

GCE Annual Report Research Findings

September 2012

Context

The central paradigm of GCE-II is that variability in estuarine ecosystem processes is mediated primarily by the mixture of fresh and salt water flows across the coastal landscape. The program is focused on 5 main, inter-related questions:

- Q1: What are the long-term patterns of environmental forcing to the coastal zone?
- 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?
- Q3: What are the underlying mechanisms by which the freshwater-saltwater gradient drives ecosystem change along the longitudinal axis of an estuary?
- Q4: What are the underlying mechanisms by which proximity of marshes to upland habitat drives ecosystem change along lateral gradients in the intertidal zone?
- Q5: What is the relative importance of larval transport versus the conditions of the adult environment in determining community and genetic structure across both the longitudinal and lateral gradients of the estuarine landscape?

Q1: What are the long-term patterns of environmental forcing to the coastal zone?

Coastal ecosystems are influenced by the characteristics of the upstream watershed (e.g., land use, slope), by those of the atmosphere (e.g., temperature, precipitation), and by those of the ocean (e.g., wave climate, sea level). The GCE LTER program collects data on local climate (temperature, precipitation, wind speed and direction) and on the water chemistry of the tributaries that discharge into the Altamaha River. We also obtain data from other organizations (NWS, USGS, NOAA, and other sources) on river discharge, watershed characteristics, human population demographics, sea level, oceanographic conditions, and climate.

Upstream forcing

The USGS gauge at Doctortown (Station 02226000) provides near-real-time data on discharge into the Altamaha River estuary. We use data harvesting technology developed by GCE to automatically download and process data from USGS so that it is documented and standardized to compatible units and date formats for comparison with other GCE monitoring data, providing GCE investigators with high quality standardized data in various file formats to support synthetic research projects. We are currently in the midst of a multi-year drought, and this past year has seen the lowest flows over the period of record (Figure 1). This has implications for many of our observations, as the discharge is an important driver of salinity in the domain.

S. Joye (UGA) continues to work with J. Sandow (Aquatic Research South) to monitor nutrients in the river water entering the GCE domain via the Altamaha River and its tributaries. The Joye lab (under the guidance of K. Hunter, UGA) analyzes samples to determine concentrations of dissolved inorganic nutrients (DIN, DIP, and DSi species) and dissolved organic nutrients (DOC, DON, and DOP). This past year, the lab processed 57 river samples (about 5 samples per month).

K. Takagi (UGA postdoc, Joye) has been hired to start in October and will be charged with synthesizing 12 y of data on temporal variations in concentrations and estimates of nutrient and dissolved organic matter loading rates to the estuary.

The GCE program is also involved in several efforts to evaluate human use of the landscape. This past year, D. Addes (UGA, Alber) began a project called “Listening for Learning” in which she is interviewing residents of McIntosh County, GA (where the GCE is located) regarding the land use changes they have seen over time. J.P. Schmidt (UGA postdoc, Alber) is studying the cost of community

services in McIntosh County in combination with an analysis of the value of ecosystem services as complementary tools to evaluate growth strategies for the county. Finally, as part of the Maps and Locals cross-site initiative, GCE data were used by a Ph.D. student and an M.A. student at Clark University to illustrate their GIS and mathematical models and to examine the statistical principles that one should consider when characterizing land change. This work was presented at the annual Association of American Geographers conference.

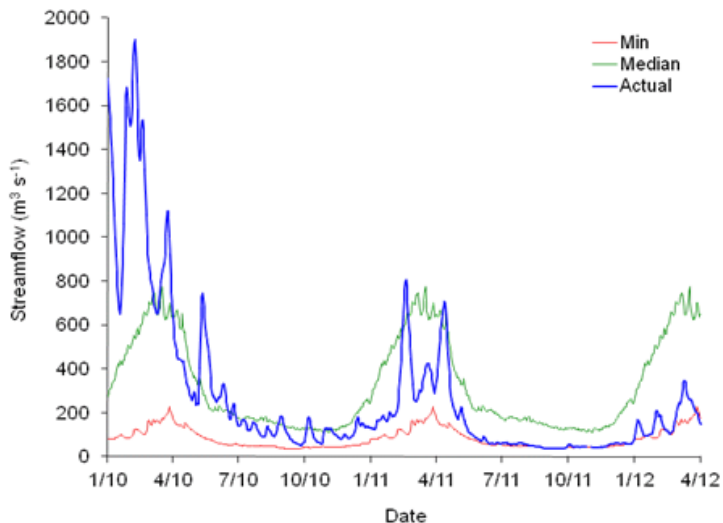


Figure 1. Streamflow in the Altamaha River measured at the USGS gauge at Doctortown. Minimum and median lines depict the annual cycle calculated over the period of record; actual shows discharge beginning in January 2010.

Atmospheric forcing

Meteorological stations, operated and maintained by various institutions affiliated with the GCE program, are used to characterize the weather and climate within the GCE domain. The station at Marsh Landing, which is operated in collaboration with SINERR, serves as our primary LTER meteorological station for inter-comparison studies and [ClimDB](#). The station at Hudson Creek in Meridian is operated in cooperation with the USGS NWIS. Both near-real-time and historic data and plots from these and other relevant climate stations are publicly accessible on the GCE Data Portal website (<http://gce-lter.marsci.uga.edu/portal/monitoring.htm>).

J. Sheldon (UGA) and A. Burd (UGA) have completed their analysis of the climate signals affecting watershed precipitation and Altamaha River discharge. A manuscript has been submitted to *Estuaries and Coasts*. The Bermuda High Index was correlated with the June-January dominant mode of precipitation and discharge, whereas the Southern Oscillation Index was correlated with the second mode of precipitation and discharge during January-April and weakly correlated with the dominant mode during November-December. The Bermuda High Index was also strongly correlated with the occurrence of tropical storms in the region.

Oceanographic forcing

We obtain real-time monitoring data on oceanographic conditions from the National Data Buoy Center's station at Gray's Reef ([Station 41008](#)) in the Gray's Reef National Marine Sanctuary, approximately 39 km from the University of Georgia Marine Institute. We also obtain sea level

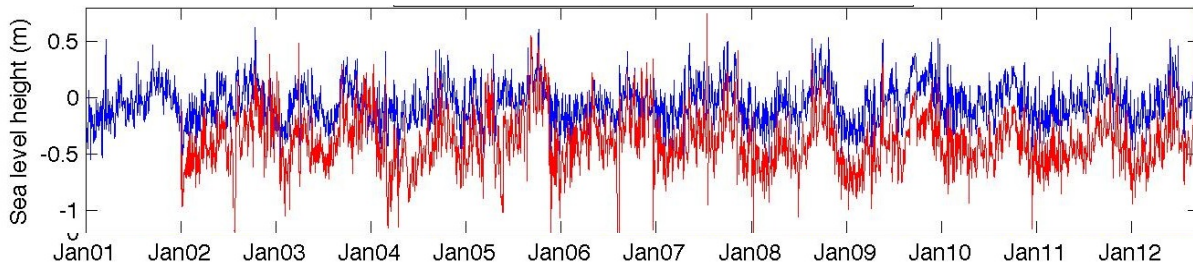


Figure 2. Sea level height measured at Fort Pulaski (blue line) and Hudson Creek (red line).

data from the NOAA/NOS Center for Operational Oceanographic Products and Services web site (<http://tidesandcurrents.noaa.gov/>) for station ID 8670870 (Fort Pulaski, GA). Data are extracted from the CO-OPS web pages, standardized, and documented using GCE metadata templates.

An analysis of sea level height variability over the past 10 y (Figure 2) shows a consistent seasonal change of 0.5 m rise and fall associated with the seasonal change in the prevailing winds. Both Fort Pulaski, GA and our USGS station at Hudson Creek, Meridian give consistent results confirming the large scale oceanographic forcing from continental shelf winds.

