GCE-IV Annual Report – Year Two (2021)

WHAT ARE THE MAJOR GOALS OF THE PROJECT?

The Georgia Coastal Ecosystems (GCE) LTER program focuses on estuarine and intertidal wetland ecosystems and how they respond to long-term change. The research activities in GCE-IV are designed to characterize perturbation patterns and their relationships to external drivers, to develop an understanding of disturbance responses, and to evaluate the consequences of these responses at the landscape scale. We divide our research into 4 inter-related programmatic areas: External Drivers of Change (Area 1); Long-term Patterns within the Domain (Area 2); Marsh Response to Changing Drivers (Area 3); and Integration and Forecasting (Area 4). Our major goals within these areas are as follows:

Area 1: to track long-term changes in external drivers such as climate change, sea level rise, and human alterations of the landscape and statistically characterize these external drivers in terms of long-term trends, spatio-temporal variability, and occurrence of extreme events (e. g. storms, droughts) so that we can investigate the links between external drivers and ecosystem response.

Area 2: to follow spatial and temporal variability in physical (estuarine salt intrusion length, residence time, and inundation), chemical (salinity, nutrient concentration and speciation, dissolved inorganic C, and pH), geological (accretion) and biological (organism distribution, abundance, and productivity) characteristics so that we can understand the biophysical template of the GCE domain.

Area 3: to characterize the ecological responses of our three key marsh habitats—S. alterniflora-dominated salt marsh, fresh/brackish marsh, and high marsh—to changing drivers so that we can develop driver-response relationships for marsh ecosystems.

Area 4: To evaluate ecosystem properties at the landscape level (habitat distribution, net and gross primary production, C budgets) so that we can produce synoptic estimates of ecosystem properties in the GCE domain, characterize how they respond and recover from disturbance and transition to new states, and assess long-term change.

WHAT WAS ACCOMPLISHED UNDER THESE GOALS?

The GCE works in four main areas. The specific objectives associated with each of these are listed below, along with initials of the primary PIs involved in each activity. AB: Burd, AS: Spivak, AW: Wilson, BS: Silliman, CA: Alexander, CC: Craft, CH: Hladik, CHA: Angelini, CM: Meile, DD: Di Iorio, DM: Mishra; JB: Byers, JS: Schalles, MA: Alber, NH: Heynen, CO: Osenberg, PM: Medeiros, RC: Castelao, SP: Pennings, VT: Thompson, WC: Cai.

Below we summarize our major activities and significant results for each of the objectives targeted for yr 2.

Area 1: External Drivers of Change

We collect long-term measurements associated with both A) environmental and B) human drivers that influence conditions in the GCE domain.

<u>Area 1A Objectives</u>

1. Collect ongoing information on climate and oceanographic conditions, sea level, and river discharge - DD, MA

> <u>Year Two Activities</u>: Several meteorological stations are used to characterize the GCE domain (Fig. 1). Marsh Landing serves as our primary long-term climate station; we also get climate data from our eddy covariance flux tower. We also track sea level, offshore wind forcing, and river discharge. Our long-term tide gage is about to be disrupted by dock renovation, so we are testing a Campbell Water Level Sensor as a potential replacement.
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> <u>Significant Results</u>: Discharge from the Altamaha River into the GCE domain averaged just over 612 m^3/s in 2020, which was the highest since the GCE project began in 2000 and double the long-term average (Fig 1).

2. Maintain an eddy covariance tower in the Duplin River - DM, DD, MA

> <u>Year Two Activities</u>: The GCE flux tower on the Duplin River measures CO2/H2O, weather conditions, radiation, water levels, and soil temperature. We have implemented a data integration methodology to gap-fill and combine CO2 flux data from two different sensors, and produced a continuous 30-min NEE dataset from 2014 to the present.
>
> <u>Significant Results</u>: The annual NEE budgets produced by our gap-filled time series provide a broad view of marsh productivity and interannual variation that can be linked with large scale changes in marsh dynamics and local climate. Nahrawi et al. (2020) reported that tidal flooding depressed NEE and that this effect varied seasonally as a function of plant phenology.

3. Monitor Altamaha River water entering the GCE domain - MA, PM, WC

> <u>Year Two Activities</u>: We routinely collect monthly samples of water entering via the Altamaha River for analysis of dissolved inorganic nutrients, DIC, alkalinity and pH. We increased sampling to weekly from Apr through Oct to capture potential changes in water quality associated with COVID19.
>
> <u>Significant Results</u>: Both DIC and total alkalinity of the water entering the estuary increases when river discharge is low; this signal can be seen throughout the system.

4. Measure exchange between the Duplin River and Doboy Sound - DD

> <u>Year Two Activities</u>: We measure current flow at the mouth of the Duplin River with a horizontal acoustic profiler. Data from 2019-2020 has been processed for quality control and used to estimate hourly averaged along-channel velocity. The instrument has been removed due to dock construction, and we are evaluating where and how it can be redeployed.
>
> <u>Significant Results</u>: Tidally averaged currents measured by the acoustic profiler show net outflow in the central channel of the Duplin River with an average velocity of -2.3 cm/s.

Increased variability in outflow starting in early 2020 corresponded with a large decrease in salinity (Fig. 2).

Area 1B Objectives

1. Evaluate how human activity relates to impervious surface and shoreline structures - NH, CA, VT, MA

Year Two Activities: We used aerial photography from 2018 to map shoreline armoring structures along the GA coast, which we can compare with 2006 and 2012. We are also conducting ethnographic fieldwork on property ownership and potential development in the Hog Hammock community on Sapelo Island and how it interfaces with flooding patterns.

Significant Results: Heynen and colleagues published both technical and popular articles on the history of land use on Sapelo Island (Heynen 2020; Bailey and Heynen 2020; Hardy and Heynen, in press). Our coastal armoring analysis showed that there has been a 15% increase in revetments and 23% increase in bulkheads in McIntosh County over the past 6 years.

2. Assess human modifications of oyster reefs - VT, CA

Year Two Activities: We measured size, distribution, and ages of oyster shells (*Crassostrea virginica*) from archeological sites along the coasts of GA and SC.

Significant Results: Thompson et al. (2020) demonstrated that oyster reefs were an integral part of the Native American landscape and that their sustainability over long periods of time were likely due to the sophisticated cultural systems that governed harvesting practices.

Area 2: Patterns within the Domain

We collect data documenting key ecosystem variables within the GCE domain. Major activities in this area consist of A) field monitoring of water and marsh attributes, B) repeat photography, and C) modeling.

Area 2A Objectives

1. Continue the GCE core monitoring program in the water column - DD, MA, WC, PM

Year Two Activities: We maintain sondes at 10 sites and collect quarterly or monthly CTD profiles and grab samples for water quality measurements at 12 sites. (Table 1, Fig. 2). We have had gaps in sonde data due to instrument failure, and several sondes have now been replaced. There have also been delays in nutrient analysis due to COVID.

Significant Results: We observed low salinities throughout the GCE domain in 2020 in response to high river discharge. We also completed our analysis of DOC samples collected after Hurricane Irma. Letourneau et al. (submitted) found that the passage of the hurricane resulted in a 27% increase in DOC content and enhanced rates of DOC biodegradation.

2. Continue the core monitoring program in intertidal marshes and tidal fresh forest - SP, CC, CHA, CO

Year Two Activities: We monitor plants, invertebrates and soils in 2 zones at each of our 10 marsh sites (Table 1, Fig. 2). In the tidal forest we measure litterfall, basal area increment, sediment elevation and vegetation cover. We continue to test biomimics to evaluate the thermal regimes experienced by macrofauna (Fig. 3).

Significant Results: Liu and Pennings (2020) used the long-term plant monitoring data to evaluate synchrony in plant production across multiple sites and two elevation zones. They found the highest correlations within a species and within a zone, and no asynchrony that might allow one species to compensate for another (Fig. 3). We also analyzed feldspar marker layers and SET data to determine if there were any effects from hurricanes Matthew (2016) and Irma (2017). We found evidence for increased sedimentation on the two mainland sites only (sites 1 and 4).

3. Characterize groundwater flow - AW, CM, CA

Year Two Activities: We monitor groundwater levels and salinities at a series of wells associated with the upland marsh transition at Marsh Landing and the high marsh manipulation site (see 3C.2). We are currently calibrating a groundwater model to hindcast hydrologic conditions coincident with changes in plant zonation.

Area 2B Objectives

1. Continue GCESapelo Phenocam and add a second site - SP, MA

Year Two Activities: The GCESapelo Phenocam, which focuses on a Spartina marsh, contributes data to the national phenocam network (Fig. 4). We have identified a location for a second camera with both Spartina and Juncus in its field of view.

Significant Results: Narron et al. (in prep) are using phenocam imagery to groundtruth a model for Landsat8 that detects marsh flooding. The results show variation in flooding patterns over both space and time (Fig. 4).

2. Continue regular aerial photographs of the GCE domain - CA, CH, CHA

Year Two Activities: We use aerial photographs of the domain to evaluate patterns in creek configuration, creekbank slumping, shoreline armoring, and shifts in tidal marsh distribution.

Significant Results: We used MODIS-derived data to document an unusual increase in vegetation greenness along the GA coast that corresponded with COVID restrictions (Fig 5). This was included in a cross-site paper evaluating ecological responses to the pandemic (Gaiser et al. in rev.).

Area 2C Objectives

1. Upgrade hydrodynamic models (Delft 3D) – DD, RC

Year Two Activities: We continue to work on applying Delft3D in the GCE domain, with a focus on implementing a water quality model.

2. Enhance soil models - CM

Year Two Activities: We are developing a model that can be used to predict temperature in marsh soils based on a radiation balance coupled with a one-dimensional heat propagation model in the subsurface (Fig. 5).

3. Enhance *Spartina* models - AB, MA

Year Two Activities: We have developed a model to predict belowground biomass in Spartina based on environmental (e.g. inundation, elevation, precipitation) in combination with vegetation (e.g. foliar chlorophyll, aboveground biomass) parameters.

Significant Results: Our Belowground Ecosystem Resilience Model (BERM) successfully predicts belowground biomass of Spartina based on above-ground proxies (O'Connell et al., in prep), and can be scaled with remote sensing to evaluate spatiotemporal patterns.

Area 3: Marsh Response to Changing Drivers

We work in each of our key marsh habitats to understand ecosystem response to major drivers. A) In the Spartina marsh, we are assessing changes in inundation and top-down control. B) In the upstream areas of brackish/fresh marsh and tidal forest, we are evaluating the effect of increases in salinity that occur as the result of droughts, storm surge, or upstream sea level intrusion. C) In the high marsh, we are assessing changes in runoff at the upland/marsh border.

Area 3A Objectives

1. Evaluate drivers of *Spartina alterniflora* production - SP, MA, AB, CHA, CM

Year Two Activities: We analyzed the effects of flooding patterns on marsh-atmospheric CO2 fluxes and are evaluating leaf area index, gas exchange and light availability at different levels within the Spartina canopy. We are also investigating relationships between environmental data and satellite-derived marsh biomass using convergent cross mapping. Our planned trials for a temperature manipulation were postponed due to COVID.

