GCE-IV Annual Report – Year Three (2022)

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 of estuary and intertidal variation (Area 2); process studies (Area 3); and integration and scaling up (Area 4). Our major goals within these areas are as follows:

Area 1: to characterize external drivers such as climate change, sea-level rise, and human alterations of the landscape 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 describe the temporal and spatial variability of habitats within the GCE study area in relation to changing external drivers (Area 1). This also provides a record that allows us to evaluate ecosystem responses to long-term change and domain perturbations.

Area 3: to develop a mechanistic understanding of ecosystem function and response to both long-term and episodic changes in order to understand ecosystem properties and driver-response relationships.

Area 4: to document and evaluate the consequences of long-term change and disturbance at the landscape scale.

WHAT WAS ACCOMPLISHED UNDER THESE GOALS?

The GCE works in four main areas (Activities Fig. 1). The specific objectives associated with each of these are listed below.

Below we summarize our major activities and highlight significant results for each of the objectives from this past year.

Area 1: External Drivers of Change

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

Area 1A Objectives

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

> Year Three Activities: Several meteorological stations are used to characterize the GCE domain (Fig. 2) and we operate climate stations at Marsh Landing and the flux tower. We also track sea level, offshore wind forcing, and river discharge. We have a Campbell Water Level Sensor ready to deploy to ensure that our long-term tide gage data are not disrupted by upcoming dock renovations.
>
> Significant Results: The NOAA Fort Pulaski sea level gage shows an increase in relative sea level

of 3.37 mm/yr for the period of 1936-2020, and a much greater increase of 8 mm/yr since the onset of the GCE project in 2000. The number of flooding events that exceed 1.7 m in sea level height relative to mean sea level also shows an increasing trend, with more than 30 events per year in 2015, 2016, 2019, and 2020 (Fig. 1).

2. Maintain an eddy covariance tower in the Duplin River

Year Three Activities: The GCE flux tower on the Duplin River measures CO_2/H_2O, weather conditions, radiation, water levels, and soil temperature. Maintenance is conducted on a regular basis including replacement of thermocouples, sensor cleaning and calibration.

Significant Results: We have developed a workflow to process raw 10Hz eddy covariance data to 30-min net ecosystem exchange (NEE). Nahrawi et al. (2020) evaluated data from 2014-15 and demonstrated that NEE responds to both seasonal and tidal variation (Fig. 2).

3. Monitor Altamaha River water entering the GCE domain

Year Three Activities: We routinely collect monthly samples of water entering the GCE domain via the Altamaha River for analysis of nutrients, DIC, alkalinity and pH. We have experienced COVID-related delays in sample processing.

Significant Results: Letourneau et al. (2021) completed an analysis of DOM composition of water entering the GCE domain (see Accomplishments). Note that the monthly median discharge of the Altamaha River exceeded 2000 $m^3 s^{-1}$ in 2020, which is the highest ever recorded since the start of the GCE project.

4. Conduct dendrochronology analysis

Year Three Activities: Napora (2021) completed an analysis of bald cypress tree ring data from the last 5,117 years (Fig. 3). This is now the longest dendrochronological record east of the Mississippi River.

Significant Results: Variation in bald cypress tree growth shows periods of drought and provides insight into long-term fluctuations in climate (Napora et al. 2019; Napora 2021).

Area 1B Objectives

1. Assess Native American oyster harvesting practices

Year Three Activities: Oyster shells from three archaeological sites in the GCE domain are being processed for ^{18}O.

Significant Results: ^{18}O data indicate sea level shifts and salinity variability during periods that coincide with the abandonment of sites by Native American communities.

2. Evaluate how human activity relates to marsh inundation patterns

Year Three Activities: We have deployed data loggers in drainage ditches to evaluate salt water incursion into populated areas of Sapelo Island. We also continue to examine how property ownership and development interface with flooding patterns. A new ROA supplement will extend our ethnographic research to incorporate information on traditional ecological knowledge of coastal resources.

Significant Results: We are examining long-term changes in land use and the combined ramifications of climate change and land loss in the Saltwater Geechee community (Hardy and Heynen 2020; Hardy et al. in press).

3. Track shoreline armoring

Year Three Activities: Our last periodic assessment was completed in 2018, with the next one targeted for 2024.

Significant Results: We are participating in an oyster conservation project that is evaluating the potential to use discarded shells for living shorelines and other green infrastructure on the Georgia coast.

Area 2: Long-Term Patterns of Estuary and Intertidal Variation

We collect data documenting key ecosystem variables across the GCE domain. Major activities in this area consist of A) field monitoring of water and marsh attributes and B) remote sensing.

Area 2A Objectives

1. Continue the GCE core monitoring program in the water column

Year Three 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. 4).

Significant Results: GCE monitoring data are being used to calibrate and validate a water quality model for the GCE domain (Sheldon et al. 2021; see Objective 4C).

2. Measure water exchange between the Duplin River and Doboy Sound

Year Three Activities: The horizontal acoustic profiler in the Duplin River was removed because the dock to which it was mounted is being replaced; we are evaluating options for re-deployment.

Significant Results: Data from the horizontal acoustic profiler demonstrate consistent net outflow from the Duplin River, which suggests a southerly buoyant flow (Fig. 3).

3. Evaluate patterns of dissolved organic matter in the water column

Year Three Activities: We conducted a focused study to characterize variability in dissolved organic matter composition in Doboy Sound.

Significant Results: Martineac et al. (2021) showed that the dominant pattern of variability in DOM composition occurs at seasonal scales (see also Accomplishments).

4. Continue the core monitoring program in the marsh and tidal fresh forest

Year Three Activities: We monitor plants, invertebrates and soils in 2 zones at each of our 10 marsh sites and the tidal fresh forest (Table 1, Fig. 4). This past year we replaced SETs at sites 4 and 6, which failed after 20 years. We also monitor vegetation dynamics along the salinity gradient of the Altamaha River estuary (see Obj. 4B1).

Significant Results: Adams et al. (2021) analyzed 20 years of data on salt marsh katydid densities at the GCE sites. They found much higher densities of *Orchemlium fidicinium* at sites with extensive adjacent upland, which may provide habitat for reproduction or escape from predators during extreme high tides (Fig. 4).

5. Characterize groundwater flow

Year Three Activities: We monitor groundwater at a series of wells associated with the high marsh manipulation and at the upland-marsh transition at Marsh Landing. We are also evaluating groundwater patterns across Sapelo Island using water level observations in ponds.

Significant Results: We constructed a 2-D variable-density groundwater flow model based on the Marsh Landing site (Sanders 2021), which is currently being refined to improve the match between simulated and observed hydraulic head and groundwater salinity.

Area 2B Objectives

1. Continue PhenoCam observations

Year Three Activities: We continue to maintain the “GCESapelo” Phenocam, which focuses on a Spartina marsh. This year we identified a site for a “GCEJuncus” camera, began field observations, and set up temperature and water level sensors.

Significant Results: Narron et al. (submitted) leveraged the multi-year archive of PhenoCam observations to develop an algorithm that detects flooding in Landsat imagery (see Accomplishments).

2. Continue regular aerial photographs of the GCE domain

Year Three 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: High resolution orthoimagery of the GCE domain was used in delineating and training image classifiers in support of Objectives 2B.4 and 4B.1.

3. Conduct drone surveys of selected sites

Year Three Activities: We are using the drone to conduct monthly flyovers of selected marshes to track disturbances (see Area 4A). We have also added an annual survey of high marsh transitional areas.

Significant Results: Monthly drone imagery is revealing high resolution patterns of Spartina biomass (Fig. 5) (See also Obj. 4A4).

4. Leverage satellite imagery to scale up observations

Year Three Activities: We are using salinity data collected by the sondes to develop tools to predict sea surface salinity from the Sentinel-2 satellite. We are also using satellites to aid in habitat classification (Obj. 4B1) and to track Spartina biomass at large spatial scales.

Significant Results: Biomass estimates derived from Sentinel 2 show strong coherence across the Georgia coast and are similar to estimates derived from Landsat (Fig. 6).

Area 3: Process Studies

We conduct A) long-term manipulations and B) focused investigations to understand ecosystem properties and driver-response relationships.

Area 3A Objectives

1. Track recovery in the SaltEx experiment

> Year Three Activities: We continue to track recovery in the SALTEx experiment following cessation of experimental dosing in December 2017.
>
> Significant Results: Analyses of the SALTEx experiment show differential response curves to salinity: porewater NH_4 increased linearly and DOC concentrations decreased as a power function, whereas other constituents showed no significant trends (Fig. 7).

2. Continue the PredEx experiment

> Year Three Activities: We continue sampling the predator exclusion experiment initiated in summer 2016. This past year we conducted additional mesopredator tethering trials.
>
> Significant Results: Mesopredators (mud crabs) have increased in the predator exclusion treatment after several years, and are likely the reason that other invertebrates have not increased dramatically as we expected. We are planning to conduct a mesopredator x nekton presence experiment in 2022 to tease apart their relative effects.

3. Continue the high marsh manipulation

> Year Three Activities: The high marsh experiment was largely ineffective at altering groundwater flow, but the data are useful for understanding hydraulic gradients. We plan to decommission this experiment in 2022.
>
> Significant Results: We are using data from the wells to monitor groundwater conditions to better understand fluxes of groundwater in the high marsh (see Objective 2A4).

4. Establish a disturbance manipulation

> Year Three Activities: We started the DRAGNET distributed disturbance experiment in 2021 and are planning experiments in which we will implement a standardized disturbance across natural gradients of salinity and elevation to test the hypothesis that underlying abiotic gradients affect marsh recovery from disturbance.
>
> Significant Results: None to date

Area 3B Objectives

1. Investigate controls of *Spartina alterniflora* production

> Year Three Activities: We have multiple efforts underway to collect information on how temperature and flooding affect plant production. In June 2021 we began monthly sampling of vertical profiles of leaf area index in *S. alterniflora* canopies to quantify the effects of tidal flooding; in December we set up a hydroponic experiment to evaluate how winter soil temperature interacts with salinity and nutrients to affect belowground processes and *S.*

alterniflora phenology (Fig. 5).

Significant Results: Hawman and Mishra (in prep) found that NEE decreased sharply under flooded conditions, and that accounting for changes in emergent leaf area index due to tidal flooding improved relationships with the Sentinel-2 near-infrared reflectance index.

2. Investigate marsh fauna

Year Three Activities: We continue to conduct focused studies to understand the relationships between marsh fauna and environmental variables. Activities this past year included studies of detritivores, variation in metabolic rate of snails, and the effects of herbivory by megafauna on salt marsh invertebrates. We also continue to refine designs for biomimic sensors.

Significant Results: Seer et al. (2021) found that the colonization of litter by infauna shifts during decomposition as litter becomes less labile (Fig. 8).

3. Enhance our understanding of coastal carbon dynamics

Year Three Activities: We are collaborating with the Univ. of Wisconsin to collect pCO_2 data at the GCE flux tower to understand CO_2 export by tidal waters. We also completed a lab experiment on decomposition controls under varying oxygen conditions and bioavailable C inputs.

Significant Results: GCE was part of a cross-site study that highlighted the significant role of transport in organic matter dynamics (Harms et al. 2021).

Area 4: Integration and Scaling Up

We are using the results from Areas 1-3, along with targeted sampling, to A) track the temporal and spatial patterns of perturbations and assess their cumulative effects, B) produce synoptic descriptions of landscape change, and C) develop models that can provide insight into the patterns of GCE data and the relationships between drivers and responses.

Area 4A Objectives

1. Assess the effects of wrack perturbations

Year Three Activities: We continued monthly drone flights at the Dean Creek site, which are used to guide selection of wrack patches for field sampling. We are currently sampling a suite of variables (plants, invertebrates, porewater, temperature, decomposition) in 16 wrack patches (plus paired controls).

Significant Results: We have not seen differences to date in areas affected by wrack in terms of decomposition, soil organic matter, or ammonium concentrations. However, there is a significant decline in Spartina, snail, and crab density; initial observations suggest they take 7-11 months to recover.

2. Assess the effects of creek perturbations

Year Three Activities: We plan to use the monthly drone flights (Obj. 4A1) and aerial photos (Obj. 2B2) to evaluate changes in creek configuration and creek slumping over time.

Significant Results: Wu et al. (2021) found sharp differences in the effects and recovery trajectories of different variables in response to headward-eroding creeks.