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?

Variability in external forcing is manifest as environmental gradients (e.g., in salinity or nutrients) within the coastal landscape. We collect data on physical oceanographic conditions and nutrients in the water column, and on intertidal marsh soil, plant, animal, and microbial dynamics. Although data are collected throughout the domain, we focus primarily on conditions in the Duplin River, which is at the heart of our system. The variables of interest to us span all five of the LTER core research areas.

Water column

Moorings

Long-term measurements of conductivity, temperature, and sub-surface pressure are collected every 30 minutes at 8 moorings distributed across the GCE domain (see http://gce-lter.marsci.uga.edu/public/research/mon/sounds_creeks.htm). MicroCAT sondes are cleaned and inspected biweekly to minimize data loss due to fouling, and logged data are manually downloaded on a bimonthly to quarterly basis by GCE field technicians (J. Shalack, UGAMI). Data are processed by W. Sheldon (UGA) and D. Di Iorio (UGA).

An analysis of sonde data shows the effect of the drought on salinities within the domain, with increases in the monthly average salinities at all sites during the current drought compared to a non-drought period (Figure 3). This is most striking at the stations along the Altamaha River, where monthly average salinities are approximately 8 at GCE8 and 20 at GCE9 during the drought. Although the increase at GCE7 was not as dramatic (from 0.1 to 0.5), this is a significant change because the organisms that are adapted to freshwater are highly susceptible to increases in salinity. Salinities at GCE1 also increased considerably, to 25.

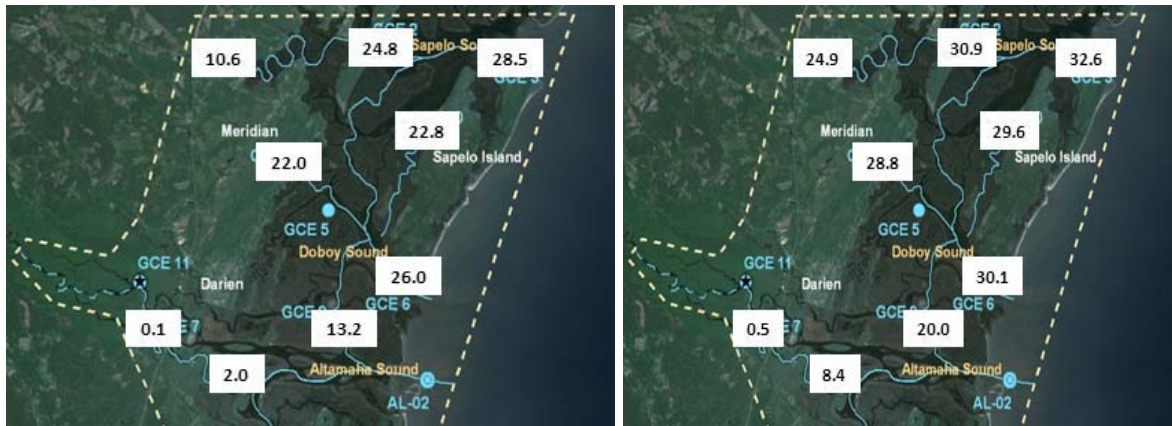


Figure 3. Monthly average salinities at GCE monitoring sites during non-drought (left; Oct 2002-Feb 2006) and drought (right; Mar 2010 – Jun 2012) conditions.

Water column nutrients

We run regular cruises to measure the surface water concentrations of dissolved and particulate materials at core stations located across the GCE domain. Samples from the monitoring cruises are collected by the GCE field crew and analyzed by the Joye lab (Joye, Hunter). Over the past year, we processed 460 samples for determination of concentrations of dissolved inorganic nutrients (NO_3^- , HPO_4^{2-} , and $\text{H}_2\text{SiO}_4^{2-}$) and dissolved organics (DOC, TDN, DON, TDP, and DOP); 1296 chlorophyll *a* samples; and 1296 samples for total suspended sediment and particulate CN. Fewer ammonium samples were processed (324) due to contamination problems in the field lab, which we are trying to address. Analyses are complete through July 2012. Takagi will be working on describing the GCE sound water quality data.

This past year, W.J. Cai (UGA) wrote a review paper for Annual Review of Marine Sciences (Cai 2011) in which he synthesized DIC measurements from GCE cruises and other data on C flow to construct a carbon budget for the South Atlantic Bight. He suggested that the marsh is a sink for atmospheric CO_2 and that it laterally exports large quantities of inorganic and organic carbon that support net heterotrophy and CO_2 degassing in first the estuaries and then the inner shelf. He also suggested that most of the OC from the Altamaha River is 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. These observations will be followed up in GCE-III.

Marshes

Soil processes

C. Craft (IU) measured soil accretion, C sequestration and nutrient accumulation in tidal freshwater forests (tidal forests) along the Altamaha River in the GCE domain, as well as in three other systems in the region: the Ogeechee, Satilla and South Newport rivers. These understudied wetlands are less common than tidal marshes, but they are ecologically sensitive to the effects of saltwater intrusion. The South Newport River is the only one of these systems that has experienced saltwater intrusion; tidal forests in the other three systems are considered healthy. The three healthy tidal forest soils sequestered C ($49\text{-}82 \text{ g m}^{-2} \text{ y}^{-1}$), accumulated N ($3.2\text{-}5.3 \text{ g m}^{-2} \text{ y}^{-1}$) and P ($0.29\text{-}0.56 \text{ g m}^{-2} \text{ y}^{-1}$) and trapped mineral sediment ($340\text{-}650 \text{ g m}^{-2} \text{ y}^{-1}$). There were no differences between these rates and those measured in the South Newport River.

Soil accretion determined using ^{137}C and ^{210}Pb averaged 1.3 mm y^{-1} and 2.2 mm y^{-1} , respectively (Figure 4, top). These values are substantially lower than the recent rate of sea level rise (SLR) along the Georgia coast (3.0 mm y^{-1}) and suggest that the tidal forests are not keeping up with SLR. In contrast, soil accretion in oligohaline and brackish marshes exceeds the current rate of SLR (Figure 4, bottom). This means that accelerated SLR is likely to lead to a conversion of tidal forest to marshes, which will result in an increase in the delivery of some ecosystem services such as C sequestration and sediment trapping at the expense of others such as denitrification and migratory songbird habitat. Unless tidal forests can migrate upriver, which is unlikely in most areas because of topographic constraints and increasing urbanization of the coastal zone, tidal forests and their delivery of ecosystem services face a tenuous future. These findings will be published in *Global Change Biology* later this year.

Plant dynamics

S. Pennings (UH) and his lab monitor plant biomass with the goal of testing the hypothesis that end-of-year biomass varies as a function of freshwater discharge from the Altamaha River (especially in low-marsh plots), local rainfall (especially in high-marsh plots), and average sea level. End-of-year biomass of *Spartina alterniflora* in creekbank plots varied more than two-fold over the past 11 years, with peaks in 2003 and 2005 (Figure 5, top). End-of-year biomass in the mid-marsh plots showed slightly less variation and did not vary in complete synchrony with biomass in the creekbank plots (in particular, there was no biomass peak in 2003, Figure 5, top).