Significant Results: NEE measured at the flux tower is net negative when water levels are below 0.3 m, signaling atmospheric C exchange under partially flooded conditions (Fig. 6). We also have evidence that Spartina is photosynthesizing when fully submerged, which means that part of the C fixed is likely exchanging in the water.

2. Continue our predator removal manipulation - BS, CHA, JB, AS, SP, CC, CO

Year Two Activities: We continue the predator exclusion experiment initiated in summer 2016, although sampling was limited this year. In 2020 we analyzed data from camera traps and quantified size-specific predation in the experiment and among marshes in the SE.

Significant Results: Experimental exclusion of nekton revealed top-down control of invertebrate populations that cascades down to affect ecosystem processes such as enhanced consumption and decomposition rates. Camera traps showed that terrestrial predators were not major visitors to the experimental plots, and both soil pore water and snail mortality varied with elevation as opposed to predator exclusion. We did not see effects on Spartina biomass, which we attribute to mesopredator release and/or compensatory facilitation by fiddler crabs. A manuscript on these results is in prep.

3. Investigate marsh fauna interactions – BS, CHA, JB, CO

Year Two Activities: Over the past 4 years we have examined the impacts of invasive hogs on die off and recovery in salt and brackish marshes (See Accomplishments).

Significant Results: Sharp and Angelini (in press) found that birds and nekton can enhance Spartina resilience to drought by increasing soil aeration via probing as well as their suppression of snail grazers and transmission of disease to snails.

Area 3B Objectives

1. Assess upstream habitat transitions - MA, CC, CH, JS

Year Two Activities: To document transitions along the Altamaha River salinity gradient, we conduct an annual survey of bankside Spartina and trees and we sample permanent plots with mixed vegetation. We are currently evaluating the use of satellite data to distinguish between oligohaline and mesohaline marsh species as well as different forest habitats.

2. Track recovery from our salt water intrusion manipulation - CC, SP, CHA, JS

Year Two Activities: We continue to track recovery in the SALTEx experiment following cessation of dosing in December 2017, monitoring porewater, sediment elevation, and vegetation. We also completed GC-MS analysis of biomarkers in soil samples collected after hurricanes Irma (2017) and Michael (2018).

Significant Results: Results from the SALTEx experiment indicate that plants control key ecosystem processes (soil surface elevation, carbon gain/loss) and microbial community structure and function. Solohin et al. (2020) found that declining soil surface elevation and associated carbon loss was due to reduced belowground biomass in press plots, and Mobilian et al. (2020) showed that decreased carbon inputs from plants resulted in reduced microbial diversity and decreased microbial carbon cycling (Fig. 7). Although porewater nutrients are at background levels, there is evidence of residual salinity in several of the press plots 2.5 years after dosing ceased.

Area 3C Objectives

1. Assess habitat dynamics at vegetation borders - SP, MA, CA

Year Two Activities: We monitor vegetation dynamics in 9 high marsh mixtures and have begun annual drone flights to scale up to the surrounding landscape. We also operate two web applications where citizen scientists align and extract data from photographs taken along transects that begin in the high marsh.

Significant Results: Parashar et al (in press) developed a machine learning approach for identifying the 6 common high marsh plant species from color photographs.

2. Continue our upland manipulation - SP, AW, RV

Year Two Activities: The high marsh experiment has had little effect on water flow, and although we continue to sample plants and invertebrates we have found no effects to-date.

Significant Results: The upland manipulation was largely ineffective at altering porewater salinities, and we have seen no consistent changes between treatments in benthic micro-algae, invertebrates or vascular plants. We are using data from the wells to monitor groundwater conditions to better understand fluxes of groundwater in the high marsh.

Area 4: Integration and Forecasting

We use the information collected in Areas 1-3, along with modeling and remote sensing, to 1) assess response and recovery from disturbance, 2) create a scaled-up disturbance-scape that tracks the temporal and spatial patterns of perturbations and their cumulative effects, and 3) produce synoptic descriptions of ecosystem properties and long-term change.

<u>Area 4A Objectives</u>

1. Quantify ecosystem effects of marsh perturbations – CHA, SP, AS, MA

> <u>Year Two Activities</u>: We began regular monitoring of wrack patches at the Dean Creek site (see Obj. 4B.1) for plants, invertebrates, porewater, decomposition, and wrack characteristics, and set up cameras to capture larger animal visits.
>
> <u>Significant Results</u>: Initial sampling of areas affected by wrack show that plant densities decreased and height increased in wrack patches, and that densities of the herbivorous marsh crab *Sesarma reticulatum* increased significantly in wrack-covered areas relative to controls.

2. Conduct standardized disturbance manipulations – SP, CHA, MA

> <u>Year Two Activities</u>: We are participating in a distributed "DragNet" experiment to evaluate how grasslands recover from disturbances under different nutrient regimes. We also plan to initiate a standardized experiment based on observations of natural marsh perturbations. We also continue to monitor recovery from a wrack disturbance experiment conducted in 2011.

<u>Area 4B Objectives</u>

1. Use drones to track disturbances over time – MA, DM, JS, CA, SP

> <u>Year Two Activities</u>: We continue a large-scale effort to track wrack perturbations via regular drone flights, completing a year of sampling over our test site. In Dec. 2019 we began monthly monitoring of a focal site at Dean Creek and are investigating the use of PLANET data to create a denser time series for these observations.
>
> <u>Significant Results</u>: PCA classification accuracies of drone imagery ranged from 90-99%, allowing us to successfully characterize wrack perturbations.

2. Construct a scaled-up disturbance-scape – DM, MA, JS, CHA

> <u>Year Two Activities</u>: We are using our regular drone flights to characterize wrack perturbations in terms of patch size, frequency, and longevity. We are also calculating rates of creekbank slumping/accretion to assess the relative importance of different geomorphic features in controlling erosion.
>
> <u>Significant Results</u>: Visualization of the cumulative distribution of wrack shows that it is concentrated at channel edges and is quite dynamic over time (Fig. 8).

3. Develop models to characterize disturbance patterns – MA, DD, CC

> <u>Year Two Activities</u>: We used field data from a study of headward-eroding creeks that were subject to *Sesarma* herbivory to evaluate patterns of marsh perturbation and recovery.

Significant Results: Wu et al. (in review) measured 19 variables affected by headward-eroding creeks and found multiple patterns of disturbance magnitude and recovery trajectory that belied any simple univariate understanding of "disturbance and recovery".

Area 4C Objectives

1. Produce synoptic habitat maps of the GCE domain – CH, JS, MA

   Year Two Activities: Sentinel-2 satellite imagery of Altamaha marsh (salt, brackish, fresh) and tidal fresh forests were acquired to map marsh and forest distributions in combination with high resolution orthoimagery.

2. Assess scaled-up biomass patterns – DM, JS, CH

   Year Two Activities: We used Spartina biomass from clip plots to calibrate a biomass algorithm based on drone reflectance, and are working to pair these high-resolution observations with satellite imagery (Fig. 6). We have also used our Spartina model (Obj. 2C.3) to generate predictions of both above- and belowground biomass from Landsat8 imagery.

   Significant Results: We used our parameterized BERM model (Obj. 2C3), with input data from Landsat 8 and Daymet, to provide synoptic estimates of both above- and belowground Spartina biomass in the flux tower marsh (Fig 9).

3. Evaluate C stocks and transport from tidal wetlands to the coastal ocean – WC, AS

   Year Two Activities: We collected cores to evaluate carbon storage as part of a leveraged project through GA Sea Grant. We received an ROA supplement to sample carbonate chemistry in summer 2020; this work was postponed due to COVID and is planned for next spring.

   Significant Results: Hopkinson et al. are writing a synthesis paper that uses flux tower data from GCE and PIE to compare carbon storage in the two systems.

4. Synthesize response to long-term change - All

   Year Two Activities: Langston et al. (2020) used a vertical accretion model to evaluate the long-term stability of GCE marshes in the face of sea level rise.

   Significant Results: Langston et al. (2020) predicted that the GCE marshes will be stable through 2100 due to existing “elevation capital”, after which time it will rapidly lose area (Fig. 10). We are also participating in a cross-site synthesis paper to evaluate long-term responses to climate drivers across LTER sites (Reed et al., in prep).

GCE Activities 2021

Area 1: External Drivers of Change

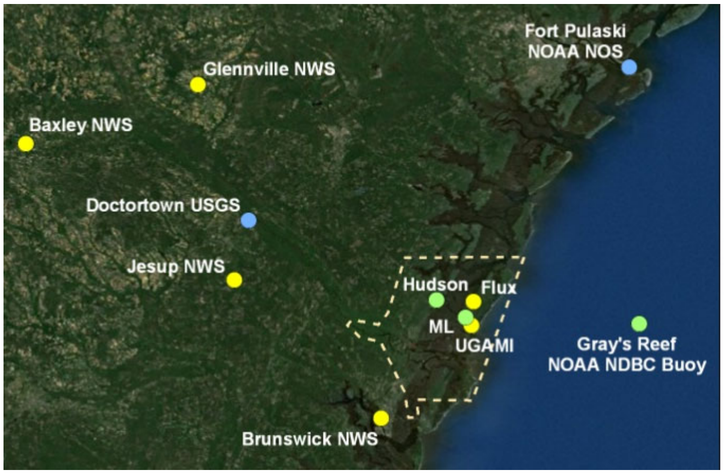


Fig. 1. Locations of observing stations used for boundary conditions (ML is Marsh Landing; UGAMI is UGA Marine Institute). Corresponds to Objective 1A.1: Collect ongoing information on climate and oceanographic conditions, sea level, and river discharge.

Area 2: Patterns within the Domain

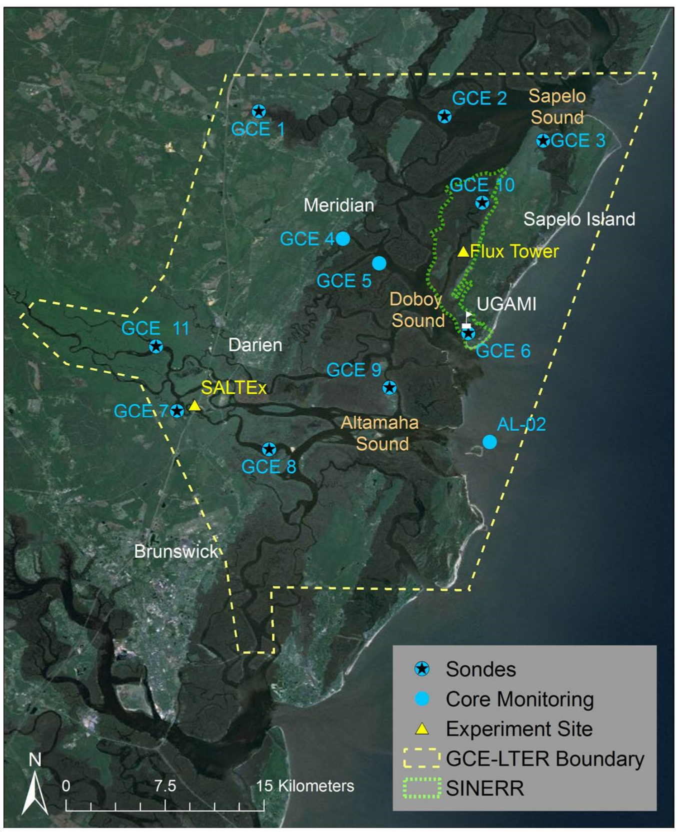


Fig. 2. GCE domain showing core monitoring stations. Corresponds to Objective 2A.1: Continue the GCE core monitoring program in the water column and 2A.2: Continue the core monitoring program in the marsh and tidal fresh water.

