PROJECT SUMMARY - Georgia Coastal Ecosystems LTER

<u>Intellectual Merit</u> – The Georgia Coastal Ecosystems (GCE) LTER is located along three adjacent sounds on the Atlantic coast and includes both intertidal marshes and estuaries. Long-term drivers of climate change, sea level rise and human alterations of the landscape will cause transitions in dominant habitat types (state changes) within the GCE domain by changing the amounts and patterns of water delivery across the landscape. These changes in water delivery can be conceptualized as presses and pulses in river inflow, local runoff, groundwater input, and tidal inundation, which will in turn manifest themselves as changes in salinity and inundation patterns in the domain. *The research proposed for GCE-III is designed to address how variations in salinity and inundation, driven by climate change and anthropogenic factors, affect biotic and ecosystem responses at different spatial and temporal scales, and to predict the consequences of these changes for habitat provisioning and carbon (C) sequestration across the coastal landscape.* The goals for this next funding cycle are to:

1) Track long-term changes in climate and human actions in the watershed and adjacent uplands, and evaluate the effects of these drivers on domain boundary conditions (riverine input, runoff and infiltration from adjacent uplands, sea surface height). We will accomplish this through long-term measurements of climate, water chemistry, oceanic exchange, and human activities on the landscape.

2) Describe temporal and spatial variability in physical (e.g. stratification, estuarine salt intrusion, residence time), chemical (e.g. salinity, nutrients, organic matter lability), geological (e.g. accretion) and biological (e.g. organism abundance and productivity) properties in the domain, and to evaluate how they are affected by variations in river inflow and other boundary conditions. We will accomplish this by tracking both water and marsh conditions at our core monitoring sites, remote sensing, and hydrodynamic modeling.

3) Characterize the responses of three dominant habitats in the domain (Spartina marsh, fresh/brackish marsh, high marsh) to pulses and presses in salinity and inundation. We will accomplish this through monitoring, large-scale field manipulations, and modeling designed to evaluate system responses to changes in inundation in the Spartina marsh, increased salinity in the fresh/brackish marsh, and changes in hydrologic connectivity in the high marsh. We are particularly interested in determining thresholds that cause habitat transitions (state changes), and in identifying signals of these changes.

4) Describe patterns of habitat provisioning and C sequestration and export in the GCE domain, and to evaluate how these might be affected by changes in salinity and inundation. We will accomplish this by using modeling and field observations to evaluate habitat provision and C flow under different scenarios of sea level rise, freshwater inflow, and coastal development that describe both the pre-colonial past conditions of the system and its likely future over the next 100 years.

These efforts will be synthesized into a synoptic understanding of both biotic and ecosystem responses to variations in salinity and inundation driven by climate change and human activities, which will be used to assess thresholds between habitats and the potential for state changes in the domain.

<u>Broader Impacts</u> – The goal of GCE outreach is to enhance scientific understanding of coastal ecosystems by teachers and students, coastal managers, and the general public. The GCE Schoolyard program, run in partnership with the UGA Marine Extension Service, is built around long-term contact and mentoring of educators. The Schoolyard program is developing activities and distribution plans for the forthcoming GCE children's book, *As the Tide Comes In*. A partnership with the GCE Peach LSAMP program will provide research opportunities for minority undergraduates, and a cross-site interdisciplinary course will provide interdisciplinary training for graduate students. GCE postdoctoral opportunities will advance the early careers of several scientists. We partner with the Georgia Coastal Research Council to promote science-based management of coastal resources. GCE scientists routinely participate in a variety of public outreach forums. GCE information is also broadly accessed via our website, which uses a state-of-the art information system to manage and display information about study sites, research, taxonomy, data sets, publications, and project administration.

Section 1: RESULTS OF PRIOR SUPPORT

The Georgia Coastal Ecosystems (GCE) LTER program was established in 2000. We are now completing GCE-II, which has 15 Principal and 13 Affiliated Investigators from 11 Institutions. During this funding cycle GCE scientists have published 126 journal publications and 69 books, theses, and other one-time publications (<u>http://gce-lter.marsci.uga.edu/public/app/biblio_query.asp</u>), and have obtained external grants from NSF, DOE and elsewhere to roughly double our overall efforts. We also have strong programs in information management, education and outreach. These accomplishments have created a foundation for the ambitious plan we propose for GCE-III.

The GCE domain is located on the central Georgia coast (Fig. 1). It encompasses three adjacent sounds (Altamaha, Doboy, Sapelo) as well as upland (mainland, barrier islands, marsh hammocks), intertidal (fresh, brackish and salt marsh) and submerged (river, estuary, continental shelf) habitats. Our general approach to studying this landscape is focused on how spatial and temporal variations in fresh and salt water affect biotic and ecosystem properties. During GCE-I we began to describe the patterns of variability in estuarine processes with an emphasis on the marked spatial variation in freshwater inflow as a primary environmental forcing in our domain. In GCE-II, we added a more detailed understanding of the movement of water between subtidal, intertidal and terrestrial habitats to this conceptualization (Fig. 2). This expansion took into account not only freshwater-marine gradients along the longitudinal axes of the estuaries, but also lateral gradients including tidal exchange on and off the marsh platform, water flow from the upland (groundwater and overland runoff), and direct precipitation and evapotranspiration. We asked 5 inter-related questions to address environmental forcing (Q1), patterns within the domain (Q2), longitudinal gradients in estuaries (Q3), lateral gradients in marshes (Q4), and their implications for landscape-level distributions of organisms (Q5). Our approach to each question, along with our accomplishments to-date, is highlighted below. References to our 10 signature publications are in **bold**, and efforts supported by supplements are denoted with an S^{*1} .

Q1: What are the long-term patterns of environmental forcing to the coastal zone? To address this, we use our core data sets of local climate information and water chemistry of tributaries that discharge into the Altamaha River. We also obtain data from other organizations on river discharge, watershed characteristics, human population demographics, sea level, oceanographic conditions, and climate. *We will continue these activities in GCE-III (Area 1).*

Atmospheric and oceanographic forcing. Two meteorological stations are used to document weather and climate patterns within the GCE domain (Fig. 1). The station at Marsh Landing, operated in collaboration with the Sapelo Island National Estuarine Research Reserve (SINERR), serves as our primary meteorological station for inter-comparison studies and <u>ClimDB</u>. The station at Hudson Creek in Meridian is operated in cooperation with the USGS. Near-real-time and historic data and plots from these and other relevant climate stations are publicly accessible on the GCE Data Portal (<u>http://gce-lter.marsci.uga.edu/portal/monitoring.htm</u>). We are currently setting up an eddy covariance flux tower (S*), which will also be a level 3 weather station. We obtain real-time monitoring data on oceanographic conditions from the National Data Buoy Center's station at the Gray's Reef National Marine Sanctuary, and sea level data from NOAA/NOS. During GCE-II we analyzed the relationships between various

¹ In addition to the supplemental funding acknowledged in the text, LTER supplements have supported the acquisition and maintenance of vehicles (boats, trucks, mules), basic laboratory equipment (e.g. drying oven, spectrophotometer, ultracold freezer), and oceanographic equipment (sondes, H-ADCP, depth sounder). Supplemental funds also supported trips by 3 GCE faculty and 3 graduate students to France and China to develop international collaborations with plant and soil scientists.

climate indices and freshwater delivery to the GCE domain and found that river discharge and watershed precipitation are related to the Bermuda High Index during summer-fall, whereas the ENSO cycle is more important in winter (Sheldon & Burd in prep). We also found that sea level is positively correlated with along shore winds and negatively correlated with cross shore winds (Di Iorio & Castelao in prep). *In GCE-III the atmospheric and oceanographic observations will be used as forcing and boundary conditions for our proposed hydrodynamic model (Finite Volume Coastal Ocean Model – FVCOM).*

Riverine forcing. The USGS gages at Doctortown (02226000) and Everett City (02226160) provide nearreal-time data on river discharge into the Altamaha estuary. This data is automatically harvested using technology developed by GCE. We also measure nutrient concentrations in the water entering the GCE domain. To-date, we have found that concentrations of dissolved organic carbon, nitrogen and phosphorus, and inorganic phosphorus are all positively correlated with flow, whereas nitrate+nitrite (NOx) is negatively correlated. This leads to a shift in the form of dissolved nitrogen entering the estuary, with NOx dominating during low river discharge and DON increasing in importance during high flow (Weston et al. 2003). Collaborative research with FCE revealed that the contribution of terrestrial DOM is greater during the spring flood pulse. At the watershed scale, we found that instability in land use over the past 30 y has come primarily from cycles of de- and re-forestation (Runfola & Pontius in review). (This was part of the "Maps and Locals" cross-site initiative (S*) to use spatial representations of land cover to identify patterns of landscape change). We have also documented an increase in N and P inputs to the Altamaha watershed over the past 50 y (Schaefer & Alber 2007b), and an increase in NOx and TN concentrations in the Altamaha River and its tributaries (Weston et al. 2009). Schaefer & Alber (2007a) evaluated the general relationship between watershed nutrient loading and riverine export for the Altamaha and 11 other southeastern rivers, and found that their average N export was only 9% of watershed nutrient loading, compared to global estimates of 25%. This analysis was featured as a Synthesis and Emerging Ideas paper in Biogeochemistry.

Q2: How do the spatial and temporal patterns of biogeochemical processes, primary production, community dynamics, decomposition, and disturbance vary across the estuarine landscape, and how do they relate to environmental gradients? We collect data in the water column and marshes at core sites distributed throughout the domain (Fig. 1), with higher resolution studies of the Duplin River. The variables of interest span all five of the LTER core research areas. *We will continue these activities in GCE-III (Area 2)*.

Water column. We record conductivity, temperature, and sub-surface pressure every 30 min at moorings distributed across the GCE domain, and we run regular cruises to measure the surface water concentrations of dissolved and particulate materials (Fig. 1). We have found that the highest NO_x concentrations are in Altamaha Sound (GCE 7 and 8), whereas organic constituents (DOC, DON, and DOP) are highest in Sapelo Sound (GCE 1). An empirical orthogonal function analysis of salinity variability found that 85.6% of the variability was negatively correlated with river discharge, with an additional 8.7% correlated with sea surface height (Di Iorio & Castelao in prep.), indicating that high water level at the coast leads to increased salinity in Altamaha Sound and freshening in Doboy and Sapelo sounds. We have also conducted directed studies in the Altamaha River estuary to evaluate physical processes, including sea surface waves, turbulence, and residual circulation, using a combination of observations and modeling (Kang & Di Iorio 2005, 2008; Di Iorio & Kang 2007). We found that an increase in river discharge changed the estuarine turbulence levels and density characteristics into a more ebb-dominated and stratified system. *These observations will be evaluated in the FVCOM domain hydrodynamic model that will be developed during GCE-III (Area 2)*.

Cai (2011) synthesized DIC measurements from GCE cruises and other data on C flow to construct a carbon budget for the South Atlantic Bight (see also Wang & Cai 2004; Jiang et al. 2008). He suggested that the marsh is a sink for atmospheric CO_2 and that it laterally exports a large quantity of inorganic and organic carbon that support net heterotrophy and CO_2 degassing in first the estuaries and then the inner

shelf (Fig. 3). He also suggested that most of the OC from the Altamaha River was likely exported directly to the inner shelf, with little processing in the estuary. This work challenges the conventional view that estuarine degassing is supported by riverine C, and thus that lateral export from marshes can be ignored. Two of the weaknesses in this budget are that the lateral flows of water and the associated DIC exchange between the marsh, the estuary, and the coastal ocean were not well constrained, and there was no direct measurement of net air-marsh/water CO_2 flux to independently validate this critical carbon flow. *Both of these gaps will be addressed in GCE-III (Area 3a)*.

Microbial research during GCE-II was done in collaboration with the Sapelo Island Microbial Observatory and as part of the cross-site MIRADA project. This included studies of microbial diversity (Gifford et al. 2011; Booth & Amaral Zettler in prep) and of processes such as transformation of aromatic monomers and organic osmolytes, two important components of the DOC pool in coastal seawater (Mou 2006; Mou et al. 2005, 2007). We also began an evaluation of the temporal dynamics of ammonia-oxidizing Archaea, a group of microbes that convert ammonia to nitrite (Caffrey et al. 2007; Hollibaugh et al. 2011). A combination of molecular and ecological measurements suggests that these Archaea are abundant when nitrite concentrations are high, but little is known about their relationship to environmental factors. *This work will be continued in GCE-III (Area 2)*.

Marshes. We monitor vertical accretion and sedimentation, plant productivity, and animal abundance at our core sites to document spatial and temporal patterns across the domain. In GCE-II we found that freshwater marshes have a higher content of organic carbon and nitrogen in the soil, and are accreting at a faster rate than those in saltier areas due to decreased rates of decomposition in freshwater (Craft 2007; Loomis & Craft 2010). Moreover, these patterns were found across a wide range of sites in the continental US. (Craft 2007). Analysis of our plant monitoring data indicated that productivity at creekbanks was strongly related to Altamaha River discharge, whereas production in the mid-marsh was most strongly related to local precipitation. *We will use the Spartina model being developed in GCE-III (Area 3a) to explore the relationships underlying these observations*. We also found that many marine invertebrates are more abundant at barrier island than mainland marsh sites (Silliman et al. in prep), and grasshoppers are most abundant after years with high plant production (Wieski & Pennings in prep). At a larger spatial scale, **Ho et al. (2010)** found that high-latitude plants are better food for herbivores. To the extent that superior foods lead to larger body sizes, high-quality plants could be one mechanism behind Bergmann's rule (animals are larger at high latitudes). This paper was published in the *American Naturalist* and attracted considerable attention from the press.

Duplin River. The Duplin River estuary is the locus of our efforts to understand the integration of water and marsh processes in estuaries. In GCE-II we studied the hydrodynamics of the River and collected remote sensing imagery that will allow us to address interactions between the water of this estuary and the extensive intertidal areas that it floods. The development of heat and salt budgets for the Duplin River (McKay & Di Iorio 2008, 2010) led us to conclude that flooding of the marsh can alter the channel heat content on subsequent ebbing tides, that groundwater input drives net water export, and that horizontal mixing varies on a spring-neap time scale. This fortnightly pulse in mixing causes the salinity gradient to reverse, which is something that has never been seen before at these time scales and could potentially create a barrier for export of material. Radium isotope data from the upper Duplin also indicated considerable groundwater discharge, which is often overlooked as a source of water and nutrients to estuaries (Porubsky et al. 2011). We further characterized groundwater inflow along the river using electrical resistivity profiling coupled with radon-222 measurements (S*). LIDAR imagery of the intertidal area (S*) and ground truth data obtained with an RTK GPS (S*) were used to create a corrected digital elevation model of the intertidal areas (Hladik & Alber 2012). We also used a multibeam echosounder to produce a detailed bathymetric map of the Duplin River itself (S*), which has been merged with the corrected LIDAR DEM to produce a continuous elevation model (Fig. 4). The LIDAR data were also used in a decision tree with hyperspectral imagery to produce an accurate vegetation map

(Fig. 4; Hladik et al. in review), which is being used to characterize above-ground biomass, soil properties, and the densities of marsh invertebrates in the sub-watersheds of the Duplin River (Schalles et al. in prep). *This work will serve as the foundation for the detailed hydrodynamic model of the Duplin River that we will develop in GCE-III (Area 2).*

Q3: What are the underlying mechanisms by which the salinity gradient drives ecosystem change along the longitudinal axis of an estuary? We are addressing this question through our studies of the Altamaha River estuary. In GCE-II we found that experimentally increasing salinity in sediments from the tidal freshwater zone of the estuary resulted in rapid and dramatic changes in microbial activity, material fluxes, and organic carbon mineralization rates (Weston et al. 2006). We also saw an upstream shift in the border between *Spartina alterniflora* and *S. cynosuroides* during an extended drought, suggesting that plant communities can respond rapidly to increasing estuarine salinity (White & Alber 2009). Studies with leveraged funding from EPA demonstrated that fresh, brackish and salt marsh wetlands provide different levels of ecosystem services and that the loss of services (primary production, N retention in soil, and potential denitrification) due to sea level rise is expected to be less than that forecast from losses of total wetland area alone (Craft et al. 2009; Wieski et al. 2010). In 2011 we initiated the Saltwater Addition Long Term Experiment (SALTEX), in which we are applying pulses and presses of higher salinities to a freshwater marsh to mimic saltwater intrusion caused by droughts and long-term sea level rise. *We will continue the SALTEX experiment in GCE-III to understand the responses of fresh/brackish marsh to increased salinity (Area 3b)*.