Data were analyzed with multiple regression, examining several potential drivers (Altamaha River discharge, sea level, local precipitation, local temperature) and critical periods for these drivers, and with multi-level modeling. For creekbank sites, end-of-year biomass was best predicted by Altamaha River discharge, but there was no evidence for a narrow critical period for discharge. At most sites, creekbank biomass increased with discharge, presumably because high discharge led to lower salinities, reducing osmotic stress on plants. This pattern was reversed at GCE8, where *S. alterniflora* was replaced by *S. cynosuroides* during wet years when salinities were low (Figure 5, bottom). This suggests that creekbank vegetation initially responds to a

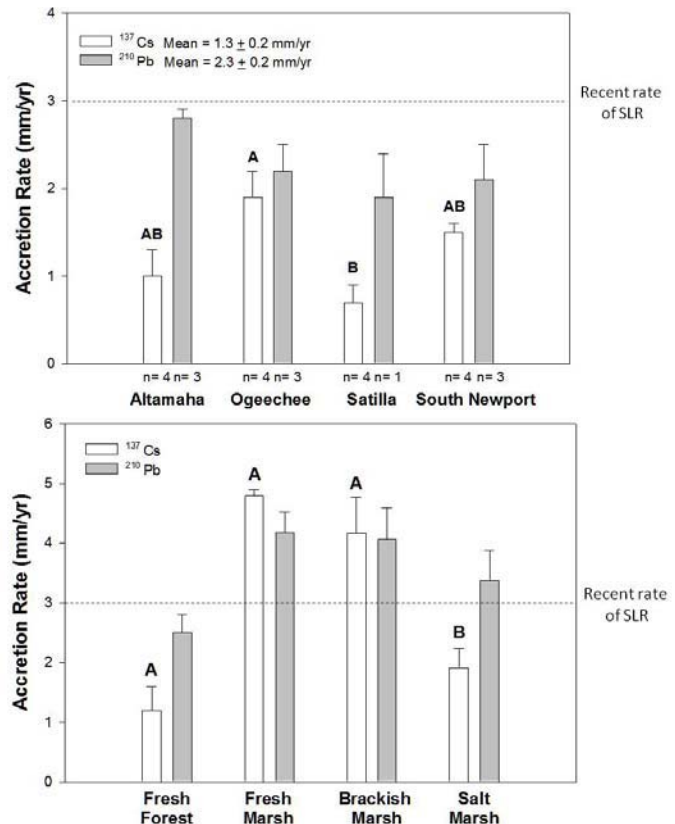


Figure 4. (top) Mean rates of ^{137}Cs and ^{210}Pb accretion of tidal forests on the Altamaha, Ogeechee, Satilla, and South Newport rivers. Means with the same letter are not significantly different ($p \leq 0.05$) according to the Ryan-Einot-Gabriel-Welsch Multiple Range test. (bottom) Mean ^{137}Cs and ^{210}Pb soil accretion of tidal forest and marshes along the Ogeechee, Altamaha, and Satilla rivers. The ^{137}Cs marsh data are from Loomis and Craft (2010). The ^{210}Pb marsh data are from Craft (unpublished). Means with the same letter are not significantly different ($p \leq 0.05$) according to the Ryan-Einot-Gabriel-Welsch Multiple Range Test.

decrease in salinity through physiological mechanisms, but when a threshold of salinity is crossed (12 or less), it responds through a change to a new dominant species.

For mid-marsh sites, there was no single unambiguous driver. At some sites, mid-marsh production correlated positively with Altamaha River discharge, whereas at other sites it correlated positively with average sea level. We are currently working on a manuscript based on these results. In addition, we obtained postdoctoral funding from the LNO to allow K. Wieski (UH postdoc) to expand these analyses to several other sites along the U.S. east coast.

Pennings also continues his ongoing monitoring of mid-summer plant composition at permanent plots located on 3 types of vegetation borders (*S. alterniflora*-*Juncus roemerianus*, *S. alterniflora*-meadow, meadow-*J. roemerianus*), to test the hypothesis that high marsh plant species composition is driven by variation in rainfall. Vegetation composition in these plots is dynamic and does appear to be related to variation in rainfall. A manuscript with preliminary analyses of these results is in preparation. In addition, Pennings is examining these data in more detail as part of an LTER working group looking at plant community stability.

Pennings and H. Guo (UH postdoc) are following secondary succession in 3 x 3 m cleared plots at all the GCE sites. Initial results indicate that succession is rapid in sites dominated by *S. alterniflora*, with plots recovering within 1-3 y, and very slow at sites dominated by *J. roemerianus*, with no signs of any succession after 3 years. At sites dominated by *Zizaniopsis miliacea*, the cleared plots were rapidly recolonized by pioneer species, but colonization by *Z. miliacea* has been slow. Together, these results indicate that succession is slower in less-stressful habitats, which is opposite to expectations. We are continuing to monitor these plots, and expect that it may take over a decade for the complete successional dynamics to play out.

This past year, M. Alber (UGA) continued a wrack disturbance study with support from GA DNR. We established experimental plots in different plant zones that were covered with wrack for varying amounts of time (from 2 weeks to 1 year). For plots where treatments began in spring 2011, wrack was removed a year later, in April 2012; for plots initiated in fall 2011, wrack is due to be removed in October 2012. This experiment was designed to allow us to determine how long it takes for wrack to affect marsh plants, whether the low marsh and high marsh respond differently, and how long it takes for affected areas to recover.

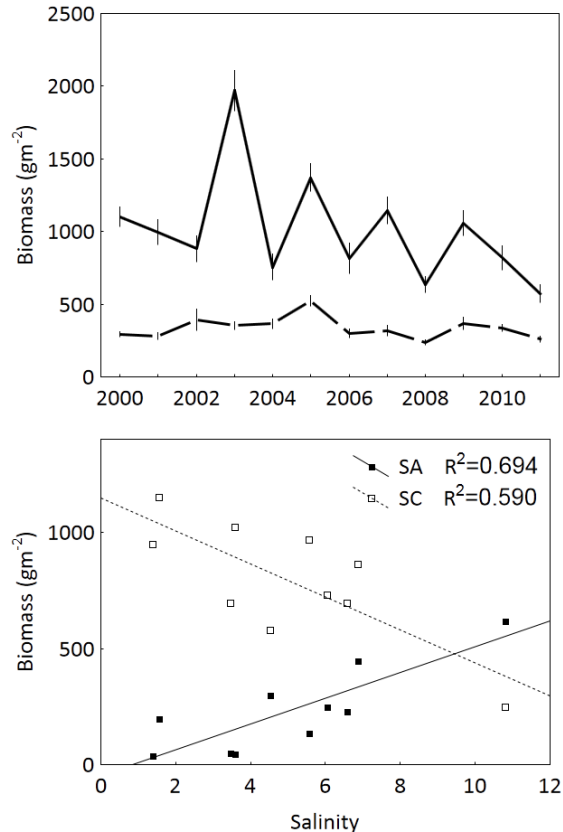


Figure 5. (top) *Spartina alterniflora* biomass in the GCE domain in years 2000-2011 (upper line: creekbank, lower line: midmarsh). Data averaged over all sites. (bottom) *Spartina alterniflora* biomass at the brackish site GCE8 increases with salinity whereas that of *S. cynosuroides* decreases. (Data from 2002-2011.)

Additional plant studies

C. McFarlin (UGA Ph.D. student, Alber) completed her dissertation on the response of *S. alterniflora* to disturbances. She evaluated two potential indicators of stress (the ratio of dimethylsulfoxide to dimethylsulfoniopropionate (DMSO:DMSP) and foliar metals) in *S. alterniflora* collected from areas affected by 4 different disturbances (sudden marsh dieback, horse grazing, increased snail densities, wrack deposition) across 20 marshes in GA. She found significantly higher DMSO:DMSP in leaves and stems collected from affected areas than in those from healthy areas at all four disturbance types. Foliar metal concentrations also differed between affected and healthy areas. Chlorophyll *a* concentrations were not significantly different between affected and healthy areas and did not correlate with either of the indicators. These results suggest that DMSO:DMSP and the foliar metal suite are sensitive indicators of sublethal stress in *Spartina*, capable of identifying stress before there are visible signs such as chlorophyll loss. A manuscript on this research has been submitted to *Marine Ecological Progress Series*.