GCE Activities 2021

Table 1. Monitoring program for GCE-IV. 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. PI initials are CC: Craft, CHA: Angelini, CM: Meile, DD: Di Iorio, DM: Mishra; MA: Alber, JO: Jessica O'Connell, PM: Medeiros, SP: Pennings, WC: Cai. Corresponds to Objectives 2A.1: Continue the GCE core monitoring program in the water column and 2A.2: Continue the core monitoring program in the marsh and tidal fresh water.

Type	Location	Frequency	Core Area & Variables Measured
Area 1			
Weather stations, with SINERR, USGS (DD)	Sites 4, 6, flux tower	15 min	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
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, PM)	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, chlorophyll *a*
	Sites 6-7	Monthly	1, 3, 4. Dissolved inorganic nutrients (NO_2^-, NO_3^-, NH_4^+, HPO_4^{2-}, $H_2SiO_4^{2-}$) and organics (DOC, TDN, DON, TDP, DOP), particulate CN, DIC, alkalinity, pH, chlorophyll *a*, total suspended sediment
	Sites 7, AL-2	Quarterly	3. DOM composition
Sound hydrography (DD)	Sites 1-4, 6-11	30 min	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.	15 min	Abiotic driver of 1-5. Horizontal ADCP measurements of water flux
Area 2 Marshes			
Soil accretion (CC)	Sites 1-11	Annual	3. Sediment accretion, elevation, compaction
Soil temperature (JO, CM)	Sites 1-11	15 min	Abiotic driver of 1-4. Loggers in root zone (10 cm deep), in 2 marsh zones adjacent to vegetation plots.
Plant productivity (SP, CC, DM, JO)	Sites 1-10	Annual	1. Stem density, height, flowering status, calculated biomass, in 2 marsh zones
	Site 11	Annual	1. Litterfall traps and stem wood growth of tupelo gum and bald cypress
	Flux tower	5 min	1. Net ecosystem exchange
	Flux tower	Monthly	1. Above- and belowground biomass in short, medium, tall *Spartina*
	Flux tower, site 4	30 min	1. Phenocam estimates of aboveground biomass in short, medium, tall *Spartina*
Disturbance (SP)	Sites 1-10	Annual	5. Disturbance in permanent vegetation plots
Plant composition (SP, MA, CC)	Sites 6, 10	Annual	2. Community composition in 4 types of salt marsh, 2 types of high marsh vegetation mixtures
	Altamaha	Annual	2. Community composition in 2 types of low-salinity marsh vegetation (3 sites). Distribution of Altamaha marsh types (~50 stations), health and survival of tidal fresh forest trees (~50 stations).
Marsh Invertebrates (CHA, SP)	Sites 1-11	Annual	2. Density and size of benthic macroinvertebrates (mollusks, crab burrows) in 2 marsh zones.
Insects (SP)	Sites 1-6, 9, 10	Annual	2. Density of grasshoppers in salt marsh transects
Recruitment (CHA)	Sites 1-11	Annual	2. Recruitment of barnacles to standard substrates

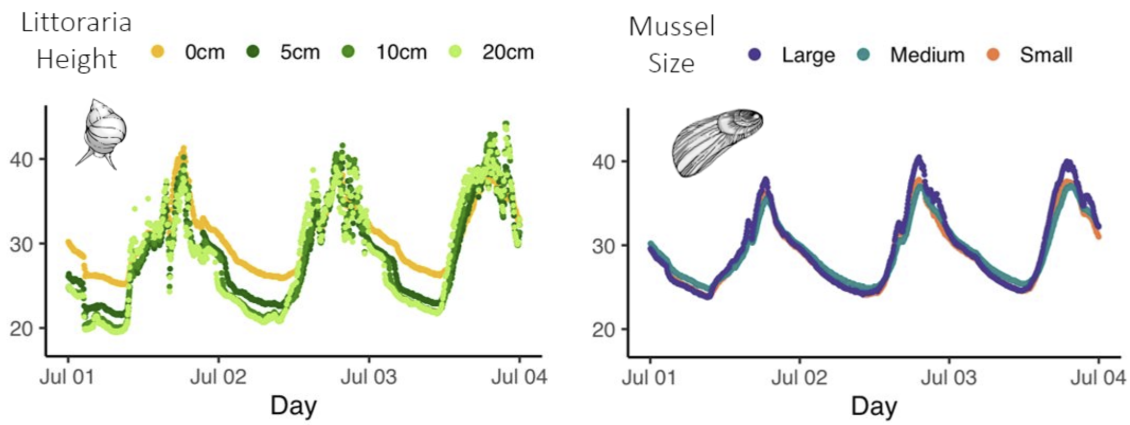


Fig. 3. Temperature logger records from biomimics of *Littoraria* deployed at different heights above the soil surface (left) and mussels of different sizes (right). Source: R. Atkins and C. Osenberg. Corresponds to Objective 2A.2: Continue the core monitoring program in the marsh and tidal fresh water.

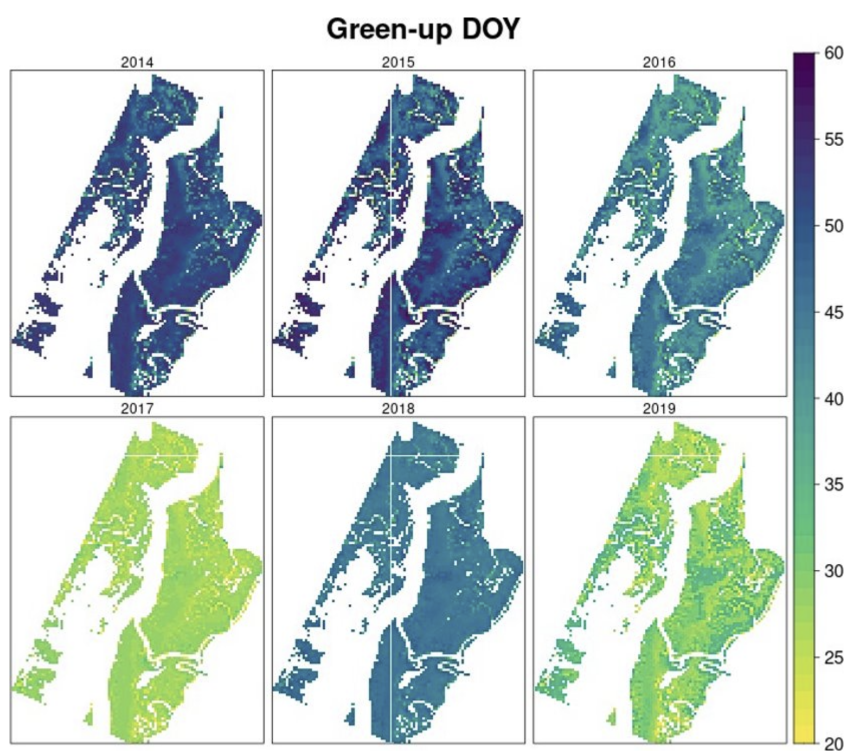
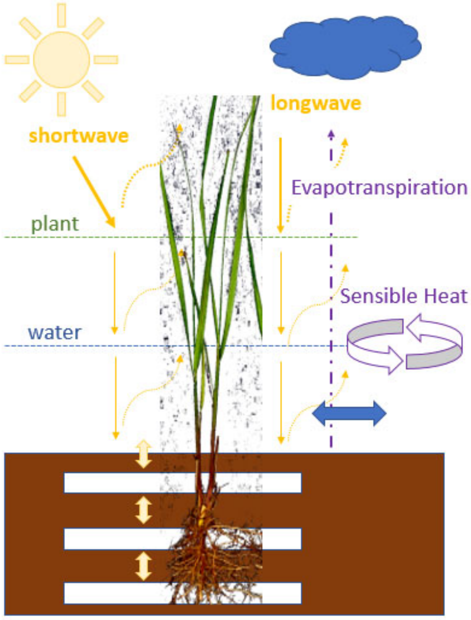


Fig. 4. Variation in salt marsh green-up observed with the Sapelo PhenoCam, which is mounted on the GCE flux tower (color bar shows Julian Day). Source: J. O'Connell. Corresponds to Objective 2B.1: Continue GCESapelo Phenocam and add a second site.



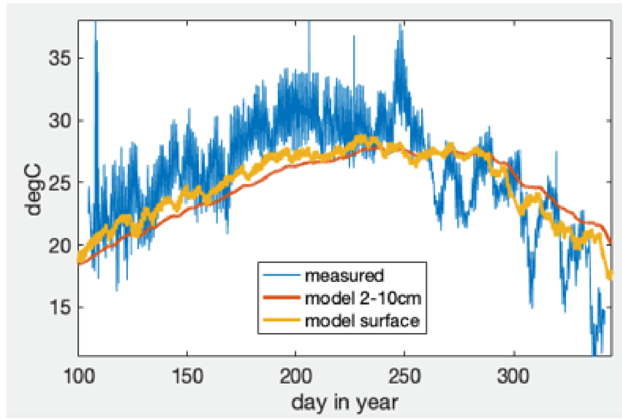


Fig. 5. Major drivers (left) and initial results (right) of soil temperature model. (Source: J. Kolb and C. Meile.) Corresponds to Objective 2C.2: Enhance soil models.

Area 4: Integration and Forecasting

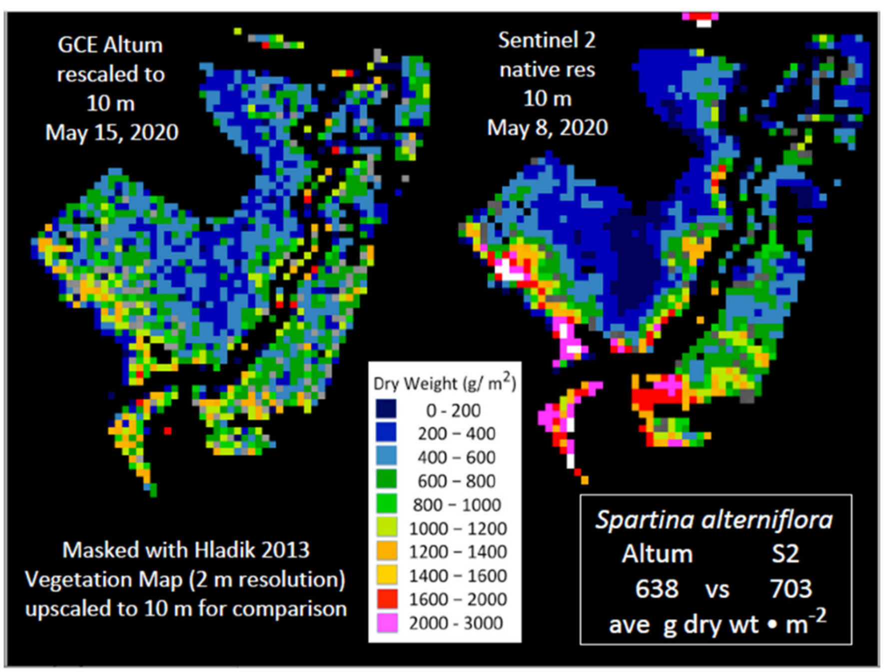


Fig. 6. Initial comparison of biomass estimates from drone (left) and satellite (right) imagery, both scaled to 10 m. (Source: J. Schalles) Corresponds to Objective 4C.2: Assess scaled-up biomass patterns.