Q4: What are the underlying mechanisms by which proximity of marshes to upland habitat drives ecosystem change along lateral gradients in the intertidal zone? We use marsh hammocks (upland areas surrounded by marsh) as natural laboratories for evaluating the influences of landscape structure and freshwater input on marsh processes. In GCE-II we surveyed 55 hammocks representing a range of sizes and origins, and used structural equation modeling (SEM) to identify a set of relationships among upland (e.g. area, age, grain size, maximum elevation) and high marsh (e.g. area, plot height, slope) variables that directly or indirectly predicted the abundances of the most common plant and invertebrate species in the high marsh (Alexander et al. in prep). In 2008 two hammocks were selected for detailed study. On each one we installed well transects that run from the nearby upland through the marsh and over the hammock to the marsh adjacent to the sound. We measure pressure, salinity, and temperature with loggers (S*) in these wells and are using this information to model groundwater flow underneath the hammocks. *These measurements will be continued in GCE-III (Area 3c)*.

We have also conducted archeological studies to evaluate past human use of hammocks in the context of large-scale environmental changes such as sea level rise (Turck & Alexander 2011). Despite sea level lowering and its concomitant effects on resource distribution, Thompson & Turck (2009) found that cultural systems rebounded to a structural pattern similar to the one expressed prior to environmental disruption. They also found that hammocks contain shell deposits and evidence of Native American occupation going back 4,500 y (**Thompson & Turck 2010**). These shell middens can affect current patterns of soil chemistry and plant distributions (Guo & Pennings in review) and are large enough to increase island elevations above present-day high tides, indicating that ancient human activity has left a variety of ecological legacies on the current landscape. *We will follow up on these observations in GCE-III (Area 1)*.

Q5: What is the relative importance of larval transport versus the conditions of the adult environment in determining community and genetic structure across the longitudinal and lateral gradients of the estuarine landscape? We use a combination of genetic approaches and experimental studies to understand the distributions of plant and invertebrate species across the GCE domain. Analyses of DNA sequence diversity conducted in GCE-II indicated that populations of marine invertebrates closer to the ocean were more than twice as diverse as those closer to the mainland (**Robinson et al. 2010**; Diaz-Ferguson et al. 2010), consistent with data suggesting that recruitment and population densities were higher at these sites (Silliman et al. in prep). Genetic diversity was positively correlated with species diversity, as predicted by ecological theory, but to our knowledge this is the first demonstration of this correlation in a marine environment. Our experimental studies suggested that different factors drive the landscape distribution of plants and invertebrates. Freshwater plants were excluded from saltier sites by physical stress, whereas salt marsh species were excluded from less saline sites by increased intensity of competition (**Guo & Pennings 2011**). The details of these results were more complicated than suggested by previous studies, and outcomes varied as a function of plant traits. In contrast, studies of the major marsh invertebrates indicated that recruitment and predation rates interact to determine invertebrate densities. Moreover, the effect of predation on marine invertebrates was a function of predator species richness (Griffin & Silliman 2011). In GCE-III, we will build on these efforts by integrating the population ecology work more fully into habitat and landscape studies

Education and Outreach. 7 MS theses and 11 PhD dissertations have been completed by students who participated in GCE-II research, and there are currently 28 students from 5 institutions engaged in GCE activities. We routinely involve undergraduate students in our research, many of whom have gone on to graduate school. During GCE-II, REU funds (S*) supported 14 of the 57 students who have been part of the program. The GCE Schoolyard program provides in-service training in field ecology for K-12 educators. From 2000 to 2011, over 80 teachers participated in one or more Schoolyard sessions. During GCE-II, one of our longest running participants (Halley Page) was one of two teachers in the state and 108 in the nation to receive the prestigious Presidential Award for Excellence in Science and Mathematics Teaching. We also partnered with the Center for Ocean Sciences Education Excellence (COSEE) Coastal Trends project, which seeks to increase literacy in ocean science through partnerships among scientists, educators and the general public. Finally, the GCE will publish a children's book, "*And the Tide Comes In*," in November 2012 as part of the LTER children's book series.

The GCE provides outreach to coastal managers through partial support of the Georgia Coastal Research Council (GCRC) (www.gcrc.uga.edu), which promotes science-based management of Georgia coastal resources by facilitating information transfer between scientists and managers. The GCRC currently has 116 affiliates representing 17 universities and 11 federal and state agencies. GCRC activities during GCE-II have included communicating via a listserv and the GCRC website, holding meetings of scientists and managers, compiling and analyzing the state's coastal water quality monitoring data, creating a database for southeastern coastal water quality metadata, and writing technical summaries about stormwater treatment in coastal areas, marsh dieback, herbicide use in marshlands, and offshore wind energy. The GCE also directly partners with the National Atmospheric Deposition Program, SINERR, the Nature Conservancy and the USGS to collect data of mutual interest.

Finally, the GCE website provides public access to information and data from the GCE program as well as decades of research on Sapelo Island and the Georgia coast. Over 580,000 visits from 227 distinct countries and territories have been logged on the GCE website since its introduction in December 2000, accounting for over 1.9 million page views, with more than 70,000 visits over the past year alone.

We will continue all of these efforts in GCE-III (see Outreach and Education).

Information Management. During GCE-II we continued to develop an IM approach that meets the highest LTER IM standards and serves as a benchmark for the ecological informatics community (described more fully in the Data Management section). Our information manager, Wade Sheldon, has served on the LTER IM Executive Committee and co-chaired NISAC, and we have provided technical assistance and software tools to 5 sites to help them improve their IM systems. *We expect to continue to lead the network in IM activities during GCE-III (See Data Management Plan)*.

Section 2: PROJECT DESCRIPTION *INTRODUCTION*

The GCE LTER project encompasses upland, intertidal and subtidal habitats (Fig. 1). Upland areas in the domain include Sapelo Island (a barrier island), the mainland of the continental US, and smaller back barrier islands (marsh hammocks). The majority of the intertidal marshes are salt marsh (dominated by *Spartina*, with high marsh plants adjacent to uplands), with fresh and brackish marsh concentrated in Altamaha Sound. Subtidal habitats include both the larger Sounds (Sapelo, Doboy, Altamaha) and tidal inlets (Duplin River). The Altamaha River, the largest source of freshwater to the GCE domain, drains a watershed of 36,700 km²; it has two dams, far upstream, and is free-flowing for 200 km. The broad expanse of the continental shelf in the South Atlantic Bight provides protection from wave and storm activity but it also serves to amplify the semi-diurnal tides, which range in height from 1.4 m (neap) to 2.9 m (spring). Patterns and processes in this complex landscape vary both spatially (within and between sites) and temporally (tidal, diurnal, seasonal, and interannual).

Overlain on this spatial and temporal variation is long-term forcing due to climate change, sea level rise, and human alteration of the landscape. In recent years the US southeast has experienced prolonged, record droughts (1998-2002, 2006-2009) and precipitation has been highly variable, with Altamaha River streamflow exhibiting several record lows at USGS gages (the latest in 2011) interspersed with nearrecord highs. Downscaled climate predictions for the Georgia coast vary: some of the model projections for the IPCC A2 scenarios show an increase in precipitation and others show a decrease or no change (Maurer et al. 2007). Sea level rise in the region currently averages 0.3 cm/y (Craft et al. 2009; NOAA 2012) and is expected to increase as higher global temperatures accelerate glacial melting and expansion of ocean and coastal waters (Meehl et al. 2007). Although population densities are relatively low, the southeast coast is one of the fastest growing regions in the country and residential construction is at an alltime high. The population in McIntosh County (where the GCE is located) increased by 25% between 1990 and 2000, and is projected to increase by 71% by 2030 (Ctr. for Quality Growth 2006). Moreover, development and human activities in the watershed are likely to affect downstream water delivery, either directly via flow diversion, channel modifications, reservoirs, and point source discharges, or indirectly via changes in land cover. Water use in metro Atlanta, which is partially located in the Altamaha watershed, is projected to nearly double by 2035, and new reservoirs are being considered in both major tributaries of the River (Metro. North Georgia Planning District 2009).

One of the primary consequences of changes in these long-term drivers will be alterations in water delivery (and associated constituents) to the GCE domain. Over the coming decades we anticipate that the following changes are likely to occur: 1) freshwater inflow will decrease due to population growth and accompanying water demand and land use changes in the Altamaha watershed; 2) runoff and infiltration patterns will be altered due to increases in impervious surface and changes in groundwater input; 3) sea level rise will push salt water further upstream and also increase the depth and duration of flooding of salt marshes; 4) precipitation and runoff patterns will be altered due to increased climate variability, leading to higher frequencies of droughts, storms and floods. These changes in water delivery can be conceptualized as presses and pulses in river inflow, local runoff, groundwater input, and tidal inundation, which will in turn manifest themselves as changes in salinity and inundation patterns (Fig. 5). *The primary goal of GCE-III is to understand how this variation in salinity and inundation affects coastal ecosystems.*

Salinity and inundation are major structuring agents for coastal ecosystems. Salinity ranges are used to define estuarine communities (from oligohaline to euryhaline), and numerous studies have shown that organisms are adapted to specific salinities. Shifting isohalines due to changes in river inflow or sea level can affect the distributions of both stationary (e.g. for sessile organisms and rooted vegetation) and dynamic (e.g. for fish and motile benthos) habitat. Salinity affects sorption of NH₄ and PO₄ (Seitzinger et al. 1991; Rysgaard et al. 1999), N accumulation and C sequestration (Loomis & Craft 2010), and the relative rates of sulfate reduction vs. methanogenesis (Weston et al. 2006). Variation in inundation is also

an important determinant of community composition in intertidal marshes, with different suites of organisms in areas of low vs. high elevation (Pennings & Bertness 2001). Gradients in elevation are associated with numerous changes in soil characteristics, including redox potential, moisture content, and concentrations of sulfides and nutrients (Adam 1990; Mendelssohn & Morris 2000).

The response of the biota to variations in salinity and inundation depend on the intensity and timescale of the alteration. Ecological responses to abiotic forcing can be thought of as occurring sequentially in a hierarchical response framework (sensu Smith et al. 2009), wherein short-term physiological and behavioral responses are followed by community reordering and, if the forcing persists (i.e. a press as opposed to a pulse), a tipping point is reached wherein immigration of new species results in a transition to a new "state". Within this framework, systems that are more resistant to change either take longer or require a stronger change in a driver to respond (Gunderson 2000). Characterizing the resistance of an ecosystem to a state change and identifying early-warning signals of an impending shift are topics that have received a great deal of recent attention (Anderson et al. 2008; Scheffer et al. 2009; Briske et al. 2010; Bestelmeyer et al. 2011; Davidson et al. 2012).

In the GCE domain, we consider salinity and inundation as long-term drivers that could cause a state change, which we define as a transition to a new habitat (e.g. Juncus replaces Zizaniopsis as the dominant plant, or submerging marsh is lost to mudflat or open water.) To operationalize this idea, we can characterize the physiological response of each species in a given habitat across a range of values in an external driver (Fig. 6, top). For example, freshwater marsh vegetation may respond to a short-term increase in salinity by reducing photosynthesis and increasing internal osmolyte concentrations, but the abundance of vegetation is not likely to change immediately. If the pulse is longer, the new conditions may favor some species (or clones), so we might see changes in abundance and community reordering. If the salinity continues to increase or the pulse is prolonged, freshwater marsh plants will die back and brackish marsh plants will invade, resulting in a transition to a new habitat (Fig 6, middle). The combined effects of individual response and changes in species abundance will be reflected in ecosystem properties such as net productivity and trophic structure. In the above example, an increase in salinity might initially result in a linear decrease in net primary production (NPP) in freshwater marsh plants, but if the press persists and the community undergoes a transition, total NPP may display complex, non-linear behavior (Fig.6, bottom). Similarly, a persistent increase in inundation would initially stress high marsh plants, but would eventually lead to the invasion of low marsh plants. In both cases, changes in dominant vegetation would be accompanied by shifts in other taxa (albeit over different time scales, depending on the population dynamics of the organisms involved; Bestelmeyer et al. 2011), with consequent effects on ecosystem properties. Moreover, because turnover in marsh plant communities across gradients of salinity and elevation are mediated in one direction (towards lower stress) largely by competition and in the other (towards higher stress) largely by stress tolerance (Crain et al. 2004; Pennings et al. 2005; Guo & Pennings in press), the system may display hysteresis (Gunderson 2000; Bestelmeyer et al. 2011) with different trajectories and transition thresholds depending on whether stress is increasing or decreasing. We predict that responses to decreases in stress will proceed gradually through competitive displacement, whereas responses to increases in stress will proceed non-linearly as competitive dominants are first physiologically stressed and then collapse abruptly.

The habitat shifts and accompanying changes in ecosystem properties described above will affect the ecosystem services provided by the coastal landscape. Although marshes and estuaries provide all categories of ecosystem services (regulating, provisioning, cultural, and supporting), two services that are tractable for our study are habitat provisioning and C sequestration. We have shown that freshwater, brackish, and salt marshes differ in terms of soil C and N content and accumulation, litter decomposition, plant diversity, net primary production, and denitrification (Craft 2007; Craft et al. 2009; Wieski et al. 2010), and several studies have valued ecosystem services based on marsh type (Woodward & Wui 2001; Brander et al. 2006). To the extent that we can identify early warning signals (Veraart et al. 2012) and

characterize transitions from one habitat type to another, we will be in a position to predict the consequences of changes in inundation and salinity for habitat provisioning and the accompanying suite of services. C sequestration by coastal ecosystems ("blue C") has received increasing attention in terms of the global C budget (McLeod et al. 2011). We will build on our existing estimates of C flux through the GCE landscape (Cai 2011) to evaluate how C transport and sequestration might vary as rates of production, the organization of the community, and the distribution of habitats are altered by changes in inundation and salinity, and explore what these alterations might mean for net C flux to the ocean.

The research proposed for GCE-III is designed to address how variations in salinity and inundation, driven by climate change and anthropogenic factors, affect biotic and ecosystem responses at different spatial and temporal scales, and to predict the consequences of these changes for habitat provisioning and C sequestration across the coastal landscape. These ideas can be summarized using the ISSE template developed by the LTER network (Collins et al. 2011) to emphasize the connections between external drivers, pulses and presses on the landscape (the biophysical template), biotic and ecosystem responses, and ecosystem services (Fig. 5). We return to this framework in the Synthesis section, below.

RESEARCH PORTFOLIO

During GCE-III we seek to build on the major programmatic elements developed in the first two funding cycles but with a more explicit focus on how variations in salinity and inundation drive biotic and ecosystem responses differently in the three major marsh habitats (fresh/brackish marsh, high marsh, and Spartina-dominated marsh) within the domain (Fig. 7). With 12 y of data (18 by the end of GCE-III) we are in a position to use long-term observations to characterize system responses to external drivers and to inform large-scale field experiments. We propose a combination of monitoring, focused studies, long-term field manipulations, and modeling to follow changes over multiple temporal and spatial scales, to explore the mechanisms that control these changes, and to assess thresholds to assess thresholds between habitats and the potential for state changes in the domain. We divide our proposed research into 4 interrelated programmatic areas (Fig. 8, which also lists the PIs primarily responsible for each sub-project).

Area 1: Climate and human drivers of change. In order to understand the effects of external drivers such as climate change, sea level rise, and anthropogenic alterations of the landscape, we need to document their patterns over time and space. This is similar to Q1 from GCE-II, and much of the proposed work is a direct continuation of those efforts, but we are adding studies of land use change, shoreline modification, and Native American use of the area to enhance our understanding of the human drivers of change. Our goals are to track long-term changes in climate (average conditions and extreme events like storms) and human actions (in the watershed and adjacent uplands), and to evaluate the effects of climate and human drivers on domain boundary conditions (riverine input, runoff and infiltration from adjacent uplands, sea surface height).