Pennings is collaborating on a large-scale project to develop a synthetic understanding of plant zonation patterns in Georgia tidal marshes, evaluating 1) spatial associations between different plant species and abiotic conditions, 2) the results of experiments transplanting plants into new habitats and removing neighbors, 3) the results of experiments altering abiotic conditions, 4) variation among 55 sites in vegetation zonation patterns, and 5) temporal variation in plant community composition. This work is being written up for *Ecological Monographs*, with a submission planned during the 2012-2013 academic year.

Animal dynamics

Marine invertebrate population monitoring is conducted at the ten GCE monitoring sites each October in conjunction with vegetation sampling. Animal sampling areas are located several meters away from each permanent vegetation plot and are sampled for epifauna and macroinfauna.

We are also conducting additional studies of animal dynamics. McFarlin studied the effects of the loss of *S. alterniflora* on the benthic invertebrate communities in Georgia and Louisiana. In GA, abundances of all invertebrate groups (epifauna, macroinfauna, meiofauna) were significantly lower in bare areas than in reference areas, as was taxon richness and diversity of macroinfauna. In LA, abundances of periwinkle snails were significantly lower in bare areas, but meiofauna densities were significantly higher in bare areas. There were no trends in the abundances of macroinfauna and infaunal crabs or in infaunal taxon richness and diversity. These results, which are being written up for publication, suggest that the idea of foundation species may not be “one size fits all” for salt marsh ecosystems across their geographical range.

J. Jimenez (UH Ph.D. student, Pennings) investigated top-down and bottom-up control of arthropod food webs. He found that both bottom-up (salinity and nutrients) and top-down (an omnivorous katydid and a planthopper herbivore) factors strongly affected the *S. alterniflora* food web. These results suggest that the trophic effects of omnivores depend on omnivore behavior, dietary constraints, and ability to suppress lower trophic levels, and that omnivorous katydids may play a previously unrecognized role in salt marsh food webs (Jimenez et al. 2012).

B. Silliman (UF), with additional funding from NSF and the Gulf Coast BP oil fund, is investigating the importance of mutualisms in buffering marshes from die off and controlling

coastal insect diversity, and the role of keystone predation and consumer diversity in controlling marsh ecosystem structure and function. Initial results from the food web work suggest that keystone species play an important role in regulating densities of marsh grazers, but consumer diversity is important in maintaining multiple ecosystem functions. Over the next year, we will be conducting experiments to look at large spatial scale variation in the role of marsh consumers by completing cross-LTER site work.

Finally, Pennings, with additional funding from NSF, is working in collaboration with D. FitzGerald at Boston University to investigate potential positive feedbacks between biotic and geomorphic processes in rapidly eroding salt marsh creeks. Headward-eroding creeks are common in southeastern U.S. salt marshes where they grow into marsh platforms that lack a high density of creeks. This response, which presumably serves to increase the ability of the creek network to accommodate an increasing tidal prism as sea levels rise, appears to be mediated by positive feedbacks between crabs and creeks. In particular, the herbivorous crab *Sesarma* reaches extremely high densities at the heads of these creeks, where it consumes *Spartina* grasses, creating unvegetated patches, and creates extensive burrow networks, potentially increasing erosion. We are conducting experiments to test the hypotheses that 1) crabs are attracted to areas of high water flow, and 2) the presence of *Sesarma* crabs increases creek growth.

Microbes

Current microbial work in GCE-II is focused on understanding the dynamics of ammonia-oxidizing organisms, primarily through our collaboration with J.T. Hollibaugh (UGA). Beginning in March 2011, Hollibaugh and B. Tolar (UGA Ph.D. student, Hollibaugh) collected DNA and nutrient samples weekly in the Duplin River and used quantitative PCR to determine the abundance of the functional *amoA* genes for ammonia oxidizing archaea (AOA), which are more abundant than their bacterial counterparts. The abundance of archaeal *amoA* increased dramatically in mid-summer. This increase was not reflected in bacterial *amoA* nor in the abundance of nitrite-oxidizing bacteria, resulting in uncoupling of ammonia oxidation from nitrite oxidation and a substantial (5-10 uM), transient spike in nitrite concentrations. Increased *amoA* abundances were weakly correlated with temperature, salinity, pH and oxygen. This study continues ongoing work on this topic by Hollibaugh and collaborator J. Caffrey (UWF) funded by the Chemical Oceanography program of NSF.

Duplin River estuary

The Duplin River estuary represents a core focus of our efforts to produce an integrated understanding of both water and marsh processes in estuaries. We are working to develop a detailed spatial understanding of the system that will allow us to address the interactions between the estuarine water and the extensive intertidal areas that surround it.

Hydrological studies

In 2011, ROA funding was used to support a continuing collaboration with R. Viso and R. Peterson (Coastal Carolina University (CCU)) to collect bathymetric data for the Duplin River. Observations were collected with CCU's EM3002 dual head shallow water multibeam sonar and RTK positioning system, which provides high quality bathymetric and backscatter intensity data. Data were collected and reduced by undergraduate and graduate research assistants at CCU and submitted to the GCE database. These observations allowed us to identify areas with bathymetric

scours as potential sources of groundwater. The team then used electrical resistivity to further evaluate one of these areas (Figure 6, left). As expected, they saw a low resistivity (higher salinity) lens develop in shallow marsh sediment layers as the tide rises, which subsequently dissipated throughout the ebb tide. A few meters deeper, however, where one would expect to see saline water at high tide, a brackish water pocket developed along the upland edge of the river (Figure 6, right). These observations are intriguing, and suggest that there is a tidal asymmetry that would have implications for groundwater pumping.

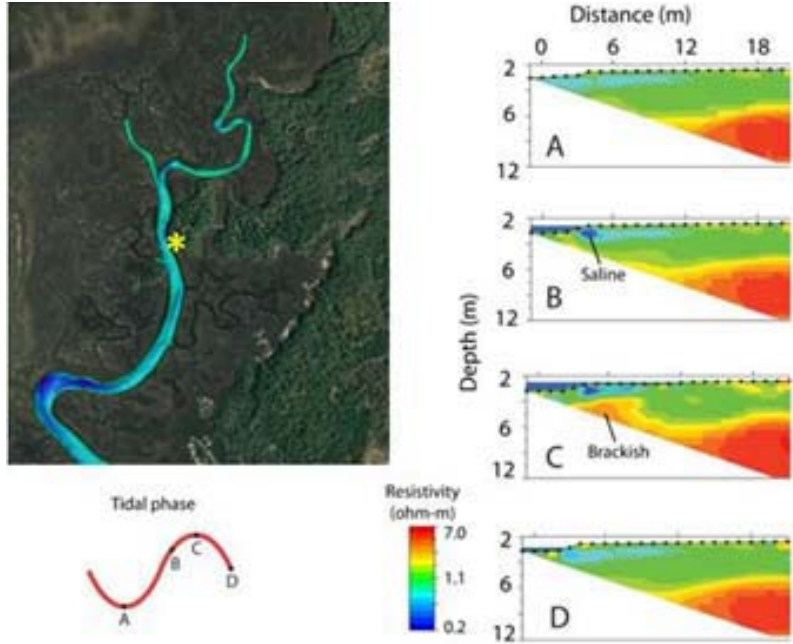


Figure 6. (left) Digital elevation model showing location of electrical transect in the upper reaches of the Duplin River (denoted by asterisk). (right) Panels A-D show electrical structure of shallow river, marsh, and upland sediments throughout a tidal cycle.

In spring 2012, Di Iorio deployed current profilers along with surface and bottom-mounted CTDs in the upper, middle, and lower segments of the Duplin River to better understand water exchange among water masses. The data revealed a change from standing wave characteristics in the lower Duplin to more of a progressive wave characteristic in the upper Duplin (Figure 7). Current profiles show a strongly ebb-dominated system with strong flows approaching 1 m s^{-1} . Tidally averaged residual flows were strongest in the middle segment, suggesting input of groundwater in the region between the upper and middle reaches. This work was done at the same time that detailed groundwater surveys were being performed (see below).

