE's summer rainfall is driven by diurnal gradients of temperature and pressure between the land surface, Atlantic Ocean, and the Gulf of Mexico resulting in thunderstorm activity. Evapotranspiration of surface water from the FCE can contribute up to 12% of the wet-season rainfall (*Price et al. 2007*). During the dry season, evaporation from the surface is diminished and precipitation is driven primarily by the passing of weather systems (Trenberth & Shea 2005) that are modulated by sea surface temperature anomalies in the tropical Pacific Ocean (Ropelewski & Halpert 1987). In addition to the local and remote modes of climate variability, tropical cyclones provide a critical source of precipitation to peninsular Florida (Knight & Davis 2009). In the past, the spatial resolution of large climate change models like the fifth Coupled Model Intercomparison Project (CMIP5) was course relative to the scales of climate forcing in Florida (Obeysekera et al. 2015; Chassignet et al. 2017). However, improvements to the resolution of global models (CMIP6) through advances in ensemble and model bias correction techniques and statistical and dynamic downscaling of model output, allow us reduce future uncertainty in the FCE hydroclimate (Sinha et al. 2018; Srivastava et al. 2019). With the explosive growth in the number of highly resolved regional climate datasets, the potential for delivering accurate climate projections, particularly high-resolution projections and predictions incorporating both meteorological and hydrologic extremes is increasingly attainable.

Work Plan: During the first phase of FCE IV, we began a downscaled analysis of FCE site and gridded satellite meteorological and hydrological data, representing approximately 20,000 stations, gridded to 211,687 points at a 1/16 degree spatial resolution from 1915 – 2011 (using Livneh et al. 2013). Moving forward, we will examine coupled feedbacks between the ocean, land, and atmosphere, and how these feedbacks may change in the coming decades using dynamically downscaled outputs from the World Climate Research Program's Coordinated Regional Climate Downscaling Experiment (CORDEX) and outputs from the High-Resolution Model Inter-comparison Project (HiResMIP) within the ongoing CMIP6 effort. To aid with the analysis and attribution, we will incorporate state of the art reanalysis products like the European Center for Medium range Weather Forecasting high resolution ERA5 product. To assess the land surface and soil moisture feedbacks on climate variability and climate change, we will analyze outputs from the Land Surface, Snow, and Soil moisture Model Intercomparison Project (LS3MIP; van den Hurk 2016). Results from the historical, intermediate (RCP 4.5) and high emission (RCP 8.5) future climate change scenarios will provide the boundary rainfall and evapotranspiration inputs to regional atmospheric, water management (SFWMM and RSM), and hydro-ecological models.

Q_2: How will the cultural and economic values of changing ecosystem functions and services influence governance of freshwater restoration? We will analyze how changes in ecosystem functions and services, influenced by shifting presses and pulses, effect and are shaped by divergent cultural and economic values that reflect the region's history of social, ecological, and technological change and feed back to restoration governance (Birkhofer et al. 2015).

H_{2a} (<u>Cultural & Economic Values</u>): The progress and objectives of freshwater restoration reflects conflicts among stakeholders relative to cultural and economic values of ecosystem services. Research on ecosystem service valuation emphasizes the need for both quantitative and qualitative assessments to examine the complex economic and cultural dynamics that create value (Redford & Adams 2009). In FCE III, we evaluated alternative restoration scenarios based on capital costs and multiple ecosystem service benefits in areas of hydrology, soil accretion, landscape processes, water quality, and small fish and wading bird dynamics (*Borkhataria et al. 2017; Wetzel et al. 2017*). However, the restoration benefits were estimated only in physical rather than economic units. At the same time, FCE research on cultural values of the Everglades points to the complex forms of value that people attach to their environments. For example, Cattelino (2015) details through ethnographic methods how ranchers in the northern Everglades link certain environmental features and processes to their identity. This can lead individuals to become defensive against changes to environmental conditions (*Price et al. 2019*), even if these changes will reduce long-term ecosystem vulnerability. We thus hypothesize that there is a divergence between the economic and cultural valuation of ecosystem services in the FCE, informing a broader dialogue about how natural resource management conflicts arise from uses of ecosystems versus the economic services they provide (Small et al. 2017).

Work Plan: We propose to extend our alternative restoration scenario analysis (*Borkhataria et al. 2017; Wetzel et al. 2017*) by converting ecological measures of ecosystem services into dollar values of carbon (*Jerath et al. 2016*), recreational fisheries (Brown et al. 2018), and water recharge (Richardson et al. 2014) benefits under a variety of market, ecological, and regulatory scenarios. We will apply the benefit transfer technique (Plummer 2009; Richardson et al. 2014) to estimate economic values of alternative climate change, restoration, and sea-level rise scenarios (see *Section III.C*). Standard economic and ecological practices will be followed while developing estimates of current and future benefits of restoration alternatives (e.g., sensitivity analysis, future performance-based benefit adjustments, discounting). We will compare multi-year aggregate benefits with initial and discounted annual operational costs of each scenario. Qualitative research will use interviews, focus groups, and participant observation with a variety of stakeholders who rely on these ecosystem services, including recreational anglers, boaters, tourists, water managers, farmers, indigenous communities, and residents. Combining qualitative and quantitative research methods will allow us to explore the divergent uses and values of ecosystem services, and bring into analytical detail the cultural, economic, and political tensions that are becoming built into restored ecosystems and are shaping conflicts over restoration priorities.

H_{2b} (Freshwater Governance): Authority over water management decision-making processes within water governance networks has only recently begun to derive from scientific expertise rather than political or economic sources of authority. Research in political geography, science and technology studies, and international relations has shown how governance is an emergent outcome of the complex interactions between formal and informal institutions (such as laws and regulations, or implicit cultural or economic values), forms of knowledge (such as technical expertise or local knowledge), social actors (competing stakeholder interest groups), and importantly, forms of authority that legitimize decisions – in this case, on water provisioning (Meehan 2014; Best 2014). Authority is not centralized in a single organization such as the state, but rather reflects a shifting and dynamic terrain of state-science-society relations (Jasanoff 2004). Governance, and its constituent components, are thus contingent and provisional – a focus of FCE human dimensions research. Environmental scientists explored the utility of different ecological indicators (from periphyton to wading birds) that respond to changing drivers at different spatiotemporal scales (*Doren et al. 2009*). Social scientists examined how restoration governance is impacted by competing stakeholders who appeal to a wide range of environmental and cultural values when supporting or opposing specific restoration initiatives (*Ogden 2011; Ogden et al. 2019*). We have also detailed how different forms of knowledge interact with wider governance dynamics, such as the introduction of ecosystem thinking into environmental management (*Ogden 2008*). Moving forward, we will focus on shifting forms of authority that legitimize water management decisions. Water governance in the region has historically involved contentious debates across water management stakeholders in the state, private sector, and scientific communities (Grunwald 2007; *Price et al. 2019*), including the introduction of novel tensions around the identification and measurement of indicators of restoration performance that could inform adaptive water management practices (Gunderson & Light 2007; *Ogden 2008*). Recently, adaptive management has begun to base water management decisions on environmental science rather than other political or economic influences suggesting an increased authority of scientific expertise, rather than other sources of authority, in water governance networks.

Work Plan: To examine the social construction of authority within water governance networks, we will conduct historical research into water management practices that determine freshwater allocations to the FCE. We will do this by disaggregating the history of water governance into three steps: (1) the history of the scientific identification of ecological indicators of restoration; (2) the incorporation (or not) of these indicators into water governance (in terms of both quality and quantity of freshwater supplies); and, (3) the practice of managing freshwater pulses to meet indicator targets. To test our hypothesis, we will look for deviation in (2) and (3) from the scientific identification of indicators in (1): no deviance indicates that authority reflects scientific expertise, while deviance indicates other forms of authority determine water management practices. We will use water management district archives and secondary archival sources of water governance and restoration debates. We will triangulate these archival and textual data with semi-structured interviews with scientists, local, regional and state policymakers, water management officials, and private sector actors involved in regional water governance from the 1990s to the present day. We will empirically demonstrate how closely water management targets reflect scientific expertise on indicators of restoration performance, and identify the shifting sources of authority that legitimize decision-making processes within regional water governance networks that determine freshwater distribution.

Q_3: How does geomorphology (elevation, soil depth) influence hydrologic connectivity to fresh and marine water pulses to determine the succession of vegetation and transport of nutrients by consumers? We will quantify how increasing wet-season fresh and marine pulses change hydrologic connectivity – through changes in inundation duration and depth, and groundwater-surface water exchange – and identify geomorphological feedbacks through changes in plant community distribution that influence elevation. We will also quantify changes in consumer-mediated nutrient transport across the landscape. By comparing responses between our two transects with established differences in vegetation and geomorphology – driven by historical differences in connectivity to fresh and marine supplies of water and P (*Troxler et al. 2013*) – we will quantify how hydrologic legacies interact with anticipated increases in hydrologic connectivity.

H_{3a} (Hydrologic Connectivity): Amplified seasonal pulses of fresh and marine water will increase hydrologic connectivity of water and constituents across the landscape and between surface water and groundwater. The propagation of fresh and marine water pulses through riverine and coastal floodplains is determined by interactions with complex geomorphic settings and habitat heterogeneity (Junk et al. 1989; Tockner et al. 2000). Extending the flood-pulse concept to our low-elevation gradient coastal environment can help conceptualize and quantify how pulses of fresh and marine water induce changes in water level, inundation duration, groundwater-surface water exchange, and the extent of saltwater intrusion in both the surface and subsurface. Brackish groundwater discharge from saltwater intrusion through the limestone aquifer is an important source of P *(Price et al. 2010; Flower et al. 2016*) that stimulates primary production (*Koch et al. 2012; Herbert & Fourqurean 2008*). Further understanding of the exchange of surface water with groundwater in peat, marl, and limestone bedrock is particularly needed as saltwater intrusion extends beyond the region of mangrove peats and into freshwater peats and marls and interacts with changing pulses from both fresh and marine water sources.