Area 2: Long-term patterns within the domain. Temporal and spatial variability in environmental forcing and human actions (Area 1) interact with the geomorphic characteristics of the landscape (e.g. soil type, elevation, drainage patterns) to produce gradients in salinity, nutrients, inundation, and larval dispersal. These in turn produce variations in habitat, biogeochemical processes, primary production, community composition, decomposition, and disturbance across the landscape. To understand these relationships, we need a long-term perspective on the temporal and spatial patterns of biotic and abiotic variables within the domain and how they relate to environmental gradients. We accomplish this through our core monitoring program (a continuation of efforts in GCE-II), with the addition of remote sensing and hydrodynamic modeling. *Our goals are to describe temporal and spatial variability in physical (stratification strength, estuarine salt intrusion length, residence time), chemical (salinity, nutrient concentration and speciation, organic matter lability), geological (accretion) and biological (organism abundance and productivity, microbial processes) properties within the domain and to evaluate how they are affected by variations in river inflow and other boundary conditions.*

Area 3: Response of marsh habitats to changes in salinity and inundation. GCE-II involved studies of marshes along the longitudinal gradient of the Altamaha River estuary (Q3), high marsh along the lateral gradient to upland habitat (Q4), and how these gradients affected organism distributions (Q5). These questions are integrated in Area 3, which focuses on how the dominant marsh habitats in the domain will respond to the changes in salinity and inundation that might be expected in the coming decades: sea level rise in Spartina marsh/tidal creek habitat, upstream salinity intrusion in fresh/brackish marsh, and changes in hydrologic inputs from adjacent uplands to the high marsh. The proposed research will provide data on the responses of each habitat to changes in these drivers over different time scales, allowing us to characterize their resilience and to compare their trajectories in forward and backward directions (evidence for hysteresis). As described above, the effects of these perturbations will depend on the timeframe over which the system is altered, with short-term pulses potentially affecting organismal behavior and physiology and long-term presses potentially resulting in a habitat (state) change. To the extent that we can characterize transitions and identify state changes (through either long-term temporal patterns or spatial patterns observed along known gradients), this work also positions us to evaluate whether habitat shifts in the marsh are associated with increases in autocorrelation and variance, and slowed recovery from perturbations (Scheffer et al. 2009; Dakos et al. 2011; Veraart et al. 2012; although see Dakos et al. in press). Our goal is to characterize the responses of the marsh habitats in the domain (Spartina marsh, fresh/brackish marsh, high marsh) to pulses and presses in salinity and inundation.

Area 4: Integration and forecasting. The changes that we document in Areas 1-3 will require integration and scaling up to the entire domain. Our approach will be to produce synoptic pictures of the GCE domain in terms of a) salinity and inundation patterns, b) dynamic and static habitat, and c) C sequestration and export. We will then use a series of linked models to assess the extent to which variations in boundary conditions affect salinity and inundation patterns and to predict how these patterns might be altered under various scenarios (e.g. IPCC climate scenarios, changes in shoreline armoring). *Our goals are to describe current patterns of habitat provisioning and C sequestration and export in the GCE domain, and to evaluate how these might be affected by changes in salinity and inundation.*

Below we describe the research proposed for each of these Areas, followed by a proposed Synthesis.

Area 1: Climate and Human Drivers of Change

Climate. Understanding how the boundary conditions that affect the GCE domain vary over time and are affected by climate and human drivers positions us to explain past dynamics of the system and predict its future. The GCE operates weather stations and collects data on the water chemistry of the Altamaha River (Table 1). We also obtain data from other organizations on river discharge, sea level, oceanographic conditions and weather (GCE data portal). For GCE-III, we will expand these activities in several ways.

<u>Weather stations.</u> We are installing an eddy covariance flux tower with a level 3 weather station in a Spartina-dominated marsh in the Duplin River to study fluxes of heat, water and carbon. A sonic anemometer and a closed-path gas analyzer (Li-7200) measure the 3D wind vector, air temperature, and concentrations of CO_2 and H_2O at 10-20 Hz. Soil heat fluxes are measured with heat flux plates, an averaging thermocouple and a soil water content reflectometer. Other instrumentation measures humidity, vertical temperature variations, atmospheric pressure, rainfall, and marsh water level. Up- and downward looking radiative sensors measure shortwave (solar), long wave and photosynthetically active (PAR) radiation. A Campbell CC5MPX digital camera takes pictures every 15 min (for 2 h at midday) to get high frequency phenology data (Richardson et al. 2007). *Use of the flux tower is discussed in Area 3a*.

<u>Water chemistry.</u> We are synthesizing 12 y of nutrient data from the main stem of the Altamaha and its 3 main tributaries. These data will serve as the basis for loading curves for inorganic (NO₃, NH₄, PO₄) and organic (DOC, DON) nutrients to the domain and for characterizing differences among sub-watersheds. *We hypothesize that the level of nutrient loading in each tributary is a function of nutrient inputs to the watershed, but that temporal dynamics are a function of streamflow.* For GCE-III we will focus on the

main stem of the Altamaha, as it integrates tributary flows and represents the actual input to the estuary, and reduce the sampling frequency from weekly to monthly. However, we will expand our analyses to include measurements of DIC, alkalinity, and pH, and will also characterize DOM composition and source. These data will inform our C budget (Area 4), and allow us to track long-term changes in acidity.

<u>Oceanic exchange.</u> We will deploy acoustic Doppler current profilers (ADCPs) with a vertical array of conductivity-temperature-depth (CTD) sensors at the mouths of the 3 Sounds and at the 10-m isobath during fall (low river discharge, downwelling favorable conditions) and spring (high river discharge, upwelling favorable conditions) to measure exchange with the coastal ocean. Cruises to deploy and retrieve these instruments (see UNOLS ship-time request) will also include synoptic sampling for nutrients and carbon constituents and measure the spatial extent of the Altamaha River plume in the coastal ocean. *These focused studies will enable us to better characterize exchange between the GCE domain and the continental shelf, and will provide data needed to calibrate the hydrodynamic model (Area 2).* We will also instrument the mouth of the Duplin River with a horizontal ADCP to track water exchange between the Duplin River and Doboy Sound. *These high frequency measurements will provide calibration and validation data for the more detailed hydrodynamic model of the Duplin (Area 2).*

Human drivers. To date, our consideration of human drivers has focused on nutrient inputs to the Altamaha watershed and land use change in the adjacent uplands (McIntosh Co.). For GCE-III, we propose to expand on these efforts by a) building on the Maps and Locals (MALS) project, b) documenting shoreline modification, and c) investigating the effects of ancient human alterations. *These studies will provide us with a deeper understanding of human drivers of change in our system*.

<u>MALS.</u> The Maps and Locals project has produced a detailed analysis of land use change in our domain (Runfola & Pontius in review). We are building on this, in partnership with Georgia Sea Grant, in two ways: 1) The "Listening Project", modeled after an ongoing project at the Coweeta LTER, involves semistructured interviews with coastal residents designed to elicit information on their experiences of land use change and how it has affected coastal habitats. *These data will enhance our understanding of human perceptions of the causes and consequences of long-term change in the region*. 2) The ecosystem services project, is evaluating market and non-market values of natural resources in McIntosh Co. (Fig. 9). *These data will help us to determine how different development scenarios or predicted changes in habitat (Area* 4) will affect ecosystem services such as C storage.

<u>Shoreline modification</u>. Several data sets are available that provide information on human modification of the shoreline within the GCE domain. These include GIS maps (Alexander) showing the locations of sea walls and other types of shoreline armoring (Fig. 9), and studies by the UGA Marine Extension Service of the locations and status of septic tanks in McIntosh Co. We also have historic and archaeological information on long-term changes in shoreline location due to changes in sea level and on shoreline accretion and erosion. We will incorporate these data sets into the GCE GIS. *These coverages will inform experimental site selection (Area 3c) and scenario development (Area 4)*.

<u>Archaeological studies.</u> Humans have been living on and physically modifying the coastal landscape for over 5,000 y. Studies conducted in GCE-II suggest that humans increased the elevation of upland areas adjacent to some marshes by over 1 m by adding shell deposits (Thompson et al. in press), and that these deposits affected the composition of high marsh vegetation (Guo & Pennings in review). In GCE-III we will conduct core transects and use a combination of optically stimulated luminescence dates, radiocarbon dates, and relative dates from buried artifacts to evaluate both the timing of human occupation and formation of new marsh habitats, both of which will be useful for hindcasting "pre-development" scenarios (Area 4). We will also conduct surveys at archaeological shell test pits and investigate correlations between shell presence (and other drivers) and current marsh vegetation patterns. *We hypothesize that human activities have a) modified the marsh/upland border, affecting the susceptibility of these areas to sea level rise, and b) modified the high marsh plant community.*

Area 2: Long-Term Patterns within the Domain

We collect data documenting key ecosystem variables to support all GCE research areas. In addition to providing a large-scale and long-term perspective on our research questions, these data stimulate new field activities as we seek to understand the mechanisms that explain how the system responds to external drivers. Our work in this area consists of a) field monitoring of water and marsh attributes, b) remote sensing of productivity and habitat shifts, and c) hydrodynamic modeling of water and salt transport.

Monitoring. Our core monitoring program (Table 1) addresses the **five LTER core areas** and is conducted at 10 sites distributed throughout our domain: 3 along an onshore-offshore gradient in each Sound, and one in the Duplin River (Fig. 1). We also collect water column samples at an offshore site (AL-2) to characterize the Altamaha River plume as it mixes with the ocean. We deploy sondes that monitor salinity, temperature, and pressure continuously at 9 of our sites and obtain vertical CTD profiles at all 11 sites during our mini-cruises, in which we collect discrete water samples to measure nutrients, chlorophyll, and suspended sediment. We monitor soil accretion, accumulation, compaction and decomposition; disturbance to plant communities; and plant and animal biomass, densities, and community composition in the marsh associated with each site.

In GCE-III, we will extend our core monitoring for an additional 6 y, with the following minor modifications: 1) add Secchi depth measurements to mini-cruise observations, as an index of water clarity, 2) add analyses of DIC concentration to water chemistry measurements, 3) reduce the frequency of water column sampling from monthly (as in GCE-II) to quarterly (as in GCE-I), with a reduced suite of analytes except at sites GCE 6 and GCE 7, where we will maintain monthly sampling of all analytes, 4) discontinue the Altamaha vegetation transect and instead address these patterns with remote sensing data, 5) reduce the frequency of sampling soil accretion from quarterly to annually. We also will add some new components to the monitoring program: 1) barnacle recruitment in marshes; these data will eventually allow us to use the domain hydrodynamic model to explore variation in larval recruitment, 2) mixed plant community (Zizaniopsis/ Spartina cynosuroides; S. cynosuroides/S. alterniflora) plots to characterize vegetation shifts between fresh, brackish and salt marsh habitats, 3) mixed plant community (Borrichia/Juncus) plots, which will augment existing plots (Juncus/S. alterniflora mixtures) to characterize vegetation shifts in the high marsh, 4) a new monitoring site in the tidal forest (GCE 11, instrumented in the same manner as our other stations with a moored sonde in the main channel and permanent vegetation, marsh plots, and sediment elevation tables) to assess the potential for salt water *intrusion into the tidal fresh forest habitat*, 5) a sonde that measures DO and pH by the flux tower.

We will also conduct additional sampling in support of Areas 3 and 4. In the Spartina/tidal creek habitat (Area 3a) we will: 1) add monthly monitoring of above and below-ground plant biomass in stands of short, medium and tall Spartina to provide higher frequency data to support plant modeling and interpretation of flux tower measurements (4 y), and 2) monitor the growth of headward-eroding creeks annually to document geomorphic change and provide context for creek growth experiments. In the fresh/brackish marsh (Area 3b) we will add quarterly transects in the Altamaha to document the extent of salinity intrusion as a function of river flow (3 y, with opportunistic sampling during extreme events thereafter). In the high marsh (Area 3c) we will continue to measure water level and salinity in groundwater wells at our instrumented hammocks (2 more years). In Area 4 we will support the hydrodynamic model by measuring net transport between the Sounds and the shelf. We will also measure radon concentrations in the Duplin as a way to constrain groundwater input (Peterson et al. 2010). We will support our projections of habitat provisioning by: 1) monitoring blue crab abundance in a creek in the Duplin River (with pop-up nets) to document temporal patterns in marsh access by an important consumer (weekly for 2 y, monthly thereafter; Area 3a), and 2) continuing weekly measurements of ammonium oxidizing bacteria to better characterize their seasonal dynamics in relation to environmental factors such as temperature (2 y). Finally, we will support the development of C budgets by: 1) characterizing DOM composition and predominant sources in water samples collected at core monitoring

sites, 2) measuring DIC, alkalinity and pH in the creek adjacent to the flux tower (quarterly for 2 y), and in the Duplin River (monthly for 2 y) and 3) measuring radioisotopes of cores (²¹⁰Pb, ¹³⁷Cs, ⁷Be) in combination with sediment plates to determine deposition (transitory settlement) and accumulation (permanent storage) in each of our major habitat types.

Remote sensing of productivity and habitat shifts. We have used LIDAR and hyperspectral imaging to develop a detailed digital elevation model and vegetation map of the Duplin River marshes (Fig. 4), which are guiding site selection and Duplin-scale research (Area 3a) and will be useful as a baseline for evaluating future change. In GCE-III we will add several new remote sensing applications to extend the temporal and spatial scales of our research. 1) We will collect high-resolution color aerial photographs (georeferenced, 0.5'-scale in 3 color bands) of Altamaha Sound (Area 3b) and the Duplin River (Areas 3a, 3c) at low tide each fall. Images of the Altamaha will be used to delineate the major intertidal habitats along the estuary and evaluate shifts over time and space (Carle 2011), and to document disturbance and recovery (e.g. bare patches due to salt marsh dieback are expected to correlate with drought (Alber et al. 2008). Imagery of the Duplin will be used to evaluate disturbance, changes in creek geomorphology (particularly headward erosion of creeks) and changes in the high marsh border. 2) We will obtain annual Landsat multispectral images (30 x 30 m pixels) centered in monospecific stands of Spartina, Zizaniopsis, and Juncus (Areas 3a, b, c). These images will be analyzed for variability in plant biomass over time, allowing us to extend our field monitoring record back by 3 decades and test whether correlations between external drivers and plant productivity in permanent plots can be scaled to new and larger sites. 3) We will obtain multispectral MODIS data (8-day composite averages) for areas centered on the flux tower (Area 3a) to evaluate changes in biomass compared to those derived from flux tower sensors, with the goal of scaling our observations of marsh-atmosphere CO_2 exchange. Where possible, this will be augmented with WorldView-2 satellite imagery to provide higher resolution information.

Hydrodynamic modeling. We are developing high-resolution, three-dimensional, numerical hydrodynamic models of the Duplin River and the larger GCE domain as *tools that will provide critical information about water circulation, the transport of materials by advection and dispersion, and residence time. The models will also provide predictions of salinity and inundation patterns across the landscape that are essential for addressing our central hypotheses regarding how these might be altered under different conditions (Area 4). We are using the Finite Volume Coastal Ocean Model (FVCOM; Chen et al. 2006, 2007, 2008) to develop a fine-scale model for the Duplin River, which will be nested in a larger GCE domain model (discussed below). FVCOM, which has been used successfully in many estuaries, has unstructured grids that make it useful for resolving complex estuarine geometry and bathymetry. It also includes a wet/dry element analysis algorithm to model the moving surface boundary required to simulate the flooding/drying process (Chen et al. 2008). We will also explore the influence of the tidal marsh vegetation canopy on the flow and related frictional drag force and on the turbulence and related production and dissipation of kinetic energy by introducing parameterizations that are dependent on plant properties such as stem diameter and density (Temmerman et al. 2005; Fagherazzi et al. in press).*

<u>Duplin River model</u>. We have comprehensive, precise information on bathymetry and marsh elevation in the Duplin River (Fig. 4) that we will use to develop our model grid, which will have a horizontal resolution of 5-20 m in tidal creeks, 20-100 m in tidal channels and marsh areas, and 100-500 m near the open water boundary; the number of vertical cells will be chosen to resolve periodic stratification. We will use an extensive data set of currents and stratification that was collected in 2003 at 5 stations in the Duplin, along with continuous data on water exchange with Doboy Sound, for calibration and validation. Groundwater will be a source of freshwater in the model: our initial salt budget (McKay 2008) suggested that it may be important in the middle and upper reaches of the river and we have found elevated ²²²Rn at bathymetric scours in these areas. We plan to measure radon concentrations and flow at the boundaries of each of the 3 tidal prisms in the Duplin (Ragotzkie & Bryson 1955) as a way to constrain this input. The model will be forced with wind, precipitation and surface heat flux data collected at the flux tower and

Marsh Landing. The ocean boundary condition will be obtained from the domain model.