Groundwater

Peterson and Viso used ROA funds to work with three CCU graduate students to follow up on the observations described above regarding potential groundwater input to the Duplin River. In April 2012 they measured radon-222 continuously in surface waters at 3 locations in the river over a period of 4 days. These radon temporal records

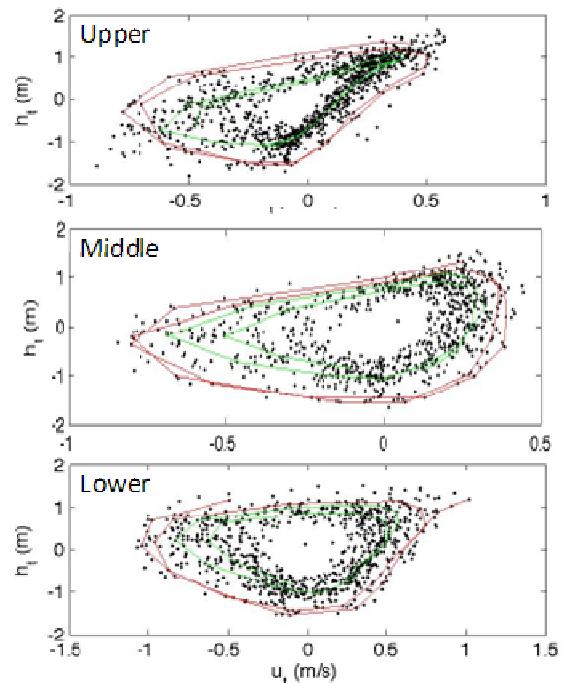


Figure 7. Plots of tidal height (h_t) versus tidal flow (u_t) in the upper, middle, and lower Duplin River measured April 2012. Red lines depict spring tide; green lines depict neap tide. Pure standing waves give a circular distribution whereas pure progressive waves give a linear distribution.

(Figure 8) will be coupled with associated current velocities (described above) to provide an estimate of real-time groundwater input rates into the river and will guide future fieldwork and analytical campaigns.

In August 2012 Peterson also obtained samples for radon measurements from the beachface at Cabretta Beach on Sapelo Island to understand groundwater movement as a function of tides. This was done in conjunction with groundwater nutrient experiments conducted over a 2-week spring/neap tidal cycle by C. Schutte (UGA Ph.D. student, Joye).

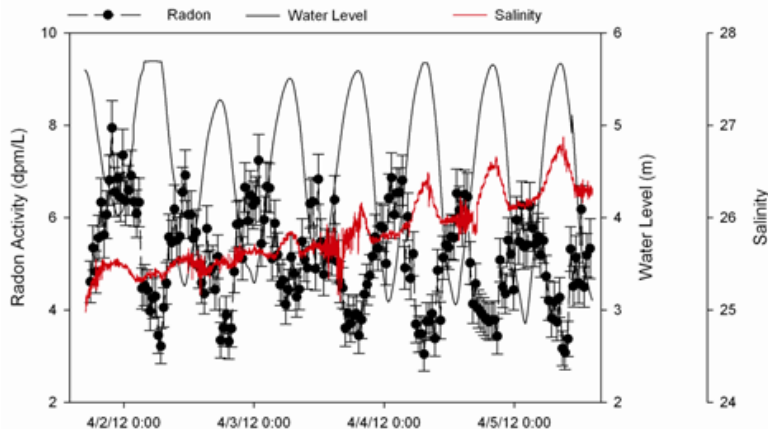


Figure 8. Radon time series measured at Moses Hammock in April 2012. Radon activities were highest at low tide and lowest at high tide (corresponding with salinity).

Water column observations

Schutte worked with C. Meile (UGA) on a synthesis of spatial and temporal patterns in river chemistry in the Duplin River system and to identify the relative influences of water exchange processes (riverine and groundwater flow, precipitation, and tides) and transformation processes that are taking place in the system. They identified four key drivers of spatial and temporal variability in the chemistry of the Duplin River: Altamaha River discharge, local groundwater inputs, exchange with the marsh platform, and processes creating sources and sinks within the Duplin River watershed. A manuscript describing these patterns is in preparation. This work was also presented as a poster at the 2012 ASM.

This past summer, J. Schalles (Creighton) collected a second set of high-resolution, spatially explicit measures of algal chlorophyll in tributary streams of the Duplin River tidal watershed to establish locations of salt marsh microbenthic algae export, groundwater seepage, and the degree of heterotrophic versus tidal stream autotrophic community metabolism. He and his students also collected data on microbenthic algae optical signals on exposed intertidal creekbank muds using an Ocean Optics USB2000 spectroradiometer. This work was undertaken as a demonstration project and was largely supported by leveraged funding to Schalles from the NOAA Environmental Cooperative Science Center and NASA Nebraska Space Grant, and from Creighton intramural funding of research for undergraduate science students.

Remote sensing

C. Hladik (UGA Ph.D. student, Alber) completed her dissertation on the use of remote sensing data to evaluate elevation and plant distributions in the salt marshes surrounding the Duplin River. As part of that work she used decision trees to combine elevation and spectral information to produce both an accurate habitat classification (nine salt marsh habitat classes were mapped with a 90% overall accuracy) and a corrected DEM for the study site (overall mean error was -0.003 ± 0.10 m (SD) and root mean squared error at the 68% confidence level was 0.10 m when validated with ground truth data) (Figure 9). This work has been submitted to *Remote Sensing of Environment*.

Schalles continued work with Hladik and Pennings to synthesize information collected from the June 2006 AISA hyperspectral flyover and ground truth survey, with an emphasis on comparing plant community composition and plant above-ground biomass in Duplin River sub-watersheds. They extended this analysis to soil properties (percent organic matter, percent moisture, and salinity) within the sub-watersheds and to the densities of three major marsh invertebrate populations (*Littoraria*, *Melampus*, and *Geukensia*). New sub-watershed mapping products of these parameters will be included in a manuscript that is now in preparation.

Flux tower

We will be setting up a flux tower that will monitor CO₂, H₂O and heat fluxes between the intertidal marsh and the atmosphere based on eddy covariance methodology. The area selected for the tower is dominated by medium (0.5-1 m) and short (0.05-0.5 m) *S. alterniflora*.

The tower will be 30 ft tall, erected on a 5'x5' platform, with access for monthly servicing and maintenance via a boardwalk. In order to minimize our impact, ThruFlow flooring system decking material

(<http://www.thruflow.com/>) will be used so that light can penetrate to the marsh surface. The boardwalk and platform materials will be purchased using an existing LTER supplemental grant. This past year we submitted permit applications detailing this project to both the Army Corps of Engineers and the Georgia Dept. of Natural Resources. This process is taking longer than expected, but we anticipate obtaining the necessary permits and licenses by October 2012, at which point installation can proceed. We also used leveraged funds from UGA (C. Hopkinson, start-up) to buy a second CO₂/H₂O IRGA and 3D anemometer that will provide fluxes at a second height above the marsh surface. In addition, we purchased extra solar panels, a second CR3000 data logger and a 10-ft extension for our existing 20-ft tower.

Q3: What are the underlying mechanisms by which the freshwater-saltwater gradient drives ecosystem change along the longitudinal axis of an estuary?