Work Plan: Space-based Synthetic Aperture Radar (SAR) observations will be used to map inundation level and extent throughout the FCE with spatial resolution of 30×30 m and accuracy of 10-15 cm (Kim et al. 2015; Zhang et al. 2016a). The SAR-based maps of similar inundation history will be verified and adjusted for accuracy by field observations of water levels and salinity and using data from the distributed Everglades Depth Estimation Network (Jones 2015). The SAR observations will complement BISECT model results, particularly inundation depth, expanding our understanding of landscape-level hydrology and salinity patterns (see H_{3c}). Saltwater intrusion into the limestone aquifer will be determined using wet- and dry-season conductivity measurements in our extensive network of groundwater wells. We will determine lateral and vertical exchange of water among the surface water, soils, and bedrock in response to seasonal and tidal pulses by measuring water level and salinity in surface water, soils, and groundwater in piezometers located along transects perpendicular to tidal creeks in both SRS and TS/Ph and at the 5 satellite sites (see H_{4e}). Hydrogeologic properties (porosity, hydraulic conductivity) of peat and marl soils will be determined. We will analyze groundwater and surface water for geochemical tracers – useful to discern mixing of waters in carbonate terrains (e.g., salinity/chloride, strontium/calcium, temperature, stable isotopes of oxygen and hydrogen; *Price et al. 2008; Stalker et al. 2009*) – and for key constituents indicative of biogeochemical processes (total and dissolved nutrients, DOC, and DIC). Fluorescent dissolved organic carbon (fDOC) can also be used as a proxy for groundwater-surface water exchange (*Regier & Jaffé 2016*), so we will deploy EXO-2 water quality sondes in groundwater wells and in the adjacent surface water to estimate groundwater-surface water exchange of fDOC over 30 days at neap and king tides. Groundwater flow calculations and hydrograph separation techniques will be used to quantify groundwater discharge. Mixing models using geochemical tracers (chloride, fDOC, temperature) will discern inputs of groundwater from peat or limestone portions of the aquifer to the surface water. Results of the hydrograph separation and mixing models will be combined with total and dissolved nutrient, DOC, and DIC concentrations to quantify potential biogeochemical processes. Hydrologic modeling will build on existing efforts to determine hydrologic connectivity across the landscape, including water-budget modeling (*Saha et al. 2012*; Livneh et. al 2015), variable-density groundwater flow modeling to quantify the groundwater discharge and extent of saltwater intrusion (Hughes & Sanford 2004), and statistical modeling of hydrologic and water quality conditions (*Dessu et al. 2020*).

H_{3b} (<u>Consumer-Mediated Nutrient Transport</u>): Increased hydrologic connectivity will lessen constraints on consumer movement, allowing consumers to better track changes in production across the landscape, resulting in enhanced food web coupling and consumer-driven nutrient transport. Animal movements can increase the fitness of organisms by optimizing energy acquisition relative to expenditure (Somveille et al. 2018), yet numerous constraints and tradeoffs prevent animals from optimizing their energy budgets (Clobert et al. 2009). As they move, animals can drive the spatial distribution of nutrients, linking the behavior of consumers to ecosystem-scale processes (McInturf et al. 2019). In the FCE, estuarine predator abundance and movements are strongly driven by dry-season concentration of freshwater prey (*Boucek & Rehage 2013; Matich & Heithaus 2014*), yet the importance of this marsh-produced energy relative to other energy sources in the landscape is unknown, and similarly the effects of these consumer movements on nutrient budgets have not been quantified. We hypothesize that increased hydrologic connectivity will remove both physical (e.g., water levels as a function of geomorphology and pulses) and chemical (e.g., oxygen and salinity concentrations) constraints on consumer movement (*Heithaus et al. 2009; Yurek et al. 2016*), increasing scales of movement and of trophic coupling (Fig. 10). Food-web theory predicts that greater scales of consumer movement (relative to those of their resources) will couple spatially isolated resources, stabilizing food web dynamics at landscape scales (Van de Koppel et al. 2005; McCann 2012). Consumers can also redistribute nutrients via active subsidies, defined as the movement of nutrients and energy by animal vectors (Polis et al. 1997; Allgeier et al. 2017). These subsidies can play a key role in nutrient budgets, particularly in oligotrophic systems, as animals can move against nutrient/energy gradients (McInturf et al. 2019) and increase nutrient transfer efficiency relative to other mechanisms (Nelson et al. 2013). We expect mobile consumers to link remote carbon sources and modify food web topology by creating new trophic links (Bartley et al. 2019), as well as redistributing nutrients across the landscape (via ingestion, egestion, excretion; 2002; Schmitz et al. 2010). By tracking movement of key consumers, the FCE program is well-poised to capture the role of this potentially important nutrient transport mechanism.

Work Plan: We will test effects of increased hydrologic connectivity during fresh and marine water pulses on consumer movements, coupled with detrital and algal abundances and trophic sampling ($H_{4b,c}$).

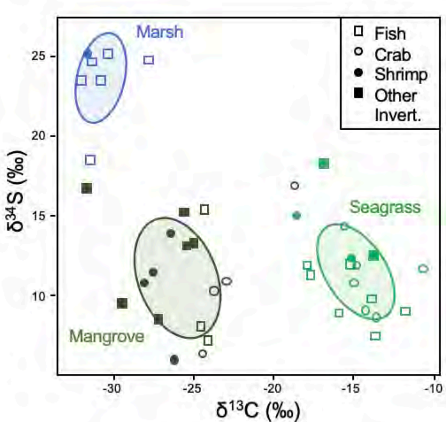


FIGURE 16. SMALL-BODIED CONSUMERS TRACK ORGANIC MATTER SOURCES. A wide separation in $\delta^{34}S$ values can be used to distinguish freshwater-derived organic matter from seagrass and mangrove habitats while $\delta^{13}C$ values can distinguish between seagrass- and mangrove-derived organic matter.

We will continue use of acoustic and radio telemetry to determine if scales of movement by dominant marsh and coastal consumer movements are changing in response to increases in wet season hydrologic connectivity (measured as in $H_{3a,c}$). Dominant consumers in our food webs – Bull Sharks, American Alligators, and Common Snook – will be tracked in the mangrove coast (*Matich et al. 2017*), and Largemouth Bass and nonnative Mayan Cichlids will be tracked in the marsh (*Parkos et al. 2011*) (Figs. 10, 11). We will use stable isotopes to examine if changes in the scales of consumer movements alter trophic dynamics by facilitating increased nutrient transport among freshwater, ecotone, and marine food webs (e.g., shifts in carbon source contribution to consumers; *Eggenberger et al. 2019*; Fig. 16). We will complement this work with estimates of biomass-specific excretion of nitrogen and P to quantify nutrient recycling by consumers (Torres & Vanni 2007; Whiles et al. 2009; Capps & Flecker 2013). We will combine these excretion rates with movement, biomass, and tracer data (stable isotopes) to derive estimates of nutrients transported by consumers relative to other sources (e.g., associated with surface and groundwater flows; Nelson et al. 2013; Wheeler et al. 2015) during the wet and dry seasons.

H_{3c} (<u>Vegetation & Geomorphic Gradients</u>): Interior-ward movement of salt-tolerant plant communities resulting from fresh and marine hydrologic pulses will increase soil elevation. Freshwater pulse restoration that reduces the rate of saltwater intrusion provides a powerful tool for managing the inland migration of mangroves and persistence of a vegetated coastal mosaic characterized by high net primary production at the landscape scale (*Troxler et al. 2013*). Hurricane-driven pulses of sediments and nutrients (*Smoak et al. 2013*) further trigger landscape changes in vegetation zonation that contribute to elevation gain (e.g., *Smith et al. 2009;* Feher et al. 2019; Fig.13). Increases in tidal extent (*Wdowinski et al. 2013*) and the brackish discharge of P-enriched groundwater to the coastal plant communities can favor species with higher productivity (e.g., mangroves), contributing to increased accretion rates and elevation, offsetting the negative effect of salinity on primary productivity (*Wilson et al 2019a;* Fig. 12). Because of the non-uniform distribution of exposure to and effects of salinity (*Breithaupt et al. 2019b*), we need to link the effects of interacting pulses and the press of saltwater intrusion on the physiological thresholds of producers (H_{4a}) to vegetation responses and changes in soil elevation throughout the landscape. Modeling interactions at this scale requires spatially explicit and exhaustive information on water depth and hydroperiods length, salinity gradients, productivity, and plant community dynamics. Expanding our spatial footprint of data collection will allow us to apply plant-soil mechanistic and ecosystem development models (H_{4e}) to the larger ecosystem and landscape scales.

Work Plan: We will inform landscape vegetation succession and soil accretion models by combining landscape-scale optical satellite data (Zhang et al. 2016b; Wendelberger et al. 2018), and LiDAR data (*Zhang et al. 2008a,b*) to detect vegetation dynamics, and radar observations for detection of changes in hydrologic conditions (*Hong & Wdowinski 2014; Feliciano et al. 2017;* see H_{3a}). Coupling modeled output of surface water and groundwater salinity (Swain et al. 2019) with models of vegetation community change (Pearlstine et al. 2010) provides an important tool for detecting and projecting landscape changes in ecosystem development trajectories, including the probability of collapse. Building off plot-scale experimental and long-term data characterizing change in topographic response (H_{4e}), in combination with vegetation (H_{4a}) and hydrologic characteristics derived from remotely-sensed data (H_{3a}), we will establish models of landscape geomorphological change. Our plot-scale, long-term, and experimental datasets will be combined with time-series of Landsat and MODIS data to model and detect long term (>30 years) landscape-scale changes in plant communities. We will first map the current vegetation at 2 m spatial resolution from World View (WV) data in combination with LiDAR-derived canopy height estimates for 2 km^2 buffer areas around SRS and TS/Ph salinity transects and new satellite sites, which captures the local variability of vegetation within and along environmental gradients. To model local variability and change of plant and periphyton communities we will scale up the vegetation patterns to spatial scales of Landsat (30×30 m) and MODIS (500×500 m), for which we have long-term spectral data (*Gann et al. 2015;* Gann 2019) – providing insight into shifts in species dominance in relation to regional gradients in fresh and marine water supplies (*Rovai et al. 2016*) across ecosystem types. Elevation gradients will be determined from bathymetric and topographic LiDAR derived digital elevation models. Surface water salinity and surface water, soil, and shallow groundwater P will be modeled from field observations using the ELM. We propose to use the SAR-derived hydrological conditions (H_{3a}), the scaled plant community dynamics, and the shallow groundwater salinity gradients resulting from the BISECT model to upscale (hundreds of km^2) the plot-scale (10×10 m) experimental results (H_{4e}). Finally, we will develop a large-scale integration of carbon dynamics using our eddy flux network across primary producer assemblages (see H_{4d}) to link wetland-atmosphere CO_2 exchange with soil elevation change.

Model calibration of landscape geomorphological change will be completed by establishing a history of vegetation change patterns from historic aerial stereo photography (since 1940) and remotely-sensed multispectral data (e.g., WV and Landsat). Applying plant-soil mechanistic model output for sites with historical soil surface elevation data, we will validate plant community transitions and soil accretion/loss predictions from the integrated soil-vegetation-hydrology model for past hydrologic records. We will model the relationship of plant community, hydrology, and soil accretion or loss processes for different soils to facilitate spatially-explicit modeling of geomorphological processes. We will then predict elevation change for a combination of freshwater pulse and sea-level press scenarios (see *Section III.C*).

Q_4: How will increased pulses of fresh and marine water and their associated resources change ecosystem structure and functions that control ecosystem development trajectories in coastal ecosystems facing the press of accelerating sea-level rise? We will address this question using a combination of: (1) long-term data from our biophysical platform to compare responses to freshwater and marine pulses between our two drainages of contrasting hydrologic connectivity and productivity, (2) the integrative experiment to examine mechanisms, and (3) ecosystem-scale modeling studies to predict long-term development trajectories from changes in ecosystem structure and functions.