<u>GCE domain model</u>. Development of this model has been funded separately by Georgia Sea Grant. However, the GCE will deploy ADCPs at the mouths of the Sounds (Area 1) to calibrate and validate exchange with the coastal ocean, and data from GCE sondes and CTD profiles will be used to calibrate and validate salinity and tidal height. The model will be forced with freshwater inflow from the Altamaha River, wind at Gray's Reef, and precipitation and heat flux from our weather station at Marsh Landing (Fig. 1). Bathymetry and surface topography will be from the NOAA NGDC Coastal Relief Model, augmented by water depths measured during field campaigns. The model domain will cover the entire Altamaha-Doboy-Sapelo estuarine complex to the 2-m elevation mark (relative to MSL) and out to the adjacent coastal ocean up to the 30-m isobath. The model will be initially implemented with a horizontal resolution of ~10-40 m in tidal creeks, 50-100 m over salt marshes, and 0.15-2.5 km in the main water channels and near the open boundary over the shelf (Chen et al. 2008; Ralston et al. 2010a, b; Zhao et al. 2010). The vertical resolution will be adjusted to capture the range of observed stratification. Salinity distribution results for the Altamaha estuary will be compared with those from an existing empirical model (Squeezebox; Sheldon & Alber 2002, 2005), which produces 1-D, tidally-averaged box models that can be used to predict salinity distribution and transit times for different river flows.

Area 3a: Spartina/Tidal Creeks

Spartina alterniflora is the dominant plant species in the salt marshes in the GCE domain, and in most salt marshes in the US, and serves as the foundation species in this habitat (Pennings & Bertness 2001). S. alterniflora is generally found between mean sea level and mean high water, with the tallest plants occurring at low elevations along creekbanks and shorter plants occurring at higher elevations in the midmarsh. Spartina habitat (hereafter, Spartina marsh) is flooded and drained twice daily through a network of tidal creeks, which serve as the primary hydrological link between intertidal and open water areas. These small creeks, which can drain almost completely at low tide, are important for nutrient and material exchange and also serve as conduits for aquatic organisms including nekton, epibenthic fauna (e.g. crabs), and planktonic larvae (Rozas et al. 1988; Kneib 1997). We expect sea level rise to be the chronic "press" *driver affecting Spartina marshes.* Thus, understanding how Spartina marshes respond to variation in inundation is critical for predicting the future state of coastal marshes in general. Increased inundation due to interannual variability in sea level (a pulse increase) has been found to increase NPP, but the relationship reverses at the highest sea levels, when increased flooding of tall Spartina, growing at the lower limit of their flooding tolerance, decreases productivity (Morris 2000; Morris et al. 2002). At very high inundation levels plants die and no longer bind sediments with their roots, creating an unstable transition between Spartina marsh and mud flat (Fagherazzi et al. 2006). Understanding plant production is only part of the story, however, as the fate of this production (respired to the atmosphere, stored in the marsh, or exported to open water) will also vary with inundation patterns. Inundation also affects the amount of time that aquatic organisms can access the marsh (Minello et al. 2011), which may feed back in complex ways to affect plant productivity. Finally, changes in inundation may alter creek drainage patterns in the marsh. Our goal is to characterize the response of Spartina marshes to changes in inundation with respect to C exchange, plant productivity, and organismal use, so that we can gain insight into the potential resilience of these systems to sea level rise. This research is focused on the Duplin River estuary, where 82% of the intertidal area is Spartina marsh and we have detailed information on elevation and vegetation patterns (Fig 4, Hladik & Alber in review).

Marsh-atmosphere exchange. We have only a very preliminary understanding of the atmospheric flux of CO_2 , H_2O , and energy to/from Spartina marshes (with their embedded drainage creeks), and how this exchange is affected by presses and pulses in inundation (Kathilankal et al. 2008). We will use data from the eddy covariance flux tower (Area 1) to address this issue (Hollinger et al. 1994; Black et al. 1996; Goulden et al. 1996). The flux tower is being set up at the head of a small tidal creek in a Spartina marsh (Fig. 10). The instrumentation is 3-4 m above ground, so we expect the footprint sampled by the tower to

have a radius ranging from 100m to 1 km (Rannik et al. 2011), depending on the wind direction and fetch, surface roughness (hence friction velocity), measurement height and atmospheric stability (Leclerc & Thurtell 1990; Leclerc et al. 2003a, b; Foken & Leclerc 2004). We will do a footprint climatology (Amiro 1998) to track the footprint over time using Lagrangian dispersion models (Leclerc et al. 1988), large eddy simulations (Leclerc et al. 1997), or higher-order closure Lagrangian Particle Dispersion Models (Sogachev & Leclerc 2011) so that we can confine our analyses to times when only the Spartina marsh is being sampled. This will allow us to quantify fluxes on an aerial basis and to relate CO₂ fluxes to primary production measurements (see below). We will evaluate gas and energy fluxes with reference to diel and tidal cycles (measured with the water level gage installed at the flux tower), as recent observations suggest a pronounced reduction in CO₂ marsh-atmosphere exchange rate as flood height and duration increases (Kathilankal et al. 2008; Polsenaere et al. 2011; Moffett et al. 2010). CO₂ flux at the tower will be related to plant phenology indices obtained from near-surface remote sensing, including daily green excess (calculated using webcam channel brightness values; Richardson et al. 2007), daily broadband Normalized Difference Vegetation Index (NDVI, calculated from radiative differences between near infrared, visible and PAR wavelengths; Richardson et al. 2009), and 8-day composite Enhanced Vegetation Index (EVI, calculated from MODIS imagery; Yan et al. 2010; Yan et al. 2008a, b). We hypothesize that marsh-atmosphere exchange will vary during tidal, diel, and seasonal cycles, with maximum CO_2 uptake occurring at spring low tides, during daytime, in the spring and summer. We further hypothesize that flood depth and duration thresholds exist that will completely suppress atmospheric CO_2 fluxes (e.g., when soil and plants are totally submerged).

This high frequency data will allow us to *characterize temporal variability in atmospheric CO₂ flux from a Spartina marsh* and evaluate how it varies in response to changes in inundation, the annual growing cycle, and other environmental controls. Such information will allow us to address how the marsh-atmosphere CO₂ exchange flux will respond to sea level rise. We will also use the atmospheric flux time series to look for changes in variability or autocorrelation that might be associated with inundation thresholds (i.e. abrupt changes in gas exchange as marsh inundation area increases). If these can be identified they will give us a metric to anticipate potential tipping points in marsh-atmosphere exchange in response to sea level. This work will be done in parallel with flux towers at the other east coast LTER sites (PIE, VCR, FCE), so we can do comparable analyses at those sites. Comparisons across sites will also enable us to evaluate broad scale controls of marsh-atmosphere exchange.

Spartina *primary production.* We will measure above- and below-ground biomass monthly in short, medium and tall *Spartina* plots near the flux tower. These observations can be scaled up to provide an estimate of NPP for the tower footprint, and will be used as ground truth data for remote sensing of EVI and NDVI. These data and our long-term data sets (e.g. irradiance, biomass, meteorology, salinity) from GCE-I and -II will be used to produce a semi-empirical model for *Spartina* areal NPP and biomass that considers both above- and below-ground production. Below-ground *Spartina* production is affected by marsh elevation and inundation (Kirwan & Guntenspergen 2012). Existing models of *Spartina* photosynthesis, however, do not consider below-ground allocation of resources (Fagherazzi et al. in press), and are unable to accurately predict long-term changes in above-ground biomass in the domain (Jung & Burd in prep). Understanding resource allocation was important for developing models in seagrasses (e.g. Burd & Dunton 2001), and we will use a similar approach here. *The model will be used to evaluate how changes in salinity and inundation affect* **Spartina** *production.* It will also provide the basis for a more mechanistic model that incorporates details of plant physiology (e.g. C4 photosynthesis, respiration, resource allocation and translocation), for which we will seek leveraged funding.

Marsh-creek exchange. The C produced in a marsh is either released to the atmosphere via respiration, stored in the soil (generally a small quantity), or exchanged through lateral transport. The flux tower measurements will allow us to estimate the amount of CO_2 that is respired and returned to the atmosphere but it will not provide information on the amount of C that is transported via the creek to open water (in

this case, the Duplin River). Numerous studies suggest that this lateral transport, which occurs via small tidal creeks, can be significant in salt marshes (Childers et al. 2000; Guo et al. 2009; Polsenaere et al. 2011; Wang & Cai 2004), but no studies have quantified this flux in coordination with measurements of atmospheric exchange. We will quantify the transport of dissolved C through the creek at the flux tower so that we can compare the relative importance of atmospheric versus lateral exchange from a Spartina marsh and evaluate how they vary over seasons and in relation to tide stage. We will estimate marsh-creek exchange by 1) determining the inundation pattern of the study creek using detailed elevation information and empirical observations, 2) developing hypsometric curves for the horizontal area of inundation versus tidal height using data from an ADCP deployed at the mouth of the creek over a period sufficient to cover a range of velocities and water level, 3) estimating C production in the creek drainage area using monthly observations of above and below-ground *Spartina* biomass in the flux tower area, scaled per m^2 , 4) quantifying DIC exchange at the mouth of the creek using measurements of DIC and alkalinity collected over several tidal cycles on a quarterly basis, for 2 y. These observations will be used with discharge velocity to estimate DIC flux over the marsh inundation area, and e) developing a C budget for the creek drainage area using estimates of C production in the creekshed and DIC exchange with the atmosphere and the creek. We will also measure C storage in soil cores using 210 Pb and 137 Cs. The remaining major C flux, organic C exchange, is challenging to quantify, as previous studies have shown that OC exchange is primarily particulate and episodic (Chalmers et al. 1985). Subsurface exchange via groundwater is also unknown. OC exchange will be estimated from DOC and POC samples collected during ebb and flood tides, and groundwater input will be constrained based on our hydrodynamic model. Net OC exchange will also be estimated by difference from the whole C budget.

The results of these efforts will enable us to quantify lateral C exchange through a small tidal creek. Based on previous observations and preliminary estimates of transport parameters, we expect to see a substantial net C export (Cai & Wang 1998; Wang & Cai 2004; Jiang et al. 2008; Cai 2011). Using lateral C exchange and atmospheric CO_2 flux, we will be able to determine gross and net C fluxes and balance for the marsh system and directly compare atmospheric and aquatic exchange of C from the marsh. We hypothesize that lateral export is the primary fate of the C fixed in Spartina marshes, with the largest export during summer months, and that export will vary with inundation patterns. As sea level rises, lateral export will be more important than degassing to the atmosphere.

Duplin River metabolism. Carbon that is exported laterally from the marsh is processed in the open water of the estuary. Hopkinson (1988) suggested that, although the open water is net heterotrophic, intertidal marsh areas are net autotrophic, and when combined the entire system is autotrophic. Preliminary C measurements from the GCE domain support this view (Wang & Cai 2004; Jiang et al. 2008). We can address this question in the open water of the Duplin River estuary by a) estimating C input by scaling from the flux tower/tidal creek observations, in combination with remote sensing of vegetation to estimate marsh NPP and marsh-atmosphere exchange, and with the Duplin hydrodynamic model to estimate C transport from the small tidal creeks and from groundwater, b) measuring ecosystem metabolism (GPP and R) using dusk/dawn transects of DO (quarterly for 2 y) to get a synoptic picture of respiration (corrected for atmospheric O_2 exchange). Salinity will be used as a conservative tracer to mark specific water masses (Vallino et al. 2005). In addition, we have funding from YSI, Inc to develop a method to use DO and salinity records from sondes to measure metabolism in waters where advection can mask biological signals (see Hopkinson & Smith 2004), which would allow us to estimate metabolism on a daily basis. There are currently sondes operated by SINERR in the water of the upper and lower tidal prisms of the Duplin River, and we will add one in the middle prism volume, just downstream of the flux tower site. c) quantifying C flux by coupling direct measurements of pCO₂ and DIC with estimates of ecosystem metabolism we will also collect discrete samples along the axis of the estuary to measure DIC, alkalinity and pH (to calculate pCO_2) and total organic C on a monthly basis, and d) evaluating net C exchange between the Duplin and Doboy Sound using C concentration at Marsh Landing (the mouth of the system) in combination with water flow (measured with an H-ADCP). We hypothesize that a) lateral

C inputs are greatest in the upper Duplin, where the density of tidal creeks is greatest; b) the highest proportion of in-system processing occurs during the summer, when temperatures are highest; and c) increases in inundation will lead to a greater export of DIC to Doboy Sound.

Organism interactions. We know far more about how Spartina marsh productivity is driven by "bottomup" forces such as salinity and flooding than by "top-down" forces from consumers (Pennings & Bertness 2001). The blue crab Callinectes sapidus is an important predator that migrates from open water to feed in Spartina marshes. Blue crabs are of particular interest because they are an important fishery in the southeastern US, their populations in Georgia waters have been in decline over the past 30 y, and they may play a strong role in controlling ecological processes in the marsh through trophic cascades (Silliman & Bertness 2002). Blue crabs can only access the marsh surface during high tides, so their density is likely to change daily with tide height, and over long time periods with changes in sea level. Blue crab distribution also changes with salinity; their abundance in the Sounds decreases at higher salinities (Kennedy 2011) as they move upstream to fresher water. Drought simultaneously reduces blue crab densities, makes plants more vulnerable to grazing by snails (Silliman et al. 2005), and reduces plant productivity. We will evaluate blue crab abundance patterns by continuing to analyze GA DNR's trawl data, and by conducting high frequency monitoring of crabs in a marsh creek over natural variations in inundation and salinity. We hypothesize that blue crabs will be more abundant in the Sounds during periods of lower salinity, and that their abundance in creeks will peak during periods of lower salinity and higher tide height. These results will inform our projections of habitat provisioning (Area 4).

Small-scale experiments suggest that blue crabs are keystone predators in southern salt marshes by suppressing Littoraria snails, which then do less damage to Spartina plants (Silliman & Bertness 2002, Silliman in prep.). These studies, however, were limited in spatial scale and realism because crabs and snails were confined in cages at fairly high densities. In GCE-III we will perform a manipulative experiment in which we exclude blue crabs from entire creek-sheds for 3 y by blocking creek mouths with large-mesh netting (2.5 cm^2) and removing crabs by trapping (n=5 exclusion and 5 control creeks). Overall nekton abundance will be assessed by periodic trapping. We will monitor plants and macroinvertebrates in permanent plots in the creekbank and mid-marsh zones of each creek-shed (n=10 plots/zone) before and during the manipulation. We hypothesize that, in the absence of blue crabs, snail densities will increase (especially at creekbank plots where blue crabs have easy access and snail densities are typically low), snail damage to plants will increase, and plant biomass will decrease. We further hypothesize that the absence of crabs will increase the densities of other important marsh macroinvertebrates, including bivalves and burrowing crabs, thereby driving a web of top-down effects that also influence decomposition, soil nutrient pools, and sediment flux (Fig. 11). By understanding how inundation and salinity mediate the abundance of this important predator and evaluating the consequent effects on plant production and soil processes, we will be able to include top-down regulation as we assess habitat provisioning and C flow in our scenarios (Area 4).

Organisms may also affect marsh inundation patterns, as exemplified by the effect of the burrowing crab, *Sesarma reticulatum*, on creek geomorphology (Hughes et al. 2009). With external funding, Pennings and colleagues are documenting rapid ($\sim 2 \text{ m y}^{-1}$) headward erosion of multiple tidal creeks in our domain (see arrow in Fig. 10) and are experimentally *testing the hypothesis that burrowing and herbivory by* Sesarma *facilitate the growth of creeks*, which will affect hydrological processes as sea level rises. Data on changes in creek geomorphology will be used to inform modeling scenarios (Area 4).