The data collected to answer Question 1 (external forcing to the domain) and Question 2 (patterns within the domain) can be used to describe the longitudinal salinity gradient of the estuary over time and space, and to examine how well salinity correlates with observed patterns in ecosystem processes. Sea level rise and the resultant saltwater intrusion, altered precipitation regimes, and increased human demand for freshwater have the potential to alter the freshwater-saltwater gradient along estuaries. To predict how future changes in salinity distributions might

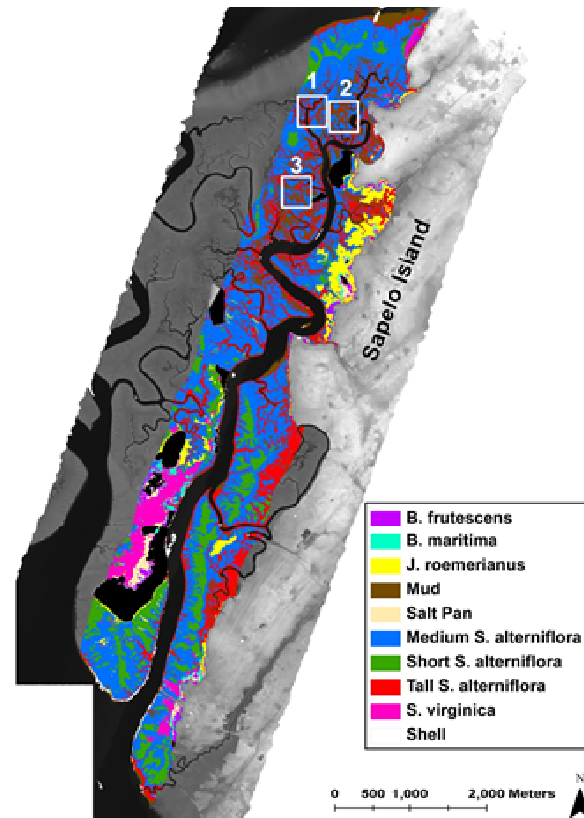


Figure 9. The final maximum likelihood (MLC) hyperspectral classification product (after application of decision tree). Areas 1, 2 and 3 represent locations where application of the decision tree most effectively reassigned medium *S. alterniflora* pixels (blue) to tall *S. alterniflora* (red) and mud (brown).

affect the ecosystem, it is necessary to understand the mechanisms that drive these estuarine responses to changes in salinity. In particular, we are interested in evaluating the effect of saltwater intrusion into tidal freshwater wetlands.

SALTEX

In spring 2012, the GCE field crew (A. Nix, C. Reddy, J. Shalack) worked with E. Herbert (IU Ph.D. student, Craft) on the Seawater Additions Long Term Experiment (SALTex). They established a pilot study in a tidal freshwater marsh of the Altamaha River to assess whether it is possible to increase salinities in the rooting zone (i.e. soil porewater). Replicate (n=3) 2 m x 2 m treatment plots were established and landscape edging was placed around the plot perimeters to retain treatment waters in the plots and limit their movement from one plot to another. Several delivery methods were tested, including surface irrigation, subsurface delivery via wells, and a combination of the two methods. Plots were treated by mixing equal amounts of seawater (salinity 30) with (fresh) Altamaha River water, then applying approximately 40 to 60 gallons to each plot during a falling tide. After several months of testing we concluded that surface irrigation was the best method for water delivery. An advantage of this is that it mimics the way saltwater will be delivered as sea level rises.

As a follow-up, we conducted an intensive 30 day dosing regimen in which we applied the treatments on five consecutive days a week for four weeks. We were able to elevate rooting zone porewaters to salinity 5 within a matter of days and were able to maintain that level during the one month period. The results conclusively demonstrated that we can effectively enrich soil pore waters with low levels of salinity, thereby mimicking the effects of sea level rise and saltwater intrusion. We also learned much along the way that will enable us to properly design and implement the full scale experiment, such as the use of acrylic sheets instead of landscape edging for walls/edges around each plot.

In fall 2012, we will build boardwalks and install acrylic sheet walls for the full scale experiment and in winter 2013 we will plumb the system. The experimental design will consist of five treatments, (1) salinity press, (2) salinity pulse, (3) freshwater additions only (to mimic sea level rise without saltwater intrusion), and two control treatments, (4) one with acrylic walls, and (5) one without. The treatments will be replicated six times and the plots will be 2.5 m x 2.5 m. After construction, we will give the site and plots several months to recover before we begin making baseline measurements.

Additional studies

We have conducted several other projects that address the general issue of variation along the estuary. E. Herbert established a mesocosms experiment at the University of Georgia Marine Institute on Sapelo Island to expand on the field experiment by quantifying biogeochemical interactions between plants and soils under saltwater intrusion and saltwater-induced changes in vegetation. Using a ^{13}C -carbon dioxide stable isotope tracer approach, she investigated the short-term fate of plant fixed-C. Intact soil cores were collected at the field site, and replicate cores were planted with *Z. miliacea* (freshwater), *J. roemerianus* (salt tolerant), or left unplanted. Cores were treated with either saltwater (salinity 5-8 to simulate saltwater intrusion) or freshwater, with simulated tides and pulse-labeled with ^{13}C - CO_2 . The transport of fixed- ^{13}C through plant tissue, microbial communities, soil, dissolved organic matter, and evolved CH_4 and CO_2 was measured.

Craft and Herbert are also collaborating with T. Royer (IU) and L. Johnson (IU) to explore how nutrient limitation of benthic and pelagic metabolism changes along the estuarine salinity gradient in the Altamaha River and have evaluated evidence of differential nutrient limitation in autotrophic and heterotrophic communities. We examined benthic and pelagic metabolic responses to carbon, nitrogen, and phosphorus amendments in a fully factorial experiment using *in situ* bioassays (nutrient diffusing substrata and nutrient amended bottles) along a salinity gradient in the Altamaha River. We believe this will provide practical information for understanding the processes regulating eutrophication and water quality in the Altamaha River. Furthermore, the study will answer important questions regarding the potential for C, N, and P limitation across a salinity gradient and add to the growing body of literature on differential nutrient limitation.

Q4: What are the underlying mechanisms by which proximity of marshes to upland habitat drives ecosystem change along lateral gradients in the intertidal zone?

Our approach to this question takes advantage of marsh hammocks as natural laboratories for evaluating the influences of landscape structure and freshwater input on marsh processes. This portion of the program is directed by Alber and C. Alexander (SkIO), with involvement from co-PIs Pennings, Joye, Burd, Meile, W. Moore (USC), and V. Thompson (OSU).

Hammock SEM

In 2007 we surveyed 55 hammocks representing a range of sizes and origins. This past year Wieski and others completed an analysis in which we used structural equation modeling (SEM) to produce two submodels: a hammock submodel and an intertidal morphology submodel. Both submodels had a very good fit (hammock: $p=0.66$, $C_{min}/dF=0.84$; intertidal: $p=0.759$, $C_{min}/dF=0.717$). SEM revealed a complex set of interdependencies between hammock abiotic factors and subsequent effects on marsh plant communities. In essence, hammock size determined the size of intertidal habitat. Hammock elevation, which was tightly related to hammock size, had a strong influence on hammock hydrology. Intertidal habitat morphology had direct and indirect effects on both local abiotic and biotic characteristics. This work is now being written up for publication.