3. Assess the effects of dieback and other perturbations

Year Three Activities: We identified several incipient dieback areas (areas where the plants turned prematurely brown) using the drone flights over Dean Creek and have set up plots in two areas where we are sampling the same variables as those being followed in the wrack patches (Obj. 4A1).

Significant Results: Hensel et al. (2021) found that hogs maintain large disturbed patches in marshes by feeding on both plants and mussels. This paper, which was in Nature Communications, has had significant news coverage, as it showed that megafauna can reduce the resilience of salt marshes.

4. Synthesize results into a scaled-up disturbance-scape

Year Three Activities: This past year we streamlined the workflow for processing drone imagery using PCA, and also collected temperature data to calibrate the drone's thermal band to aid in identifying wrack patches.

Significant Results: Regular drone flights over the airport marsh site (7 flights from Jul-2019 through May-2020) showed that most wrack is found close to the water's edge, but it persists longer at higher elevations. Although wrack only affected ~5% of the site, wrack patches can be persistent or re-occur in the same spot repeatedly: 1/3 of the wrack-affected pixels were covered in more than 1 image (Fig. 9).

Area 4B Objectives

1. Track habitat shifts along the Altamaha River estuary salinity gradient

Year Three Activities: We collected ground reference data in the tidal fresh forest to improve and validate our habitat classification of Sentinel-2 imagery. We also continue annual bankside surveys along the Altamaha River salinity gradient, as well as monitoring of mixed vegetation on Broughton Island.

Significant Results: Hierarchical clustering using ground reference data were used to create a dataset that will be used for classification of Sentinel-2 data. An initial classification using the MLC classifier was quite promising (Fig. 10).

2. Conduct synoptic assessments of productivity

Year Three Activities: We collected ground observations of Juncus biomass, which we are using to calibrate biomass estimates derived from Sentinel-2 imagery. This will complement our existing estimates of Spartina biomass. We are also poised to get scaled-up GPP estimates of the domain from MODIS based on our parameterized Light Use Efficiency model for *S. alterniflora*.

Significant Results: Hawman et al. (2021) evaluated the annual cycle of GPP and light use efficiency measured at the flux tower and found that the cloudiness index and daily maximum tide height were the primary factors that explained deviation in *S. alterniflora* light use efficiency.

3. Evaluate long-term change in vegetated marsh area

Year Three Activities: We continued analyzing soil cores collected along elevation, salinity, and disturbance gradients, to provide insight into how shifts in vegetation and changes in creek morphology affect accretion rates and carbon accumulation.

Significant Results: O'Connell et al. (2021) found that belowground biomass is declining in some interior marsh areas over time, perhaps indicating areas of low marsh resiliency to sea-level rise. We also participated in a cross-site effort (Zinnert et al. 2021) that described the state changes expected in coastal wetlands in response to long-term changes in temperature and sea level (Fig. 11).

Area 4C Objectives

1. Upgrade hydrodynamic models

Year Three Activities: We have successfully implemented the hydrodynamic, heat flux, and water quality modules of Delft3D in the GCE domain.

Significant Results: Output from the Delft3D hydrodynamic model indicate that variability in temperature and salinity are realistically represented (Fig. 12).

2. Enhance soil model

Year Three Activities: We are using data collected at the flux tower (Obj. 1A2) to validate and revise our soil temperature model.

Significant Results: The soil model simulates radiative forcing and heat propagation in the marsh subsurface.

3. Model plant production

Year Three Activities: Our Belowground Ecosystem Resilience Model uses extreme gradient boosting to predict below-ground biomass of *S. alterniflora* (O'Connell et al. 2021).

Significant Results: The BERM model (O'Connell et al. 2021) is based on above-ground proxies and can be scaled with readily available remote sensing data to evaluate spatiotemporal patterns in belowground biomass (Fig. 13).

4. Develop driver-response models

Year Three Activities: We are using empirical mode decomposition and wavelet coherence analysis to investigate patterns in hydrological forcing to the GCE domain and assess the correspondence between them. We have also developed a series of nonlinear driver-response models in which the driver and response obey different mathematical forms.

Significant Results: We have analyzed the timeseries of satellite-derived marsh productivity data (Objective 2B4) and flux tower-derived net ecosystem exchange fluxes (Objective 1A2) using entropy-based approaches and methods in dynamical systems analysis to identify causal connections to timeseries reflecting environmental forcing (Fig. 14).

GCE Activities Year 3 Figures

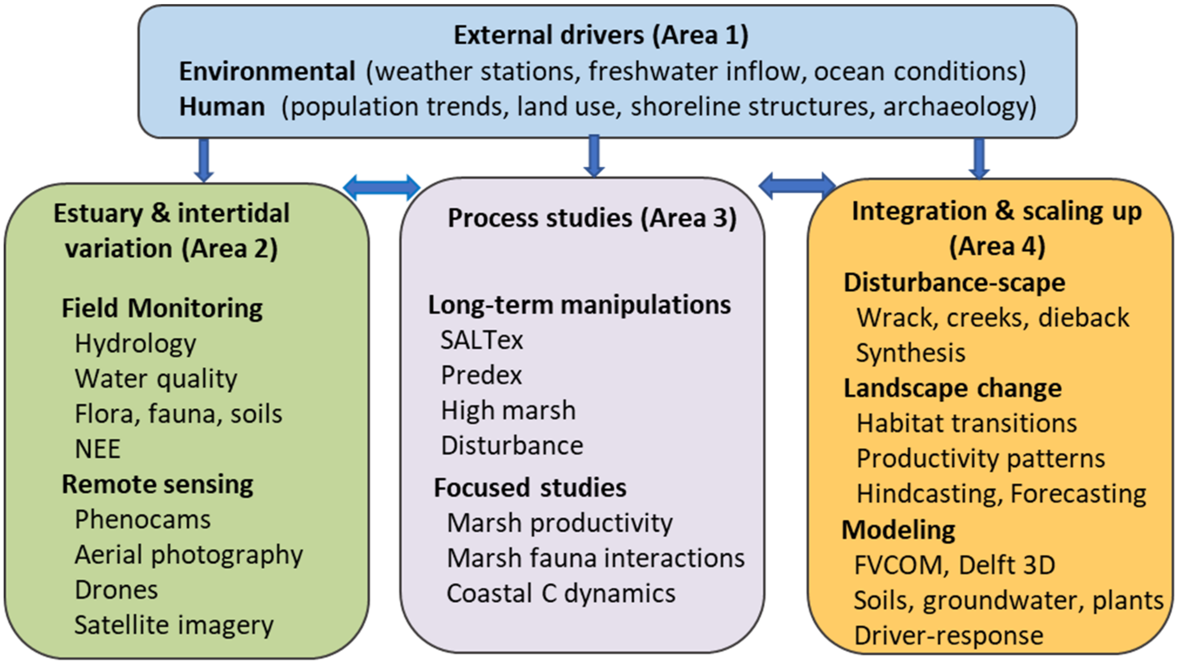

Fig. 1. GCE-IV Research Portfolio showing major components of each program area.

Area 1: External Drivers of Change

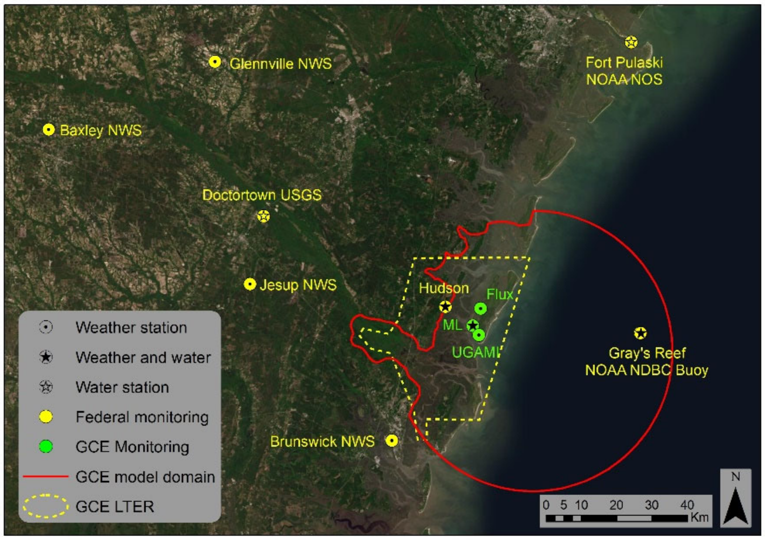

Fig. 2. Locations of observing stations used for boundary conditions (ML is Marsh Landing; UGAMI is UGA Marine Institute). Corresponds to Objective 1A.1: Collect ongoing information on climate and oceanographic conditions, sea level, and river discharge.

GCE Activities Year 3 Figures

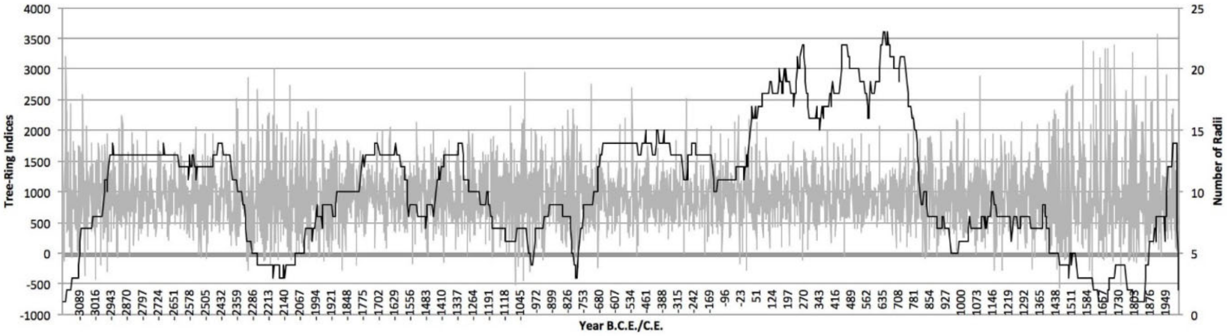

Fig. 3. Dendochronology from bald cypress tree cookies collected at the mouth of the Altamaha River, showing changes in annual tree rings over 5177 years (left axis) along with the number of radii available for each year (right axis). Source: Napora 2021. Corresponds to Objective 1A.4: Conduct dendrochronology analysis.

Area 2: Patterns within the Domain

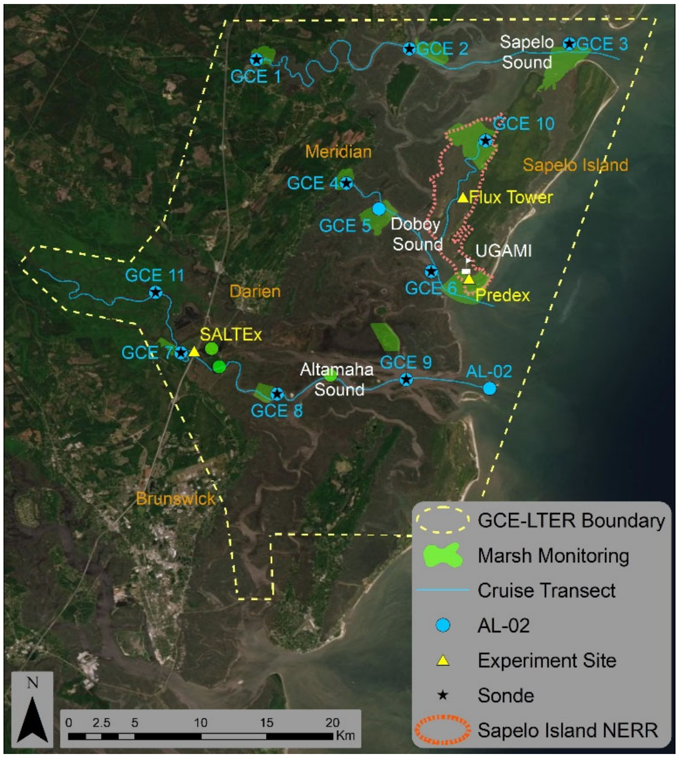

Fig. 4. GCE domain showing core monitoring stations. Corresponds to Objective 2A.1: Continue the GCE core monitoring program in the water column and 2A.2: Continue the core monitoring program in the marsh and tidal fresh water.