Area 3b: Fresh/Brackish Marsh

Riverine estuaries such as the Altamaha have a longitudinal gradient of habitats (fresh marsh, brackish marsh, salt marsh) that vary in their delivery of ecosystem services (Craft et al. 2009). Our previous studies have shown that the distribution of plants along this gradient is largely defined by salinity (Higginbotham et al. 2004; White & Alber 2009), interacting with competition (Guo & Pennings 2011),

and that changes in vegetation are accompanied by shifts in community structure, biogeochemical cycling, and other processes (Craft 2007; Craft et al. 2009). *We expect salinity variation, in response to changes in river inflow or salt water intrusion, to be the major driver affecting fresh and brackish marshes.* Understanding how these habitats respond to salinity variation is therefore important for predicting potential state changes along the estuary. *We hypothesize that biotic and ecosystem responses to changes in salinity will be nonlinear (e.g. the system will display hysteresis), and that freshwater marshes will be less resistant than brackish habitat to increasing salinity.* We will investigate these ideas using a combination of long term observations and field manipulations.

Long-term observations. Our existing monitoring transect along the Altamaha River (GCE 7, 8 & 9) grades from fresh to brackish to salt marsh. We will continue to monitor these sites, and will add an additional core monitoring site upstream in the tidal freshwater forest (GCE 11) as well as quarterly transects to track the upstream extent of saltwater (Area 2), as we expect this upstream area to be vulnerable to salinity intrusion over the long term. We will also establish permanent vegetation monitoring plots at the transitions between fresh and brackish (*Zizaniopsis/ Spartina cynosuroides*) and between brackish and salt marsh (*S. cynosuroides/S. alterniflora*) vegetation. These will be analyzed for changes in relative abundance and plant production over time to allow us to track forward and backward trajectories in response to changes in external drivers. We will also obtain aerial photographs that cover the salinity gradient of the Altamaha River estuary annually to document larger scale changes in plant communities. These will be analyzed with geostatistical techniques to characterize the transitions between habitats and track disturbance and recovery over time (Kent et al. 2006).

Field manipulation. Most experimental studies of saltwater intrusion on low-salinity tidal marshes have been over small spatial and short temporal scales. SALTEX (Seawater Addition Long Term Experiment) is a long-term field experiment that we recently initiated in a *Zizaniopsis* marsh in the Altamaha River. Due to the unprecedented spatial and temporal scale of this experiment, we anticipate that it will generate new insights into how low-salinity tidal marshes respond to saltwater intrusion. We are increasing porewater salinity in 3 m x 3 m replicated (n=6) plots from the ambient salinity of <0.5 to a target range of 5–8 in two treatments: constant (press), with salinities elevated continuously to simulate sea level rise, and episodic (pulse), with salinities elevated temporarily to simulate drought. The pulse treatment, which has not yet begun, will be designed using an analysis of the frequency and duration of high salinity at the SALTEX site that will be generated using the SqueezeBox modeling application (Sheldon & Alber 2002, 2005). The study includes unmanipulated control plots and "inundation control" plots that are pressed or pulsed with equivalent amounts of freshwater. Water is delivered from a head tank connected to a surface irrigation system. Porewater salinity is measured in samples collected several times per week from wells in each plot, and treatment water delivery adjustments are made as necessary to keep salinity within the target range. Once the treatments are established, we will measure changes in porewater chemistry (Cl⁻, SO₄²⁻, H₂S, DIC and DOC (monthly)), soil biogeochemistry (decomposition and sulfate reduction (quarterly)), vegetation (photosynthesis and respiration (quarterly)), above- and belowground biomass and species composition (annually), leaf N and herbivory (quarterly), fauna (insects and invertebrates (biannually)) and soil properties and processes (chromium reducible S, organic C, N, P and organic matter quality (annually), sedimentation and surface elevation/subsidence using SETs sediment elevation tables (biannually)). We plan to run this experiment throughout GCE-III and into GCE-IV.

We hypothesize that episodic (pulse) additions of saltwater will have short-term effects on porewater (increase in CI and SO_4), plant physiology (increased respiration/decreased photosynthesis due to salt stress), and plant interactions with fauna (increased susceptibility to herbivory), but that community composition and soils will be largely unaffected. Once the pulse is withdrawn, we expect the system will recover to baseline conditions over a period of months to one year. In contrast, we hypothesize that the press treatment will begin by showing the pulse effects, but that these will be followed by a cascade of medium- and longer-term responses as the various components of the system move through the different

levels of the hierarchical response framework (Fig. 12). These will include increased organic matter decomposition and decreased N retention and C sequestration in soils, a decrease in biomass of freshwater plant species over the medium-term and a shift towards brackish or salt marsh vegetation over the long-term, and a concurrent increase in favorable habitat for benthic fauna that generally inhabit brackish areas (Thomas & Blum 2010). *We also hypothesize that, over the very long term, soil subsidence will create a negative feedback loop that leads to greater inundation and salinization* of the area. A handful of previous studies have evaluated the response of tidal freshwater vegetation to increasing salinity using small-scale experiments (i.e. Neubauer 2011; Andrew Baldwin unpubl.) and uncontrolled studies (i.e. tide gate removal, Pearlstine et al. 1993). Other studies show the effects of salty storm surge on low-salinity marshes (Chabreck & Palmisano 1973; Guntenspergen et al. 1995; Michener et al. 1997; Doyle et al. 2007). We will review these studies along with our experimental results in a synthesis paper that will compare the directions and magnitudes of responses of tidal freshwater marshes to pulses and presses in salinity over different time scales.

Area 3c. High Marsh/Upland Border

The high marsh is the intertidal area closest to the upland, and is typically dominated by the plants Borrichia frutescens and Juncus roemerianus. High marsh plant and animal communities are more diverse than those at lower elevations (i.e. Spartina marsh), and the high marsh is more likely than other marsh habitats to exchange materials and organisms with upland areas (Brittain et al. 2011). Our survey of marsh hammocks in GCE-II found that the nature of the upland predicted multiple aspects of the high marsh habitat. High marsh habitat is potentially vulnerable to the long-term press of sea level rise, which could cause a lateral shift in its borders, to pulses in precipitation, which cause variation in salinity, and to the long-term press caused by anthropogenic alteration of the uplands, which may alter *hydrologic connectivity.* The vegetation in the high marsh is influenced by inundation and salinity; greenhouse experiments in which we varied both factors suggested that increasing inundation restricts Borrichia to the high marsh, whereas Juncus was more affected by increased salinity. The Juncus results support our observations that drought induces a shift in the *Spartina/Juncus* border towards dominance by Spartina, and with experiments that show that reducing salinity increases Juncus abundance (Pennings 2005). Once removed by a disturbance, the *Juncus* is slow to recover, leading to hysteresis. The high marsh is also affected by shoreline modification and upland development; a number of studies have correlated human activities in the upland to high marsh abiotic and biotic variables (Bertness et al. 2002; Silliman & Bertness 2004; Fitch et al. 2009; Walters et al. 2010). We hypothesize that the spatial extent of the high marsh is primarily determined by geomorphology and hydrologic connectivity with the upland (both of which can be altered by humans), and that temporal variation in community composition is primarily due to variation in salinity. We will investigate these ideas using a combination of long term observations, field surveys, experimental manipulations and modeling.

Long-term observations. We monitor a high marsh stand of *Juncus* at GCE 10, and we also have a 15-y record of high marsh plots in mixtures of *Juncus/S. alterniflora*. We are adding additional high marsh plots in *Borrichia/Juncus* mixtures (Area 2). As with the fresh/brackish mixtures, we will measure relative abundance and plant production to test the ideas in Fig. 6. We will also use annual aerial photos of the Duplin River to evaluate changes in the extent of high marsh associated with hammocks over time. We have two hammocks with instruments that continuously measure groundwater conductivity (salinity), temperature and pressure (water level) in well transects that run from the upland through the adjacent high marsh habitat. We will continue these observations to better understand how precipitation and tidal inundation affect the groundwater regime. Ongoing analyses focus on the role of tidal inundation, tidal pumping (Schultz & Ruppel 2002), hammock and barrier island freshwater heads, and their integration into a marsh subsurface flow model. We are also measuring precipitation, soil moisture, and porewater salinity, which can be used in the soil model (Area 4).

High marsh survey. Studies in other regions suggest that upland development immediately adjacent to marshes can impact high marsh salinity, nutrients and plant communities (see above). However, these studies were inconsistent, and it is not clear whether our domain, which has less intense development, will show similar responses. We will survey high marsh characteristics at 15 sites in each of 3 land-use categories: 1) marshes where the upland is developed and the upland/marsh interface has been modified by bulkheads, 2) marshes where the upland is developed but the upland/marsh interface is not armored, and 3) marshes where the upland/marsh interface is adjacent to undeveloped forested borders. We will use our GIS data on the locations of armored shoreline and land use to select appropriate sampling sites (Fig. 9). Each site will be at least 20 m in length along the upland/marsh edge, separated by at least 30 m from the next site, with treatments interspersed. At each site, we will locate 3 transects perpendicular to the marsh edge, with plots located at 2, 4, and 8 m along each transect. We will use GIS and ground observations to characterize the adjacent upland at each site (land cover, percent impervious surface, upland buffer width). In the marsh, our approach will be similar to the survey of undeveloped hammocks in GCE-II so that data can be directly compared. We will characterize the high marsh geomorphology (slope, origin, elevation) and sedimentology (stratigraphy, grain size) at each site, and the soil characteristics (grain size, organic matter content, sediment C and N), pore water (salinity, nutrients), flora (vegetation composition, height, N content) and fauna (snail, bivalve and crab abundance and sizes. stable isotope values, macroinvertebrate parasite loads) in each plot. We will also delineate the upland border and the edge of the high marsh (defined by a transition to Spartina alterniflora) with DGPS, and survey the elevations of each plot and the edge of the high marsh with RTK GPS.

We hypothesize that upland modification will alter the extent and composition of the high marsh community, with marshes adjacent to armoring having the least extensive high marsh zones and the most modified plant and invertebrate communities. Shoreline modification is likely to affect subsurface and surface hydrological connections, as well as sediment supply and erosion rates. Consequently, these marshes may have different plant distributions, lower elevations and different sediment composition compared to control areas. Marshes adjacent to developed (but not armored) areas will not be modified as extensively, but increased surface runoff in these areas will allow less time for nutrient uptake and processing by upland buffer vegetation, potentially leading to increased nutrient concentrations in marsh soils. Higher N availability is predicted to increase plant biomass and shift community composition towards *Spartina alterniflora* at the expense of *Borrichia* and *Juncus* (Pennings et al. 2002, 2005). We will analyze these results using MANOVA, to evaluate differences among land use categories, and structural equation modeling (SEM), to evaluate inter-relationships among variables. We will compare these results with the SEM model that we developed for the hammock survey in GCE-II.

Upland manipulation. The importance of upland-marsh connections is implied by the differences in high marsh communities between developed and undeveloped sites, and by our data showing that the structure of high marsh communities is a function of hammock size (Alexander et al. in prep). These connections likely operate through runoff and shallow groundwater flow, but to our knowledge this has never been tested directly. Here, we propose to experimentally test the hypothesis that water flow from the upland to high marsh directly affects high marsh function. We will work in high marsh areas adjacent to Sapelo Island where the vegetation is a mixture of *Juncus* and *Borrichia*. Our experiment will have 3 treatments: 1) upland water reduction (to assess how upland connections, as opposed to elevation, mediate high marsh community composition); 2) impervious surface addition (to assess how increased runoff and decreased groundwater alter high marsh community composition); and 3) controls. Plots (n=8/treatment) will each extend 10 m along the upland/high marsh border and be separated by at least 10 m, with treatments fully interspersed. The water reduction treatments will have vertical plastic barriers (sheeting that extends from 60 cm deep to 30 cm above the soil surface) that will divert shallow groundwater and runoff away from the plots. The impervious surface treatment will use corrugated plastic roofing just above the soil surface to cover the upland immediately adjacent to the marsh plot (with gaskets around tree trunks to intercept stemflow). A ditch will be dug and then filled back in in the control and

impervious surface treatments to control for the disturbance of installing the barrier in the water reduction treatment. The experiment will be set up in year 4 and will last a minimum of 3 y. We will use DGPS to delineate the edge of the high marsh, and establish permanent sub-plots in each plot located 2, 4 and 8 m from the upland edge, which we will survey with an RTK GPS along with the elevation of the high marsh edge. We will use standard GCE protocols to monitor pore water salinity, plant photosynthetic rates, plant biomass and composition, and benthic invertebrate density and composition in each sub-plot. Measurements will be weekly for the first 8 weeks to capture the short-term response, monthly for the next year, and guarterly thereafter. We expect pore water salinity to increase rapidly in the water reduction treatment, leading to a rapid decrease in photosynthesis and increase in nitrogen-based osmoregulatory compounds by the existing plant community, followed by increased herbivory (due to higher N content). Over longer time scales, we expect a shift towards more salt-tolerant plants (Borrichia and Sparting at the expense of Juncus) and a decrease in high marsh width (Fig. 13). We expect parallel shifts in the macroinvertebrate community. We hypothesize that the "flashiness" of freshwater delivery to the high marsh in the impervious surface treatment will have effects similar to the water reduction treatment. Data will be analyzed using MANOVA and SEM as described above for the survey. We will write a conceptual paper building on the results of these efforts and the high marsh survey, to summarize existing knowledge about upland-marsh linkages and identify knowledge gaps for future work.

Modeling. We will use a spatially structured model of clonally growing plants (Mony et al. 2011) to evaluate interactions among the dominant high marsh plants at our study sites. The model will be parameterized with information from greenhouse experiments in GCE-II on the responses of each plant to variations in salinity and inundation, augmented by information from the Spartina physiology model. It will allow us to evaluate the dynamics of habitat shifts that might occur in response to changes in freshwater delivery or sea level rise, and to identify conditions promoting hysteresis in habitat transitions. The plant community model will also be integrated into our large-scale modeling efforts (Area 4).

Area 4: Integration and Forecasting

In Area 4 our objectives are to synthesize information collected in Areas 1-3 to produce an integrated picture of habitat provisioning and carbon flow across the landscape, and evaluate how changes in salinity and inundation may change these services in the future. We will accomplish this with a combination of integrative modeling, empirical observations, and remote sensing.

Integrative modeling. Hydrodynamics play a critical role in the distribution and transport of water and materials across the GCE domain. Consequently, an accurate hydrodynamic model is a necessary first step for our integrative modeling efforts. FVCOM will provide information on salinity and inundation patterns of the water that floods the marsh, which will be used in a soil model to predict porewater salinity and soil water content (described below), and in 3 different semi-empirical plant models. The Spartina productivity model (Area 3a) will provide information on individual plant responses to salinity and inundation; the plant community model (Area 3b) will provide spatial information on vegetation dynamics during transitions; and a modified version of the SLAMM model (described below) will predict habitat shifts at the landscape level. Although these models will exchange information offline (Fig 14), they could inform each other, and our goal in GCE-III is to lay the groundwork for fully integrated mechanistic models with multiple feedbacks. The effects of parameter sensitivity (e.g. bottom friction on the marsh in the hydrodynamic model, below-ground production parameters in the Spartina productivity model) will be investigated for each model individually and for how sensitivities and uncertainties propagate between models.

Soil model. Marsh porewater salinity varies over relatively long time scales (seasonal rather than tidal) and is generally higher than water column salinity due to evaporation and transpiration. We will build a soil model that tracks the inundation history (provided by FVCOM) of intertidal and subtidal cells in the hydrodynamic model on an aereal basis. The model will initially be run in each cell individually, and will

use basic ET information, with plant transpiration parameterized from the literature (e.g. Giurgevich & Dunn 1982), to predict porewater salinity and soil water content in the top 10 cm of soil for each cell individually. Model calibration and validation will be performed using 2 existing ground surveys of porewater salinity and soil moisture collected in different vegetation classes (n=370 plots each). Porewater salinities predicted for areas of *Spartina* will be used as input to the Spartina production model to predict individual plant growth, which in turn will guide improvements to the parameterization of plant response to salinity in the community model. At the community level, we will use the porewater data to predict vegetation composition and class, which can be calibrated with our observations that have shown good separation of plant species based on porewater salinity and soil moisture (Lynes 2008).