H_{4a} (<u>Vegetation</u>): Increased pulses of fresh and marine water and their associated resources will increase the salinity and inundation duration thresholds of dominant soil-building plant species, measured by their productivity, above- and below-ground production, and stoichiometry. In coastal ecosystems, the productivity, production (above- and below-ground), and tissue stoichiometric ratios of primary producers influence soil formation, organic matter quality, and responses of consumers to freshwater delivery and tidal and storm surge pulses. Inundation depth and duration, salinity, and nutrient supplies together define the ‘production envelope’ for coastal plant communities (*Cardona-Olarte et al. 2013*) through physiological traits (*Twilley & Rivera-Monroy 2009; Madden 2013*). We have used long-term data to parameterize models that evaluate these physicochemical limits to production, and to predict recovery trajectories, and resilience of dominant primary producer species to disturbance (*Malone et al. 2015; Danielson et al. 2017; Rivera-Monroy et al. 2019b*). However, we need a better understanding of how these drivers interact to influence above- and below-ground production and, ultimately, plant community transitions in freshwater marshes, mangrove forests, and seagrass meadows. We anticipate that increased freshwater pulses will increase P loading (even at expected ambient concentrations) that will increase P uptake and primary production, punctuated by dry-season reduction in inundation stress to upstream marsh producers. In the mangrove-marsh ecotone, mangrove forests, and seagrass meadows, freshwater pulses will reduce salinity stress while marine P pulses (Fig. 7, 13) will fuel production. Continued long-term data collection along P, salinity, and inundation gradients and our ecosystem vulnerability experiment will enable us to quantify how pulses: (1) increase species-specific uptake of P and their capacity to adapt to salinity and inundation extremes to a measurable threshold (*Cardona-Olarte et al. 2013;* McKee & Vervaeke 2018), and (2) allow vegetation to keep pace with sea-level rise by increasing root production, the primary contributor to soil elevation (Kirwan & Megonigal 2013; *Morris et al. 2016*).

Work Plan: We will continue to measure net annual primary productivity, above- and below-ground production, species composition, and nutrient concentrations of primary producer species using established methods (*Fourqurean & Zieman 2002; Armitage et al. 2005; Childers et al. 2006b; Ewe et al. 2006; Castañeda-Moya et al. 2011, 2013; Rivera-Monroy et al. 2013*) along our two transects that differ in pulse frequency and magnitude, and to track legacies of the mineral P pulse delivered by Hurricane Irma (2017). We will explore above- and below-ground production envelopes freshwater, mangrove, and seagrass plant species using salinity-days (the number of days surface and porewater exceed set values), mean soil and tissue nutrient concentrations, and maximum inundation depth and duration (freshwater and mangrove plants only), and evaluate differences between our two transects and over time. We will use the ecosystem vulnerability experiment to determine P-modulation of salinity thresholds of sawgrass and red mangroves. Annual net primary production values will inform our net ecosystem carbon balance (H_{4d}), and experimentally and observationally-derived production-inundation, -salinity, and -P relationships will be used to improve our point-based and landscape models (see H_{3c}, H_{4e}).

H_{4b} (<u>Detritus & Microbes</u>): Increased pulses of fresh and marine water and their associated resources will synchronize microbial communities, increase microbial activities, and mobilize the algal and detrital base of the food web. Hydrologic pulses replenish coastal ecosystems with energy, nutrients, and organic matter that build carbon stores (Odum et al. 1995). Fresh and marine water pulses alter biogeochemistry in coastal ecosystems (Herbert et al. 2015; *Kominoski et al. 2020*; Fig. 7) and interact with long-term increases in water levels to enhance and synchronize activities of microbial communities and organic matter processing (*Servais et al. 2019a; Kominoski et al. 2020*). In the FCE, DOC concentrations have been declining over time in estuaries, particularly carbon derived from upstream marshes (*Regier et al. 2016*). We have detected decreases in humic (terrestrial) sources from upstream soil losses and increases in bacterial sources of DOC from increased saltwater intrusion (Fig. 8). As saltwater intrudes into brackish and freshwater ecosystems, soil organic carbon accumulation rates decline with enhanced soil oxidation and microbial respiration (*Chambers et al. 2015*), causing elevation loss (*Charles et al. 2019*; *Wilson et al. 2019a*). Burial rates of organic carbon are lowest where plants are osmotically stressed by salt and anoxia, reducing belowground productivity and root decomposition rates (*Castañeda-Moya et al. 2013; Charles et al. 2019*). Increased P supplies from marine pulses (Fig. 7) and saltwater intrusion may increase decomposition of organic matter (*Servais et al. 2019b; Mazzei et al. 2018, 2020*). In freshwater marshes, restoration-driven increases in water depth, inundation duration, and P loading should increase the ratio of palatable to unpalatable species in periphyton mats (*Gaiser et al. 2006a; Sargeant et al. 2010*) that enhance food web utilization of algal and detrital organic matter.

Work Plan: We will characterize variation in dissolved and particulate organic matter sources and sinks using long-term DOC and particulate organic carbon (POC) measurements along SRS and TS/Ph. We will measure biochemical complexity, accumulation, and age (*Xu et al. 2006*). Sources will be characterized through $\partial^{13}C$ stable isotope measurements, lignin phenols and optical properties (base extract fluorescence, pigments - *Cawley et al. 2014*). We will deploy standard substrates (e.g., green and red tea) and litter of dominant plant species (*Cladium jamaicense*, *Eleocharis cellulosa*, *Rhizophora mangle, Thalassia testudinum*) to measure rates of microbial processes (e.g., organic matter breakdown and respiration rates) using standard methods (Keuskamp et al. 2013; *Pisani et al. 2017*). Incubated microbial mat and litter will be sampled quarterly for metazoan invertebrates and analyzed for isotopic content by the *Consumers* working group (see H_{4c}). We will deploy litter from representative plant species at marsh, mangrove, and seagrass sites and in the ecosystem vulnerability experiment in fine- and coarse-mesh litter bags to measure breakdown from microbial and metazoan detritivores (Woodward et al. 2012). We will maintain monthly long-term data collections of bacterioplankton productivity (Bell et al. 1993). We will characterize microbial communities from seasonal samples of surface water, floc, microbial mat, and incubated litter (marsh, mangrove, seagrass vegetation; see H_{4a}), using Next-Generation DNA sequencing (Ngugi et al. 2017). We will supplement our long-term datasets on periphyton mat chemistry, production, metabolism, and community structure with assessments of fatty acid ratios to characterize changes to the nutritional landscape for consumers (*Gaiser et al. 2015b; Trexler et al. 2015*). We will measure these periphyton characteristics in the ecosystem vulnerability experiment, refining functional responses to salinity, P, and water level and incorporating them into the ELM model (*Naja et al. 2017*).

H_{4c} (<u>Consumers</u>): Increased pulses of fresh and marine water and their associated resources will result in a greening of food webs, shifts in consumer communities from detrital- to algal-feeding, and an increase in trophic efficiency. Consumption of both green (living autotroph) and brown (detrital) energy sources, termed multichannel feeding, is widespread in food webs (Wolkovich et al. 2014). Theory suggests that food web stability is enhanced by the behavioral responses of mobile consumers to the asynchrony of fast (green/algal) and slow (brown/detrital) energy channels (Rooney et al. 2006; Rooney & McCann 2012). For instance, continuous availability of detrital food sources can lend stability to food webs relying mostly on herbivory by buffering temporal variability in primary production. Green energy channels tend to be composed of small-bodied populations with high biomass turnover rates and high interaction strengths. They are also characterized by faster rates of energy transfer to upper trophic levels, higher proportions of primary production transfer to consumers (i.e., trophic efficiency), and greater responsiveness to perturbations (Cebrian 1999; Rooney et al. 2006). FCE food webs cycle energy derived from a mix of green and brown energy channels (*Williams & Trexler 2006*; *Belicka et al. 2012*), whose relative importance across the FCE gradient is poorly understood and expected to change with amplified pulses of fresh and marine water (Fig. 10). We expect that greening of food webs resulting from increased P loads (marshes) and P concentrations (mangroves, seagrass; see H_{4b}) will be accompanied by a shift in consumer community structure, and a reduction in the number of pathways from producers to top consumers, increasing trophic efficiency with implications for the provisioning of ecosystem services by economically valuable top consumers (e.g., recreational fisheries, Brown et al. 2018; and wading birds, *Lorenz 2014a,b*; *Beerens et al. 2017*). Alternatively, we may find that chronic osmotic stress of saltwater exposure has stronger impacts on trophic structure than resource pulses (Gutiérrez-Cánovas et al. 2012).

Work Plan: We will test these hypotheses by tracking shifts in aquatic consumer populations along our transects and over time and in response to experimental nutrient and producer manipulations in the ecosystem vulnerability experiment. Food webs along the SRS and TS/Ph transects will be sampled annually using stable isotopes to track shifts in production sources and food web architecture in relation to changing in fresh and marine water pulses. We will use throw traps, seines, and electrofishing to quantify abundance, composition, stoichiometry (carbon:nitrogen:P), and biomarkers (carbon, nitrogen and sulfur stable isotopes, and fatty acids) to identify shifts in carbon sources and trophic channels for a subset of representative functional groups. Our hypotheses are based on the assumption that consumers are currently P-limited (*Trexler et al. 2015*) and the expectation that pulses will lessen P limitation and reduce salinity stress. To test our hypotheses, we will use stoichiometric analyses of key consumers, particularly changes in consumer carbon:P ratios to match homeostatic expectations (Sterner & Elser 2002; Evans-White & Halvorson 2017). This work will complement description of the nutritional landscape (Hunter 2016) in H_{4b}. We will deploy enclosures (*Liston et al. 2008; Sanchez & Trexler 2018*) within the ecosystem vulnerability experiment to examine effects on consumer control of food webs. Enclosures will be stocked with a standardized community of local freshwater and brackish species to evaluate salinity-by-nutrient effects on food-web complexity and energy routing across basal resources, primary and secondary consumers (macroinvertebrates and small fish). Stoichiometry, fatty acid profiles, and stable isotopes of floc, biofilms, microbial mat (if present), primary and secondary consumers will be quantified in key food web components. We will also analyze metazoan invertebrates colonizing incubated microbial mat and litter for community and isotopic composition (see H_{4b}).