GCE Activities Year 3 Figures

Table 1. Monitoring program for GCE-IV. LTER core areas are 1: primary production, 2: populations, 3: organic matter cycling, 4: inorganic nutrients, 5: disturbance. 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	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	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	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	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	Mouth of Duplin R.	15 min	Abiotic driver of 1-5. Horizontal ADCP measurements of water flux
Area 2 Marshes			
Soil accretion	Sites 1-11	Annual	3. Sediment accretion, elevation, compaction
Soil temperature	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	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	Sites 1-10	Annual	5. Disturbance in permanent vegetation plots
Plant composition	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	Sites 1-11	Annual	2. Density and size of benthic macroinvertebrates (mollusks, crab burrows) in 2 marsh zones.
Insects	Sites 1-6, 9, 10	Annual	2. Density of grasshoppers in salt marsh transects
Recruitment	Sites 1-11	Annual	2. Recruitment of barnacles to standard substrates

Area 3: Marsh Response to Disturbance

Fig. 5. Greenhouse experiment set up in Dec. 2021 to determine how over-wintering Spartina plants respond to different levels of temperature, salinity and nutrients. Plants are being grown hydroponically to allow us to follow both above- and below-ground production. Source: J. O'Connell and S. Pennings. Corresponds to Objective 3B.1: Investigate controls of Spartina alterniflora production.

GCE Significant Results Year 3 Figures

Area 1: External Drivers of Change

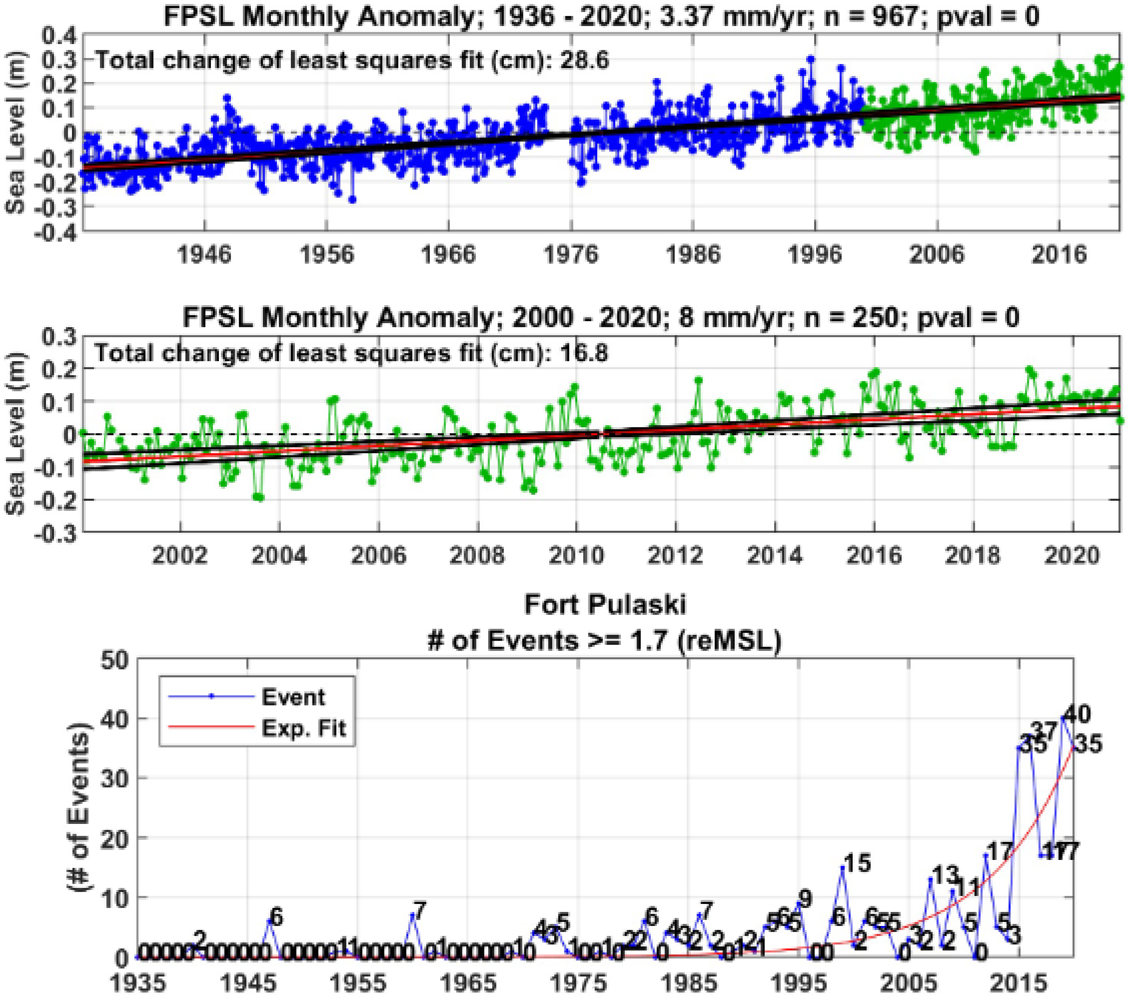

Fig. 1. Trends in sea surface height and flooding events on the Georgia coast based on data from the NOAA Fort Pulaski sea level gage. There has been an increase in monthly anomalous sea level height of 3.37 mm/yr for the period of 1936-2020 (top); and a much greater increase of 8 mm/yr since the onset of the GCE project in 2000 (middle). The number of flooding events that exceed 1.7 m relative to mean sea level also shows an increasing trend, with more than 30 events per year in 2015, 2016, 2019, and 2020 (bottom). Source: D. Di Iorio. Corresponds to Objective 1A.1: Collect ongoing information on climate and oceanographic conditions, sea level, and river discharge.

GCE Significant Results Year 3 Figures

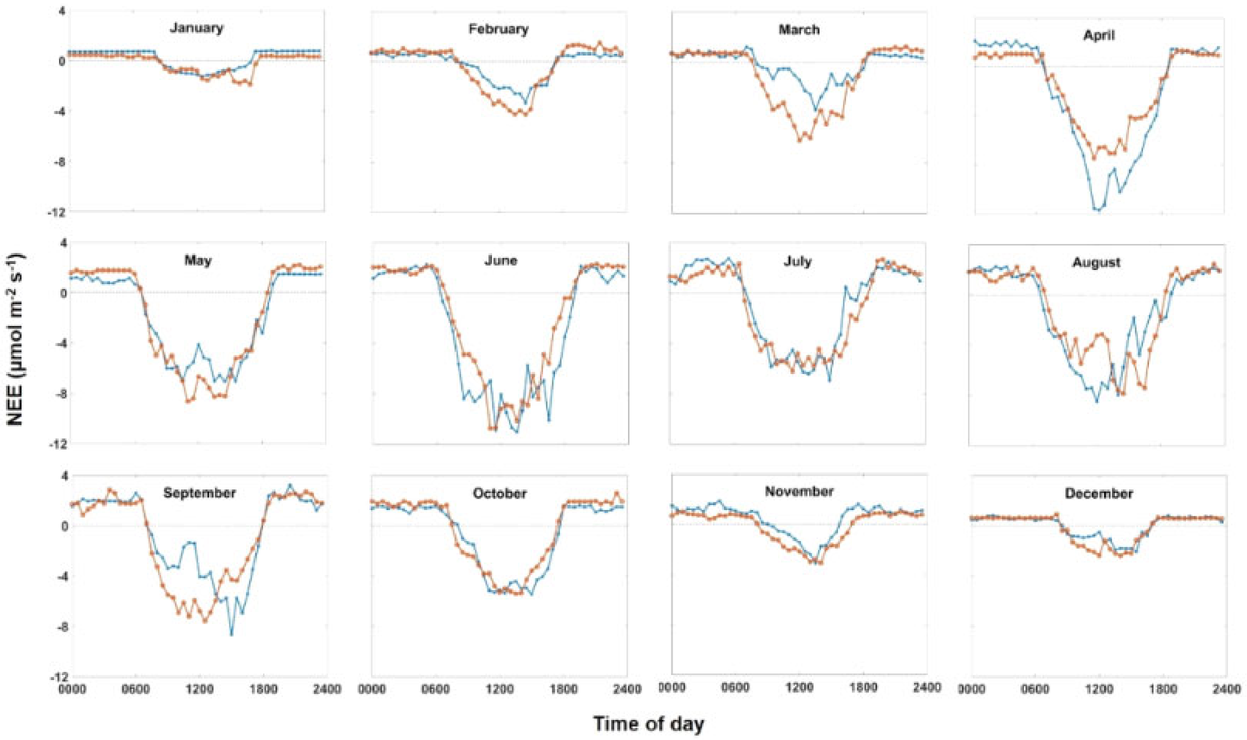

Fig. 2. Diurnal patterns in monthly average NEE estimated from the GCE flux tower during 2015. Blue and orange lines represent spring and neap tides, respectively. Source: Nahwari et al. 2020. Corresponds to Objective 1A.2: Maintain an eddy covariance tower in the Duplin River.

Area 2: Patterns within the Domain

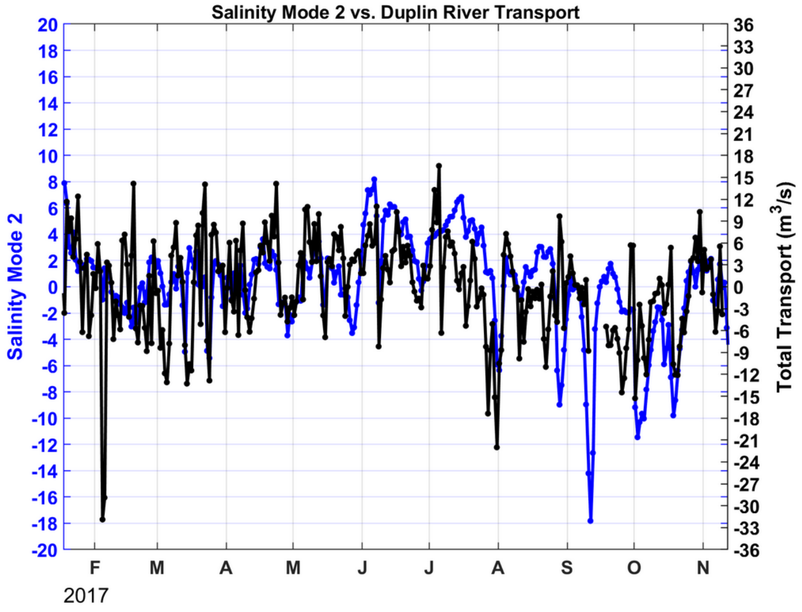

Fig. 3. The tidal and synoptic transport at the mouth of the Duplin River reveal a consistent net outflow (right axis), which is related to the EOF mode 2 salinity variations (left axis). This is consistent with a southerly buoyant flow that connects estuaries all along the GA coast. Source: D Di Iorio and J. Kelly. Corresponds to Objective 2A.2: Measure water exchange between the Duplin River and Doboy Sound.

GCE Significant Results Year 3 Figures

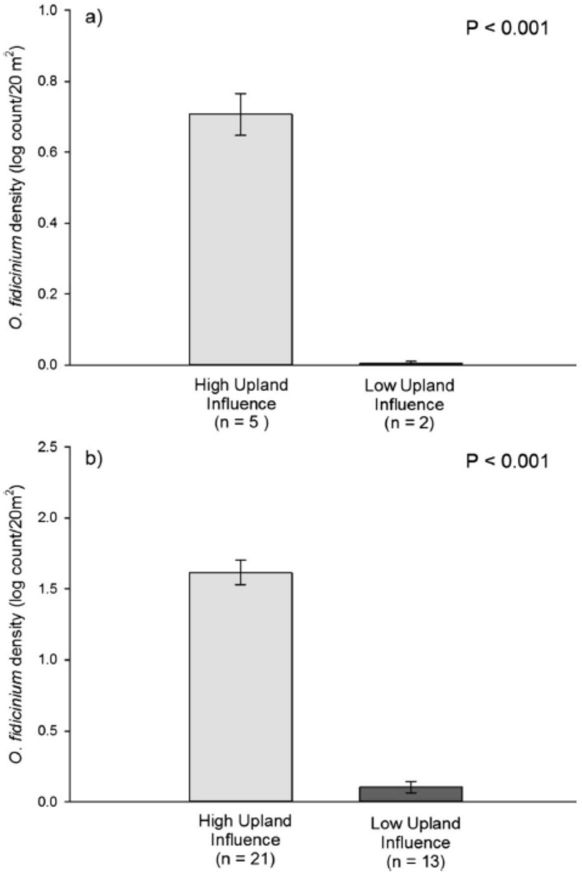

Fig. 4. Mean densities of *Orchelium fidicinium* in GCE marshes with high versus low upland influence. a) data from 7 long-term sites monitored from 2003-19; b) data from a one-time sampling of 34 sites in 2003. Bars represent standard errors. Source: Adams et al. 2021. Corresponds to Objective 2A.4: Continue the core monitoring program in the marsh and tidal fresh forest.