GCE Significant Results 2021

Area 1: External Drivers of Change

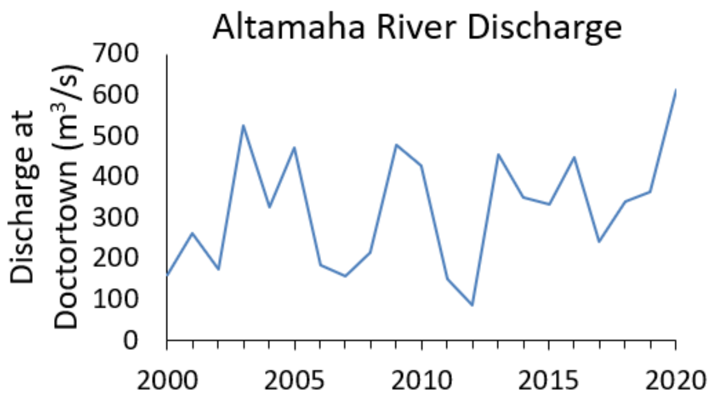


Fig. 1. Annual average discharge in the Altamaha River during the GCE project. Discharge in 2020 was 616 m^3s^{-1} compared with the 20-y average of 318. Source: USGS gage at Doctortown, GA. Corresponds to Objective 1A.1: Collect ongoing information on climate and oceanographic conditions, sea level, and river discharge.

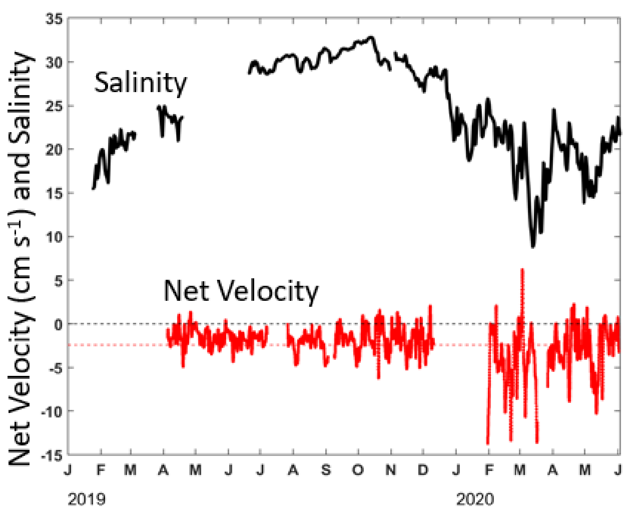


Fig. 2. Net velocity (red) measured at the mouth of the Duplin River by the GCE horizontal looking ADCP, in relation to salinity (black). Note marked increase in variability early in 2020 when salinity decreased. Dotted red line denotes overall mean net velocity of -2.4 cm s^{-1}; black line denotes zero, for reference. Source: J. Kelly and D. Di Iorio. Corresponds to Objective 1A.4: Measure exchange between the Duplin River and Doboy Sound.

GCE Significant Results 2021

Area 2: Patterns within the Domain

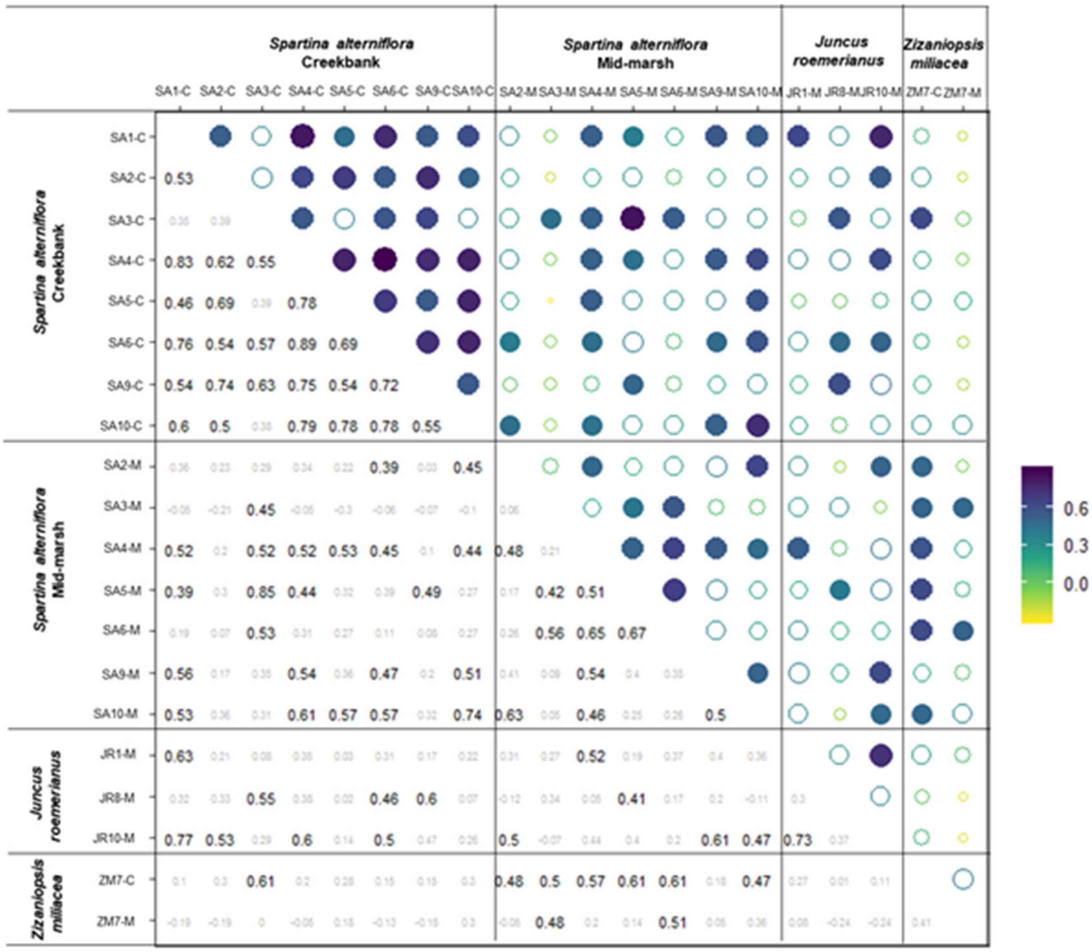


Fig. 3. Correlations between annual (2000-2017) fall biomass of *Spartina alterniflora*, *Juncus roemerianus* and *Zizaniopsis miliacea* at different sites and different marsh zones. Upper right: larger circles and darker shading indicate larger r values. Lower left: r values for the correlations. Significant relationships are indicated by bold numbers and filled circles. Source: Liu and Pennings, in press, Ecology. Corresponds to Objective 2A.2: Continue the core monitoring program in the marsh and tidal fresh water.

GCE Significant Results 2021

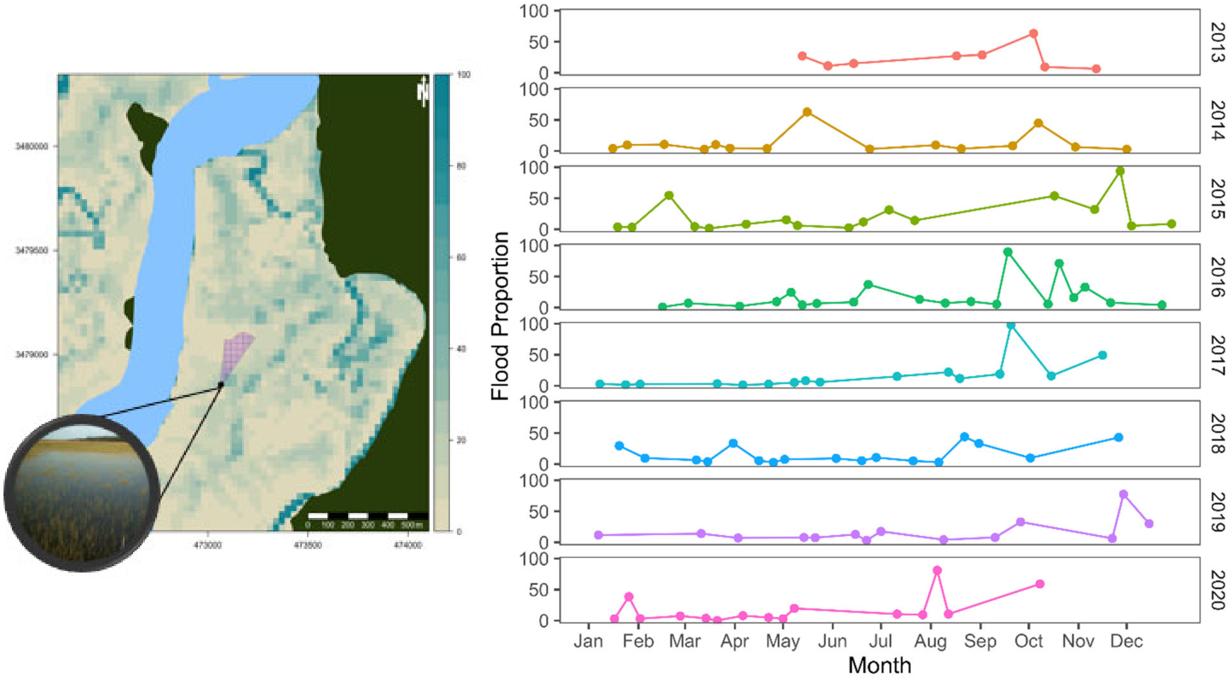


Fig. 4. Spatial (left) and temporal (right) variation in salt marsh flooding frequency at the GCE flux tower based on Landsat 8 satellite imagery. Image on the left shows % time each pixel was flooded over period 2013-2020 (see scale bar); inset shows image from GCE Phenocam, with field of view shown in purple. Panels on right show annual patterns of % flooding. Source: Narron et al., in prep. Corresponds to Objective 2B.1: Continue GCESapelo Phenocam and add a second site.