SLAMM. To predict habitat shifts over long time-scales, we will use a modification of the EPA SLAMM model (Brittain & Craft 2012). In its most basic form SLAMM uses elevation, habitat distribution and other variables to predict how tidal freshwater forest, fresh, brackish and salt marshes, and other land cover types (e.g. open water) will respond to different sea level rise scenarios. We have used SLAMM previously to evaluate the ecosystem services provided by different marsh habitats (Craft et al. 2009), and are currently running an updated version of the model for the South Atlantic Bight (with separate funding). The new forecasts will use new coastwide LIDAR and an update of habitat types from the National Wetland Inventory. We will also evaluate the effects of different Altamaha River inflows on salinity patterns, using our SqueezeBox analyses (Sheldon & Alber 2002, 2005). We recognize that SLAMM has limitations and are working to incorporate biophysical feedbacks (Morris et al. 2002) into the model, using detailed measurements of elevation and plant distribution collected across the domain.

Scenarios. We will use these models to run a series of scenarios to evaluate, through hindcasting and forecasting, how pulses and presses in our major drivers (sea level, river flow, precipitation, temperature, groundwater input, and overland runoff) will affect the domain. The models will be used to predict salinity and inundation patterns, porewater salinities, and plant responses over different time scales. Predictions will be evaluated in terms of habitat provisioning and C flow (see below). Climate change will be examined using bias-corrected, downscaled projections of the IPCC model results (Maurer et al. 2007). Human alterations will be evaluated by simulating potential modifications to shoreline armoring and overland runoff based on build-out scenarios from McIntosh County, as well as modifications in the greater Altamaha watershed (e.g. new reservoirs upstream). We will also consider scenarios with feedbacks to human behavior (e.g. building sea walls as sea levels rise, green developments). Our archeological studies will allow us to consider patterns in the pre-development landscape. We will also be able to modify our scenarios in response to experimental results showing changes in creek geomorphology or the top-down effects of blue crabs on plant production.

Habitat provisioning. Estuarine environments can be described in terms of dynamic habitat, which is tied to water movement and is relevant to planktonic and nektonic organisms, and static habitat, which is most relevant to rooted vegetation and the benthos. The overlap between these is also important: a blue crab lives in the water but forages in the marsh. Hence, a drought that shifts isohalines upstream, or a decrease in inundation time, may not provide appropriate overlap of the two habitat types. *We are interested in how habitat availability varies across the domain over different time scales (tidal to decadal), and the strength of forcing that triggers community reordering and habitat shifts.* To evaluate dynamic habitat, we will use the continuous salinity data from our sonde network to map the locations of fresh, oligohaline (<5 PSU), mesohaline (5-15) and polyhaline (15-30) conditions across the domain, and determine how these habitat locations vary over lunar, seasonal, and annual cycles. These will be compared with results from FVCOM which will also be used to evaluate how these salinity ranges might shift given different scenarios. We will assess static habitat in terms of the major plant communities described elsewhere in the proposal: tidal freshwater forest, fresh, brackish, and Spartina marsh, and high marsh. We will use a combination of remote sensing, GPS mapping, and our observations of the borders between different plant communities to estimate the current area of each marsh habitat and how they have changed over

time. We will also use SLAMM to evaluate how these borders may change over time in response to directional climate or anthropogenic presses. To assess the **overlap** of these habitat types, we will overlay the salinity ranges from the dynamic habitat analyses on a base map of static habitat conditions to determine the amount and type of intertidal area associated with each salinity range. When this is done in the context of the hydrodynamic and soil models, we can add information on inundation and porewater salinity as well: that is, what proportion of the time is brackish marsh flooded, and what does that mean for porewater salinity? These can be further coupled to predictions of how changes in inundation and salinity might change vegetation production and distribution. *These analyses will provide us with a synoptic picture of habitat availability across the domain and the tools to evaluate the implications of changes over time*. For example, we can overlay measurements of plant productivity in different marsh types, use of these habitats by marine vs. terrestrial organisms, and C sequestration in vegetation and soil to gauge how these ecosystem services will change under different conditions. We can also couple these predictions with valuations of marsh type (Woodward & Wui 2001; Brander et al. 2006) to assess how the value of ecosystem services will change under different scenarios.

Carbon flow. Two major questions for global and regional C cycling are 1) whether the coastal zone is a net source or sink of CO_2 to the atmosphere and the ocean, and 2) how such C fluxes might change over time. A C budget for the South Atlantic Bight based on preliminary studies in the GCE domain (Cai 2011) suggested that the marsh is a sink for atmospheric CO_2 and that the marsh-estuarine complex exports large quantities of carbon to the coastal ocean (Fig. 3). Two of the uncertainties in this budget, estimates of atmospheric exchange and lateral exchange from the marsh, are being addressed directly in Area 3a. We will also have a greatly improved understanding of water transport from the hydrodynamic model, and can use plant distributions and our monitoring data to estimate NPP throughout the domain. Finally, we are adding observations of DIC, DOM composition and source and soil C storage (Area 3a) to better quantify other aspects of the C budget. Taken together, these measurements will allow us to greatly improve our estimates of C flow, and in particular to test the hypotheses that 1) marsh vegetation is the dominant source of OC that drives net heterotrophy and CO₂ degassing in estuarine waters whereas most riverine OC is exported to the coastal ocean; and 2) the importance of lateral transport of C from the marshes varies spatially (across the 3 GCE Sounds) and with time. We can also, in combination with the habitat analyses, evaluate how the changes that might occur in response to changes in salinity and inundation will affect these conclusions, with the goal of developing new hypotheses about the implications of climate and human activities for the coastal C budget.

SYNTHESIS

The focus of GCE-III is on understanding how variations in salinity and inundation, driven by climate change and anthropogenic factors, affect biotic and ecosystem responses at different spatial and temporal scales, and predicting the consequences of these changes for habitat provisioning and C sequestration across the coastal landscape. The guiding framework for our research (Fig. 7, 8) shows these connections, starting with the effects of climate drivers and human behavior on boundary conditions (riverine input, runoff and infiltration from adjacent uplands, sea surface height) (Area 1). These changes in boundary conditions, manifest as changes in salinity and inundation, cause biotic and ecosystem responses (Areas 2 and 3), with implications for ecosystem services (Area 4). The modeling scenarios provide us with a means to explore the interactions among all parts of the framework, though with less emphasis on linking back to the social template. As described below, there is synthesis integrated into each research area:

Area 1: Our goals are to track long-term changes in climate (average conditions and extreme events like storms) and human actions (in the watershed and adjacent uplands), and to evaluate the effects of climate and human drivers on domain boundary conditions (riverine input, runoff and infiltration from adjacent uplands, sea surface height). We will evaluate how climate (temperature, precipitation, frequency and intensity of storms) affects river inflow and quality through analyses of data from weather stations throughout the watershed and USGS data on flow in the Altamaha River, as well as our long-term measurements of water quality in the main tributaries entering the estuary. We have already developed a multiple regression model that uses precipitation at 6 National Weather Service stations throughout the watershed to predict discharge (r=0.69), and are using this to forecast river discharge using downscaled precipitation projections from climate change models (Sheldon & Burd in prep) We will address whether watershed land use and population density have altered river inflow by comparing precipitation-discharge relationships by decade during the period of record (1930s to the present). We will also use the Index of Hydrologic Alteration (Richter et al. 1996) or a similar metric to evaluate changes in the river hydrograph in relation to the construction of dams and other upstream alterations. We will address the relationship between climate (temperature, wind) and sea surface height using data from the NDBC station at Gray's Reef, and sea level data from NOAA/NOS. We have only limited measurements of inputs from adjacent uplands and groundwater, but by GCE-IV we should have a long enough record from our instrumented wells to evaluate responses to climate.

Area 2: Our goals are to describe temporal and spatial variability in physical (stratification strength, estuarine salt intrusion length, residence time), chemical (salinity, nutrient concentration and speciation, organic matter lability), geological (accretion) and biological (organism abundance and productivity, microbial processes) properties within the domain and to evaluate how they are affected by variations in river inflow and other boundary conditions. With ~12 y of monitoring data, we are positioned to begin to produce a climatology of the GCE domain and to evaluate the extent to which our observations are related to external drivers. Analyses of salinity observations taken from our sonde network indicate that river inflow explains 86% of the salinity variability within the domain, with an additional 9% correlated with sea surface height (Di Iorio & Castelao in prep). The domain hydrodynamic model will allow us to extend these analyses to evaluate the relationships between other physical characteristics (e.g. residence time, storminess), and how these patterns would be affected by changes in forcing and boundary conditions. We also found that nitrogen concentrations in the Altamaha are strongly driven by inputs (Kaufman 2011), that soil accretion is positively correlated with discharge (Craft unpubl.), and that Spartina productivity is driven by a combination of discharge, local precipitation and sea level (Pennings in prep). We will extend and refine these analyses using multivariate spatial and time series analysis techniques, and develop a synthesis paper that uses our monitoring data to evaluate the relative importance of river discharge versus other drivers in structuring patterns across the domain.

Area 3: Our goal is to characterize the short, medium and long-term responses of the marsh habitats (Spartina marsh, fresh/brackish marsh, high marsh) in the domain to pulses and presses in salinity and inundation. We will use the data collected in Areas 2 and 3 to evaluate biotic (plant composition) and ecosystem (primary production) responses across the various marsh habitats as functions of salinity (from 0 to 35) and elevation (mean sea level to the upland border) (Fig. 15). We will use our monitoring data to evaluate the conditions at sites with respect to these drivers, and compare these observations to patterns observed at PIE, VCR and other (non-LTER) coastal sites with similar data sets (Fig. 15). We will also evaluate the relationships between plant composition or primary production and the range of salinity or inundation observed at each site, to evaluate whether these responses are nonlinear. The shapes and slopes of these relationships will indicate the relative resistance of each site to change. We will use data collected from the mixed community plots and from remote sensing to characterize the transitions between the different marsh types, again in terms of plant composition and primary production. Evaluating these border areas over time will also allow us to observe whether there are differences in response to a forward vs. a backward shift in the driver. The mixed zones may also allow us to determine whether variance increases close to a transition. Once the transitions are defined in terms of a range in salinity or inundation, the distance of each monitoring site from these values will provide a measure of its relative precariousness (how close it is to tipping points), whereas the widths of the transitions between states will provide insight into the relative intensity of the press that would be required to produce a habitat change. The data collected from the field experiments in Area 3 will provide information on the responses of each marsh habitat to the major pulses and presses they are expected to experience over the

coming decades: changes in inundation in the Spartina marsh, increased salinity in the fresh/brackish marsh and changes in hydrologic connectivity in the high marsh. Over the long term they should provide direct observations of state changes (although transitions to new habitat and other longer term responses predicted in Figs. 11-13 may not be apparent until GCE-IV). Taken together, this work will provide a synoptic picture of the relative responsiveness of each of the habitats in our domain to changes in salinity and inundation. This understanding will be used in Area 4 as input for building realistic scenarios and to inform predictions of the effects of future changes on biotic structure and ecosystem function.

Area 4: Our goals are to describe current patterns of habitat provisioning and C sequestration and export in the GCE domain, and to evaluate how these might be affected by changes in salinity and inundation. As described above, we will quantify dynamic and static habitat area and C flows across the domain, and use the linked hydrodynamic-soil-plant models to determine how these services might change under different scenarios. We will vary forcing and boundary conditions to quantify system response in terms of salinity and inundation patterns, and determine the combination(s) of external drivers that result in the largest changes in habitat or C flow. We will use our analyses in Area 3 to evaluate these results in terms of the thresholds that might cause a habitat shift, and explore how different policies and other human responses might affect these outcomes. The tools developed here will provide a means to evaluate all of the connections in Fig. 7 and to assess the effects of predicted long-term changes (e.g. river inflow, sea level rise, increased development) on ecosystem services.

RESPONSE TO MID-TERM REVIEW

The GCE mid-term review team complimented our site science and the creativity of our research team, our education and outreach efforts, and our leadership role in the network, particularly in IM. They had 4 main recommendations, which are addressed as follows: 1) Foster synthetic activity at the GCE site, e.g. through enhanced integrative modeling efforts. We have made the connections among the research areas proposed in GCE-III explicit (Fig 8) and believe they are well-integrated in our conceptual framework (Figs 5, 7). The work proposed in Area 4 (Integration and Forecasting) establishes the framework for an integrative modeling effort designed to take advantage of these linkages (Fig. 14), which we will build on further in GCE-IV. 2) Consider increasing the discretionary funding. We have set aside \$120,000 as unallocated funding in the management budget, along with funding for an unassigned graduate student, both of which will allow us more flexibility in GCE-III operations. 3) Produce review articles and synthetic volumes. The GCE PIs collaborated on a chapter in a book on Wetland Habitats of North America (Pennings et al. in press), which prominently features GCE research in discussing the distinctive features of South Atlantic coastal wetlands. We are also currently analyzing data to synthesize i) longterm trends in estuarine water column chemistry, ii) relationships between plant productivity and climate forcing in the domain, iii) landscape patterns of flora and fauna in the Duplin River, and iv) drivers of variation in marsh-upland linkages. Our proposal includes plans for review papers in GCE-III that will synthesize our research and other published studies regarding saltwater inundation in tidal fresh marshes, upland marsh linkages, and the relationship between river forcing and marsh processes. 4) Develop a plan to expand diversity in the GCE population. As described under site management, we now have a GCE Diversity plan (http://gce-lter.marsci.uga.edu/docs/473) and are partnering with the Peach State LSAMP program to increase minority participation in our research. We also have added 2 PIs of Latin American origin and 2 women in the physical sciences. Other recommendations from the panel and NSF are also *being addressed*: 1) We have added experimental research on blue crabs, a key predator in the system; 2) We have identified signature publications on our website; 3) We have added data and metadata from noncore projects (see IM section); 4) We have added larval settlement to our core monitoring to position us to evaluate the link between larvae and water movement in GCE-IV; 5) We continue to strengthen interactions with SINERR and other partners; 6) We have amended our bylaws to include a graduate student liaison; and 9) UGA has provided institutional support of the project (see letter from David Lee).

OUTREACH AND EDUCATION

In GCE-III we will continue our K-12 Schoolyard activities, train undergraduate and graduate students, work in partnership with coastal managers through the Georgia Coastal Research Council, and provide information to the general public.

<u>Schoolyard Program</u>. Each year approximately 10 K-12 science and math teachers spend a week at the GCE field site on Sapelo Island immersed in hands-on research activities alongside GCE scientists and graduate students. The program is built around a model of long-term contact: we use a mix of returning and new teachers as a way to promote mentoring and continuing engagement of veteran teachers. Participants are supported throughout the year by electronic contacts and return trips to Sapelo Island to share classroom activities developed based on GCE science. In 2010 the program began a partnership with the UGA Marine Extension Service (MAREX), which operates extensive programs through its education center and aquarium on the Georgia coast (<u>http://marex.uga.edu/aquarium/</u>). We will continue this arrangement, with MAREX staff organizing and advertising the workshop. We will also distribute the GCE children's book (*As the Tide Comes In*) to teachers are developing activities (tied to State standards) to accompany the book that will be available to visiting groups. The children's book and accompanying lessons will also be distributed through the Glynn County 4H, the Savannah State Univ. K-12 Marine Science Camp, SINERR, and the Oatland Island Wildlife Center.

Undergraduate and Graduate Training. We routinely incorporate undergraduate and graduate students in our research, and expect to maintain an excellent record in this area. To enhance our undergraduate training in GCE-III we are starting a partnership with the NSF-funded Peach State LSAMP program, which is an alliance of 7 institutions in Georgia (led by UGA) designed to increase the number of underrepresented minority students in STEM fields (www.pslsamp.uga.edu/). Peach State LSAMP students participate in learning communities, peer and faculty mentoring, and have the opportunity to present their research at an annual conference (last year's conference had 400 participants). We will identify 1-2 LSAMP Research Scholars each year who will work with GCE scientists either at UGA or at the field site on Sapelo Island and will participate in the annual GCE meeting. To enhance graduate training, the Atlantic coastal LTER sites (PIE, VCR, GCE, FCE) will collaborate to teach a crossdisciplinary graduate course during years 3 and 6 of our proposal cycles. The course will be taught by video-conferencing and offered to students at each of our participating institutions. It will feature readings and lectures from PIs at each site and will incorporate both natural and social science, as well as provide experience in accessing and analyzing LTER data. Our goal is to expose graduate students to the breadth of coastal research, and to provide tools that will allow them to function comfortably in a highly interdisciplinary research environment. The initial meeting of the course will be coordinated by GCE.