H_{4d} (<u>Carbon Fluxes</u>): Increased pulses of fresh and marine water and their associated resources will enhance net ecosystem production and horizontal carbon exchange in freshwater marshes, mangrove forests, and seagrass meadows and increase long-term carbon sequestration. To better understand the carbon dynamics of subtropical wetlands, we need to evaluate the conditions controlling the relationship between ecosystem respiration and gross ecosystem production and the greenhouse carbon balance (net CH_4:CO_2 exchange) (Hopkinson 2019). In karstic ecosystems, net ecosystem exchange of CO_2 is a function of photosynthesis and carbon fixed in the carbonate cycle and losses via respiration and carbon emitted in the calcium carbonate cycle (*Macreadie et al. 2019;* Fig. 17). Although calcification produces mineral sediments, it releases CO_2 to the surrounding water, and reduces alkalinity. There is significant uncertainty in the fate of CO_2 released by calcification and the fraction of that released CO_2 used by aquatic primary producers. We will test this hypothesis by measuring pCO_2 and pO_2 concentrations and fluxes between the air and water. Ecosystems with high organic and inorganic carbon production are seldom examined to determine the relative importance of net primary production and net calcification in ecosystem carbon sequestration. The dissolved O_2 balance is an imperfect measure of net ecosystem primary production, as dissolved O_2 is only a good indicator of anaerobic respiration when the reduced products are oxidized (Barrón et al. 2006). Calcium carbonate production and dissolution prevents direct inferences of organic carbon fluxes from dissolved inorganic carbon (DIC) measurements, requiring the joint analysis of organic carbon and calcium carbonate fluxes, which are rarely measured simultaneously in wetland ecosystems (*Van Dam et al. 2019*). Measuring lateral fluxes of DIC and alkalinity at eddy flux sites will allow us to estimate horizontal oxygen and CO_2 fluxes (Wanninkhof 1992; Ho et al. 2017) and determine the contribution of net carbonate precipitation or dissolution fluxes of CO_2 to net ecosystem exchange, a key uncertainty in coastal carbon budgets (*Troxler et al. 2013*).

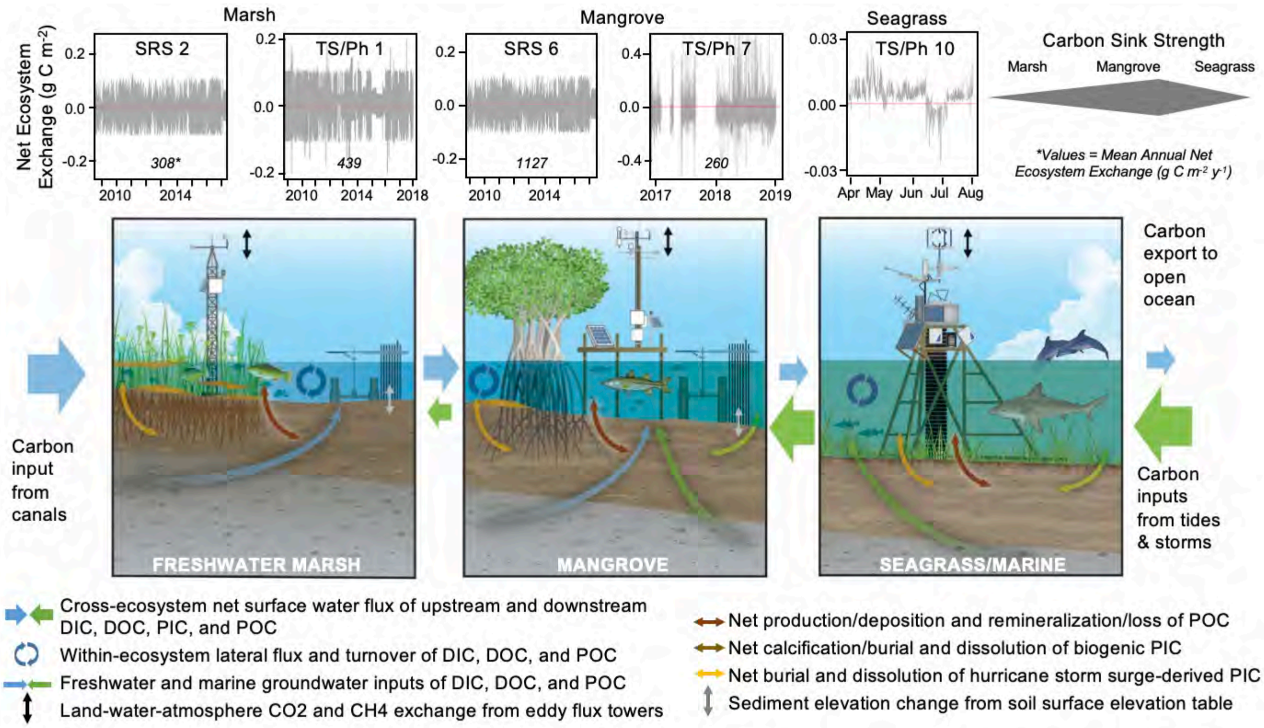


FIGURE 17. NET ECOSYSTEM CARBON BALANCE in the FCE is measured by the net ecosystem exchange of CO_2 and CH_4 (from our eddy flux tower data in upper graphs), the production, mineralization, and fluxes of dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), particulate inorganic carbon (PIC), and particulate organic carbon (POC) within and between marsh, mangrove, and seagrass/marine ecosystems. Net soil elevation change is measured with surface elevation tables.

Work Plan: We will measure how pulses of fresh and marine water and associated resources alter fluxes of CO_2 and CH_4 using eddy flux sites in each ecosystem type (Fig. 17). The eddy flux technique is the most efficient method for measuring the interaction between the biosphere and the atmosphere on an ecological scale (Baldocchi 2008) and is increasingly being used to understand coastal wetland carbon balance (*Barr et al. 2012; Malone et al. 2014*). Comparisons of the greenhouse carbon balance (net CH_4:CO_2) between a carbonate and peat-based freshwater marsh experiencing increased freshwater pulses, between scrub and fringing mangrove forests with contrasting exposure to surge and tidal pulses, and in a recovering seagrass meadow will inform how salinity, water level variability, and P pulse legacies influence organic carbon stock changes. At each site atmospheric CO_2 and CH_4 concentrations (eddy flux), and surface water DIC, and DOC will be measured. We will enhance the existing eddy flux network (Box 2; Fig. 17) with water pH, pO_2, temperature, and salinity measurements to determine the contribution of water column metabolism and net calcification to air-water CO_2 fluxes. We will include measurements of carbonate parameters (alkalinity, [CO_2], [HCO_3^-], [CO_3^{2-}] and calcite/aragonite saturation states) using grab samples with the CO_2SYS Excel macro (Lewis et al. 1998), and the dissociation constants of Mehrbach et al. (1973), refit by Dickson & Millero (1987). An Apollo SciTech model AS-ALK2 alkalinity titrator will be used to validate alkalinity estimates monthly at each site. We will compare the $^{13}C/^{12}C$ of aquatic plants to $^{13}C/^{12}C$ in the water. Samples will be taken at least twice a year, during the wet and dry seasons to identify if the CO_2 produced in calcification is used in aquatic primary productivity. At each site and in the ecosystem vulnerability experiment we will also deploy feldspar marker horizons to assess gross deposition of PIC and POC on a biennial interval (Cahoon & Turner 1989) and use the proposed expanded suite of soil surface elevation tables to address net soil carbon deposition (see H_{4e}). To evaluate lateral exchange-discharge and estimate net organic carbon and inorganic carbon fluxes, we will: (1) deploy EXO-2 Sondes for high-frequency determinations of turbidity, pH, DOC fluorescence, and salinity (*Regier & Jaffé 2016*), (2) quantify DOC in surface water and POC in sediment traps at flux tower sites in wet and dry seasons, and (3) use long-term water chemistry data including DOC fluxes (Fig. 8; *Regier et al. 2016*) to compare net ecosystem carbon sources and sinks across spatiotemporal scales. Fluxes of DOC/POC will be coupled with measurements of DIC and alkalinity to estimate the net ecosystem carbon balance (Fig. 17).

H_{4e} (<u>Ecosystem Trajectories</u>): Increased pulses of fresh and marine water and their associated resources will increase organic and inorganic carbon accumulation rates, and soil elevation in freshwater marshes, mangrove forests, and seagrass meadows. Our paleoecological research shows that freshwater marshes and mangrove forests of SRS captured and sequestered carbon into peat soils (*Breithaupt et al. 2014*), whereas short-hydroperiod, freshwater marshes of TS/Ph and seagrass ecosystems of Florida Bay built soils with low organic carbon and high carbonate content (*Gaiser et al. 2006b; Howard et al. 2018*). In SRS, sustained primary production maintains soil carbon pools through the stabilizing effect of belowground root production in organic soils (*Rivera-Monroy et al. 2011*), although significant regional differences exist along the coastal P gradient (*Breithaupt et al. 2019b*; Fig. 18). In TS/Ph, mineral soil production is driven by periphyton mats in freshwater marshes (*Gaiser et al. 2012*) and seagrasses in Florida Bay (*Howard et al. 2018*). Biogenic inputs are subsidized by P-rich mineral inputs derived from storms (*Castañeda-Moya et al. 2020*; Fig. 13). Models suggest a wetter future with elevated CO_2 concentrations will increase coastal vegetation cover if soil elevation gains offset inundation stress (Cherry et al. 2009; *Osland et al. 2018*). Predicting development trajectories using our ecosystem-scale process models requires a better understanding of the shape of ecosystem functional responses to drivers (Abdul-Aziz et al. 2018) and generalizability of the functions across the landscape (*H_{3c}*).

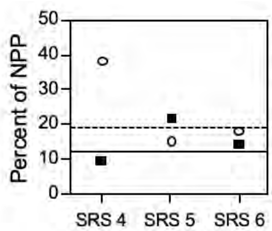


FIGURE 18. ORGANIC CARBON BURIAL (black squares) and soil carbon respiration (open circles) as a percentage of site-specific mangrove net primary productivity (NPP) for SRS. Solid and dashed line represent global average burial:NPP and respiration:NPP, respectively.

Work Plan: We will augment data at FCE sites by introducing 5 new 'satellite' sites in the marsh-mangrove ecotone of TS/Ph and SRS where we will measure aboveground and belowground biomass and productivity, water level, porewater salinity, soil P and inorganic and organic carbon, and surface elevation change, to improve our ability to test and validate our two mechanistic plant-soil dynamics models (marsh-EvPEM and mangrove-MEM) that simulate elevation change in peat and marl soil types. We will determine the extent to which vegetation responses influence soil accretion/loss and subsequent elevation. Explorations of EvPEM using existing data on leaf and root growth and decomposition, and soil carbon oxidation (Fig. 19) highlight a need for a more comprehensive dataset across the landscape to reduce modeling uncertainty. We will also advance ELM with refined rates of organic matter breakdown by heterotrophic microbes to determine the potential role of these rates in driving long-term soil stability, and periphyton mat attributes (*Naja et al. 2017*) to improve early detection of marsh-mangrove ecotone shifts (*Mazzei & Gaiser 2018*) and expectations for aquatic consumer production. Our measurements of net ecosystem production across spatiotemporal gradients of water level, ponding duration, and salinity will promote the refinement of a dynamic carbon budget to enhance the vegetation productivity sub-model in the ELM (*Fitz et al. 2011; Flower et al. 2017c*). We will estimate organic carbon storage using methods of *Jerath et al. (2016)* and *Howard et al. (2018)* and examine the social value (see *H_{2a}*) of this service in a global blue carbon context (Twilley et al. 2018; Vegh et al. 2019).