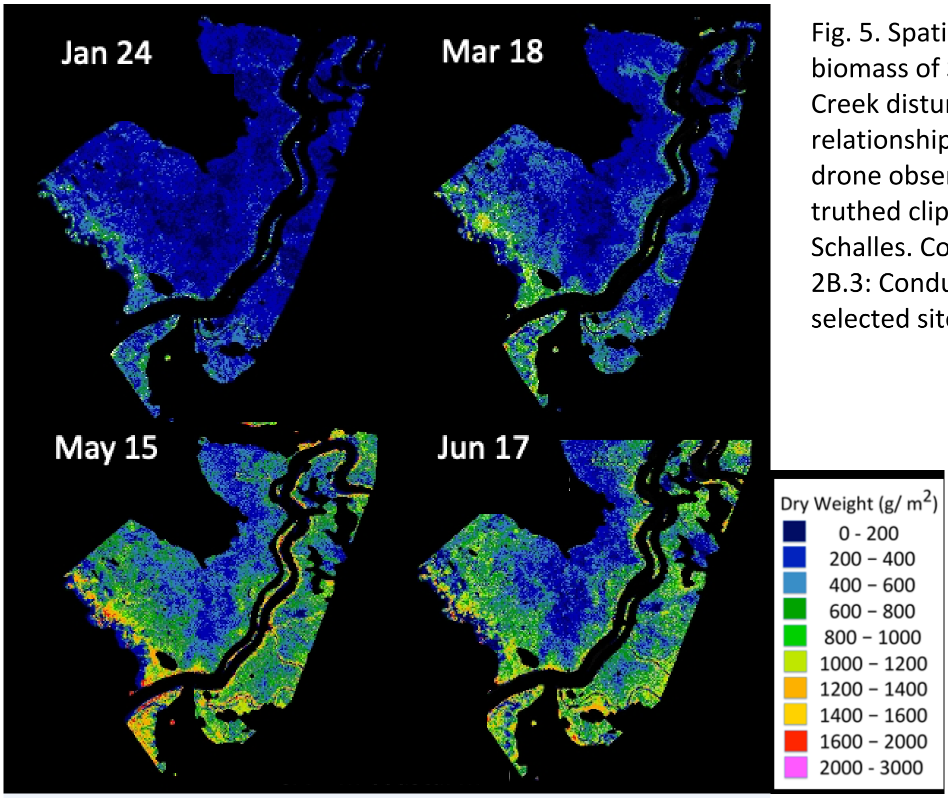

Fig. 5. Spatio-temporal patterns of biomass of Spartina at the Dean Creek disturbance site, based on relationship between NDVI from drone observations and ground-truthed clip plot data. Source: J. Schalles. Corresponds to Objective 2B.3: Conduct drone surveys of selected sites.

GCE Significant Results Year 3 Figures

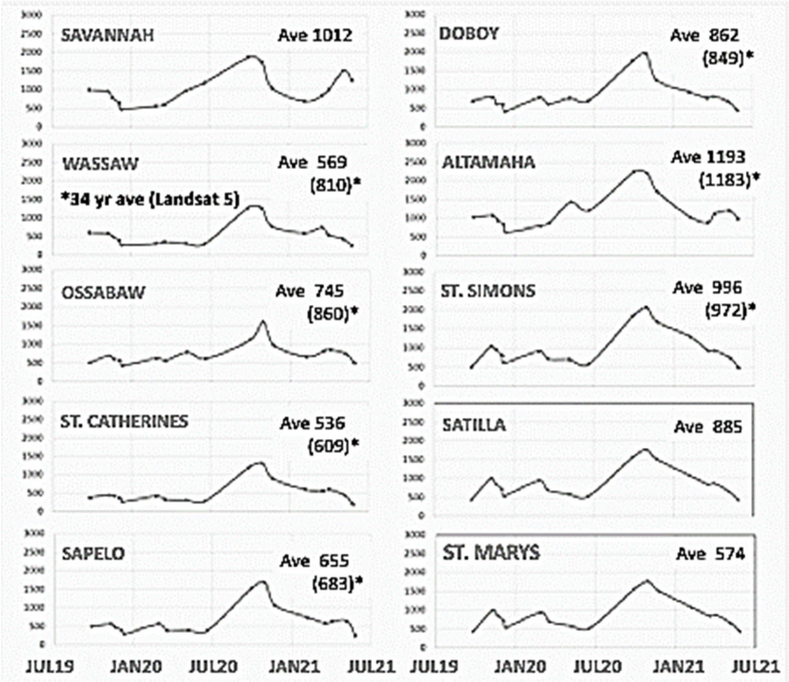

Fig. 6. Patterns of above-ground Spartina biomass for major watersheds along the Georgia coast, estimated from Sentinel-2 satellite data for the period Sept. 2019-Mar 2021. Numbers in parentheses represent averages based on 34 years of Landsat5 observations. Source: J. Schalles. Corresponds to Objective 2B.4: Leverage satellite imagery to scale up observations.

Area 3: Marsh Response to Disturbance

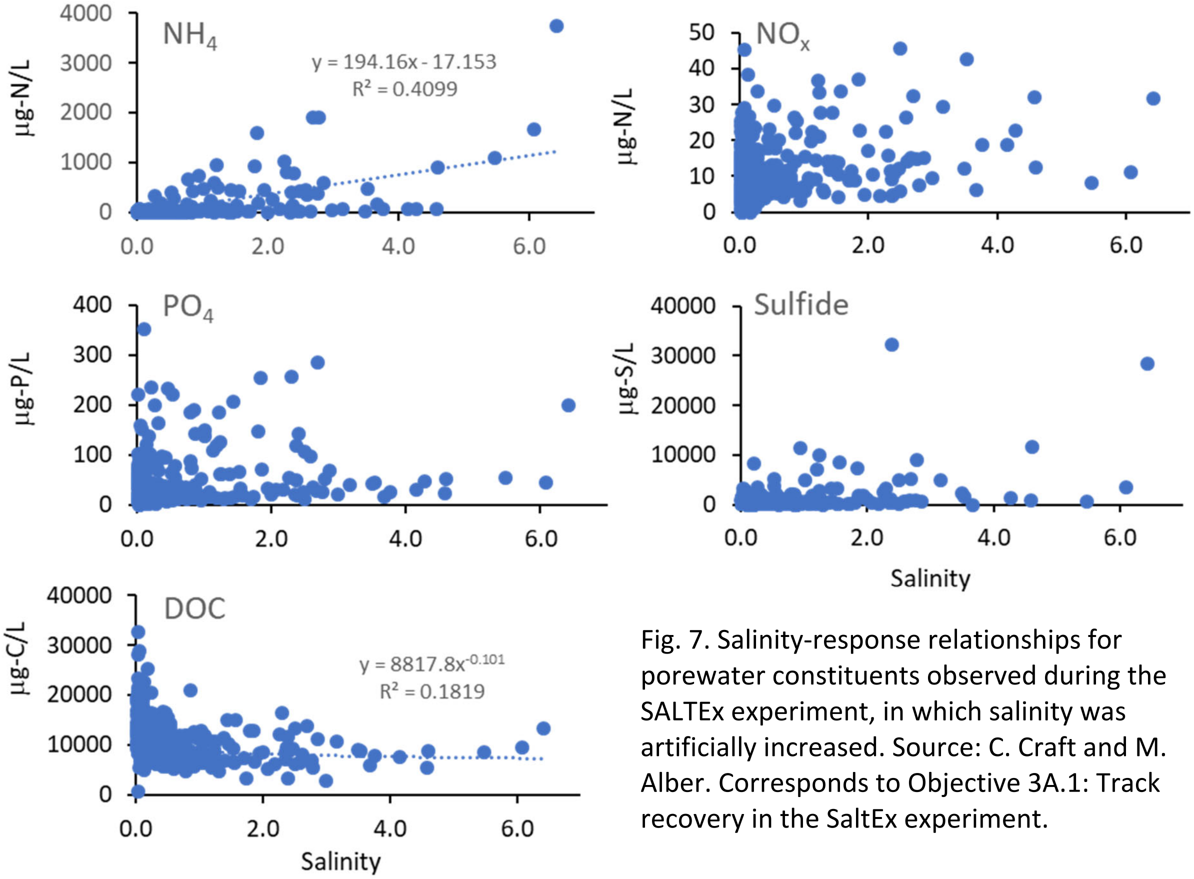

Fig. 7. Salinity-response relationships for porewater constituents observed during the SALTEx experiment, in which salinity was artificially increased. Source: C. Craft and M. Alber. Corresponds to Objective 3A.1: Track recovery in the SaltEx experiment.

GCE Significant Results Year 3 Figures

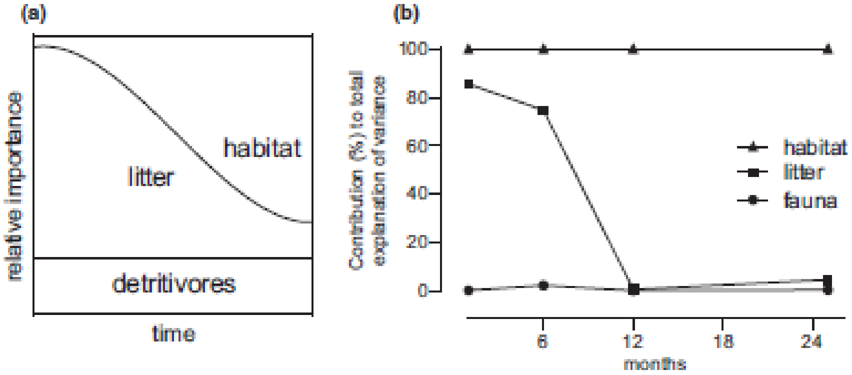

Fig. 8. Conceptual model (a) and experimental data (b) showing the shift from litter characteristics to habitat type in explaining the variance in the faunal composition of the decomposer community. Source: Seer et al. 2021. Corresponds to Objective 3B.2: Investigate marsh fauna.

Area 4: Integration and Scaling Up

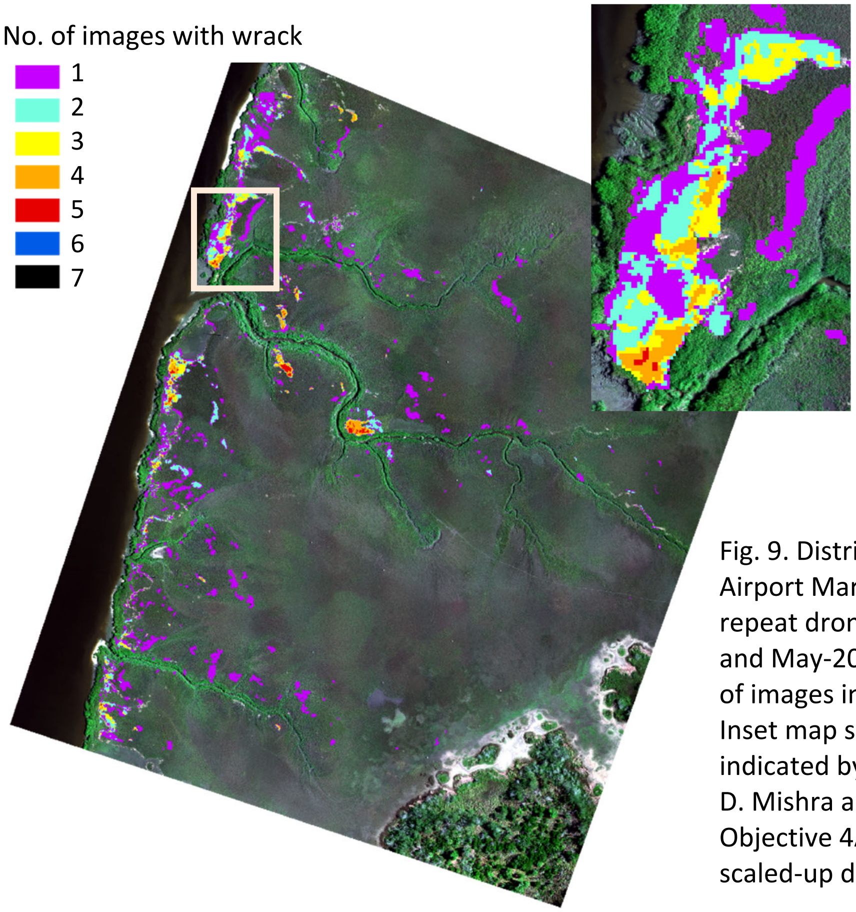

Fig. 9. Distribution of wrack cover at the Airport Marsh disturbance site based on repeat drone imagery between Jul-19 and May-20. Colors indicate the number of images in which an area had wrack. Inset map shows close-up of area indicated by white box. Source: T. Lynn, D. Mishra and M. Alber. Corresponds to Objective 4A.4: Synthesize results into a scaled-up disturbance-scape.