Intensive hammock research

In 2008 two hammocks were selected for detailed study: HNi1 is west of and adjacent to Blackbeard Island to the north of Sapelo Island, and PCi29 is adjacent to the south end of Sapelo Island. These hammocks are of similar size, with similar vegetation zones in the high marsh. This past year, J. Ledoux (UGA Ph.D. student, Meile) and Meile evaluated data from shallow piezometers along a

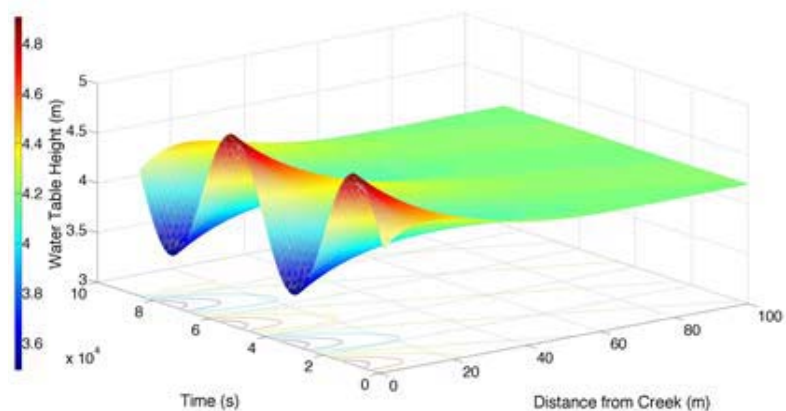


Figure 10. Propagation of a tidal signal through the subsurface. The influence of this pressure signal propagated through the subsurface is likely negligible after 70 meters.

transect running behind Blackbeard Island, GA, across HNi1 and into the adjacent marsh. They also used grain size information from vibracores (collected by Alexander) to estimate sediment permeability. The role of propagating the pressure signal in the subsurface was investigated using a one-dimensional model. Results show that pressure propagation in the subsurface likely has only a minor effect at our well transect 70 m away from the tidal creek (Figure 10). To investigate the role of variations in salinity, measured pressure gradients between adjacent wells were then separated into contributions associated with freshwater head and density changes. Density changes were most predominant near the hammock and can be responsible for approximately 10% of groundwater flow. Next, to delineate the contribution of tidal flushing, the pressure time series were studied using Fourier time series analysis. Preliminary results of this ongoing effort indicate that tidal flushing plays the primary role, with other forcings becoming apparent during periods with smaller tidal excursions. This work was presented as a poster at the LTER ASM.

Plant modeling

Burd and Y. Jung (UGA Ph.D. student, Burd) have been examining models of *S. alterniflora* production and growth with the intent of developing a baseline model that can account for time-dependent changes in *Spartina* biomass under different environmental conditions. To date, we have assembled a consistent database (using data from the GCE database) of above-ground biomass that can be used to compare with model results and associated environmental forcing parameters that can be used to drive the models. We are concentrating on

the model developed by Morris et al. (1984) because of ease of parameterization. We have now coded the model using Matlab and are developing alternative parameter values that improve agreement with observations. When initialized with data from site GCE2 and run for 6 years using appropriate environmental forcing parameters, the model results drift significantly from observed data after 2 years (Figure 11). Our working hypothesis is that this is a result of the simple below-ground biomass production component in the model, which uses a constant proportion of above-ground production. We are currently working on developing more realistic resource allocation models, as well as developing relationships based on a combination of previous greenhouse experiments conducted during GCE-II and literature data for the effects of salinity and pore-water nutrients on the growth of these plants.

Archeological studies

We have conducted archeological studies to evaluate past human use of hammocks in the context of large-scale environmental changes such as sea level rise. This past year, Thompson et al. (in

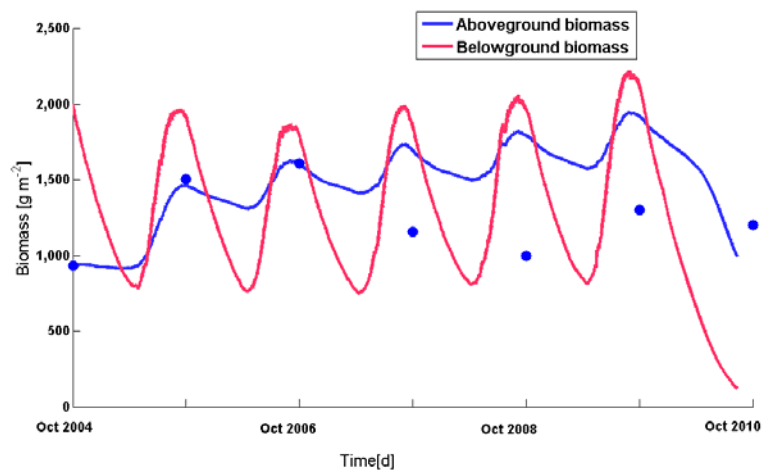


Figure 11. A comparison of observed above-ground biomass (blue dots) with modeled above- and below-ground biomass (blue and red lines respectively) predicted using a simple allocation model.

press) published results suggesting that humans increased the elevation of upland areas adjacent to some marshes by over 1 m by adding shell deposits. Guo and Pennings investigated the role of upland influence on the distribution of the saltmarsh annual *Suaeda maritima*. This plant is strongly associated with oyster deposits in the soil, which can originate either from dead oysters whose shells wash into the low marsh or from Native American middens that collapse into the high marsh. A manuscript based on this work is in press at *Oecologia*.

Q5: What is the relative importance of larval transport versus the conditions of the adult environment in determining community and genetic structure across both the longitudinal and lateral gradients of the estuarine landscape?

We have documented a variety of distribution patterns of different plant and invertebrate species across the GCE domain. Some of the variation in population densities is likely driven by longitudinal and lateral gradients in the estuarine environment (Questions 3 and 4). However, population density may also be affected by transport mechanisms and larval shadows that affect larval delivery, habitat suitability for adults, and competition. We are using a combination of recruitment studies, transplant studies, and genetic approaches to begin to understand these patterns. This portion of the program is led by Pennings in conjunction with Silliman, J. Wares (UGA), and T. D. Bishop (No Bones Coastal Biology Consultants).

Mechanisms explaining plant distributions

Guo and Pennings have conducted a series of transplant experiments to explain patterns of vegetation composition in the GCE domain (see Q3, above). Their results indicate that the freshwater plants were excluded from saltier sites by physical stress (they died with or without neighbors), and that the intensity of competition increased at less saline sites, excluding salt marsh species. There were hints of facilitation of some plant species by background vegetation at the saltiest sites. Their results suggest that salinity and plant-plant interactions are the primary drivers of vegetation pattern along the estuarine salinity gradient. A number of differences between these results and similar previous studies suggest that previous studies have been too simple in design (too few sites or too few study species) to fully explain the vegetation patterns. A manuscript based on this work is in press at *Ecology*.

Mechanisms explaining animal distributions

The Silliman lab continued their analysis of data collected during 2008-2010 on the relative effects of habitat quality, larval transport, and predation in governing invertebrate densities across the GCE domain. This work will be written up and submitted for publication to *Ecology*.

In addition, the Pennings laboratory is investigating the distribution of grasshoppers across the estuarine landscape. An initial analysis of temporal variation in grasshopper densities (means and SE averaged over the three sites with highest densities) showed that densities have varied more than five-fold among years, with highest biomass following years of high creekbank *Spartina* biomass. We hypothesize that vigorous growth of creekbank *Spartina* in one year leads to high egg production by grasshoppers, leading to high grasshopper population densities the following year. A larger data set (2000-2012) will be analyzed in the 2012-13 academic year.

Information Management

Overview

Information Management at the GCE site is led by W. Sheldon (UGA). T. Douce (UGA) assisted Sheldon until February 2012, and we are in the process of hiring his replacement. The major focus of IM effort during the past year has been improving discovery and accessibility of GCE data by enhancing metadata content and web-based data search tools. We also leveraged GCE cyber-infrastructure to develop new workflow-support software for the LTER Network Information System and a National Park Service-funded water quality monitoring database.

Enhancing Metadata Content

Data availability is a current area of concern in LTER, so we have focused on augmenting data set keywords, titles and abstracts to improve discoverability of GCE data in LTER network and other data catalogs. We have incorporated the LTER controlled keyword vocabulary in our metadata management system (GCE_Metabase), and we have assigned relevant LTER keywords in addition to taxonomic and other thematic keywords to all GCE data sets. This past year we also significantly enhanced location name and geospatial coverage metadata for data collected at GCE marsh plots. All long-term plant and invertebrate monitoring data sets now have added coordinates from real-time kinematic GPS surveys, and we have programmatically generated location name and bounding box coordinates for inclusion in data set metadata. This process has been automated so that it can generate geo-reference columns and geospatial metadata for any future data sets collected in these locations.