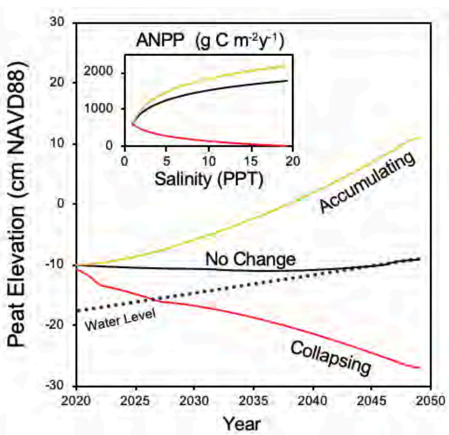


FIGURE 19. SIMULATED PEAT ELEVATIONS in sawgrass marsh under 3 mm yr^{-1} seal-level rise using experimental data showing examples of accumulating, stable, and collapsing peats in response to aboveground net primary productivity (ANPP), salinity, and hydrology. Inset shows different threshold levels of ANPP as a function of salinity used to simulate the corresponding peat elevation changes. Ratios of above/below primary productivity, turnover rates, and soil bulk density remain constant during the simulation period.

C. Synthesis and Integration

The FCE IV program will achieve synthesis through our hierarchical, nested research structure, integrated modeling approaches across FCE, and cross-system comparisons with other social-ecological systems facing similar changes to disturbance regimes. By incorporating unusually rich data on coastal ecosystem carbon stocks and fluxes into robust numerical models, we will advance syntheses that build on FCE and other coastal research, both LTER and non-LTER (Craft et al. 2016; Windham-Myers et al. 2019), reduce key uncertainties about the future of globally important blue carbon pools (Osland et al. 2020; Kauffman et al. 2020), and better understand the role of feedbacks to atmospheric greenhouse gas concentrations (McNicol et al. 2019; Tan et al. 2019). In addition, we continue increased attention to how shifting carbon pools interact with food webs have implications for how global increases in DOC will change green and brown food web channels, and whole ecosystem metabolic balance (Demars et al. 2020).

Scenario Modeling: We described our strong regional, integrative modeling approach used to quantify phenomena at ecosystem-to-landscape scales (H_{3c} & H_{4e}), predict rates of change as a function of long-term cumulative impacts, and distinguish drivers and stressors that operate at previously poorly known spatial and temporal scales. By applying this approach to multiple plausible scenarios of climate change (rainfall and evapotranspiration), freshwater restoration, and sea-level rise rates, we will evaluate how freshwater and marine pulses and the rate and extent of saltwater intrusion (using BISECT) influences wetland elevation via changes quantified by soil-plant mechanistic models (EvPEM, MEM). These outputs provide the inputs for modeling marsh surface dynamics, including vegetation, periphyton mat community, and P dynamics driving ecogeomorphological responses and resulting feedbacks to assess scenarios of coastal vulnerability. The baseline digital elevation model will be collected from LiDAR data for the initial simulation periods and will subsequently be updated using the information from the peat elevation dynamics soil-plant mechanistic models. Climatic (sea-level rise and storm) and restoration events can also be directly responsible for state transitions of the vegetation community, which will, in turn, impact coastal ecosystem services, whose economic value will be quantified. These outcomes will be used to understand drivers of ecosystem trajectories across the landscape gradient, reveal key uncertainties, generate hypotheses to be tested through future FCE, LTER coastal, and other comparative studies.

Comparative Studies: Building on our synthesis of contemporary challenges in disturbance ecology (*Gaiser et al. 2020*), we will advance national and global research to better understand how chronic presses and increasing pulses determine ecosystem trajectories (*Kominoski et al. 2018*), with a particular focus on neotropical coastal social-ecological systems. Through a meta-analysis of long-term data from national and international research networks, we will address the hypothesis that regions with greater water availability and warmer climate will have a greater capacity to adapt to disturbance. By comparing long-term dynamic responses of neotropical wetlands to accelerating sea-level rise and changing tidal regimes (Arnaud et al. 2020) to tropical forested watersheds organized by disturbance (Lodge et al. 1994) but faced with increasingly severe hurricanes, to dry grasslands facing changing temperatures, fire, and precipitation regimes (Collins et al. 2017), we may reveal underlying processes that determine the persistence of ecosystems and their services under changing disturbance regimes. This effort will be paired with several other ongoing national and global synthesis efforts to better understand cross-ecosystem vegetation and trophic responses to hurricanes (*Patrick et al. 2020; Hogan et al. 2020*) and saltwater intrusion (*Tully et al. 2019*). Through the coastal Water Futures Initiative, we are developing priorities for coastal adaptation research which will drive further cross-system comparisons of social-ecological response to saltwater intrusion. We have built on US LTER Network collaborations to expand the social-ecological context for our work through the Urban Resilience to Extremes Sustainability Research Network, resulting in new international LTER collaborations as part of the NATURA ACCELNET. In the coming year, we will conduct a large-scale synthesis of maximum photosynthetic rates across ecosystems using eddy flux data from the National Ecological Observatory Network, LTER, and AmeriFlux. We will evaluate changes in maximum photosynthetic rates, methane emissions, and canopy structure across and within coastal ecosystems to examine effects changing patterns of inundation and salinity on carbon dynamics. We will continue to advance partnerships in the neotropics that have been a pillar of FCE international synthesis (*Gaiser et al. 2015a*), including studies of mangrove and seagrass ecosystem response to sea-level rise in Mexico, interactions between introduced mangrove and *Spartina* species in China, and divergent evolution of mangrove from non-mangrove plant ancestors in Costa Rica.

IV. Proposed Research - Broader Impacts

A. K-12 Schoolyard Activities. In FCE III, we learned that students in Miami Dade County Public Schools struggle to master the Nature of Science benchmarks of Florida's *Next Generation Sunshine State Standards* and the *Next Generation Science Standards* recommended by the National Research Council's. In FCE IV, we will develop programming that addresses the NSF's Strategic Plan Goal to "*advance the capability of the Nation to meet current and future challenges with K-12 programs that will support the development of the next generation of researchers"* by: (1) providing mentoring to K-12 students and teachers through our new LTeaER participatory science program, (2) facilitating presentation of their findings at science fairs, professional meetings, and annual FCE All Scientists Meetings, and (3) pursuing supplemental sources of funding to support high school and teacher participants. Under the direction of Education & Outreach Coordinator N. Oehm, we will coordinate with the FIUteach program to design and deliver new professional development for teachers that will address the *Next Generation* standards. As faculty in the STEM Transformation Institute's FIUteach program, Oehm works directly with more than 240 Miami-Dade County Public Schools and provides us with access to a large number of teachers and a K-12 student population that identifies as > 90% underrepresented. In addition, through our partnership with the Everglades Foundation, we will expand the classroom use of the FCE children's book, engage new teachers/students in our participatory science initiatives (described below), and collaborate to strengthen the Everglades Literacy and Champion Schools Programs.

B. Training of Undergraduates and Early Career Scientists. FCE scientists train and mentor all levels of early career scientists. We will recruit diverse undergraduates to assist FCE research, engaging them in the challenges of convergence research on coastal research through co-mentoring by both academic and agency scientists. Each year, FCE will recruit two undergraduates from diverse communities as more formal REUs. In addition to FCE mentoring and stipend support, these students will be included as members of FIU's Coastal Ecosystems REU Site where they will participate in cohort-building, networking opportunities, social events, and weekly field trips. Each participant will present their results at the REU Site Symposium, at the annual FCE All Scientists Meeting, and at a national or international conference.

FCE scientists are dedicated to mentoring our large graduate student organization. Graduate students will be engaged in all elements of the FCE program including working group research, mentoring of teachers, undergraduate, and high school students, and in communicating FCE research to public and scientific audiences. Graduate students will participate in working group and annual meetings, enroll in LTER network-wide and FCE-specific distributed seminars, and apply for synthesis opportunities through the LTER Network Office. FCE scientists will continue offering distributed credit-earning graduate seminars to the LTER Network. Through long-term training collaboration with Senator Robert Graham, FCE graduate students will be paired with a State or Federal legislator with whom they will work to communicate the relevance of science for policy-making. A subset of these students will participate annually in the American Institute of Biological Sciences Communications Training Boot Camp in collaboration with our FIU office in Washington, DC to further put this training into action.

C. Participatory Science: The FCE Schoolyard program has created several participatory citizen science projects. In FCE IV, we will integrate the newly launched *FCE LTeaER* decomposition project, modeled after the Tea Bag Index (TBI) study (Keuskamp et al. 2013) and aligned with the research objectives of the *Detritus & Microbes* working group. The LTeaER program engages our community in a long-term decomposition study to test hypotheses about the drivers of organic matter transformation while contributing to this global research project. Teabags are currently deployed at each of our research sites in SRS and TS/Ph, and are being studied by an REU student and a Research Experience for Teachers fellow. In FCE IV, we will recruit a new cohort of teachers to participate in the LTeaER project. Teachers will design experiments to compare teabag decomposition rates along new spatiotemporal pulse gradients. They will also work within a publicly-accessible wetland at the Deering Estate (an FCE partner) where a tidal creek has been reconnected to upstream wetlands as a small-scale urban representation of Everglades restoration. Teachers will have the opportunity to adopt an FCE site and accompany our scientists on a field trip to retrieve, deploy, and process samples. These data will be analyzed in the classroom with their students and the results will be submitted to the LTeaER and Tea Bag Index webpages. Working in collaboration with the FIUteach program, we will administer formative and summative assessments to evaluate LTeaER participant (undergraduate students, REU students, and teachers) understanding of the global carbon budget, use the LTeaER data to test FCE hypotheses, evaluate the progress and effectiveness of the research experiences, improve the STEM literacy of our citizens, and inform about the local and global effects of climate change. These evaluation methods, led by a graduate student and faculty mentor in biology research education, will inform how we are achieving the student learning goals of understanding the scientific method and the global carbon budget, and determining if mentoring activities meet participant expectations. Surveys will be administered before and after students engage in research, results will be analyzed, and the outcomes will be shared with the mentors. All data will be compiled and maintained in newly developed database that will be used to ascertain their professional development and assess the longitudinal impact of our program.

D. Broadening Participation: FCE is addressing the Big Idea of NSF INCLUDES and contributing to broadening participation of underrepresented communities in STEM fields with guidance from the NSF Strategic Plan (FY 2018-2022). FCE will provide access to underrepresented students to conduct research and inspire students to pursue STEM careers by recruiting from diverse populations and using best practices developed by our STEM Institute to retain these students in STEM fields. Using the FCE *Diversity and Inclusion Plan* (see *Project Management Plan*) as our guide we will enhance representation and advancement of students, early career scientists, and faculty from underrepresented groups and promote the inclusion, equity, and well-being among FCE collaborators.'

E. Dissemination: The FCE Communications Team, consisting of the PI, Program Manager, Education & Outreach Coordinator, and collaborator S. Davis (Director of Communications for Everglades Foundation), will coordinate communications including regular updates through our *News from the Sloughs* monthly newsletter, press releases and social media, our *Wading Through Research* student blog, public events and exhibits, and an annual partnership impact report. We recognize the value of our collaborations with artists as a means for engaging citizens that may not be part of the typical STEM community or would not otherwise learn about the Everglades. Our next project with the Tropical Botanic Artists will generate a new exhibit on aquatic flowering plants of the coastal Everglades that will tour K-12 classrooms and engage students in studying and painting the dominant plants of the FCE. We will also work with FIU journalists on a new video production of the role of coastal ecosystems in mitigating climate change through a coastal cross-LTER site initiative.