<u>Georgia Coastal Research Council (GCRC)</u>. We will continue our partial support of the GCRC, which facilitates science-based management of coastal resources for Georgia and the southeast region (<u>www.gcrc.uga.edu</u>). The GCRC, which is headed by Alber, provides a direct mechanism for sharing the results of GCE research with State managers. It hosts workshops and other meetings, assists management agencies with scientific assessments, and produces materials that summarize coastal research. GCRC current activities synthesizing state-wide water quality and beach monitoring data, and analyzing the relationships among climate signals, freshwater inflow, and fisheries catch.

<u>General Outreach.</u> GCE scientists regularly participate in public forums and provide information about their research to the media. They also provide tours of the research site to visitors to SINERR, UGAMI, and the Sapelo Island Cultural and Revitalization Society. Our broadest reach is through the GCE website, which provides public access to information and data from the GCE program as well as decades of research on Sapelo Island and the Georgia coast (see Data Management section).



showing longitudinal flow in three coastal sounds. GCE-II (both panels) incorporated lateral movement of water, including river discharge (A), tidal flow (B), tidal exchange with the marsh platform (C), precipitation (D), runoff (E), groundwater inflow (F and G), and evapotranspiration (H).



Fig. 3. Carbon transport and mass balance analysis for the South Atlantic Bight. Units are 10^{12} g C y⁻¹. Red question marks indicate uncertainties that will be improved in GCE-III. Modified from Cai 2011.





Fig. 5. Integrated Science for Society and Environment (ISSE) framework for GCE III (modified from Collins et al. 2011).



Fig. 4. Merged Digital Elevation Model (left) and vegetation classification (right) for the Duplin River estuary. DEM is relative to NAVD 88. Star denotes proposed flux tower site (see Fig. 10).

Fig 6. Top: Physiological responses of 6 species to a changing external driver (individual responses). Middle: Accompanying shifts in species composition, with three phases indicated. (A) Shifts within the existing community (community reordering); (B) a tipping point wherein a new dominant species immigrates; (C) full transition to a new habitat or "state". Bottom: The resultant effect of changes in physiology and abundance on an ecosystem property (the product of top*middle). "Total" is the sum for all species.



External Driver



Fig. 7. Conceptual model for GCE-III, showing longitudinal (left) and lateral (right) distribution of habitat and water flows across the landscape.

GCE-III Research Portfolio Drivers of c

Drivers of change (Area 1)



Fig. 8. GCE-III Research Portfolio, showing the major program components and initials of the primary PIs involved in each activity. AB: Burd, BS: Silliman, CA: Alexander, CH: Hopkinson, CM: Meile, DD: Di Iorio, JB: Byers, JH: Hollibaugh, JS: Schalles, MA: Alber, MG: Garbey, ML: Leclerc, PM: Medeiros, RC: Castelao, RP: Peterson, RV: Viso, SJ: Joye, SP: Pennings, VT: Thompson, WC: Cai, WS: Sheldon.

Table 1. Monitoring program for GCE-III. Initials of PIs responsible for supervising each aspect of the monitoring program are indicated in parentheses. **LTER core areas** are 1: primary production, 2: populations, 3:organic matter cycling, 4: inorganic nutrients, 5: disturbance. **GCE PIs:** AB: Burd, BS: Silliman, CA: Alexander, CH: Hopkinson, CM: Meile, DD: Di Iorio, JB: Byers, JH: Hollibaugh, JS: Schalles, MA: Alber, MG: Garbey, ML: Leclerc, PM: Medeiros, RC: Castelao, RP: Peterson, RV: Viso, SJ: Joye, SP: Pennings, VT: Thompson, WC: Cai, WS: Sheldon.

Туре	Location	Frequency	Core Area & Variables Measured			
Area 1 Atmospheric	Area 1 Atmospheric					
Weather stations, with SINERR, USGS (DD)	Sites 4, 6, flux tower	Every 15 min	Abiotic driver of 1-5. > level 2 stations: PAR, temp, rH, precip, wind speed and direction, barometric pressure, total solar and long wave radiation; flux tower also measures CO ₂ , humidity and heat fluxes			
Wet deposition, with SINERR, NADP (MA)	Site 6	Weekly	 Hydrogen (acidity as pH), sulfate, nitrate, ammonium, chloride, base cations (such as calcium, magnesium, potassium, sodium) 			
Area 1 Water						
Altamaha River chemistry (MA, WC)	Head of tide	Monthly	3, 4. Dissolved inorganic nutrients (NO_x , NH_4^+ , HPO_4^{2-} , $H_2SiO_4^{2-}$) and organics (DOC, TDN, DON, TDP, DOP), particulate CN, DIC, alkalinity, pH			
Area 2 Water						
Sound chemistry (MA, WC)	Sites 1-5; 8-11, AL-2	Quarterly	1, 3, 4. Dissolved inorganic nutrients (NO _x , HPO ₄ ²⁻) and organics (DOC, TDN, DON), particulate CN, DIC, alkalinity, pH, Secchi depth, chlorophyll <i>a</i>			
	Sites 6-7	Monthly	1, 3, 4. Dissolved inorganic nutrients (NO ₂ ⁻ , NO ₃ ⁻ , NH ₄ ⁺ , HPO ₄ ²⁻ , H ₂ SiO ₄ ²⁻) and organics (DOC, TDN, DON, TDP, DOP), particulate CN, DIC, alkalinity, pH, Secchi depth, chlorophyll <i>a</i> , total suspended sediment			
Sound hydrography (DD)	Sites 1-4, 6-11	Every 30 min	Abiotic driver of 1-5. Salinity, temperature, pressure at moorings; CTD profiles at all stations in conjunction with sound chemistry; sea level station at GCE4			
Duplin-domain exchange (DD)	Mouth of Duplin R.	Every 15 min	Abiotic driver of 1-5. Continuous horizontal ADCP measurements of water flux			
Area 2 Marshes						
Soil accretion (CC)	Sites 1-11	Annual	3. Sediment accretion, elevation, compaction			
Plant productivity (SP)	Sites 1-11, 2 zones	Annual	1. Stem density, height, flowering status, calculated biomass, in 2 marsh zones			
	Flux tower	Monthly	1. Monthly measurements of biomass in short, med, tall <i>Spartina</i> using Jim Morris's methods (cite)			
Disturbance (SP)	Sites 1-11	Annual	5. Wrack and biotic disturbance in permanent vegetation plots			
Plant composition (SP)	Site 3, 6, 7, 8, Altamaha	Annual	2. Community composition in 4 types of salt marsh, 2 types of low-salinity and 2 types of high marsh vegetation mixtures			
Marsh Invertebrates (SP BS)	Sites 1-11, 2 zones	Annual	2. Density and size of benthic macroinvertebrates in 2 marsh zones			
Recruitment (BS)	Sites 1-11	Quarterly	2. Recruitment of barnacles to standard substrates			
Insects (SP)	Sites 1-6, 9, 10	Annual	2. Density of grasshoppers in salt marsh transects			

Fig. 9. Habitat distribution in McIntosh County, with modified shoreline and potential development indicated. Table shows current value of C storage in the county.



Habitat	ha	mt C ha	\$ ha ⁻¹ y	\$ x 10 ⁶ y	
Fresh marsh	3509	175	257	0.9	
Brackish marsh	2797	122	179	0.5	
Salt marsh	24733	125	183	4.5	
Forested wetland	30602	162	238	7.3	
Upland forest	39040	92	135	5.3	
mt C in aboveground biomass and top 30 cm of soil					
valued at \$21 mt C^{-1} , discounted at a rate of 7%					







Fig. 10. Flux tower site in the Lower Duplin, showing idealized tower footprint (circle) and creek shed. **Left**: elevation (arrow indicates creek head modified by crab activity); **Right**: vegetation classification. SS, SM, and ST are short, medium, and tall height forms of Spartina, respectively. See Fig. 4 for larger-scale view.



Fig. 11. Conceptual model showing the hypothesized effects of increases in fresh water input and sea level on the Spartina marsh at different time scales via a trophic cascade. Predicted changes are indicated as positive (-), negative (-), or variable (Δ) .

Fig. 12. Conceptual model showing the hypothesized effects of increases in sea level or decreases in river inflow on the fresh/brackish marsh over different time scales. Predicted changes are indicated as positive (+), negative (-), or variable (Δ).





Fig. 15. Hypothetical changes in aboveground biomass across the salinity and inundation gradients at GCE (red lines) and PIE (blue lines). GCE lines shown with envelope of variance associated with the mean, with increased variance during habitat transitions (shaded grey). Line segments depict year to year variation at long-term monitoring sites, with long-term means indicated as dots. We predict that biomass will be lower at PIE than GCE, and that responses to salinity will be more negative at PIE than GCE (more negative slopes of line segments versus salinity). Responses at VCR should be intermediate (not shown for clarity). Habitat transition points may also differ among sites (not shown for clarity).



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Site Management

<u>Project Organization</u> - M. Alber has served as Director of the GCE-LTER since early in GCE-II (when she took over from Hollibaugh); S. Pennings has served as co-PI since the outset of the program. Alber and Pennings work together to oversee the project and ensure that the research is on track. She and Pennings also handle routine administrative issues and are in touch on a daily basis. Alber is responsible for communication with NSF and the LTER network, overseeing GCE staff at UGA, and managing the budget. Pennings serves as director of field operations at the UGA Marine Institute on Sapelo Island (UGAMI), which is the base of our field program. Although he holds a faculty position at the University of Houston, Pennings is in residence at UGAMI for most of the summer. Day-to-day GCE operations at the field site are supervised by our lead technician, Jacob Shalack (Research Coordinator, who is in regular contact with Pennings by email and telephone (at least 2-3 times per week).

The GCE is governed by a set of bylaws, which describes the roles and responsibilities of the project, as well as provisions for election and removal of individuals (http://gce-lter.marsci.uga.edu/docs/94). As described in the bylaws, the overall research direction of the project is vested in an Executive Committee (EC), which makes major decisions about project direction. Almost all major funding and research decisions are made by the EC, with the exception of items that are highly sensitive, which are handled in confidence by Alber and Pennings. Both the PI and the members of the EC are elected for 6-year terms that begin a year before the proposal is due. The EC members take the lead in writing the proposal and also take administrative responsibility for specific aspects of the project. The EC currently consists of Alber, Pennings, Burd, Di Iorio, and Craft, and the Information Manager (W Sheldon) (Table 1). EC members are in touch on at least a weekly basis, with meetings approximately every month (non-UGA participants attend by video-conference or travel to UGA when necessary). One goal of administering the GCE through an EC is to develop a pool of scientists who have a good overview of the project, and who could be considered as potential successors if the PI were to step down.

Other GCE scientists are classified as either Project Investigators or Affiliated Investigators, again as defined in our bylaws. The former are scientists with a major commitment to GCE research, are typically funded through the GCE, and are expected to regularly and fully participate in site research, project meetings and decision-making. Affiliated Investigators have an interest in GCE research, many by pursuing independently-funded research at the GCE site, and follow our data reporting protocols, but are not expected to participate in GCE activities at the same level as Project Investigators. Project level postdocs (see post-doc mentoring plan) are sponsored by a specific PI, but their overall progress is also supervised by the EC. They attend project meetings, and interact with various GCE scientists and students in accordance with their research tasks. Finally, GCE graduate students are defined as students working in the domain with a Project Investigator. There is a graduate student liaison (elected by the students), who serves as a bridge between GCE Investigators, GCE students, and the network.

The GCE also has a 6-person Advisory Committee, comprised of scientists from both inside and outside LTER. The Advisory Committee members attend our annual meeting and provide us with an evaluation of project research and administration. Three members of the GCE-II Advisory Committee, George Jackson (Texas A&M), Cathy Pringle (UGA and LUQ LTER), Wim Kimmerer (San Francisco State Univ.), have agreed to stay on to provide continuity for GCE-III, and we are in the process of soliciting three new members with the appropriate expertise to balance the group.

<u>Project Meetings</u> - The entire GCE membership, including post-docs, students and technicians, meets once a year, usually in January. Meetings last 2 days and focus on reviewing research progress and planning future activities. These annual meetings allow us to formally evaluate our progress and have been instrumental in helping us plan research activities, prepare for our mid-term site review, and discuss new ideas. The meeting typically includes a poster session during which we encourage students and post-docs to present their research. We hold a business meeting as part of the annual meeting, during which we discuss project issues such as research registration and permitting, and also elect new GCE scientists (this

can also be done via web-based voting). In addition to the planned activities, the annual meetings provide an opportunity for small groups to work on papers, receive training from our IM, etc. We also invite our partners from state agencies to attend the meeting, as well as potential new collaborators. Subsets of investigators within the project meet monthly or as needed to advance collective field projects or analysis tasks.

To advance cross-site synthesis and collaboration, the four Atlantic Coast wetland sites (PIE, VCR, GCE, FCE) have agreed to meet annually. Meetings will rotate among the sites, and will be held in conjunction with site annual meetings. Visitors will attend the annual meeting of the host site, and then meet on the following day(s) to address topics ripe for cross-site work. Likely initial topics of cross-site synthesis include 1) the drivers of wetland accretion, 2) the role of lateral flux in the carbon budget of coastal wetlands, 3) controls of coastal plant productivity and 4) food web dynamics.

<u>New Scientists</u> - We encourage non-LTER scientists to become affiliated with the GCE site by extolling the twin benefits of working at Sapelo Island and working with the LTER. The UGA Marine Institute is a world-renowned center for marsh research, allowing access to pristine marshes that have a rich history of previous research that provides context for new studies. The LTER program offers the opportunity to coordinate with ongoing and past research at a network of sites, with ready access to datasets through our web site. We expose new scientists to GCE research through seed funding and postdoctoral positions, with the hope that they will generate external funding to continue their work. We work with these scientists to develop new research proposals, and we write letters of support for related proposals. As mentioned above, we also invite them to participate in our annual meeting.

We are adding several new scientists to the GCE project in GCE-III. Byers (UGA) will provide expertise in oyster reef ecology and host-parasite interactions. Castelao (UGA) will play a key role in hydrodynamic modeling. Garbey (UH) will provide expertise in plant community modeling. Hopkinson (UGA) will work with Cai on carbon cycling and ecosystem metabolism. Leclerc (UGA) will provide expertise in micro-meteorology to assist the flux tower work. Medeiros (UGA) will characterize organic matter sources to the estuary. Peterson and Viso (Coastal Carolina U) were funded by ROA supplements during GCE-II to develop a DEM of the Duplin River and identify sources of groundwater; they now join the project as PIs. Schalles (Creighton U) assisted us with remote sensing work during GCE-II; he also now joins the project as a PI. Our goals in involving these new scientists have been to provide necessary new areas of expertise that will allow us to pursue the research directions that we have identified for GCE-III, and to maximize potential collaborations with scientists who are already invested and working within our study domain.

Diversity - To date, the GCE has been successful at including female participants. The GCE is led by a woman, and women represent a third of the PI and AI ranks and almost half of the ranks at the level of graduate students and above. According to the NSF study "Women, Minorities, and Persons with Disabilities in Science and Engineering: 2011" (http://www.nsf.gov/statistics/wmpd/pdf/nsf11309.pdf), women's participation is the lowest in physical sciences and engineering positions, and two of our new PIs for GCE-III are women in the physical sciences (Medeiros, organic chemist; Leclerc, atmospheric physicist). During GCE-II, our ranks were 92% white and 8% Asian; however, two of our new PIs for GCE-III are minorities of Latin America origin (Medeiros and Castelao). We have also developed a plan to increase diversity at the site during GCE-III (http://gce-lter.marsci.uga.edu/docs/473). A key element to implementing this plan is a new partnership with the Peach State Louis Stokes Alliance for Minority Participation program, a collaborative effort between seven colleges and universities in Georgia, led by UGA, to increase minority participation in STEM fields. We will work with Peach State LSAMP to identify 1-2 undergraduate students each year who will be funded to conduct research projects within the laboratories of GCE scientists and given opportunities to present their results at annual GCE meetings. By fostering relationships between students and investigators we will encourage graduates from this program to consider postgraduate studies in science.