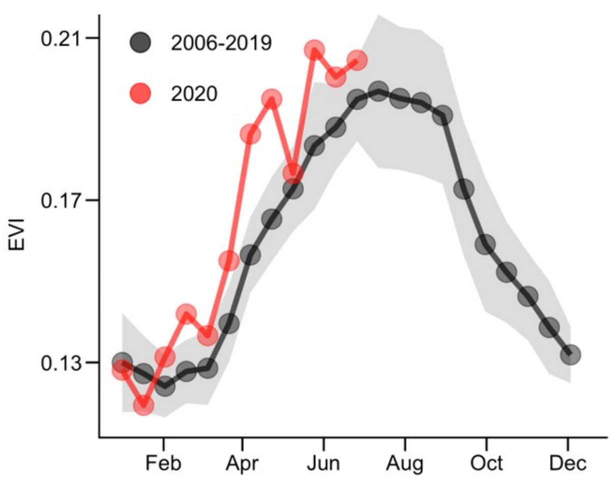
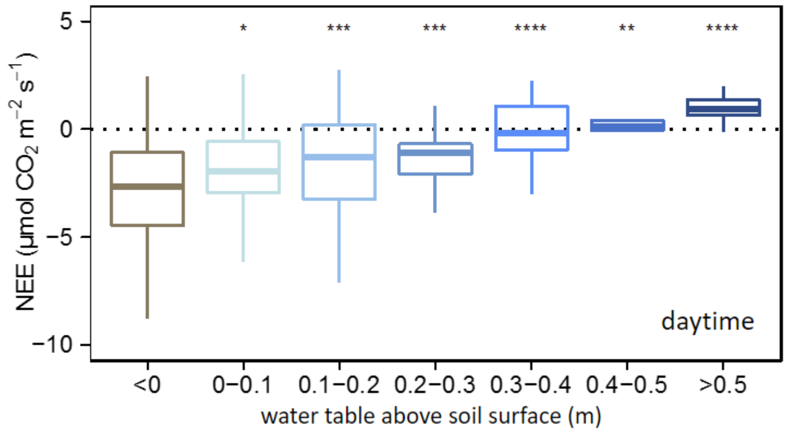


Fig. 5. Sixteen-day mean enhanced vegetation index (EVI) during COVID19 lockdown was higher than the previous long-term average. Time series for estuarine and marine wetlands along the Georgia coast derived from NASA MODIS MOD90GA surface reflectance (n = 800). Source: D. Mishra, In: Gaiser et al., in review. Corresponds to Objective 2B.2: Continue regular aerial photographs of the GCE domain.

GCE Significant Results 2021

Area 3: Marsh Response to Changing Drivers

Fig. 6. NEE measured at the GCE flux tower under conditions of tidal flooding. NEE is negative when water level is less than 0.3 m. Source: Hawman et al., in review. Corresponds to Objective 3A.1: Evaluate drivers of *Spartina alterniflora* production.



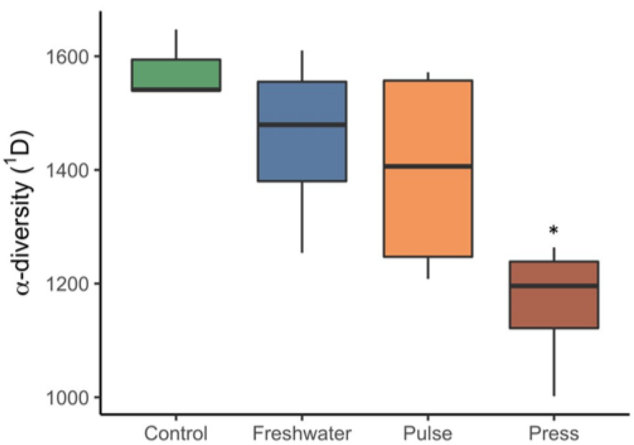


Fig. 7. Alpha diversity of total DNA community in each treatment group of the SaltEx experiment.
* indicates Press was significantly different from Control (p<0.02).
Source: Mobilian et al. 2020.
Corresponds to Objective 3B.2: Track recovery from our salt water intrusion manipulation.

GCE Significant Results 2021

Area 4: Integration and Forecasting

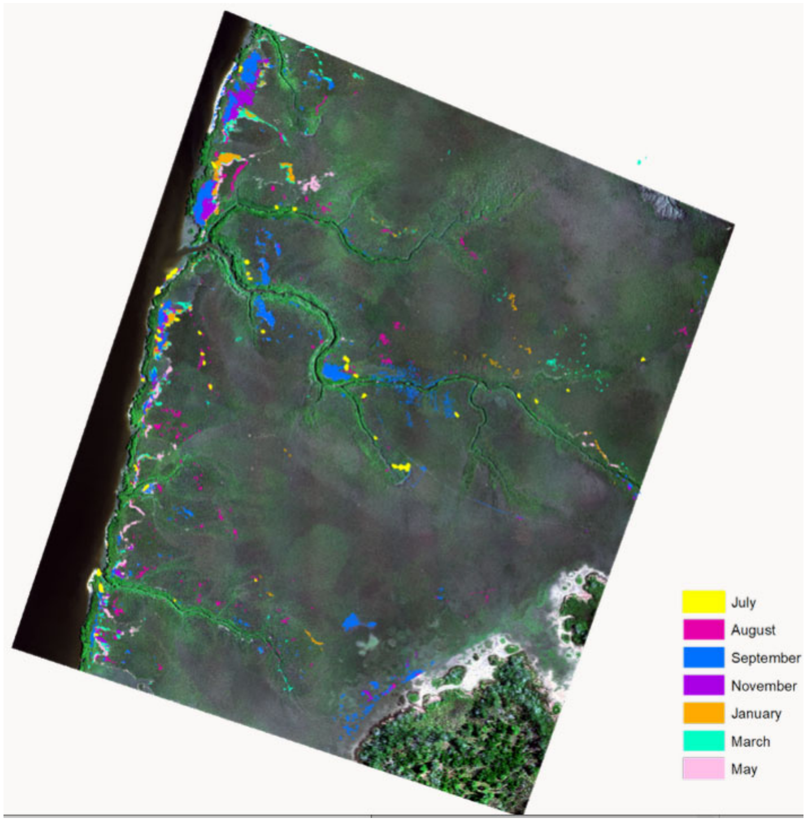


Fig. 8. Wrack packets identified from drone flights at airport marsh, July 2019 – May 2020. Source: T. Lynn, M. Alber, and D. Mishra. Corresponds to Objective 4B.2: Construct a scaled-up disturbance-scape.

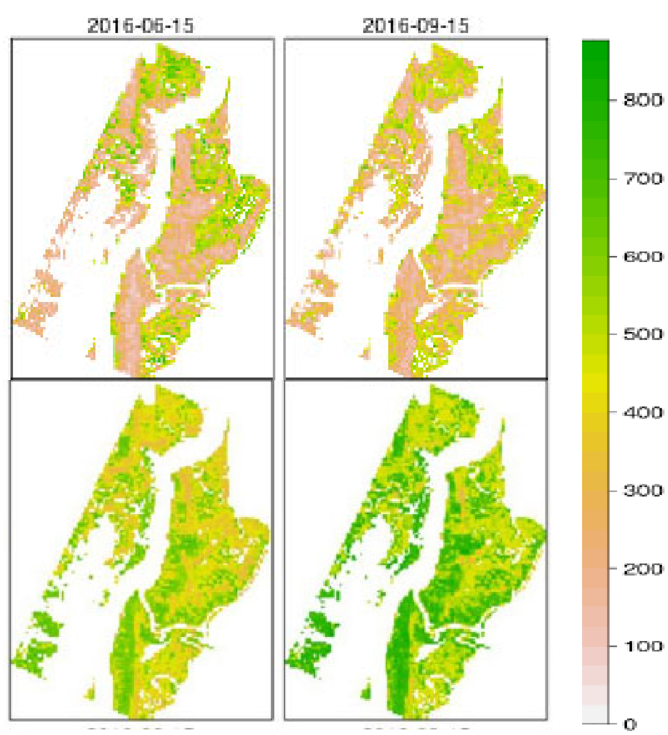


Fig. 9. Above (top) and belowground (bottom) biomass of Spartina at the GCE flux tower marsh on 6/15/16 (left) and 9/15/16 (right), estimated with our BERM model. Color ramp indicates biomass in g/m2. Source: O'Connell et al., in prep. Corresponds to Objective 4C.2: Assess scaled-up biomass patterns.

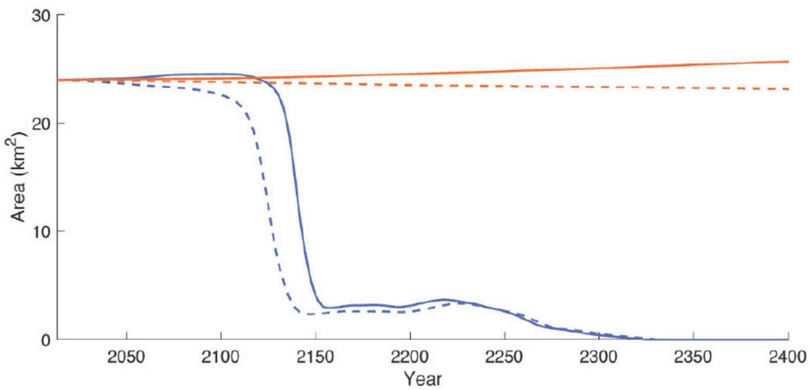


Fig. 10. Modeled salt marsh extent under historical (orange) and high SLR (blue) scenarios through 2400. The solid lines denote model results with dynamic marsh accretion, whereas the dashed lines denote model results with a fixed accretion rate. Corresponds to Objective 4C.4: Synthesize response to long-term change.

WHAT WERE THE KEY OUTCOMES AND ACCOMPLISHMENTS?

Key accomplishments this past year include research on historical marsh change, the far-reaching effects of marsh crabs on salt marshes, and the role of megafauna.

Patterns of marsh change at three LTER sites

The vegetated area of a salt marsh can shift over time as the result of advance and retreat of the marsh edge, but it can also change due to channel widening and contraction, formation and drainage of ponds, interior mud flat formation and revegetation, and migration of the marsh onto the upland (Fig. 1). Understanding patterns of vegetation loss and gain can provide insight into what factors are important in controlling marsh dynamics, as each of these shifts responds to different processes. As part of a cross-site coastal SEES project that leveraged LTER data, Burns et al. (2020 a) used historical aerial photos to measure changes in marsh features over approximately 70 years at study areas located in the GCE domain as well as the Virginia Coast Reserve (VCR) and Plum Island Ecosystems (PIE) LTER sites. The net change was neutral at the GCE site, as losses, which were primarily due to channel widening, were largely offset by channel contraction in other areas (Table 1). The study marsh at VCR increased over time due to migration onto the upland, despite the fact that low-lying areas experienced extensive loss as the result of interior mud flat expansion. In contrast, vegetated marsh area at PIE decreased over time due to losses from ponding, channel widening, and erosion at the open fetch marsh edge. In a companion study, Burns et al. (2020 b) focused specifically on the marsh edges of each site and again found differences in the open fetch edge that were offset in part by changes in the interior channels. This demonstrates the importance of assessing shoreline changes throughout the marsh, as rates of retreat and advance at the open-fetch marsh perimeter may not be indicative of the overall change. These studies offer a reminder that marshes are dynamic environments and that multiple processes are occurring simultaneously that affect the extent of vegetated marsh habitat. Understanding what factors are important in driving losses and gains provides a useful context for identifying site-specific management options.