F. Benefits to Society: FCE builds partnerships with Federal, State and local agencies and non-government organizations with the efforts of the FIU office in Washington, D.C. to ensure science-based restoration guidance (e.g., *Borkhataria et al. 2017; Sklar et al. 2019a*). We will continue reporting long-term findings to these agencies, including directly to the U.S. Congress through our System-Wide Indicators for Everglades Restoration (Brandt et al. 2018, a process being studied by our *Freshwater Governance* working group (H_{2c}) and indirectly via advising The National Academies Committee on Independent Review of Everglades Restoration Progress (CISRERP 2018). In coordination with our FIU D.C. office, we will visit congressional offices to discuss the progress of Everglades restoration. We will share our results with high profile and key political figures through PI Gaiser's role on the State of Florida Governor's Blue Green Algae Task Force which will ensure that FCE research informs the management of upstream nutrient sources. Globally, we will continue to use science to inform policy, including through our leadership in the International Blue Carbon Science and Policy working group establishing policy guidelines for protecting valuable carbon stored in vegetated coastal ecosystems. By co-developing research with scientists from non-government organizations and government agencies at local to global scales, the FCE epitomizes the process of convergence science in the field of ecology (AC-ERE 2018).

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DATA MANAGEMENT PLAN

Overview:

The mission of the FCE LTER Information Management System (FCE IMS) is to provide easily accessible, high quality, well-documented data to support research, outreach, and education at the FCE LTER and in the broader community. The FCE IMS complies with LTER Network and NSF standards and policies. It produces comprehensive metadata encoded in the Ecological Metadata Language (EML) standard. Protocols are in place to assure data integrity and security at the site prior to their deposition in the Environmental Data Initiative (EDI) Data Repository. Consistent with NSF and LTER Network Policy, FCE datasets are made publicly accessible through the EDI Data Repository within two years of data collection. During FCE IV, the FCE IM Team will continue core information management support activities while streamlining the FCE IMS to increase data and metadata processing efficiency.

FCE IM Resources:

The FCE Information Management Team: IM personnel include a 0.75 FTE Information Manager (IM), Dr. Kristin Vanderbilt, who joined the FCE team in 2016 after serving as the IM for the Sevilleta LTER for 16 years. She also works 0.25 FTE for EDI, which operates the EDI Data Repository where many LTER sites deposit their data. The other IM Team member is FCE's full-time Project Manager, Mike Rugge, who has worked at FCE since the project's inception. He specializes in GIS and programming and maintains the website and webserver in addition to completing his program management duties.

Infrastructure: The FCE IM team manages three virtual Linux servers, three virtual Windows servers, and two desktop workstations. The virtual servers are maintained by Florida International University's (FIU) Division of Information Technology, for which FCE LTER pays a fee each year. Three Oracle 12c database servers (production, development, and disaster-recovery) run on Windows, while two web servers (production and disaster-recovery) and an FTP server run on Linux. The virtual server environment is a robust and inexpensive way to serve the FCE website and secure FCE LTER data.

FCE's Oracle 12C database is used to manage FCE publications, presentations, research site information, personnel and project information for display on the FCE website. The Project Manager also uses it as a back end to store registration information for the annual FCE All Scientists Meeting. The IM maintains a system for tracking dataset submission compliance in the Oracle database.

Server and Data Security: Multiple back-ups ensure that the website stays operational and that FCE data are secure. Two Synology Network Attached Storage (NAS) units are used for website backups. Each has 27 TB of storage, about 3.3 TB of which are being used. One is on the Modesto Maidique Campus (MMC) of FIU in Miami, Florida, while the other is 27 miles away on the Biscayne Bay Campus (BBC) in North Miami, Florida. Incremental backups are made daily of the webserver's files, which include all FCE data files, to the MMC NAS unit. The MMC NAS is then backed up to the NAS at the BBC campus each night. A full backup of the webserver is done once a week to the NAS units. FIU's Division of Information Technology makes daily incremental and weekly full backups of the production Windows and Linux servers. The production Oracle server and production webserver are synced daily to identical virtual servers at the Northwest Florida Regional Data Center (NWRDC) located roughly 400 miles from Miami on the campus of Florida State University in Tallahassee, Florida. These remote images would be used to restore the website in case of a disaster at the two Miami-area campuses.

Policies:

FCE LTER shares data in accordance with the NSF Proposal & Award Policies & Procedures Guide (PAPPG) and the LTER Network's Data Access Policy. In the FCE Data Release and Access Policy, FCE has adopted the Type I and Type II dataset designations from the LTER Network policy. Type I datasets are collected using FCE funds and are publicly available on the FCE website and in the EDI Data Repository within two years of data collection. Datasets are released under the Creative Commons' CC-

BY 2.0 license. A few datasets are considered Type II and have restricted access. Type II datasets, often datasets collected by graduate students, are embargoed for up to five years so that the student can publish them before others gain access. Some datasets have been embargoed indefinitely because, although the PI is an FCE LTER collaborator, the data are from projects not funded by the NSF LTER grant and the sponsor or researcher has restricted access to the data. Most of these latter Type II datasets are available upon request.

IM Integration with FCE Research – Supporting the Data Life Cycle:

Information management is an integral part of all phases of the FCE research program. FCE scientists have access to IM services throughout the research process and life cycle of their data. Both the IM and Project Manager attend meetings of the FCE LTER Internal Executive Committee so that they are aware of new research developments and new datasets that will require management. The IM also makes a presentation at the annual FCE LTER All Scientists meeting, highlighting any changes in FCE or LTER Network-level information management policies or procedures. Because FCE researchers are distributed throughout the United States, this meeting serves as an important time for the IM and FCE scientists to connect and discuss information management needs.

FCE has an Information Management Advisory Committee (IMAC) that meets once a year to provide general guidance to the IM team. The IMAC consists of a member of the FCE Internal Executive Committee, a project collaborator, a student, a technician, and an Education and Outreach representative. The IMAC primarily assists the FCE IM Team with input about the FCE website.

Planning and Experimental Design: The FCE IM Team advises researchers and students, as they design and conduct their research projects, about data collection, documentation and organization best practices. The IM gives presentations to the FCE LTER Graduate Student Association so that the students understand how to submit data and metadata, as well as their obligation to do so. The IM is also available to provide input on data management plans for any proposal written by FCE researchers.

Data Submission, Validation, and Processing**:** To assure timely data contributions by researchers, the FCE IM schedules biannual data collection events each spring and fall by sending email reminders to all participating researchers. The IM also tracks the time since a dataset was last updated, and contacts researchers whose data are approaching the point in time where they will become out-of-compliance with the LTER Network's two-year data release policy. The FCE PI follows up with researchers who do not submit their data on time.

Data are typically submitted to the FCE IM as MS Excel or text files. FCE researchers are responsible for data entry, quality assurance, validation, and analysis for their respective projects. The IM does a thorough quality assurance check on dataset structure and completeness of metadata before the data are archived in the FCE IMS and the EDI Data Repository. The data and metadata must pass multiple congruency checks made by the EDI Repository's quality engine before being uploaded.

Documentation: Metadata for *ongoing* datasets are submitted to the IM in the FCE MS Excel metadata template. This template is designed to collect information that conforms to the LTER's EML metadata standard and aligns with the "EML Best Practices for LTER Sites" document. To ensure compatibility with metadata from other LTER sites and to improve data discoverability, most FCE keywords are selected from the LTER Controlled Vocabulary. The FCE's XLSX2EML Perl program is used to convert the information in the Excel metadata template into EML. The FCE XLSX2EML program and FCE MS Excel metadata template have been updated three times to support new versions of EML and will soon be updated again to support EML 2.2. The EML produced via the FCE's system is rich in detail. Gordon & Haberman (2019) found that FCE was one of the LTER sites with consistently highest percentage of completed metadata elements during a 14-year period following the 2004 release of the first version of the "EML Best Practices for LTER Sites" recommendations.

Metadata for *new* FCE datasets are submitted to the IM using the EDI MS Word metadata template and converted into EML using the EMLAssemblyline (Smith 2020). EMLAssemblyline supports the archive of multiple data entities in a single data package, which the FCE MS Excel metadata template and XLSX2EML program do not. The EMLAssemblyline is an R package developed by EDI for generating EML that is itself based on the R EML package (Boettiger & Jones 2019).

Preservation and Discovery: FCE data are archived in ASCII text or zip files on the FCE server and deposited into the EDI Data Repository. FCE LTER has 176 data packages discoverable through the EDI Data Portal. DataONE, an international data aggregator, harvests FCE metadata from the EDI Data Repository and makes FCE data widely discoverable and accessible through the DataONE portal. Statistics on dataset downloads suggest significant interest in FCE data. The FCE website recorded 973 non-robot dataset downloads between 10/1/2018 and 10/1/2019. The EDI Repository recorded 3,425 non-robot downloads of FCE datasets during the same period. These numbers are inflated by automated download agents that aren't eliminated by filtering out known robots and webcrawlers.

Local Access to FCE Information Products: The FCE website's Data page links to the FCE LTER Data Catalog, which is the primary source of FCE data. The FCE LTER Data Catalog includes datasets collected by the FCE LTER, which are publicly accessible, in addition to some datasets collected by FCE collaborators who are not directly funded by the LTER. These latter datasets are not bound by the 2-year LTER Data Access Policy and may have extended embargo periods. The FCE Data Catalog can be queried by dataset originator, LTER core area, title and keywords. A spatial query tool on the FCE Data Catalog page facilitates discovery of datasets associated with FCE's core research sites. The FCE website's Data page also links to LTER Network Data Resources, FCE LTER GIS and Maps, and Other Data Resources. For the convenience of FCE researchers, the latter page links to Everglades data not collected by FCE (e.g., NOAA "Tides & Currents" and "Hurricane" data portals).

Catalogs of publications and photographs, as well as the intranet, are popular components of the FCE website. FCE publications are updated frequently, and are searchable by date, author, keyword, and publication type. The FCE photo archive can be searched by keywords, category (e.g., "Field Work" or "Plants"), and core research sites. All FCE LTER personnel have access to the password protected FCE Intranet site. Users can browse the intranet site for important FCE documents such as Everglades National Park Sampling Permits.

FCE IM Contributions to Network and Community Activities:

Since becoming an LTER IM in 2000, FCE IM K. Vanderbilt has been involved in LTER Network-level information management activities and outreach. Recently, she co-organized sessions at the 2018 LTER All Scientist Meeting and 2019 International LTER (ILTER) Open Science Meeting that included invited ontology experts and discussion of future semantic developments for the US LTER. Long involved with the ILTER Network, she was co-editor of an Ecosphere special issue about the ILTER (Vanderbilt & Gaiser 2017) and has contributed to ILTER research (Dick et al. 2018). She has also co-authored several publications on information management (Gries et al. 2018, Vanderbilt & Blankman 2017, Vanderbilt et al. 2017, Wheeler et al. 2017). She is presently the Associate Editor for Data Science for the journal *Ecological Informatics*. In her role with EDI, she trains new LTER IMs and is the liaison between EDI and the Information Management Executive Committee.