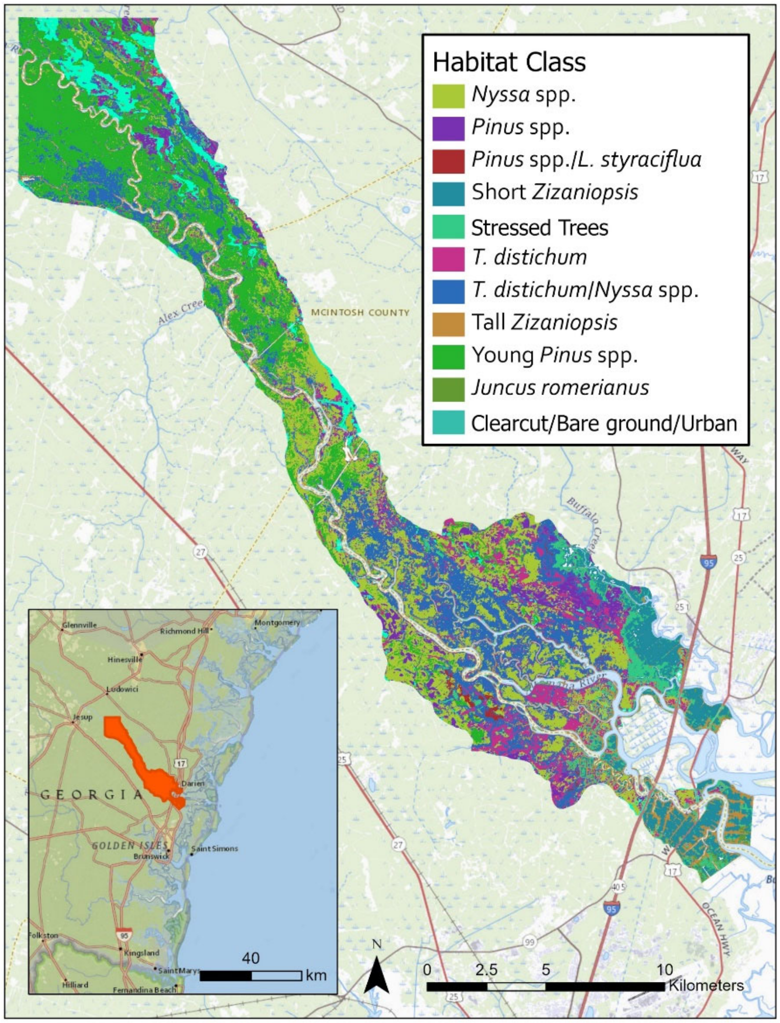

Fig. 10. Habitat classification of Sentinel-2 imagery of freshwater wetlands in the upstream portion of the Altamaha River estuary (inset). Maximum likelihood classification used all spectral bands plus the soil adjusted vegetation index (SAVI). Overall accuracy: 97.5%. Source: C. Hladik and G. Costomiris. Corresponds to Objective 4B.1: Track habitat shifts along the Altamaha River estuary salinity gradient.

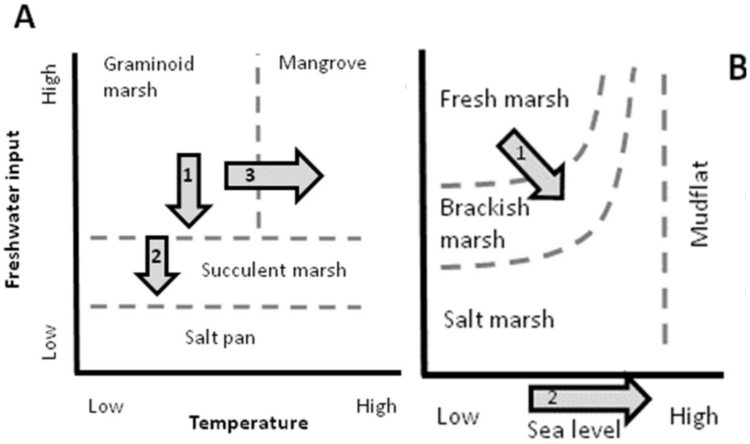

Fig. 11. Response of coastal wetlands to changes in freshwater input and A) temperature, and B) sea level. Conceptual models show how variation in these parameters result in different habitat types in estuarine wetlands. Source: Zinnert et al. 2021. Corresponds to Objective 4B.3: Evaluate long-term change in vegetated marsh area.

GCE Significant Results Year 3 Figures

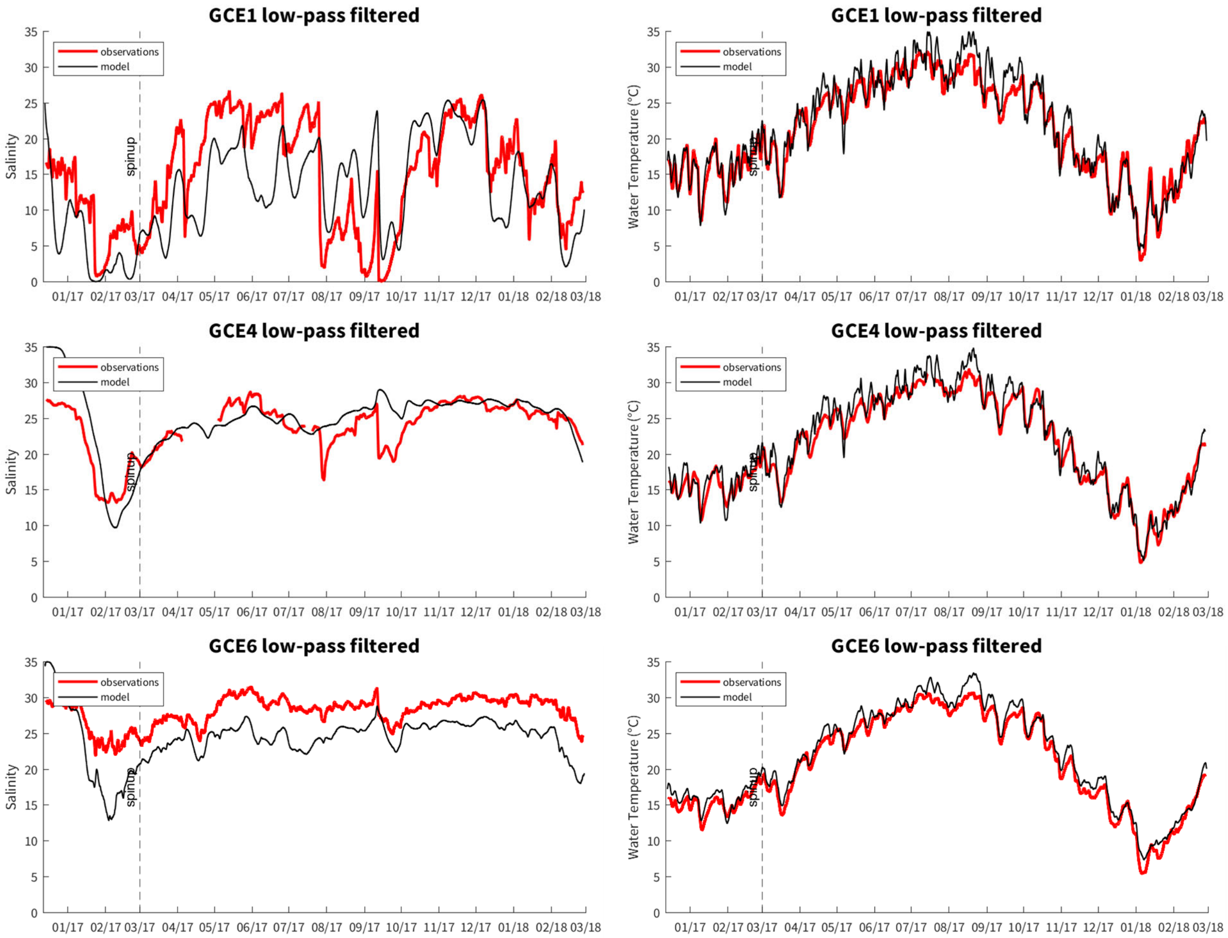

Fig. 12. 119-hr low-pass filtered salinity (left) and water temperature (right) from the sondes (red) and the hydrodynamic model (black) at sites GCE1 (top), GCE4 (middle), and GCE6 (bottom). A flow proxy of 2% of Ogeechee River discharge used at the (ungauged) head of Sapelo Sound fits the salinity variation at GCE1 well. Source: J. Sheldon and R. Castelao. Corresponds to Objective 4C.1: Upgrade hydrodynamic models.

GCE Significant Results Year 3 Figures

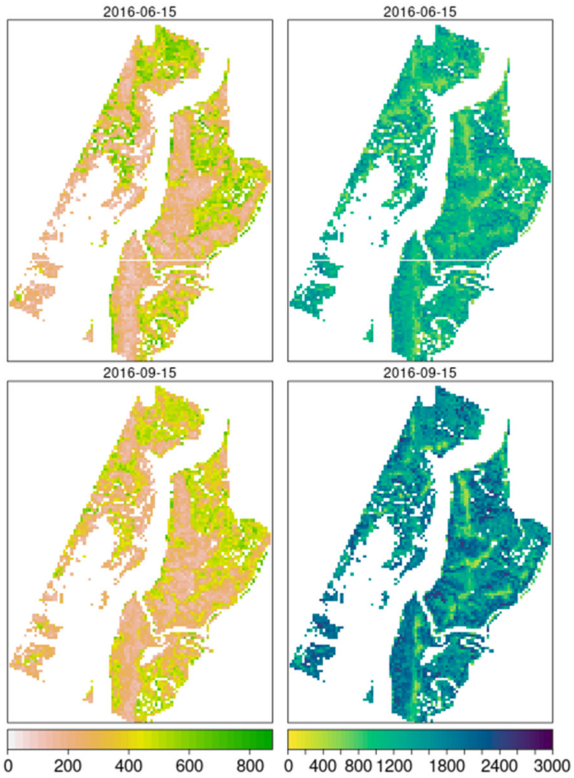

Fig. 13. Above (left) and belowground (right) biomass of Spartina at the GCE flux tower marsh on 6/15/16 (left) and 9/15/16 (right), estimated with our Belowground Ecosystem Resilience Model. Color ramps indicates biomass in g m^{-2}. Source: O'Connell et al. 2021. Corresponds to Objective 4C.3: Model plant production.

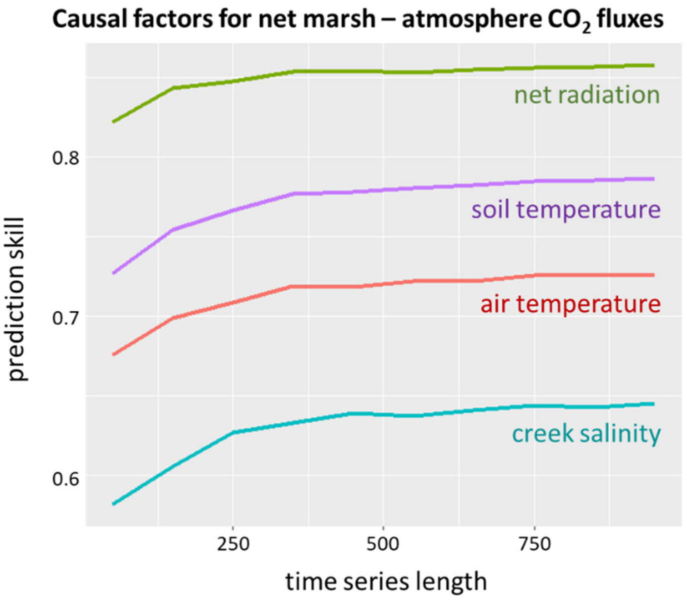

Fig. 14. Implementation of Convergent Cross Mapping to identify environmental factors that determine net CO2 fluxes measured at the flux tower. The time series length denotes the number of data points inputted to the method. The prediction skill gives the correlation between the predicted and observed values of the variables. A causal impact is inferred when the prediction skill increases with increasing time series length. Source: K. Bice and C. Meile. Corresponds to Objective 4C.4: Develop driver-response models.