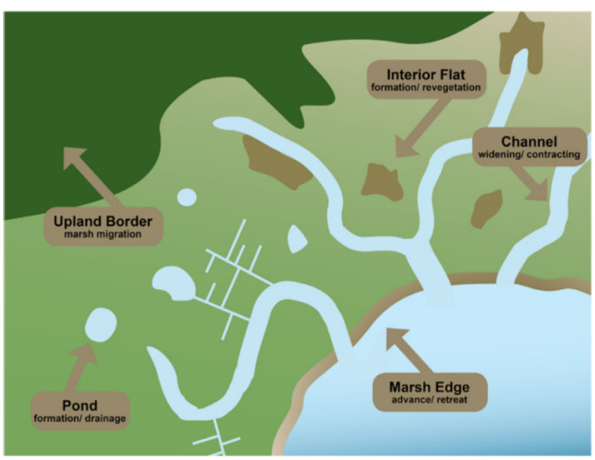


Fig. 1. Conceptual cartoon showing different types of lateral marsh contraction and expansion. Source: Burns et al. 2020 a. Corresponds to Year Two Accomplishment: Patterns of marsh change at three LTER sites.

Change		GCE 1942 – 2013	VCR 1949 - 2013	PIE 1938 - 2013
Vegetated marsh losses	Conversion to flats/ponds	-0.25 km^2	-0.59 km^2	-0.86 km^2
	Channel widening and extension	-1.15 km^2	-0. 30 km^2	-0.51 km^2
	Open fetch marsh loss	-0.03 km^2	-0.06 km^2	-0.09 km^2
Vegetated marsh gains	Migration onto upland	+0.17 km^2	+1.05 km^2	+0.20 km^2
	Colonization of flats/ponds	+0.28 km^2	+0.13 km^2	+0.19 km^2
	Colonization of channel edge	+0.83 km^2	+0.45 km^2	+0.13 km^2
	Colonization of open fetch marsh	+0.04 km^2	+0.09 km^2	+0.00 km^2
Net change in vegetated marsh		**-0.3 km^2**	**+0.75 km^2**	**-1.15 km^2**

Table 1. Summary of vegetated marsh losses and gains in three LTER sites (GCE: Georgia Coastal Ecosystems; VCR: Virginia Coast Reserve; PIE: Plum Island Ecosystems. Source: Burns et al. 2020 a. Corresponds to Year Two Accomplishment: Patterns of marsh change at three LTER sites.

The biogeomorphic and ecological effects of the marsh crab *Sesarma reticulatum*

In recent decades, the headward erosion of salt marsh creeks associated with the activities of the herbivorous marsh crab, *Sesarma reticulatum*, has become increasingly common in salt marshes in the southeastern US. *Sesarma* aggregates in high densities at the heads of creeks, and GCE researchers have found that they excavate large amounts of soil, consume plants at the creekbank (increasing erodibility), and probably also enhance decomposition of soil organic matter through burrow networks that serve to increase oxygen penetration (Vu et al. 2017; Vu and Pennings 2018). As a result, grazed creeks have been shown to elongate onto the marsh platform at a rate of 1 to 4.5 m y^{-1}. In a study in *PNAS,* Crotty et al. (2020) analyzed aerial imagery and found that Sesarma-grazed creekheads have increased in prevalence over the past 25 y, and in so doing have increased drainage density by 8 to 35% across the southeast. They postulate that this increase in grazed creeks is a consequence of sea level rise, which serves to soften the substrate and make it easier for crabs to burrow. They also show that the biomass of other marsh invertebrates is severely decreased adjacent to grazed creeks, likely due to increased predator access to the marsh platform in denuded areas (Fig. 2). In order to understand the response and recovery of areas affected by this perturbation, Wu et al. (in revision) measured a suite of variables along three transects: one that ran from the marsh platform, through the denuded creek head, and onto newly-formed creekbank; another where the enlarged creek head had passed through but was no longer in evidence; and a third that had never been affected and served as a control. There was a strong response to the headward-eroding creek in most variables that were assessed, with most effects persisting for 5-10 y and following multiple trajectories of recovery; some variables never recovered (i.e. a state change to tall *Spartina*). These studies demonstrate the far-reaching and long-lasting effects of *Sesarma* and the feedbacks between crabs, marsh drainage, and ecosystem function. Crotty et al. (2020) was also featured in Scientific American, which highlighted the intriguing idea put forth in the paper that crabs have emerged as keystone grazers in this system as a consequence of climate change.

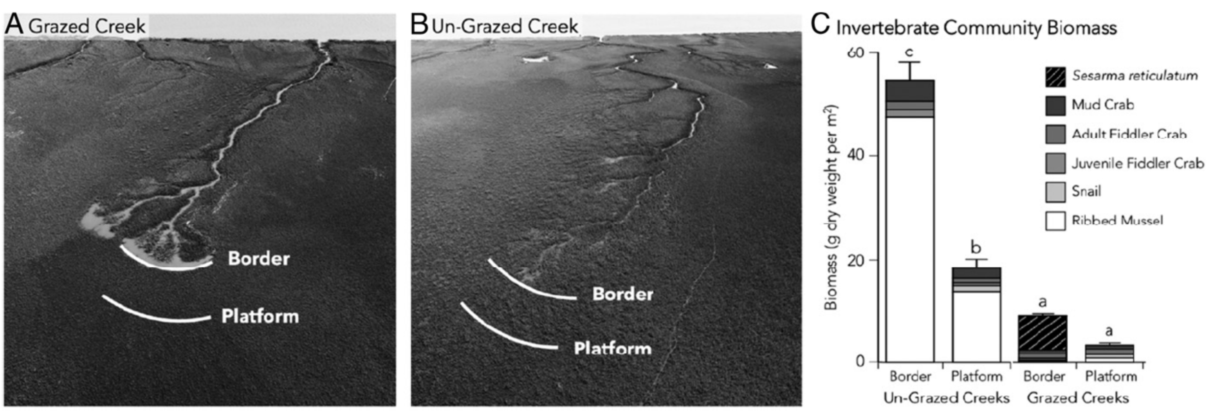


Fig. 2. Surveys of the border and platform zones in Sesarma-grazed (A) and ungrazed (B) marshes reveal differences in invertebrate community biomass and composition (C). Error bars represent standard errors of 56 replicate survey quadrats per marsh type and zone. Photo credit: C. Ortals. Source: Crotty et al. 2020. Corresponds to Year Two Accomplishments: The biogeomorphic and ecological effects of the marsh crab *Sesarma reticulatum.*

The role of megafauna in salt marsh ecosystems

Feral hogs are known to cause disturbances in salt marshes, negatively affecting *Spartina* growth and recovery via activities such as rooting, trampling and wallowing (Sharp and Angelini 2019). In a new study, Hensel et al. (in revision) documented that they also consume mussels, based on the presence of mussel shells in hog fecal material. Previously, Angelini et al. (2016) had demonstrated that there is a mutualism between *Spartina* and mussels in which *Spartina* patches associated with mussels are more resilient to drought because mussels enhance water storage and reduce soil stress. In order to understand how hogs affected this relationship, Hensel et al. (in review A) did an experimental manipulation that crossed hog exclusion with mussel additions in patchy areas that were recovering from drought. In treatments where hogs were excluded, *Spartina* patches recovered 40% faster than in controls over three years. As expected, plant densities increased even more when mussels were added due to their positive effect on *Spartina*. When hogs were present, however, the effect of adding the mussels switched, such that plants in these treatments did worse than those affected by the hogs alone (Fig. 3). This was likely due to foraging activities, as the hogs destroy both plants and crab burrows while consuming mussels. In a separate study, Hensel et al. (in review B) found that the presence of hogs in a brackish marsh increased plant diversity, decreased plant cover, and changed the identity of the spatially dominant plant to a species that was competitively inferior. Both of these studies show that the presence of wild hogs can change the outcome of interactions among important marsh species. In addition to improving our understanding of the ecological role of megafauna in coastal marshes, this work is relevant to management because densities of exotic hogs in the southeastern US have approximately doubled since the 1980s (Hensel et al, in review A). These papers, along with ongoing research by GCE scientists and colleagues on the impacts of horse grazing in coastal marshes, build on our previous studies of alligators as megafaunal predators in salt marshes. As a group, they illustrate that the GCE study area supports a suite of large-bodied consumers that can have strong effects on marsh structure and function. In general, however, both the historical and current role of megafauna in salt marshes is poorly understood, as highlighted in a recent meta-analysis (Gaskins et al. 2020).

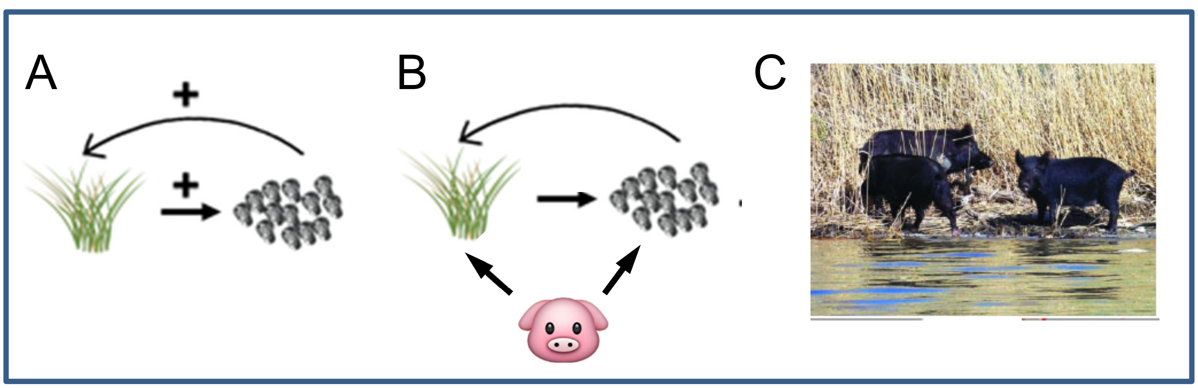


Fig. 3 Interactions between Spartina and mussels are positive when hogs are excluded (A), and negative when they are present (B). Photo in (C) depicts feral hogs in the salt marsh. Photo credit: Brandon Messick. Adapted from Hensel et al., in review A. Corresponds to Year Two Accomplishments: The role of megafauna in salt marsh ecosystems.

WHAT OPPORTUNITIES FOR TRAINING AND PROFESSIONAL DEVELOPMENT HAS THE PROJECT PROVIDED?

The GCE provides training and professional opportunities to K-12 educators, to undergraduate students, and to graduate students. GCE personnel are also involved in international collaborations and LTER network activities.

GCE Schoolyard Program

The GCE Schoolyard immerses science and math teachers (K-12) in hands-on research activities alongside GCE scientists and graduate students. Teachers participate in field research, attend lectures, and develop ways to use this experience in the classroom. We had to cancel this year's Schoolyard workshop due to COVID19, but were able to host 2 teachers who took video footage to be used in virtual lessons in the classroom. They focused on ecological comparisons of an undeveloped and a developed barrier island, with an emphasis on experimental design for field studies, data collection, and analyses. We also re-designed the GCE education and outreach website so that all of our activities can be found in one place.