FCE Project Manager M. Rugge has developed tools that others in the LTER Network and at EDI have used. He created an XSLT stylesheet that renders EML metadata in a human readable format. It is used on the FCE website and EDI has implemented it in the EDI Data Portal. He wrote the FCE's Perl XLXS2EML program for generating EML metadata from an MS Excel metadata template. He updates this program when necessary to comply with new EML versions and recommendations. This tool is openly available on the FCE website and via the LTER Network's github repository.

2018 FCE Proposal Milestones Met:

New FCE Website: FCE LTER met a major IM milestone stated in the 2018 proposal when a new FCE website was launched in late 2019. The old FCE website was hand-coded and laborious to maintain. The new website takes advantage of Cascade, the content management system used by FIU, to make website updates easier. While the Project Manager did most website updates himself on the old website, migrating the website into Cascade enables other FCE staff to have permissions to sections of the website in order to update their own content. The information on the new website has been refreshed and reorganized for ease of navigation with input from PIs, staff, and students. Cascade facilitates integration with social media, newsfeeds, and offers website search functionality. The new website significantly improves on the old one by being mobile device friendly and resolving to a size appropriate to the device on which it is being viewed.

Unfortunately, Cascade does not support dynamic web pages, such as the popular custom query interfaces to data, bibliography, and personnel databases found on the old FCE website. The FCE Project Manager therefore used the Foundation Framework, a responsive front-end software framework for web design, to produce a template mimicking the Cascade FCE website. He re-wrote all the query scripts on the old website in PHP in order to replace near-obsolete Embperl scripts. He preserved the many options from the old website for filtering datasets, publications, personnel and photographs for ease of discovery, while offering the new look and feel of the Cascade website. The dynamic part of the FCE website is served via an Apache webserver that is managed by the Project Manager on a Linux virtual machine, while the Cascade part of the website is served by FIU Communications. This new, hybrid FCE website has improved the experience of web visitors seeking data or information about the FCE LTER.

New FCE Website Data Catalog: FCE has updated its approach to generating and querying the FCE website's Data Catalog. The new method takes advantage of RESTful web services provided by EDI's PASTA+ data repository software. Previously, the FCE IM had submitted EML documents to the EDI Data Repository and then captured a subset of that metadata in a local Oracle database to drive the FCE Data Catalog. Maintaining two copies of the metadata, one in the EDI repository and the other local, was inefficient. With the new system, the IM submits EML to the EDI Data Repository as before, but then the EDI Repository becomes the source of metadata to populate the FCE Data Catalog. Further, PASTA+'s Solr repository can be queried from the FCE website to discover FCE datasets based on metadata stored in keywords, author, and title EML fields. This new approach for generating and querying the FCE Data Catalog expedites updates of FCE datasets.

The new FCE Data Catalog improves over the old catalog because EDI's web services allow the retrieval and display of the DOI associated with each dataset citation on the new FCE website. Having complete dataset citations on the FCE website will make it easier for FCE scientists to cite the datasets they use. As more FCE scientists include dataset citations in the papers they author, the better FCE LTER will be able to track data usage in the future.

FCE IMS Future – Ongoing Activities:

Timely Archiving of FCE Data and Metadata from New and Continuing FCE Research: FCE will continue to update existing long-term data sets within two years of data collection per the LTER Data Access Policy. New long-term, experimental, or short-term datasets supported by the FCE grant will be archived in the same timely fashion. Graduate students will be strongly encouraged to submit their data, which will be made accessible per the FCE LTER policy which allows students a longer data embargo period in which to have exclusive access to the data. FCE IM resources are limited, and data products related to the core FCE funding and mission are considered highest priority for archive. If time permits, data will be archived that were collected by FCE affiliated researchers who are not funded by the FCE grant. Of lower priority are data already archived by entities such as NOAA that FCE has traditionally harvested to maintain local copies for the convenience of FCE researchers.

Deliverable: New and updated FCE LTER datasets with rich metadata accessible from the EDI Data Repository and DataONE.

The FCE IMS Future – New Activities:

Adopt New Software for Generating EML for FCE Datasets: EML for FCE datasets has been generated since 2003 using the homegrown Perl FCE XLSX2EML program. This program ingests metadata from an MS Excel template filled out by the dataset creator. This system works beautifully, but only for datasets with one data table. More and more frequently, however, FCE researchers want to archive related data tables together in one data package or want to include code or other relevant documents in a data package. So far, the EML AssemblyLine, an R package produced by EDI, has been used to create FCE data packages with more than one entity. The EMLAssemblyline is adequate, but a more centralized, scalable solution for generating FCE EML is desired.

Core Metabase is a centralized solution that FCE plans to adopt for generating EML for data packages with one or more entities (Gastil-Buhl et al. 2019). This solution stores metadata in a postgreSQL relational database from which EML is generated using the MetaEgress R Package (Nguyen & Kui 2019). LTER IMs at Santa Barbara Coastal (SBC), Moorea Coral Reef (MCR), and Beaufort Lagoon Ecosystems (BLE) are converging on a common EML database model with the intention of this so-called "Core Metabase" becoming a collaboratively supported database and set of tools for creating EML. Collaborating on this system will reduce the need for each LTER site IM to develop a custom solution to challenges that face all LTER sites, such as implementing the new release of EML, version 2.2. FCE personnel are attracted to Core Metabase because it offers 1) a central location to edit content for all FCE datasets; 2) a means to control vocabulary entered in the metadata; and 3) the ability to migrate content, should that ever be necessary. For FCE, adopting Core Metabase means that as new requirements for EML are established, the central database and MetaEgress code can be updated and new EML generated for all FCE datasets. FCE will implement new EML 2.2 features, including semantic annotations and the structured funding element, using Core Metabase.

Deliverable: *A centralized, scalable FCE metadata management system supported by a collaborative IM community that will keep the database and code current.*

Archive Model Code and Model Products: FCE IV calls for a significant amount of modeling research. The models often rely on remote sensing imagery, such as MODIS and WorldView. FCE does not purchase these datasets but has access to them through the FIU GIS Center, which has the infrastructure to handle datasets that are several terabytes in size. FCE will archive the model code, model inputs, and the many spatial data products and algorithms that the modeling research will yield.

Deliverable: FCE modeling research products accessible through the EDI Data Repository.

Data Management Training for FCE Graduate Students: It is increasingly important that graduate students be knowledgeable about the importance of data management to the scientific enterprise. In the future, the FCE IM will hold an information management training session for students in conjunction with the annual FCE All Scientists Meeting. While the process of publishing data will be emphasized, other topics that may be discussed include Findable, Accessible, Interoperable, Reusable (FAIR) data, data citation, data repositories, data management plans, and data cleaning.

Deliverable: A "research data management aware" FCE LTER student population.

PROJECT MANAGEMENT PLAN

The FCE program is managed according to our *Project Administration and Management Guidelines* available to FCE members that strive to: (1) maximize transparency in decision-making, (2) increase the potential for each participant to realize their best collaborative and integrative research and educational outcomes and efficiently co-produce knowledge, data, and products, (3) nurture early career scientists and students and guide them into leadership roles, and (4) promote the recruitment of underrepresented groups in all aspects of our program.

1. Transparent Decision-Making: The FCE program is led by an Internal Executive Committee (IEC) designed to ensure that important project decisions are equitable, democratic, and reflect both long-term consistency and project history (Fig. 1). The IEC helps the Lead PI by: assisting in coordinating program-wide activities (regular meetings, organization of NSF site visits, writing of renewal proposals), advising budgetary and personnel decisions, recommending cross-site collaborations, proposing IEC membership changes, and recommending and approving collaborator additions or removals according to procedures outlined in our *Guidelines*. The FCE IEC includes the 5 Co-PIs, a leader of each working group, the Education & Outreach Coordinator, Project Manager, Information Manager, Graduate Student Organization President, a Diversity Committee representative, external advisors, agency/NGO representatives, and an external representative senior scientist. Gaiser will continue as Lead PI through 2020, with a plan for transition to J. Kominoski in 2020 and before our mid-term review. Kominoski, Co-PI since 2015, has been instrumental in co-developing ideas in this proposal, involved in all levels of site management since 2017, and he has participated in LTER Network Science Council meetings since 2012. Gaiser and Kominoski will oversee program management and participate in working group research. Administrative activities will continue to be overseen by our Project Manager (M. Rugge), who works closely with our Information Manager (K. Vanderbilt) on the website and database mechanics. Rugge will be responsible for central office accounting and procurement, maintenance of all FCE office hardware and software, and all non-field related travel. Vanderbilt will continue to manage the FCE datasets and information dissemination activities (see *Data Management Plan*). Our Education & Outreach program will continue to be run by N. Oehm (FIUteach Coordinator), with communications assistance from staff from FIU's College of Arts, Science & Education. Our Diversity Committee, described below, has rotating representation to the IEC and the LTER Network Executive Board. Agency/NGO representatives include F. Sklar, S. Davis, and D. Rudnick who coordinate collaborations with South Florida Water Management District, Everglades Foundation, and Everglades National Park, respectively. External advisors include K. McGlathery (VCR), C. Hopkinson (PIE, GCE), and *ex-officio* Lead PI D. Childers (CAP, FCE), while J. Nelson (FCE, PIE) represents non-FIU senior scientists.

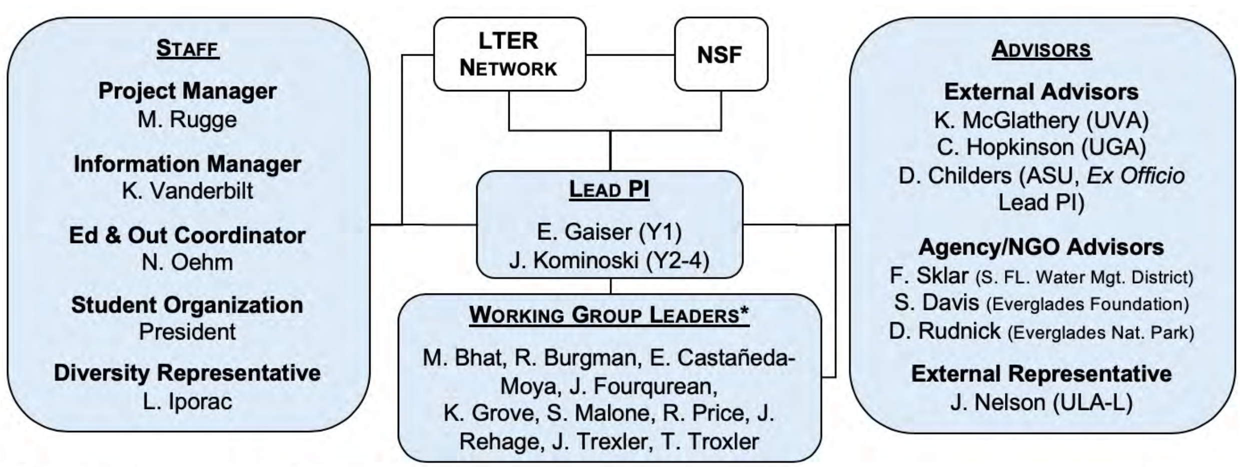

FIGURE 1. ORGANIZATIONAL CHART FOR FCE IV PROGRAM ADMINISTRATION. Lines represent communications and connections for key decisions by the Internal Executive Committee, comprised of members in the blue boxes (*working group leaders are voting members, while staff, advisors, and the lead PI hold non-voting roles).