WHAT WERE THE KEY OUTCOMES AND ACCOMPLISHMENTS?

Key accomplishments this past year include research on organic matter processing in estuaries, remote sensing tools for identifying wetland flooding, and comparisons with Chinese wetlands.

What Drives DOM Composition in Estuaries?

Dissolved organic matter is an important component of the carbon pool in estuaries, but it is difficult to characterize because it is not homogenous. DOM is comprised of a heterogenous mixture of aromatic and aliphatic compounds that can originate from a variety of terrestrial and in situ sources. Moreover, DOM is subject to microbial degradation as it transits through the system, and different compounds have differing availability. In recent years, GCE researcher P. Medeiros has conducted a series of studies aimed at teasing apart the sources and transformation patterns in DOM in order to understand what drives variability in estuarine DOM composition. These studies used a combination of approaches including measurements of bulk DOC concentration, optical (CDOM) and molecular (FT-ICR) analyses, as well as bacterial incubations and metatranscriptomics. Letourneau and Medeiros (2019) evaluated the DOM signatures of river water entering the coast via the Altamaha River. They found increased biodegradation of DOC when the discharge was high and the DOM composition was more terrigenous in character. This paper, in JGR Biogeosciences, was featured as an EOS research spotlight. Within the GCE domain, Letourneau et al. (2021) showed that the gradient from terrigenous to marine inputs was the dominant driver of DOM composition along the salinity gradient of the entire estuarine complex (Fig. 1). Although bacterial degradation rates were elevated in DOM with a higher terrigenous character, it was the less aromatic DOM that was preferentially degraded. They were also able to demonstrate large increases in both DOC concentration and biodegradation associated with the passage of Hurricane Irma. Finally, Martineac et al. (2021) showed that the dominant pattern of variability in DOM composition occurs at seasonal scales, which is likely associated with the seasonality of river discharge. Microbial data revealed a similar pattern, with variability in gene expression also occurring primarily at the seasonal scale (Fig. 2). Taken together, these analyses suggest that future changes in river discharge have the potential to significantly impact DOM composition and cycling in coastal systems.

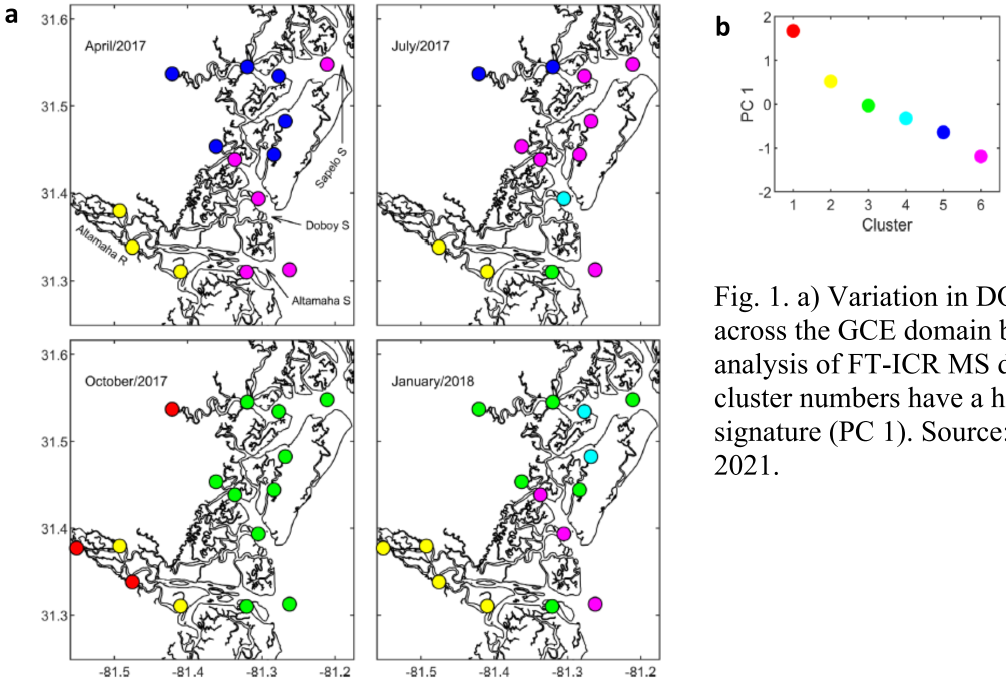

Fig. 1. a) Variation in DOM composition across the GCE domain based on cluster analysis of FT-ICR MS data. b) Lower cluster numbers have a higher terrigenous signature (PC 1). Source: Letourneau et al. 2021.

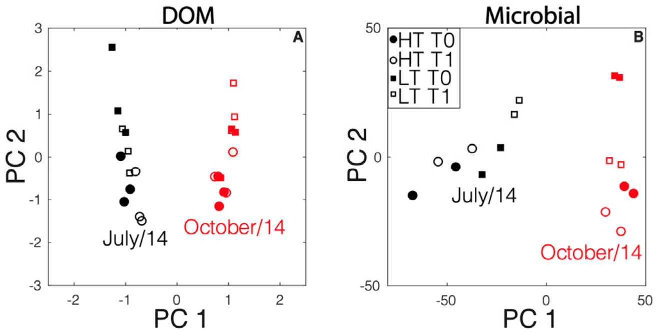

Fig. 2. PCA analysis of a) DOM composition and b) gene expression of samples collected in Doboy Sound at high (HT, circles) and low tide (LT, squares); before (T0, shaded symbols) and after 1-day incubations (T1, open symbols); during July (black) and October (red). In both data sets seasonal differences are the primary source of variability. Source: Martineac et al. 2021.

Tools for Tidal Filtering of Remote Sensing Imagery

One of the challenges in using aerial imagery to evaluate intertidal wetlands is the fact that they are regularly covered by water. Aerial images are most useful when the area is exposed, and airplanes and drone flights to assess wetlands are often strategically timed for low tide. However, most satellites that orbit the earth capture images regardless of flooding conditions. This provides a challenge for researchers interested in studying wetlands, as flooding reduces spectral reflectance, making vegetation indices and other characteristics inaccurate and highly variable. In 2017, GCE researcher J. O'Connell developed a tool called the Tidal Marsh Inundation Index (TMII) that automatically filters out inundated pixels in MODIS imagery. The TMII, which was validated based on imagery from the GCESapelo PhenoCam, has proven broadly useful for producing time series of wetland vegetation. It has been used extensively by GCE researchers (e.g. Tao et al. 2018; Alber and O'Connell 2019; Hawman et al. 2021; O'Connell et al. 2021) as well as by researchers at the Plum Island LTER (e.g. Forbrich et al. 2018), and

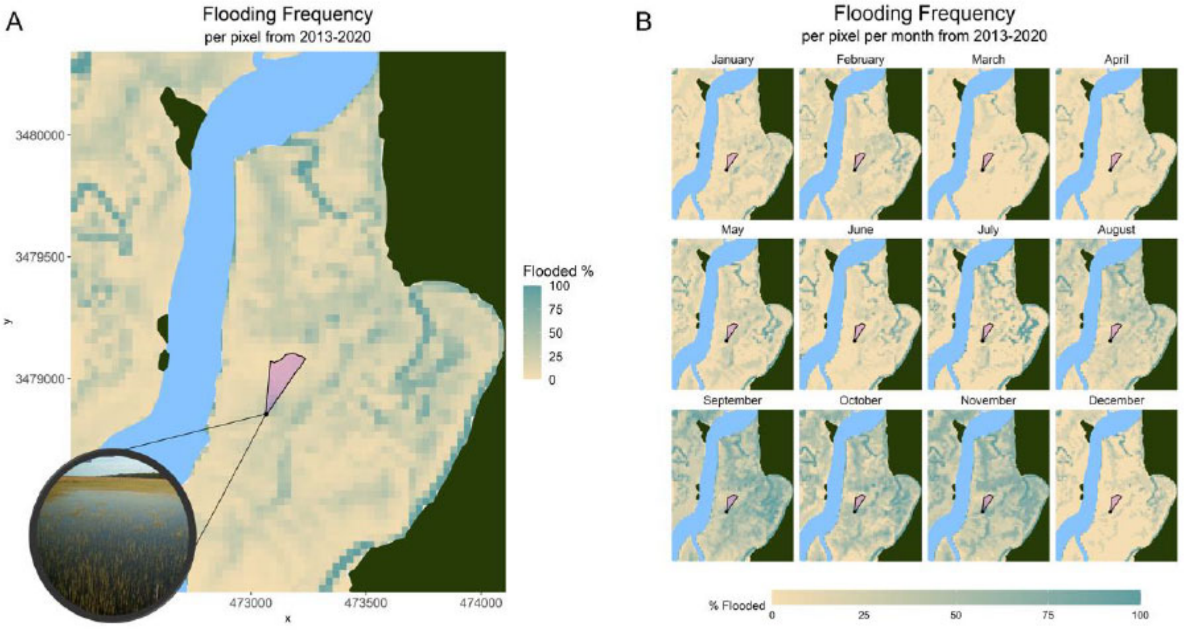

Fig. 3. Evaluation of flooding frequency in the Duplin River based on analysis of Landsat8 imagery using FLATS. The overall average (A) and seasonal pattern (B) showcase the spatiotemporal distribution of flooding across the study area. The pink polygon in panel A shows the field of view of the GCESapelo PhenoCam camera along with an example image, which was used for groundtruthing. Source: Narron et al., subm.

has been cited more than 30 times – including several review papers that have pointed out that a tool like TMII would be useful for other satellite platforms. Building on this work, we have now created a similar application for Landsat-8 and the recently launched Lansat-9 satellites (Narron et al., subm.). The tool, called Flooding in Landsat Across Tidal Systems (FLATS), was again ground-truthed with data from the GCESapelo PhenoCam. It shows how flooding patterns vary over both space and time at a much higher resolution than MODIS, and can also be used to examine changes in flood frequency and flooding patterns (Fig. 3). The strong seasonal pattern in marsh flooding revealed by this analysis may have important implications for marsh ecology. We anticipate that both of these tools will have widespread use for landscape scale analyses of wetland dynamics.

Comparisons with Chinese Wetlands Provide Insight into Salt Marsh Ecology

Spartina alterniflora was introduced into China in 1979 and now covers almost all of the Chinese coastline. This invasion presents powerful opportunities for comparative research, and GCE scientists Pennings and Craft have ongoing collaborations on several topics. **1) Soil development.** Carbon sequestration is driven by both salinity and plant species composition (Xue et al. 2020; Yuan et al. 2020), but *S. alterniflora* traps sediment and sequesters substantial carbon in both China and the U.S. (Li et al. 2013; He et al. 2016). These gains, however, may be offset by conversion of marshes to aquaculture and other land uses (Li et al. 2018). **2) Interactions between mangroves and salt marsh plants.** Exotic mangroves, So*nneratia apetala*, that have also been introduced to China are likely to suppress *S. alterniflora*, replacing one exotic species with another (Peng et al. 2018; Peng et al. in press). **3) S. alterniflora traits.** *S. alterniflora* displays latitudinal clines in height, biomass and phenology (Liu et al. 2020a; Chen et al. 2021). In the US these clines are largely genetically based (Chen et al. 2021; Liu et al. 2016, 2017, 2020b), whereas in China they are due to phenotypic plasticity. The main exceptions are clines in seed set and phenology in China that are genetically based, reflecting strong selection at high latitudes (Chen et al. 2021, Fig. 4). **4) Marsh community structure.** In the native ranges of *S. alterniflora* in the US and *Phragmites australis* in China the diversity of soil nematodes decreases at high latitudes (Zhang et al. 2019, 2020). Where *S. alterniflora* has been introduced in China, however, these latitudinal patterns are absent, and nematode diversity is relatively low (Zhang et al. 2019). **5. Habitat restoration.** Coastal habitat restoration projects have focused on different habitats in the two countries, have been funded in different years, and use different techniques. In both countries, public information about these projects is incomplete, and it is unclear to what extent projects are achieving their goals or using optimal techniques (Shanze et al. 2019).