Data Catalog Search Tools

We significantly enhanced our web-based data catalog this year by adding a quick search form to the top-level data page (<http://gce-lter.marsci.uga.edu/public/data/data.htm>) as well as an advanced data search page (http://gce-lter.marsci.uga.edu/public/app/data_search.asp). These additions improve consistency with the LTER Network Data Catalog and address GCE-II proposal and mid-term reviewer recommendations to improve web-based searching for GCE data. Search results are displayed in the legacy GCE Data Catalog (http://gce-lter.marsci.uga.edu/public/app/data_catalog.asp), which was augmented to include geographic bounds and additional text search fields in the filter panel. In addition, we continue to support automatic synchronization of version-controlled EML 2.1.0 metadata with the LTER Data Catalog and KNB Metacat to support search and distribution of GCE data through these systems and associated cyber-infrastructure (e.g. Kepler).

Leveraged Projects

Software developed by GCE, including the GCE Data Toolbox for MATLAB (https://gce-svn.marsci.uga.edu/trac/GCE_Toolbox) and Metabase metadata management system, are actively used by other LTER sites and informatics programs. We have also leveraged GCE cyber-infrastructure for LTER working groups and other research projects at UGA. For example, as part of an LTER NIS Tiger Team, W. Sheldon developed software to automatically import EML-described data and metadata into the MATLAB analytical environment. MATLAB-based analytical workflows can now be developed for any tabular data available through the LTER Network Information System (i.e. PASTA), as well as Metacat and site data catalogs. This software is now integrated into the GCE Data Toolbox and an EML-based statistical program

generator web service hosted at VCR (<http://www.vcrlter.virginia.edu/data/eml2/eml2stat.html>). Alber and W. Sheldon also leveraged GCE data mining software and web application middleware to develop a comprehensive SE USA water quality monitoring program database and web portal for the National Park Service (<http://www.gcrc.uga.edu/wqmeta>).

Web Site and Data Access Statistics

Since January 2001, over 2.2 million GCE web pages have been viewed by more than 615,000 visitors (excluding web indexing spiders). Web activity has steadily increased over this period and approximately 10,000 visits per month were logged in the 2011/2012 academic year. Public data downloads have also steadily increased, with 2754 downloads in 2011-2012. We fully support data distribution through the LTER Data Catalog and KNB Metacat, via Data Access Server URLs in GCE EML metadata; however, the majority of public data requests are still made through the GCE Data Catalog.

Program Management

GCE administration

Day-to-day program administration is shared by Alber and Pennings, with support from the GCE Executive Committee. Program management involves submitting supplementary proposals, overseeing the core budget (including setting up subcontracts, approving purchase orders, travel, etc.), taking care of routine reporting, supervising core program personnel, and writing letters of support for collaborative projects. Pennings also continued his administrative duties related to field efforts, including supervising field technicians at Sapelo Island and overseeing repair and maintenance of boats and field instruments.

LTER network activities

As detailed below, GCE scientists are actively collaborating on cross-site comparisons and are involved in network planning and governance.

- Alber attended the LTER Science Council Meeting at Andrews Experimental Forest in May 2012.
- Pennings is a member of an LTER cross-site synthesis group examining whether the traits of plant species can predict different responses by different taxa in fertilization experiments. This work will enhance our ability to predict the impacts of anthropogenic inputs of nitrogen into natural systems. The group has published five manuscripts based on this work, one in PNAS, one in Ecology Letters, two in Ecology and one in Oikos. They have another manuscript in review and several more in preparation.
- Pennings is a member of an LTER cross-site synthesis group examining plant community stability over time. He is leading an effort to understand the causes and extent of community change in long-term records of 21 different salt marsh communities.
- Burd is a member of the LTER Network Climate and Waters Committee.
- Silliman is working with H. Lenihan from Moorea LTER on a study of comparative impacts of top-down control on ecosystem resilience.
- Craft and the Wetlands lab (IU) continued their collaboration with R. Jaffe and his lab (FCE LTER) to collect samples to characterize DOC along the salinity gradient of the Altamaha River.

We also have a strong network presence in terms of information management, through the activities of W. Sheldon. Over the past year our IM office has served the network in the following capacities:

- W. Sheldon is a member of a LTER NIS Tiger Team that is helping LNO software developers design and test web services for running analytical workflows using data stored in the PASTA framework.
- W. Sheldon developed new EML-based software for running analytical workflows in MATLAB using data from the PASTA framework or any other EML-described data source.

- W. Sheldon is a member of the LNO Visioning Committee that is preparing a report for the LTER Executive Board and NSF regarding recommendations for structure and function of a future LNO.
- W. Sheldon is chair of the EML metadata best practices IM Committee working group.
- We continue to work closely with the IM programs at the CWT, SBC and MCR sites, which are adopting GCE technology for their data management programs.
- We continue to host the USGS Data Harvesting Service for HydroDB (see [http://gce-
lter.marsci.uga.edu/public/im/tools/usgs_harvester.htm](http://gce-
lter.marsci.uga.edu/public/im/tools/usgs_harvester.htm)). Data from 85 USGS stream flow gauging stations are automatically harvested on a weekly basis for 12 LTER sites (AND, BES, CAP, CWT, FCE, GCE, KBS, KNZ, LUQ, NTL, PIE, SBC) and one USFS site.

Leveraged Funding

GCE investigators receive leveraged funding from multiple sources.

LTER Network Office. Climate effects on ANPP of saltmarshes of the North American Atlantic coast—a hierarchical model approach. \$37,648. S. Pennings and K. Wieski. (2012-2013).

National Science Foundation. Collaborative Research: Biophysical alteration of wetland geomorphology in response to rising sea level. \$105,854. S. Pennings. (2011-2014).

NSF Graduate Research Fellowship. E. Herbert (Indiana University PhD student, Craft). (2011-2015).

USDOE, National Institute of Climatic Change Research. Effects of accelerated sea level rise and variable freshwater river discharge on water quality improvement functions of tidal freshwater floodplain forests. \$343,181. C. Craft. (2008-2012).

National Science Foundation, Chemical Oceanography. Collaborative Research: Outwelling of dissolved organic carbon from salt marshes. UGA amount \$166,487. C. Meile. (2009-2013).

National Oceanic and Atmospheric Association. Top-down impacts, movement and feeding patterns of invasive hogs in southern salt marshes. \$60,000. B. Silliman and M. Hensel. (2012-2015).

NSF, Biological Oceanography, REU Supplemental grant. Context-dependency of consumer impacts on marsh plant production. \$8,900 B. R. Silliman. (2012).

NSF, Biological Oceanography. CAREER: Small grazers, multiple stressors, and the proliferation of fungal disease in marine plant ecosystems. \$805,797. B. Silliman. (2011-2016).

NSF, Biological Oceanography. Are blue crab declines leading to a trophic cascade and massive loss of U.S. southern marshes? B. Silliman. \$196,081. (2010-2013).

National Oceanic and Atmospheric Association. Alligators as Apex Marine Predators. \$60,000. B. Silliman and J. Nifong. (2010-2013).

NOAA. Crab herbivory and drought interact to cause die-off in southern salt marshes. \$60,000. B. Silliman and S. von Montfrans. (2009-2012).

Georgia Sea Grant. The Georgia Coastal Research Council. \$108,779. M. Alber. (2012-2014).

Georgia Coastal Management Program. The Georgia Coastal Research Council. \$111,178. M. Alber. (2010-2012).

Georgia Sea Grant. Estuarine Response to Land and Water Use Changes and Development at the Georgia Coast. \$99,906. R.Castelao and D. Di Iorio. (2012-2014) .

Georgia Department of Natural Resources, Coastal Resources Division. The Effects of Sea Level Rise and Increased Frequency of Storms on Inundation and Salt Intrusion on Georgia's Estuaries. \$144,858. R. Castelao and D. Di Iorio. (2012-2014).