2. Fostering Collaboration: FCE IV research will be conducted by 24 senior scientists (5 principal investigators and 14 other senior scientists, 2 consultants, and 3 post-docs, Table 1), 24 additional unfunded collaborators (listed in *Facilities, Equipment and Other Resources*), and 7 partially-supported graduate students (an additional 37 graduate students conduct FCE research through leveraged funding). FCE participants are organized by hypothesis-guided working groups led by senior personnel nested within four focal areas (Table 1). Integration is explicit because most participants are affiliated with more than one working group. Working group leaders are nominated by the membership and one leader represents the group's interests to the IEC. Each participant plays a unique role conducting research within these working groups while leaders keep projects on track, organize working group meetings, provide opportunities for leadership of collaborative activities, and drive synthesis of results. The *Climate Variability & Change* working group will be led by long-time collaborator R. Burgman, joined now by J. Obeysekera, recently hired to direct FIU's Sea Level Solution Center. The *Cultural & Economic Values* working group will be led by an economist, M. Bhat, and anthropologist, S. Wakefield. K. Grove will lead the *Freshwater Governance* working group with close collaboration with agency/NGO scientists and aided by a post-doc. The *Hydrologic Connectivity* working group will continue leadership by groundwater hydrologist, R. Price, and a remote sensing specialist, S. Wdowinski. J. Rehage will lead the *Consumer-Mediated Nutrient Transport* working group with contributions from new collaborator J. Nelson, who will aid in analyzing and interpreting stable isotope data to track mobile food webs, and M. Heithaus, who will oversee apex predator studies. The *Vegetation & Geomorphic Gradients* working group will be led by T. Troxler, who will coordinate landscape-scale modeling with consultant J. Morris, and D. Gann, who specializes in remote sensing. E. Gaiser oversees the *Abiotic Resources & Stressors* platform in support of all working groups, and will co-mentor (with R. Price and J. Kominoski) a project-wide post-doc to aid the quantification of hydrologic presses and pulses and the cross-site meta-analysis. The *Detritus & Microbes* working group is led by J. Kominoski who oversees organic matter processing research, and microbial ecologist, U. Stingl, who will conduct microbial molecular analyses through his subaward. The *Vegetation* working group is led by mangrove ecologist, E. Castañeda-Moya, joined by T. Troxler (marsh macrophytes), and J. Fourqurean (seagrass). The *Consumers* working group will continue to be led by J. Trexler in collaboration with E. Gaiser (periphyton). The *Carbon Fluxes* and *Ecosystem Trajectories* have shared oversight by J. Fourqurean (who also represents FCE to the International Blue Carbon working group) and S. Malone, who will advise modeling efforts by consultant C. Fitz, and a modeling post-doc (co-advised by T. Troxler). Integration among working groups within focal areas will be by led by Co-PIs (; *Social Landscape*– K. Grove; *Ecological Landscape* - J. Rehage; *Ecosystem Structure & Functions* - J. Fourqurean). Progress toward addressing our four focal area questions will be achieved through monthly project-specific webinars, an annual winter meeting organized by focal area, and our annual All Scientists Meeting. We will continue to exchange participants from the three other Atlantic coast wetland LTER sites (PIE, VCR, GCE) and the LUQ LTER at our annual meetings to promote cross-site studies and synthesis.

TABLE 1. AFFILIATIONS, EXPERTISE & ROLES OF FCE PRINCIPAL INVESTIGATORS AND SENIOR PERSONNEL

Focal Area	Primary Working Group	Funded Collaborator	Institution	Position	Expertise	Primary Role	Joined
	Climate Variability & Change	**Robert Burgman**	FIU	Assoc. Professor	Climatology	Sr. Scientist	FCE III
		Jayantha Obeysekera	FIU	Professor	Climatology	Sr. Scientist	FCE IV
	Cultural & Economic Values	**Mahadev Bhat**	FIU	Professor	Economist	Sr. Scientist	FCE IV
		Stephanie Wakefield	FIU	Res. Asst. Professor	Urban ecology	Sr. Scientist	FCE IV
	Freshwater Governance	**Kevin Grove**	FIU	Assoc. Professor	Human geography	Co-PI	FCE II
		Post-doc	FIU	Post-doc	Anthropology	Post-doc	FCE IV
	Hydrologic Connectivity	**René Price**	FIU	Professor	Ecohydrology	Sr. Scientist	FCE I
		Shimon Wdowinski	FIU	Assoc. Professor	Hydrogeology	Sr. Scientist	FCE III
	Consumer-Mediated Nutrient Transport	**Jennifer Rehage**	FIU	Assoc. Professor	Community ecology	Co-PI	FCE II
		Jimmy Nelson	ULA-L	Asst. Professor	Coastal ecology	Sr. Scientist	FCE IV
		Mike Heithaus	FIU	Professor	Coastal ecology	Sr. Scientist	FCE II
	Vegetation & Geomorphic Gradients	**Tiffany Troxler**	FIU	Assoc. Professor	Ecosystem ecology	Sr. Scientist	FCE I
		Daniel Gann	FIU	Asst. Professor	Landscape ecology	Sr. Scientist	FCE III
		Jim Morris	USC	Professor	Coastal ecology	Consultant	FCE III
	Abiotic Resources & Stressors	**Evelyn Gaiser**	FIU	Professor	Aquatic ecology	Lead PI (2007-2020)	FCE I
		Post-doc	FIU	Post-doc	Quantitative ecologist	Post-doc	FCE IV
	Detritus & Microbes	**John Kominoski**	FIU	Assoc. Professor	Ecosystem ecology	Co-PI (Lead 2021)	FCE III
		Uli Stingl	UF	Asst. Professor	Microbial ecology	Sr. Scientist	FCE IV
	Vegetation	**Edward Castañeda-Moya**	FIU	Res. Asst. Professor	Coastal ecology	Sr. Scientist	FCE III
	Consumers	**Joel Trexler**	FIU	Professor	Aquatic ecology	Sr. Scientist	FCE I
	Carbon Fluxes	**Jim Fourqurean**	FIU	Professor	Coastal ecology	Co-PI	FCE I
	Ecosystem Trajectories	**Sparkle Malone**	FIU	Asst. Professor	Ecosystem ecology	Sr. Scientist	FCE III
		Carl Fitz	Ecolandmod	Scientist	Ecological modeler	Consultant	FCE I
		Post-doc	FIU	Post-doc	Ecosystem modeler	Post-doc	FCE IV

3. Fostering Leadership: An important goal of the FCE *Project Management Plan* is to balance the continuity of experience and memory, critical to any long-term program, with active engagement of new leadership and management from early career scientists. This model has been very successful, resulting in a leadership structure infused with both new talent and foundational experience. The program has a 10-y management plan that includes opportunities for junior faculty to become working group leaders and working group leaders to become Co-PIs, while also identifying needs for targeted engagement. The FCE program benefited from a recent surge in FIU hires, resulting in 6 new collaborators in senior scientist and leadership roles (E. Castañeda-Moya, D. Gann, S. Malone, J. Obeysekera, S. Wakefield, S. Wdowinski). Co-PIs are no longer in administrative roles but work closely with administrators to continue faculty growth in coastal environmental science at FIU to benefit the FCE program. We will engage new collaborators in research and encourage their participation in ongoing research, leveraged proposals, as well as leading workshops and subcommittees as they arise.

4. Fostering Diversity and Inclusion: The goal of FCE's Diversity and Inclusion plan is to *foster an intellectually vibrant environment that is inclusive, open to all, respectful of diversity, and where our individual differences are recognized, valued, and seen as a source of strength that is integral to the discoveries we make as scientists.* We embrace the notion that our community is enriched and enhanced by diversity along a number of dimensions and is committed to increasing the representation of those populations that have been historically excluded from participation, including as a function of race, ethnicity and national origins, gender and gender identity, sexuality, socio-economic class, age, spirituality, physical and mental ability, and military status. FIU is the nation's fourth largest university (n = 58,063) and largest Hispanic Serving Institution (n = 37,272; 64%) and over 90% of FCE undergraduate students (n = 202) identify as underrepresented groups (87% Hispanic; 7% Non-Hispanic Black; 63% female). The leadership team of FCE (the IEC, Fig. 2) is diverse, with 7 women, 3 Hispanics, 1 Asian, 1 Non-Hispanic Black, and 3 LGBT members representing a membership where 42% and 42% of senior personnel, collaborators and postdocs and 38% and 41% of graduate students identify as female and underrepresented ethnic groups, respectively. The FCE program honors the identity of all participants and maintains an atmosphere that represents and embraces diverse cultures, backgrounds and life experiences that reflect the multicultural nature of South Florida and the global society.

The FCE *Diversity and Inclusion Committee* consists of the Lead PI, the Education and Outreach Coordinator, one graduate student, one FIU collaborator, and an off-site collaborator. It is currently represented to the IEC and LTER Network Executive Board by graduate student L. Iporac. The committee established three objectives for FCE IV, each with measurable outcomes. ***(1): Enhance representation and advancement of early career scientists from underrepresented groups*** by annually hosting a workshop with FIU's Multicultural Programs and Services (MPAS) office to equip students for advocacy on issues related to diversity, inclusion, and equity, and awareness of related programs; strategically recruiting students from underrepresented groups through the *Ecological Society of America's Strategies for Education in Ecology, Diversity and Sustainability Partnerships for Undergraduate Research Fellowship, Hispanic Association of Colleges and Universities*, and the *National Association for Equal Opportunity in Higher Education* programs; funding student research exchanges among coastal LTER sites; and, engaging teachers and high school students (and their parents) from Miami Dade County Public Schools (90% underrepresented groups, 60% female) in science and professional development through our Research Experience Programs. ***(2): Enhance representation of faculty from underrepresented groups*** by the FCE PI's service on the internal advisory board of FIU's ADVANCE program in the Office to Advance Women, Equity & Diversity to advance institutional structures, processes, and climate to recruit and promote FCE faculty from underrepresented groups. Through the ADVANCE program we will also continue to recruit FCE post-docs from underrepresented groups into a prestigious FIU Postdoctoral Fellowship program. ***(3): Promote diversity, equity, inclusivity, and well-being among FCE collaborators*** by fostering leadership through our structure described above, encouraging membership in more than one working group, inclusion of multiple working groups on student advisory committees and co-production of publications with agency/NGO scientists, and encouraging personnel to participate in public education, community engagement and outreach activities and frequent FCE social events. FCE's progress toward each goal will be annually assessed by Associate Dean of Research, Dr. Rita Teutonico, through interviews and focus groups, and an anonymous survey of quantitative demographic and qualitative inclusion data.