Undergraduate Education

There were limited field opportunities for undergraduate students this past year, but many students were able to conduct research virtually. 17 undergraduate students from 8 institutions worked with GCE LTER scientists:

- An REU student from the College of Coastal Georgia worked with S. Pennings and J. O'Connell developing and testing hydroponic experimental designs for Spartina; a second REU, from UGA, worked with N. Heynen and D. Hardy to digitize and map historical land use changes.
- At the field site on Sapelo, 1 student from Creighton Univ. and 1 from Elon Univ. worked with J. Schalles on vegetation mapping using drone imagery; 2 from UF worked with C. Angelini to assess disturbance effects.
- Seven UGA undergraduates worked with GCE investigators on (largely) virtual projects: 2 with J. Byers on photo analyses from the PredEx experiment; 1 with C. Meile on the soil model; 2 with A. Spivak on data collected at PredEx and in headward eroding creeks; 1 with B. Hopkinson and S. Pennings on automated feature identification for marsh mapping; 1 with C. Osenberg on biomimetic temperature sensors.
- Undergraduates also worked with investigators from other institutions: 1 from IU worked with C. Craft on decomposition studies; 1 from Creighton worked with J. Schalles analyzing remote sensing imagery; 1 from UH worked with S. Pennings on headward-eroding creeks; 1 from GA Southern worked with C. Hladik on habitat mapping.
- J. Schalles (Environmental Remote Sensing; Marine and Freshwater Ecology) and P. Medeiros (Migrations in the Sea) used GCE data in their undergraduate courses.

Graduate Education

Graduate students are an integral part of the research at the GCE LTER. There are currently 30 students from 7 institutions engaged in LTER activities. Graduate students have also been authors on numerous publications that have resulted from this work. Other graduate activities include:

- S. Williams (UF student, Angelini) is the GCE grad rep for the LTER network. This past summer she organized a virtual meeting in lieu of our usual in-person brownbag seminar series on Sapelo Island. The meeting featured 14 research presentations (11 by students) and had approximately 50 participants.
- The GCE grad students have established a slack channel to enhance communication and field coordination.
- C. Hladik used GCE data in her graduate course (Geospatial Techniques and Applications).

International Collaborations

The GCE has graduate students and post-doctoral associates from a variety of countries, including Turkey and China. S. Pennings also hosted a visiting graduate student from East China Normal Univ. We also have active collaborations with scientists in China (East China Normal Univ., Fudan Univ., Xiamen Univ.), the Netherlands (Radbound Univ., Utrecht Univ., Univ. of Groningen, Netherlands Institute of Ecology), and the Czech Republic (Czech Univ. of Life Sciences).

Diversity, Equity and Inclusion

GCE has a Diversity Plan, which was originally written in 2012. This past year the Executive Committee agreed that this plan was in need of updating. As a first step, we developed a demographic survey that was sent to all of those who have participated in the GCE project since it began in 2000. We have received 117 responses to date (out of 358) and will use this information to get a more complete picture of the demographics of our personnel and how they have changed over time. We have also started a DEI committee, which met in January 2021 and is tasked with updating the GCE Diversity Plan and identifying practical action items for the coming year. C. Hintz (Savannah State) represents GCE on the LTER network DEI committee, and both M. Alber and S. Pennings attended the LTER Lead PI meeting convened in December 2020 to share DEI strategies.

Network Activities

As detailed below, GCE scientists are actively collaborating on cross-site comparisons and are involved in network planning and governance, both within the LTER and with other groups.

- M. Alber and S. Pennings attended the LTER Science Council Virtual Meeting in May 2020.
- GCE investigators were part of a paper comparing state changes across the LTER network (Zinnert et al. 2020). D. Mishra contributed to a cross-site effort to evaluate environmental effects of the “anthropause” due to COVID (Gaiser et al., in review); A. Burd is working on a synthesis of the responses of coastal ecosystems to climate change (Reed et al., in prep.).
- C. Meile is collecting inundation data in the GCE domain as part of a cross-site effort organized by J. Stegen at the Pacific Northwest National Lab to evaluate response to hydrologic disturbance.
- S. Pennings represents GCE in both the “Nutnet” and “Dragnet” distributed experiments, collecting data that contribute to global syntheses of grasslands. A. Spivak is part of the coastal carbon research coordination network (RCN) and participates in the soil carbon working group.
- The high-resolution digital camera on the GCE flux tower is part of the National Phenocam network and the eddy covariance data from the tower are part of the Ameriflux network.

We also have a strong network presence in terms of information management, through the activities of W. Sheldon and A. Sapp (UGA). Over the past year, GCE IM staff served the network in the following capacities:

- Continued to collaborate with BCO-DMO personnel to refine cross-listing of relevant GCE data sets to enhance discovery
- Concluded our hosting of the CWT LTER site and helped them transition to a legacy website on a UGA server
- Continued to leverage GCE-IMS components and protocols to operate a data catalog and bibliographic, taxonomic and geographic databases for the Savannah River Ecology Laboratory
- Provided support and training on using the GCE Data Toolbox for MATLAB for processing and quality controlling sensor data at other LTER sites
- Worked with the EDI/LTER working group to complete the transition of the LTER Climate/Hydrography Database (ClimDE/HydroDB) to modern cyber infrastructure
- Continued to host the USGS Data Harvesting Service for HydroDB, in which 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 1 USFS site
- Participated in EDI/LTER working group developing best practices for archiving large data files associated with drone imagery

How have the results been disseminated to communities of interest?

The GCE disseminates information to multiple audiences: we share information within the project itself; we distribute data and metadata; we provide information to the general public via our website; we work with coastal managers through the Georgia Coastal Research Council; we reach schoolchildren through our children's book and our comic book; we host two community scientist web applications; and we conduct various specialized activities.

Project Personnel

We use a wide variety of approaches for disseminating information internally. We maintain multiple email lists and a password-protected project website that provides GCE participants with role-based access to provisional data and private documents as well as web forms for submitting metadata, data files, announcements, calendar events and other content. We maintain restricted email lists and file exchange services to facilitate collaboration on several large projects (SALTEx, Flux Tower, High Marsh, PredEx, Modeling), and publish a weekly newsletter for GCE participants and other interested parties.

We hold training sessions on data and metadata submission at our annual meetings, and provide downloadable versions of presentation and sample data submission forms online as well as one-on-one consultation for participants. We also operate a Subversion (SVN) software code repository server for both IM and researcher-led software development projects.
We have developed dashboard displays for the eddy covariance flux tower, the HADCP and our new tide gage that enable researchers to identify potential problems with their instrumentation in near real-time.

This past year we implemented a workflow tracking system for our routine monitoring that automatically sends reminder emails to the responsible party when a task is coming due. We also set up automatic synchronization of drone imagery and imagery/video from wildlife cameras to a Synology server at UGA and provide secure access to GCE working groups.

Data and Metadata

We operate an integrated information management system based on relational database and dynamic web application technology to manage, archive and distribute data, metadata and other research products. We provide GIS support to GCE researchers and students, including ArcGIS licenses and software, and maintain an archive of GIS reference data as file geodatabases. We are handling drone imagery in increasingly higher volumes and are participating in an EDI/LTER working group to develop best practices for archiving these large data sets.

As of Dec 2020, 633 public data sets have been uploaded to the LTER Data Portal and new and updated data sets are uploaded monthly as they reach their public access date (i.e. within 2 years of collection). We also continue to provide online access to both public and private GCE data sets through the GCE Data Catalog. A total of 646 catalog data sets are currently online, representing 20.6 million tabular data records in 958 files, plus 30 GB of raster GIS data. An additional 863 public data sets are also available through the GCE Data Portal. Collectively, we provide online access to over 32 million tabular data records from GCE research and affiliated monitoring programs as well as over 100 GB of GIS data, with an additional 24 million records being finalized for inclusion.

GCE data are downloaded by a diverse group of web visitors, including academic researchers, educators, and personnel from other LTER programs (Table 1). We also actively collaborate with staff of the Biological and Chemical Oceanography Data Management Office (BCO-DMO) at Woods Hole to include dynamic data links on the GCE project page at BCO-DMO, and we will continue to refine this approach to enhance discovery. Over 165,000 data files have been downloaded by the public since our data catalog was put online in 2001.

General Public

We continue to maintain a GCE program website and public data portal for disseminating information and products including publications, reports, research data, photographs and remote sensing imagery. Use of the GCE website has increased steadily since 2001, with over 1 million page views from 145,675 visitors between Sept 2019 and Dec 2020. Over 8 million page views from 1.8 million distinct web visits have been recorded since 2001. This past year we updated and refactored the research description on the GCE website to showcase key research findings and signature data sets. We also maintain a dedicated WordPress website for our Education and Outreach activities.

We continue to host a support website for the GCE Data Toolbox for MATLAB software, an open source data management tool developed by W. Sheldon used for data processing and analysis at GCE and many other LTER sites (over 4,500 public downloads to date). This software is broadly used at other LTER sites.

Georgia Coastal Research Council

The GCE provides outreach to coastal managers through partial support of the Georgia Coastal Research Council (GCRC). Core activities of the GCRC include communicating via the GCRC listserv to affiliated members interested in coastal Georgia (the GCRC currently has 126 affiliates from 16 universities, 4 federal agencies, and 3 state/regional organizations). The GCRC website (www.gcrc.uga.edu) has member biographies, project summaries, and research needs, and serves an important role as a conduit of coastal research information.

This past year the GCRC held a virtual meeting (GCRC Gathering) to facilitate networking and research updates that included 90 speakers and was broadly attended, with 89% of follow-up survey respondents fully or mostly agreeing that the meeting provided a beneficial exchange of information. One respondent wrote, "it was extremely useful to find out the needs and perspectives of managers (as I'm a scientist)" and another that "Hearing about what everyone is working on, where our efforts are complimentary, what management needs are, and funding opportunities. It is great that all of that happens in one meeting!" One outcome of the meeting was the need to develop a consensus regarding the status of GA marshes with respect to sea level rise, which we are planning to do this coming year. We also completed a technical synthesis on the effects of seismic surveys on marine organisms at the request of Georgia DNR.

Additional Activities

- We continue to distribute the GCE children's book, "*And the Tide Comes In*" as well as our new comic book, "*The Adventures of Jacob the Technician*" (and the Spanish language version, *"Las Adventuras de Jacob el Tecnico*"), to environmental educators.

- The GCE continues to host two community science web sites developed by S. Pennings and M. Garbey: "Scaling Up Marsh Science" and "Marsh Explorer" to align and identify marsh features in photo transects. We plan to develop a new version of Marsh Explorer in 2021.

- GCE continues to provide web hosting for the Georgia Coastal Research Council, as well as a searchable bibliographic database for the UGA Marine Institute.

GCE Dissemination of Results 2021

Table 1. Public data file downloads for 2013-2020 and 2001-2020 by data set theme and user affiliation, excluding downloads by GCE participants and GCE-to-LNO/EDI file transfers.