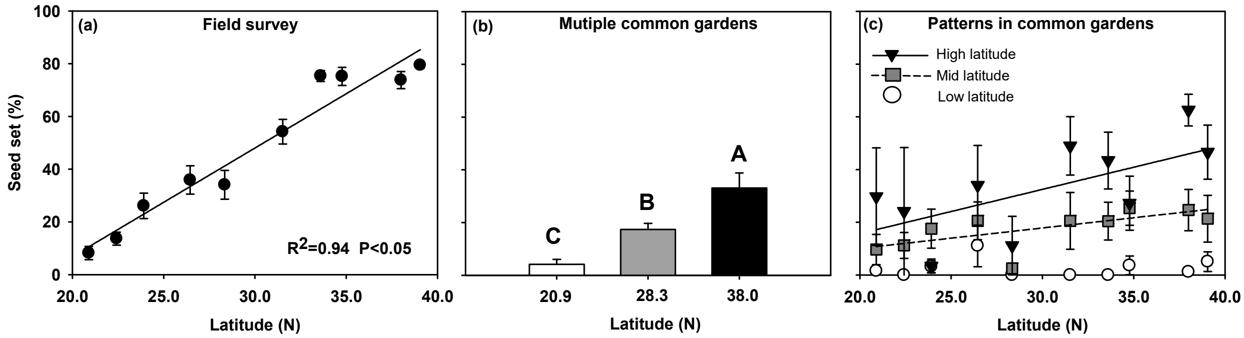

Fig. 4. (a) In China, Spartina alterniflora displays striking latitudinal variation in seed set, which ranges from ~10% at low latitudes to >80% at high latitudes. (b) In three common gardens, seed set increased with latitude of the garden, indicating an environmental effect on seed set. (c) Within the high- and mid-latitude gardens, seed set also increased with the latitude from which the plants were collected, indicating genetic control of seed set. Source: Liu et al. 2017.

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 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. The 2021 program included 4 new and 9 returning participants. The teachers worked on projects including sampling the disturbance project; water quality monitoring; tracking recovery in the SALTEx experiment; and surveying long-term vegetation plots. We tweaked the program this past year based on the retrospective analysis conducted in 2019, including asking teachers to set out their goals for the week and pairing up new attendees with mentors. Participants reported an increase in their knowledge of both coastal systems and the scientific process, and many of them cited the ability to spend time in the field and participating in “real science” as their favorite part of the program. One of the participants wrote in their evaluation, “*Now I can tell my students I helped collect the data in this study.*” We also solicited feedback from the GCE researchers (including a range of interns, graduate students, technicians and PIs) who worked with teachers. They were highly satisfied with their interactions with the teachers and found their assistance valuable. One wrote, “*From this experience, I will change my way of communicating and thinking through what we are doing to explain it both simply and technically.*”

Undergraduate Education

21 undergraduate students from 7 institutions worked with GCE LTER scientists this past year:

- Two REU students worked with S. Pennings and A. Spivak to set up the DRAGNet global distributed disturbance experiment.
- At the field site on Sapelo Island, 3 students worked with J. Schalles on vegetation mapping using drone imagery; 1 with C. Angelini to collect data on disturbance effects; and 1 with C. Hladik on field surveys of tidal fresh forest.
- Two students worked as summer interns with the GCE field crew, helping in both the field and the lab with water quality and other sampling.
- 12 students worked with GCE investigators in their laboratories: 2 with A. Spivak analyzing soil temperature and decomposition data; 2 with J. Byers analyzing wildlife camera data; 1 with C. Meile on the soil model; 1 with C. Osenberg on biomimetic temperature sensors; 1 with J. O’Connell and C. Hladik on developing a Juncus classifier; 1 with S. Pennings and J. O’Connell on methods for growing *Spartina alterniflora* hydroponically; 1 with S. Pennings and B. Hopkinson to use photos for marsh monitoring; 1 with D. Mishra on belowground biomass estimates; 2 with C. Hintz on DIC analyses.
- J. Schalles (Environmental Remote Sensing) and P. Medeiros/R. Castelao (Migrations in the Sea) used GCE data in their undergraduate courses.
- A. Burd used GCE data extensively in a freshman seminar concerning how the oceans affect our coasts.

GCE Dissemination of Results Year 3

Graduate Education

Graduate students are an integral part of the research at the GCE LTER. There are currently 27 students from 7 institutions engaged in LTER research. Graduate activities include:

- S. Williams (UF student, Angelini) is the GCE grad rep for the LTER network. She and J. Schalles organized a weekly brown bag seminar series for all GCE-LTER personnel at the UGA Marine Institute during summer 2021. Speakers included faculty, visiting scientists, GCE graduate students, and undergraduates.
- The GCE grad students have established a slack channel to enhance communication and field coordination.
- A. Burd (Quantitative Methods in Marine Science) and C. Hladik (Remote Sensing; Geospatial Techniques and Applications) used GCE data in their graduate courses.

International Collaborations

GCE investigators worked with students and scientists from several institutions this past year:

- S. Pennings worked with J. Kominoski (FCE-LTER) to organize a session on Long-Term Ecological Research for Coastal Ecosystems at the 1st International Symposium on Coastal Ecosystems and Global Change, held April 2021 in Xiamen China. Pennings also served on the Scientific Committee for the conference.
- A. Burd is a project advisor and Mercator Fellow in a large, interdisciplinary project in the Elbe Estuary led by Univ. of Hamburg, Germany.
- The GCE has graduate students and post-doctoral associates from a variety of countries, including China, Turkey and Brazil.

Diversity, Equity and Inclusion

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. We held a project-wide DEI workshop in January 2021 and started a DEI committee, which is updating the GCE Diversity Plan. We have developed a GCE code of conduct, which is posted on our web site and in GCE laboratories.

We made a number of changes to improve minority participation, particularly for undergraduates. First, we added a question about perseverance in overcoming obstacles to our application for summer intern positions, which provided additional insight into the applicants' motivation, and recruited more extensively from minority-serving institutions. The result was a more diverse applicant pool and undergraduate cohort. Second, we held a more extensive "onboarding" session to orient new GCE participants (and their families) to Sapelo Island, the University of Georgia Marine Institute, and the GCE-LTER program. Finally, the GCE hosted an overnight trip of participants in the Savannah State "Bridge to Research in Marine Sciences" REU program, which targets groups underrepresented in marine and geosciences.

Network Activities

GCE scientists collaborate on cross-site comparisons and are involved in network activities, both within the LTER and with other groups.

- M. Alber and S. Pennings attended LTER PI meetings, and V. Thompson and A. Spivak attended the 2021 Science Council Meeting.
- D. Mishra contributed to a cross-site effort to evaluate environmental effects of the “anthropause” due to COVID (Gaiser et al., in press); A. Burd is working on a synthesis of the responses of coastal ecosystems to climate change (Reed et al., in prep.); P. Medeiros participated in data analyses as part of a cross-site initiative on “pulse dynamics in LTER research”.
- C. Meile is collaborating on cross-site efforts organized by J. Stegen at the Pacific Northwest National Lab to evaluate response to hydrologic disturbance; A. Spivak is part of the coastal carbon research coordination network and participates in the soil carbon working group.
- S. Pennings is part of the “Dragnet” distributed experiment, a global study of grassland responses to disturbance.
- The GCE phenocam is part of the National Phenocam network and the eddy covariance tower is 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:

- Collaborated with BCO-DMO personnel to refine cross-listing of GCE data sets to enhance discovery
- Leveraged 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
- Continued to host the USGS Data Harvesting Service for HydroDB for 12 LTER sites (AND, BES, CAP, CWT, FCE, GCE, KBS, KNZ, LUQ, NTL, PIE, SBC) and 1 USFS site
- A. Sapp was elected to the Information Management Executive Committee

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; and we conduct various specialized activities.

Information Dissemination within the GCE Program

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, Disturbance), and publish a weekly newsletter for GCE participants and other interested parties.

GCE Dissemination of Results Year 3

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 provide GIS software and support to participants and operate a Subversion (SVN) software code repository server for software development projects. All finalized data sets are available to GCE participants immediately.

We have developed dashboard displays for the eddy covariance flux tower and our tide gage that enable researchers to identify potential problems with their instrumentation in near real-time. 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. Finally, we have linked our research request and permitting web application to our project management database, to support more efficient registration of new projects. Approved research applications are shared with our partners on Sapelo Island (SINERR, UGAMI) to facilitate coordination.

Information Dissemination to the Public

The GCE has a comprehensive public web site where visitors can search for data, publications and other research products directly or discover them based on dynamic cross-links (e.g. personnel pages, study site descriptions, Google maps, and species list entries). In addition, we have a public "Data Portal" web site to provide access to relevant ancillary data from federal programs and monitoring partners, documented and standardized for comparison with GCE data. Use of the GCE website has increased steadily since 2001, with over 1.4 million page views from 114,168 visitors between Dec. 2020 and Dec. 2021. Over 9 million page views from 1.95 million distinct web visits have been recorded since 2001. 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 and was identified as a high priority for support by the Environmental Data Initiative.

Data and Metadata Dissemination

All GCE data sets comply with LTER network standards and protocols, and are available through the GCE data catalog. Data summaries and metadata are publicly available immediately, and the accompanying data files are automatically released within 2 years in compliance with LTER and NSF data access policies. Publicly released data sets are also synchronized to the EDI Data Portal monthly for federated distribution through EDI, DataONE, BCO-DMO and related repositories. As of Dec. 2021, 678 publicly available GCE data sets have been uploaded to the EDI Data Portal, representing 21.4 million tabular data records in 1030 files, plus 30 GB of raster GIS data. An additional 936 public data sets are also available through the GCE Data Portal. Collectively, we provide access to over 34 million tabular data records from GCE research and affiliated monitoring programs as well as over 150 GB of GIS data.

Tracking of data downloads from the GCE Data Catalog and EDI Data Portal shows that over 170,000 individual data files have been downloaded since our data catalog was put online in 2001. GCE data are downloaded by a diverse group of web visitors, including academic researchers, educators, and personnel from other LTER sites (Table 1).

GCE Dissemination of Results Figures Year 3

Table 1. Public data file downloads for 2015-2021 and 2001-2021 by data set theme and user affiliation, excluding downloads by GCE participants and GCE-to-LNO/EDI file transfers.

Downloads by Theme	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2001-2021**
Algal Productivity	329	232	74	71	40	79	38	1383
Anthropology	226	211	28	15	23	48	7	1044
Aquatic Invertebrate Ecology	5212	4750	1379	1202	909	1318	252	25407
Bacterial Productivity	2094	2073	505	216	225	419	16	10349
Botany	49	69	31	15	5	41	42	252
Chemistry	425	277	90	70	60	120	1	1545
Fungal Productivity	351	351	101	32	47	89	27	1824
General Nutrient Chemistry	366	251	115	100	61	97	65	1822
Geology	396	273	181	491	87	158	88	2188
Geospatial Analysis	632	646	206	173	94	235	53	3160
Groundwater Hydrology	0	0	26	32	29	42	48	177
Hydrography/Hydrology	502	154	121	87	50	91	2	1292
Marsh Ecology	0	0	0	0	45	18	59	122
Meteorology	1315	888	194	179	157	389	72	5055
Microbiology	0	0	25	34	16	24	0	99
Multi-Disciplinary Study	563	459	107	74	52	137	16	2250
Organic Matter/Decomposition	1238	877	321	207	143	281	25	5171
Physical Oceanography	18906	11481	2468	2961	1794	4327	731	64502
Phytoplankton Productivity	1081	1014	310	152	128	193	19	5468
Plant Ecology	5269	4297	1446	803	694	1744	701	22818
Population Ecology	198	1322	427	288	133	325	155	3042
Pore-water Chemistry	499	341	308	109	72	215	41	2185
Real-time Climate	110	223	832	116	190	131	191	2581
Terrestrial Insect Ecology	1252	1277	472	163	171	383	60	6833

Downloads by Affiliation	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2001-2021**
Academic Research Program	112	264	1018	110	296	236	126	3959
Educational (K-12)	26	41	5	1	14	0	1	201
Educational (Post-secondary)	44	8	34	81	76	37	113	1214
Environmental Advocacy Group	0	0	0	0	0	6	0	14
Government Agency	14	3	21	1	9	8	3	456
International LTER Site	0	0	1	0	0	0	0	47
LTER Network Office (Metacat)	38	1	0	884	126	950	81	2395
LTER NIS	40672	31029	8467	6422	4681	9603	1865	159359
Other LTER Site	4	4	134	5	5	5	8	420
Other/Unspecified	103	118	92	89	18	63	512	2576

Total Data Downloads	**41013**	**31468**	**9772**	**7593**	**5225**	**10908**	**2709**	**170641**

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 141 affiliates from 19 universities, 7 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 we began compiling a coastal resiliency spreadsheet designed to provide local governments in coastal Georgia with information on how to find funding to implement their community resiliency activities in support of a coastal resiliency guidebook being planned by the state. We are also working with GCE investigators to evaluate and analyze information about sediment accumulation on Georgia marshes and what it can tell us about whether the rate of sediment accumulation is keeping up with the rate of sea-level rise.