Table 1. Executive Committee. Members are elected for renewable 6-year terms, to include the year preceding and the first five years of each NSF proposal, following procedures detailed in GCE bylaws (<u>http://gce-lter.marsci.uga.edu/docs/94</u>).

Personnel	Administrative Responsibilities
Merryl Alber, Lead PI	Represent GCE to NSF and LTER network
	Lead administrator
	Oversee Climate and Human Drivers of Change (Area 1)
	Oversee High Marsh/Upland Border research (Area 3c)
Steven Pennings, Co-PI	Field operations
	Oversee Long-term Patterns Within the Domain (Area 2)
Daniela Di Iorio	Oversee Spartina/Tidal Creeks research (Area 3a)
Christopher Craft	Oversee Freshwater/Brackish Marsh research (Area 3b)
Adrian Burd	Oversee Integration and Forecasting research (Area 4)
Wade Sheldon	Information Management
	Represent GCE IM program to LTER and other networks

Data Management Plan

1. Overview. The GCE has a comprehensive information management program that supports the entire GCE research enterprise as well as project logistics, administration and governance. During GCE-I and -II we developed procedures and technology to facilitate acquisition, standardization, analysis and synthesis of all core GCE data. We developed an integrated information management system (GCE-IMS), based on relational database and dynamic web application technology to manage, archive and distribute data, metadata and other research products. We also established an enterprise-class GIS system for managing geospatial data and developed software to link the GIS to the GCE-IMS to support unified metadata generation for tabular and spatial data. All LTER network standards and protocols are fully supported by the GCE-IMS, and comprehensive EML 2.1 metadata are automatically generated for all data sets and synchronized with the LTER Network Information System (NIS) to support data search and download through the LTER Data Catalog and Data Access Server (DAS). We have also provided software and assistance to other LTER sites and eco-informatics programs, allowing them to leverage GCE technology and approaches to improve network standardization in these areas. During GCE-III we will continue our core data management efforts and expand support for high volume streaming data, routine processing of remote sensing data, and managing model code and output. We will also place more emphasis on documenting our information system and user training to ensure efficiency and continuity of our information management program, as recommended by the NSF mid-term review committee.

2. Data and Information Management System.

IT Resources. We currently operate 4 servers at UGA to support GCE research and operations, including a database server, web server, GIS server and software development server. All systems are equipped with UPS and RAID-5 storage for fault tolerance, and collectively provide 6.5 TB of secure data storage. We also manage multiple workstations, field notebook computers, and a 16-slot LTO-3 tape autoloader for backing up these systems. In addition, we operate two computer clusters at UGA that are leveraged for modeling work. Email and VTC services are provided by UGA and LNO, and each sub-contracting institution provides network connectivity and computer support. Network- and application-layer firewalls, intrusion protection systems and secure transport protocols are used to prevent unauthorized access. We also share some IT resources with the CWT LTER program (administered at UGA), including backup storage and web application hosting, to lower cost, provide redundancy and improve standardization.

In 2011 we established a basic 900 MHz wireless network on Sapelo Island for acquiring data from the newly-installed eddy flux tower and other equipment. The UGA Marine Institute (UGAMI) received an NSF FSML award in 2010 to upgrade telecommunications to the mainland, which will increase Internet bandwidth from <5 mbps to approximately 300 mbps. Once complete, we will connect our wireless network to the UGAMI LAN to provide real-time access to field equipment and data from UGA.

Software, Database and Website Development. Pre-built environmental data management software was not available when our program began in 2000, so we developed the GCE-IMS using general purpose scientific software (e.g. MATLAB, Python), commercial database systems (e.g. Microsoft SQL Server, ESRI ArcSDE) and web application frameworks (Microsoft IIS/ASP, eXist). All custom software code is well documented and managed in a centralized version control repository (SVN), and follows best practices for scientific software (Wilson, 2006). Source code for all MATLAB and Python programs is available under an open source license (<u>http://gce-lter.marsci.uga.edu/public/research/tools/software.htm</u>), and SQL databases and web application code are freely shared with other LTER sites on request.

A major component of the GCE-IMS is the GCE Data Toolbox, a MATLAB software library for metadata-based processing, analysis, quality control and synthesis of ecological data sets (<u>https://gce-svn.marsci.uga.edu/trac/GCE_Toolbox</u>). During GCE-II we extended this software to support advanced, rule-based quality control analysis (Sheldon, 2008), and to import data files from a wide variety of

environmental data loggers to facilitate development of automated data processing workflows. We also added support for harvesting and integrating data from many online databases (e.g. LTER ClimDB, USGS NWIS, NOAA NCDC) to allow creation of synthetic data sets for regional and cross-site analyses.

We developed comprehensive relational databases to manage all project information (Fig. 1). These databases are tightly integrated and support automatic metadata generation and web-based access to GCE research products and related information. During GCE-II we added an enterprise-class GIS system, including ArcGIS license servers at UGA and UGAMI and a centralized ArcSDE geo-database server for managing GPS data and over 200 GB of vector and raster GIS data sets. We also developed a geospatial software library (PyGIS; <u>https://gce-svn.marsci.uga.edu/trac/Python-GIS</u>) for automating GIS data management, as well as databases for managing research project information and tracking field research.



The GCE has a comprehensive public web site (<u>http://gce-lter.marsci.uga.edu</u>) as well as a passwordprotected web site for project participants containing submission forms, proprietary files, provisional data and other project resources. Web applications based on server-side code (e.g. ASP) and REST web services (e.g. AJAX, SQLXML) provide dynamic content from GCE databases and automatic links to information. Visitors can search for data, publications and other research products directly, or discover them based on dynamic cross-links on pages across the GCE web site (e.g. research projects, personnel pages, study site descriptions, Google maps, and species list entries). In addition, we have a public "Data Portal" web site (<u>http://gce-lter.marsci.uga.edu/portal/</u>) to provide access to relevant ancillary data from federal programs and monitoring partners, documented and standardized for comparison with GCE data.

3. Support for Site Science

Integration of IM with the Research Program. Information Management (IM) is integrated into all phases of the GCE research program. The lead Information Manager is a voting member on the GCE Executive Committee and regularly interacts with PIs and students in research planning, data analysis, and publication and proposal development. Specific examples of IM involvement are listed in Table 1.

Research Phase	Information Management Support
Study Design	Provide data, logistical resources (e.g. GPS, tide tables, maps, reg forms)
Data Collection	Provide advice on standards/practices, data harvesting, import filters
Data Analysis	Provide data processing, software tools, statistical reports, re-scaling
Quality Control	Provide guidance, software tools for data validation and QA/QC, reports
Publication	Provide analytical assistance, ancillary data, statistics, maps and aerial photos
Metadata	Provide metadata forms, templates, metadata importing, EML generation
Archival	Provide data and metadata cataloging, document/reprint archive, secured storage systems, offsite replication and backup, LTER NIS synchronization
Reporting	Compile personnel information, publication lists and data usership profiles
Synthesis	Provide ancillary data, software for data search, re-sampling and integration
Governance	Manage email lists, databases for votes and research reg., IM on GCE-Exec

Table 1. Integration of Information Management with the GCE Research Program.

Data Acquisition and Submission. IM staff work proactively with GCE investigators, technicians and students to ensure data are preserved, processed and documented as efficiently as possible. Whenever practical, raw data from instruments, data loggers and transcribed field data sheets are automatically harvested or uploaded to GCE servers. Data that are collected infrequently or are derived from lengthy laboratory analyses are submitted to the IM office at varying intervals, depending on project schedules. Web forms and spreadsheet-based templates are provided for preparation of metadata and web-based data submission forms are provided for uploading files to GCE servers for post-processing and archiving. We are also developing a data and report submission tracking module for the research registration database developed in 2011 in order to ensure that data are submitted in a timely manner. All raw data and supporting files are organized in a data file management system that is backed up to disk daily, mirrored between servers across campus and backed up to LTO-3 tapes that are stored off-site.

Data Processing and Quality Control. Tabular data from instruments and spreadsheets are processed using the GCE Data Toolbox, based on data parsing and quality control workflows designed in collaboration with GCE investigators. Metadata are added from pre-defined templates or imported directly from the GCE metadata database and then augmented with information derived from analyzing the data set itself (e.g. geographic lookups, date/time analysis, numeric ranges and code values). All transformations and data changes are automatically documented, resulting in metadata that describe the complete processing lineage. Finalized data are archived in both MATLAB and standard text formats to provide broad compatibility. Geospatial data are processed using commercial GIS software (e.g. Trimble Geomatics Office, ESRI ArcGIS), then augmented with content from the GCE metadata database and registered in the GCE ArcSDE geo-database server. Both tabular and GIS data set files are then distributed through the GCE Data Catalog (<u>http://gce-lter.marsci.uga.edu/public/app/data_search.asp</u>), and EML metadata are automatically generated and harvested to provide access through the LTER NIS.

Data Archiving. During GCE-I and -II we focused on archiving and distributing primary data collected with GCE funding, including monitoring program and directed study data, but encouraged submission of other data as well (e.g. student project data, non-LTER-funded data). In the absence of LTER standards for database organization, we archived study data as submitted by the contributor (e.g. discrete annual surveys, quarterly cruises) and continuous monitoring data as annual data sets (e.g. sondes, climate stations). We then developed and shared metadata-based software (see above) to integrate and re-sample

GCE data dynamically to produce long-term data sets for analysis and interpretation. However, based on emerging consensus in LTER and NSF, in GCE-III we will focus on archiving a broader cross-section of data, and we will archive integrated, long-term data sets in addition to discrete primary data sets to simplify use of GCE data for broad-scale synthetic science (see section 5).

Data Distribution. Data summaries and metadata are publicly available as soon as data sets are added to the data catalog. The accompanying data files are available to GCE participants immediately, then released to the public within 2 years in compliance with LTER and NSF data access policies. Data sets are versioned to indicate changes since initial release and change notification emails are sent to users on request. Data files are provided in multiple text and MATLAB formats optimized for various end-user applications, and are automatically streamed through the LTER DAS via links in EML metadata to support data distribution through the LTER Data Catalog and data access in EML-based software tools, including Kepler. As of February 2012 there are 480 online data sets in the GCE data catalog (and NIS), and 455 in the GCE data portal, representing over 6 million data records which are accessed by a diverse user community (see Appendix: Online GCE-LTER Data Sets).

4. Support for LTER Network Science and Standards.

GCE has actively contributed to standardization and CI development in LTER in terms of both site-level data management and the NIS. We fully support the EML 2.1 metadata standard and have developed applications to generate and harvest EML for all data sets in our catalog dynamically. GCE was the first LTER site to support EML 2, and our rapid implementation facilitated adoption of this standard and aided in development of EML-based applications by LNO, NCEAS and SEEK. Our EML implementation is among the most comprehensive in LTER, supporting metadata-mediated data access and integration using Kepler and the NIS PASTA framework. We also helped define and prototye standards for harvesting EML for the KNB Metacat repository and protocols for streaming data through the LTER DAS.

The GCE-IMS natively supports all LTER NIS modules (e.g. Personnel, SiteDB, Biblography, ClimDB), and we have implemented automatic harvesting and synchronization wherever supported by LNO. We have contributed all available data from 7 long-term climate stations and 5 streamflow stations to ClimDB/HydroDB. Additionally, we used the GCE Data Toolbox to develop a data harvesting service for HydroDB that automatically contributes streamflow data from USGS stations near 13 LTER sites and 2 USFS sites (<u>http://gce-lter.marsci.uga.edu/public/im/tools/usgs_harvester.htm</u>). We also implemented the LTER controlled keyword vocabulary in our EML metadata to improve discovery of GCE data sets.

W. Sheldon has co-chaired the NIS Advisory Committee and served on Tiger Teams to help guide development of the LTER NIS. We have collaborated with other LTER Information Managers to develop an EML-based project management database (ProjectDB), mapping tools linked to site information (LTERMapS), and a new personnel database schema and web services (PersonnelDB). We have also implemented these technologies in the GCE-IMS. To futher increase IM standardization across the network we have helped CWT, SBC and MCR adopt or adapt GCE-IMS components (e.g. Metabase, Bibliography, ProjectDB) for their use, and have facilitated use of the GCE Data Toolbox at 7 other LTER sites. We will host a workshop in 2012 to provide training to encourage further adoption.

5. Proposed Changes for GCE-III

Add Support for New Research Initiatives. We will need to adapt or develop procedures to support several new research activities in GCE-III. Managing high volumes of streaming flux tower data and assisting researchers with complex quality control analyses will be a significant challenge and will require evaluation and adoption of new approaches and technology (e.g. Ameriflux protocols, DataTurbine). Routine processing of remote sensing data will require IM staff training on suitable software (e.g. ENVI, ERDAS) and ongoing collaboration with investigators to implement algorithms and workflows. Support for modeling will require new protocols for archiving model code, along with test data and model output. We will develop procedures to support these activities in coordination with each research team.

Increase Emphasis on Documentation and Training. Software code documentation and version control are not sufficient to ensure long-term operation of the GCE-IMS through technology migrations and staff turn-over. We have begun using database analysis tools (e.g. DBScribe) to document the structure and dependencies of GCE database systems, and will develop user guides and complete API specifications for all GCE web applications. We will also develop a web-accessible knowledgebase and tutorials on data and metadata submission, and conduct training sessions in conjunction with annual project meetings.

Establish Team-based Approach to Data Quality Control and Synthesis. We have collected over a decade of monitoring data and acquired over a century of ancillary environmental data, and synthesizing these data is a high priority. However, many long-term data sets contain qualified values and time gaps or require re-scaling (temporally or spatially) prior to use. The approaches used for gap-filling and re-scaling data can profoundly affect outcomes of analyses, though, so we will create a *Data Quality Control and Synthesis* working group (led by A. Burd and W. Sheldon) to establish procedures to address these issues and to identify standard derived data products that will best support research activities. IM staff will then implement workflows to routinely produce derived data sets as new primary data are acquired. The group will be task-focused, and will recruit members as necessary.

Implement a Laboratory Sample Analysis Database. Generating metadata and archiving data from laboratory measurements (e.g. water quality analyses) is complicated by the large number of people and steps involved and the discontinuous nature of laboratory work. This can create delays getting laboratory data online and available through the LTER NIS. We used funds from a 2010 NSF supplement to begin designing a web-accessible database for managing data and metadata from analytical lab studies, and we will complete this work in GCE-III. This database will be integrated with the GCE IMS to support data distribution and EML generation. This database will also support dynamic integration of analytical data with environmental observations from moorings, weather stations and CTD profiles to aid interpretation.

6. Milestones and Deliverables

Routine work. 1) Add datasets and metadata from all GCE research (i.e. monitoring, long-term field studies and short-term investigator projects). *Deliverables*: annual increases in EML-described data sets available through the LTER NIS, within standard data release time frames. 2) Collect GPS data for all field studies. *Deliverables*: include location information in all GCE data sets. 3) Implement report and data submission tracking for all research projects. *Deliverables*: automated research tracking, including prompting for annual reports and data sets, implemented by year 2.

Proposed changes. 1) Support for new research initiatives. *Deliverables*: documented procedures and data products from the flux tower by year 3, documented workflows and data from remote sensing by year 3, centralized management of model code and archiving of supporting data and calibration results by year 4. 2) Documentation and training. *Deliverables*: Web application API documentation and user guides for existing applications posted on web by year 2, training sessions conducted in association with every annual meeting. 3) Team-based Q/C and data synthesis. *Deliverables*: establish working group in year 1, develop and document new workflows and long-term synthetic data sets starting in year 1, add synthetic data sets and metadata to data catalog and LTER NIS as produced. 4) Laboratory sample database. *Deliverables*: prototype available for testing by year 2, implement database for cruises and other large sampling efforts in year 3. Post design documents and schemas on the web and provide database and application code to other LTER sites in year 2.

7. Literature Cited

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