Downloads by Theme	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2001 -20**
Algal Productivity	49	430	329	232	74	71	40	79	1345
Anthropology	60	426	226	211	28	15	23	48	1037
Aquatic Invertebrate Ecology	445	9164	5212	4750	1379	1202	909	1318	25155
Bacterial Productivity	293	4269	2094	2073	505	216	225	419	10333
Botany	0	0	49	69	31	15	5	41	210
Chemistry	33	444	425	277	90	70	60	120	1544
Fungal Productivity	49	748	351	351	101	32	47	89	1797
General Nutrient Chemistry	77	487	366	251	115	100	61	97	1757
Geology	32	440	396	273	181	491	87	158	2100
Geospatial Analysis	47	1064	632	646	206	173	94	235	3110
Groundwater Hydrology	0	0	0	0	26	32	29	42	129
Hydrography/Hydrology	27	221	502	154	121	87	50	91	1290
Marsh Ecology	0	0	0	0	0	0	45	18	63
Meteorology	157	1499	1315	888	194	179	157	389	4983
Microbiology	0	0	0	0	25	34	16	24	99
Multi-Disciplinary Study	41	764	563	459	107	74	52	137	2234
Organic Matter/Decomposition	201	1707	1238	877	321	207	143	281	5146
Physical Oceanography	1631	18972	18906	11481	2468	2961	1794	4327	63773
Phytoplankton Productivity	107	2297	1081	1014	310	152	128	193	5449
Plant Ecology	348	7117	5269	4297	1446	803	694	1744	22121
Population Ecology	8	186	198	1322	427	288	133	325	2887
Pore-water Chemistry	44	518	499	341	308	109	72	215	2144
Real-time Climate	79	125	110	223	832	116	190	131	2411
Terrestrial Insect Ecology	155	2498	1252	1277	472	163	171	383	6773

Downloads by Affiliation	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2001-20**
Academic Research Program	42	185	112	264	1018	110	296	236	3834
Educational (K-12)	7	10	26	41	5	1	14	0	200
Educational (Post-secondary)	26	78	44	8	34	81	76	37	1122
Environmental Advocacy Group	0	0	0	0	0	0	0	6	14
Government Agency	3	1	14	3	21	1	9	8	455
International LTER Site	1	2	0	0	1	0	0	0	47
LTER Network Office (Metacat)	9	4	38	1	0	884	126	950	3196
LTER NIS	3641	52979	40672	31029	8467	6422	4681	9603	157498
Other LTER Site	29	3	4	4	134	5	5	5	414
Other/Unspecified	132	114	103	118	92	89	18	63	1182

What is the impact on the development of the principal discipline(s) of the project?

GCE scientists have published 27 journal articles and other one-time publications this past year. Papers cover a broad range of ecological topics, including disturbance (e.g. Mobilian et al. 2020), top down effects (e.g. Sharp and Angelini 2020), plant ecology (Liu and Pennings 2020), diversity (Zhang et al. 2020), invasive species (e.g. Liu et al. 2020), and C cycling (e.g. Nahrawi et al. 2020). We have also made contributions in anthropology (e.g. Thompson et al. 2020), geomorphology (e.g. Burns et al., in press), remote sensing (e.g. Pahlevan et al. 2020), and political ecology (e.g. Heynen 2020). A complete list of publications can be found at http://gce-lter.marsci.uga.edu/public/app/biblio_query.asp. Key accomplishments this past year include research on patterns of marsh change, biogeomorphic and ecological effects of the marsh crab *Sesarma reticulatum*, and the role of megafauna in salt marsh ecosystems.

What is the impact on other disciplines?

The GCE is an interdisciplinary program, with biologists, geologists, chemists, physicists, and anthropologists engaged as PIs on the project.

What is the impact on the development of human resources?

There are currently 17 undergraduate students, 30 graduate students and 6 post-doctoral scientists associated with the project. We had 2 REU participants this past year. We also have active collaborations with international students and scientists in the Netherlands (Radboud University, Utrecht University and University of Groningen) and China (East China Normal University, Fudan University, Xiamen University, Fujian University).

What was the impact on teaching and educational experiences?

Teachers who participate in the GCE Schoolyard program have developed a series of lesson plans for broad use. Lessons are organized by grade level and cover a range of GSE standards in Science, Math and ELA and are available in the “Teaching Resources” tab of our Education and Outreach website. The site also includes materials that are directly tied to the GCE children’s book, *And the Tide Comes In*. The teachers are also producing “Meet the Scientist.”

What is the impact on physical resources that form infrastructure?

The GCE has installed an extensive boardwalk system that provide access to plots associated with our long-term salinity addition experiment (SALTEx). We also installed boardwalks and photovoltaic cells in support of our eddy covariance flux tower, which is a 20-foot tall tower located in a salt marsh adjacent to Sapelo Island. We maintain sondes that continuously measure conductivity, temperature and salinity at 10 water quality monitoring sites in Altamaha, Sapelo, and Doboy Sound, and in the adjacent marshes we have RSETs that measure sediment elevation (there are also RSETs in the SALTEx plots). We have groundwater wells installed to measure flow in support of our upland observations. We partner with the Sapelo Island National Estuarine Research Reserve to run our weather station and to provide support for a USGS water quality monitoring station. We operate a wireless, outdoor data server on Sapelo to acquire, store and relay real-time data from the flux tower and other field instruments to servers at UGA.

WHAT IS THE IMPACT ON INSTITUTIONAL RESOURCES THAT FORM INFRASTRUCTURE?

The UGA Marine Institute (UGAMI) on Sapelo Island provides the base of field operations for the GCE-LTER. The project has 3.5 technicians who work at UGAMI, and all of our scientists use the facility while in the field. Two GCE labs (Pennings, Alber) maintain year-round housing and operations at UGAMI and at any given time there are students, technicians and other personnel at the facility. We maintain two 22' small boats, four Kawasaki mules and one truck at the field station to access sampling sites. We also operate a GIS lab at UGAMI in collaboration with the Sapelo Island National Estuarine Research Reserve.

WHAT IS THE IMPACT ON INFORMATION RESOURCES THAT FORM INFRASTRUCTURE?

The GCE Information System currently includes three dedicated, fault-tolerant servers collectively providing 14 TB of secure hard disk storage and a 24 TB LTO-5 tape library for near-line and off-site backups. Raw data, processed data, version-controlled distributable data products and other digital resources are organized in a data file management system that is mirrored between servers and backed up daily. Backup files are mirrored to redundant hard disks in multiple buildings at UGA and are copied to magnetic tape weekly and stored off-site to protect against data loss. We also operate an ArcGIS license server and provide GIS software and support to affiliated researchers and students, and operate a Subversion (SVN) repository for management of software code developed by GCE personnel. In 2020 we continued to maintain and operate these systems, updating software and expanding storage to accommodate new data collection activities and for hosting more imagery for leveraged community science web applications (Scaling Up Marsh Science and Marsh Explorer).

WHAT IS THE IMPACT ON TECHNOLOGY TRANSFER?

The GCE Information Management program has developed a number of software products, database systems and web applications that have been released as open source software. These tools, including the GCE Data Toolbox for MATLAB, our Metabase Metadata Management System, our bibliographic database, our file archive and our geospatial library, are widely used across the LTER Network and in other environmental informatics programs. The GCE Data Toolbox software has been downloaded by over 4500 registered users (812 since 2016) and is actively used at 9 other LTER sites for sensor data harvesting, data analysis or general data processing tasks. We are currently collaborating with the Environmental Data Initiative to register the GCE Data Toolbox and training materials in their new IM Code Repository co-hosted with Earth Science Information Partners (ESIP). Our Metabase metadata management system was adopted by 3 other LTER sites (CWT, MCR and SBC) and the Savannah River Ecology Lab. In 2020, we generated new automated workflows for generating flux tower data products using the GCE Data Toolbox and published long-term products to EDI. We also implemented a workflow reminder and tracking system for our yearly fall monitoring project. What is the impact on society beyond science and technology?

WHAT IS THE IMPACT ON SOCIETY BEYOND SCIENCE AND TECHNOLOGY?

The GCE website and public data portal are used to disseminate publications, reports, research data, photographs and remote sensing imagery. Over 1.8 million distinct web visits have been recorded since 2001, with over 1 million page views from 145,675 visitors this past year. In addition, GCE scientists regularly give seminars and public presentations, contribute articles to newsletters and other popular publications, and talk to the media about coastal issues. This past year our work was featured in Scientific American and we hosted a PBS film crew for an upcoming show on salt marshes as part of their

“Changing Seas” series. Our Schoolyard program brings K-12 teachers to the field site, and our children’s book and accompanying lesson plans are widely distributed to grade school teachers and environmental educators. GCE outreach is served by partial support of the Georgia Coastal Research Council (GCRC, www.gcrc.uga.edu), which works to promote science-based management of Georgia coastal resources by facilitating information transfer between scientists and managers.

CHANGES IN APPROACHES AND REASONS FOR CHANGE?

We had to cancel our Schoolyard workshop this past summer due to COVID19. As described in the "Opportunities for Training and Development" section, we were able to provide 2 teachers access to the field site (along with a videographer) to take footage for video lessons. We have also been in active communication with the teachers who were supposed to participate, and are giving them priority for this coming year.

We also had to cancel our planned sampling for our ROA supplement, and communicated with NSF regarding postponing the sampling until 2021.

Finally, we terminated our subcontract with Coastal Carolina University due to changes in the responsibilities of both of the CCU investigators (R. Viso and R. Peterson). Although this means foregoing the groundwater measurements that they were planning to carry out, this was a minor component of the project and there are other key personnel who are continuing to evaluate groundwater. These change, which did not affect the overall objectives or scope of work of the project, were shared with our program officer.

Products and Publications

<u>Book Chapters</u>

Alber, Merryl and Blair, John M. and Driscoll, Charles and Ducklow, Hugh and Fahey, Timothy and Fraser, William R. and Hobbie, John E. and Karl, David M. and Kingsland, Sharon E. and Knapp, Alan and Rastetter, Edward and Seastedt, Timothy and Shaver, Gaius and Waide, Robert B. (). Sustaining Long-Term Ecological Research: Perspectives from Inside the LTER Program. *The Challenges of Long Term Ecological Research: Historical Analysis.*

<u>Conference Papers and Presentations</u>

Bice, Kadir and Schalles, John F. and Meile, Christof (2020). *Factors determining GA salt marsh biomass: A dynamical systems approach*. 7th Annual Southeastern Biogeochemistry Symposium. Atalnta (online due to COVID-19).

Bice, Kadir and Wrighton, K.C. and Daly, R.A. and Schopflin, L. and Danczak, R. and Song, H.-S. and Schalles, John F. and Meile, Christof (2020). *Investigating subsurface biogeochemistry in tide-impacted Altamaha River sediment using microbial metagenomics and metabolomics*. AGU Fall meeting. San Francisco (online due to COVID-19).

Martineac, Rachel P. and Medeiros, Patricia M. (2020). *What controls DOM composition variability in marsh-dominated estuaries?* Ocean Sciences Meeting. San Diego, CA.

Schalles, John F. (2020). *High resolution salt marsh vegetation biomass mapping with an Altum 6 band camera and Matrice 210 drone*. Drones in the Coastal Zone - U.S. Southeast and Caribbean Regional Workshop.

Schalles, John F. and Peffer, Colby (2020). *Regulatory, Legal, and Ethical Considerations for Drone Operations - The view from coastal Georgia* . Drones in the Coastal Zone - U.S. Southeast and Caribbean Regional Workshop.

Schalles, John F. (2020). *Using satellite, airborne, and drone remote sensing to study spatial-temporal patterns and responses to stressors in coastal wetlands*. Lamar University Biology Department Invited Speakers Program.

Journals

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Gaskins, Leo C. and Paxton, Avery B. and Silliman, Brian R. (2020). Megafauna in Salt Marshes. *Frontiers in Marine Science*. 7.

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<u>Thesis/Dissertations</u>

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