Additional Activities

- GCE researchers were featured in the PBS series "Changing Seas" in a show on salt marshes that aired in June 2021.
- 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.
- GCE continues to provide web hosting for the Georgia Coastal Research Council, as well as a searchable bibliographic database for the UGA Marine Institute.

WHAT IS THE IMPACT ON THE DEVELOPMENT OF THE PRINCIPAL DISCIPLINE(S) OF THE PROJECT?

GCE scientists authored 39 journal articles and other one-time publications that were added to our bibliography this past year. Papers cover a broad range of ecological topics, including state change (e.g. Zimmer et al. 2021), top down effects (e.g. Hensel et al. 2021), patch dynamics (Michaels 2021), disturbance (Wu et al. 2021), trophic interactions (e.g. Prince et al. 2021), and production efficiency (e.g. Hawman et al. 2021). We have also made contributions in genomics (e.g. Damashek al. 2021), computer science (e.g. Parashar et al. 2021), physical oceanography (e.g. Ortals 2021), and political ecology (e.g. Hardy and Heynen 2021). 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 DOM composition in estuaries, tools for tidal filtering of remote sensing imagery, and comparisons with Chinese wetlands.

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 21 undergraduate students (including 2 REU participants), 27 graduate students and 5 post-doctoral scientists associated with the project.

WHAT WAS THE IMPACT ON TEACHING AND EDUCATIONAL EXPERIENCES?

K-12 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” videos.

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 30-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 Sounds, 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 Island 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 a new 10-core Dell server with 10TB drive array that hosts four production virtual servers (database, web, file and software development), a 4-core Dell server with 3TB drive array that hosts auxiliary virtual servers, and a 12-core Dell server with 12TB drive array that functions as a backup server and host for additional virtual machines. All servers are equipped with redundant power supplies, UPS and RAID-5 or -10 drive configurations, collectively providing 25TB of fault-tolerant hard drive storage. We acquired a 60TB Synology RAID server and 10TB backup drive to provide centralized shared storage for drone and satellite imagery, modeling output, and working files generated by research groups. We also maintain workstation and laptop computers at UGA and UGAMI for data processing, and a network file server at UGAMI for local computer backups.

GCE computer systems and data are backed up using a multi-tiered disk-to-disk-to-disk strategy. High volume data from remote sensing studies, aerial photography, field cameras and drone flights are backed up on the GCE Synology server by research teams, then automatically mirrored onto an external hard drive. We also operate and maintain the wireless data hub on Sapelo Island to provide on-site storage, real-time data telemetry and remote management of the GCE flux tower, PhenoCam, and other instruments installed near the ferry landing. The system includes a waterproof computer, outdoor UPS, 900MHz radio modem, WiFi router and 4G cellular modem for internet access, and streams over 300Mb of data to UGA daily for post-processing and analysis.

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 4995 registered users (476 since the beginning of GCE IV) 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.

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. Almost 2 million distinct web visits have been recorded since 2001, with 1.4 million page views from 114,168 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 GCE research was featured by PBS as part of their “Changing Seas” series. The program aired June 2021. 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 APPROACH AND REASONS FOR CHANGE

We have added Dr. Jessica O’Connell as a PI on the project, and set up a subcontract with Univ. of Texas. O’Connell is a wetland ecologist who previously was a Research Scientist with the project. She played an important role in conceiving the ideas in the GCE-IV proposal and is actively involved in the project. This modification did not alter the scope of work.

ACTUAL OR ANTICIPATED PROBLEMS OR DELAYS AND ACTIONS OR PLANS TO RESOLVE THEM?

We have had delays in carrying out both our 2020 and 2021 ROA supplements with Savannah State. The 2020 sampling of DIC was postponed due to COVID-related restrictions. We were able to sample in February 2021, although instrument failures shortened the field window. Two grad students and two undergrads participated in 2021 sample collection and analysis. One of the undergraduates is now working for the GA Dept. of Natural Resources and the other is at Rutgers Univ. We plan to complete this work in 2022. Our 2021 ROA supplement involves human subjects and required IRB review through both Savannah State and UGA. This was a lengthy process, but the reviews have now been completed and the supplement funds were released to SSU in January 2022.

GCE Dissemination of Results and Other Information Year 3

PRODUCTS AND PUBLICATIONS

The following publications were added this past year:

Books and Book Sections

Pennings, S.C. and He, Q. 2021. Community ecology of salt marshes. Pages 82-112 in: Fitzgerald, D. and Hughes, Z. (editors). Salt marshes. Cambridge University Press, New York.

Langman, O. and Craft, C.B. 2018. Carbon and Nutrient (N, P) Cycling of Created and Restored Wetlands. Pages 2009-2016 in: Finlayson, M., Everard, M., Irvine, K., McInnes, R., Middleton, B., van Dam, A. and Davidson, N. (editors). The Wetland Book.

Morris, J., Cahoon, D., Callaway, J., Craft, C.B., Neubauer, S.C. and Weston, N.B. 2021. Marsh Equilibrium Theory: Implications for Responses to Rising Sea Level. Pages 157-177 in: Fitzgerald, D. and Hughes, Z. (editors). Salt marshes: Functions, dynamics, and stresses. Cambridge University Press.

Alber, M., Blair, J.M., Driscoll, C., Ducklow, H., Fahey, T., Fraser, W.R., Hobbie, J.E., Karl, D.M., Kingsland, S.E., Knapp, A., Rastetter, E., Seastedt, T., Shaver, G. and Waide, R.B. 2021. Sustaining Long-Term Ecological Research: Perspectives from Inside the LTER Program. In: Waide, R.B. and Kingsland, S.E. (editors). The Challenges of Long Term Ecological Research: Historical Analysis. Springer Nature, Switzerland.

Conference Posters and Presentations

Martineac, R.P., Vorobev, A., Moran, M.A. and Medeiros, P.M. 2021. Presentation: Environmental drivers controlling DOM composition variability in a marsh-dominated estuary. ASLO 2021 Aquatic Sciences Virtual Meeting, June 2021.

Martineac, R.P. and Medeiros, P.M. 2021. Presentation: Which biogeochemical drivers most impact DOM composition of a marsh-dominated estuary? American Chemical Society 2021 Fall Meeting, August 2021, Atlanta, GA.

Schalles, J.F., Hladik, C.M., O'Donnell, J., Miklesh, D.M., Pudil, T., Nealy, N. and Currin, H. 2021. Presentation: Serious multidecadal declines in aboveground biomass of the keystone salt marsh species, Spartina alterniflora, are related to climate change in coastal Georgia, USA. Wetlandscapes: Understanding the Large-scale Wetland Functions in the Landscape Symposium. 11th INTECOL International Wetlands Conference, October 14, 2021, Christchurch, New Zealand (virtual, prerecorded).

Schalles, J.F., Hladik, C.M., O'Donnell, J., Miklesh, D.M., Pudil, T. and Nealy, N. 2021. Presentation: Satellite and drone remote sensing to study decadal scale and high resolution spatial-temporal patterns and declines of Spartina alterniflora above-ground biomass in Georgia, USA salt marshes. Session 2. 1st International Symposium on Coastal Ecosystems and Global Change (CoEco1), April 18, 2021, Xiamen University, Xiamen, China.

O'Connell, J.L., Alber, M., Mishra, D. and Byrd, K. 2020. Presentation: Structural heterogeneity in above vs belowground biomass pools differ for Spartina alterniflora monocultures, with consequences for forecasting ecosystem resiliency. Ecological Society of America.

Narron, C., Mishra, D., O'Connell, J.L., Cotten, D.L., Hawman, P. and Mao, L. 2019. Presentation: Assessing tidal wetland above- and belowground net primary production using field and in situ measurements. Carbon fluxes in coastal systems. 2019 CERF 25th Biennial Conference, 11/05/2019, Mobile, AL.

Journal Articles

Adams, T., Vu, H. and Pennings, S.C. 2022. Variation in Densities of the Salt Marsh Katydid Orchelimum fidicinium over Space and Time. Estuaries and Coasts. 45:260-271. (DOI: 10.1007/s12237-021-00953-y)

Burns, C., Alexander, C.R. Jr. and Alber, M. 2021. Assessing long-term trends in lateral salt-marsh shoreline change along a U.S. East Coast latitudinal gradient. Journal of Coastal Research. 37(2):291-301. (DOI: 10.2112/JCOASTRES-D-19-00043.1)

Chen, X., Liu, W., Pennings, S.C. and Zhang, Y. 2021. Plasticity and selection drive hump-shaped latitudinal patterns of flowering phenology in an invasive intertidal plant. Ecology. 102. (DOI: 10.1002/ecy.3311)

Damashek, J., Okotie-Oyekan, A., Gifford, S., Vorobev, A., Moran, M.A. and Hollibaugh, J.T. 2021. Transcriptional activity differentiates families of Marine Group II Euryarchaeota in the coastal ocean. Springer Nature. (DOI: 10.1038/s43705-021-00002-6)

Hammann, L., Silliman, B.R. and Blasius, B. 2021. Optimal Planting Distance in a Simple Model of Habitat Restoration With an Allee Effect. Frontiers in Marine Science. (DOI: 10.3389/fmars.2020.610412)

Hardy, D. and Heynen, N. 2021. "I am Sapelo": Racialized Uneven Development and Land Politics within the Gullah/Geechee Corridor. Environment and Planning E: Nature and Space. (DOI: 10.1177/2514848620987366)

Hardy, D., Milligan, R.A. and Heynen, N. 2017. Racial coastal formation: The environmental injustice of colorblind adaptation planning for sea-level rise. Geoforum. 87(December 2017):62-72. (DOI: 10.1016/j.geoforum.2017.10.005)

Hawman, P., Mishra, D., O'Connell, J.L., Cotten, D.L., Narron, C. and Mao, L. 2021. Salt Marsh Light Use Efficiency is Driven by Environmental Gradients and Species-Specific Physiology and Morphology. Journal of Geophysical Research: Biogeosciences. 126. (DOI: 10.1029/2020JG006213)

Hensel, M.S., Silliman, B.R., Hensel, E. and Byrnes, J. 2021. Feral hogs control brackish marsh plant communities over time. Ecology. (DOI: 0.1002/ecy.3572)

Hensel, M.S., Silliman, B.R., von de Koppel, J., Hensel, E., Sharp, S., Crotty, S.M. and Byrnes, J. 2021. A large invasive consumer reduces coastal ecosystem resilience by disabling positive species interactions. Nature Communications. 12(1). (DOI: 10.1038/s41467-021-26504-4)

Letourneau, M.L., Schaefer, S.C., Chen, H., McKenna, A.M., Alber, M. and Medeiros, P.M. 2021. Spatio-temporal changes in dissolved organic matter composition along the salinity gradient of a marsh-influenced estuarine complex. Limnology & Oceanography. 66:3040-3054. (DOI: 10.1002/lno.11857)

Martineac, R.P., Vorobev, A., Moran, M.A. and Medeiros, P.M. 2021. Assessing the contribution of seasonality, tides, and microbial processing to dissolved organic matter composition variability in a Southeastern U.S. estuary. Frontiers in Marine Science. 8:781580. (DOI: 10.3389/fmars.2021.781580)

Michaels, T. 2021. Can Nucleation Bridge to Desirable Alternative Stable States? Theory and Applications. The Bulletin of the Ecological Society of America. (DOI: 10.1002/bes2.1953)

O'Connell, J.L., Mishra, D., Alber, M. and Byrd, K.B. 2021. BERM: A belowground ecosystem resilience model for estimating Spartina alterniflora belowground biomass. New Phytologist. (DOI: 10.1111/nph.17607)

Ortals, C. 2021. Flows, transport and form drag in intertidal salt marsh creeks. Journal of Geophysical Research - Oceans. 126(11):e2021JC017357. (DOI: 10.1029/2021JC017357)

Parashar, J., Bhandarkar, S.M., Simon, J., Hopkinson, B. and Pennings, S.C. 2021. Estimation of Abundance and Distribution of Salt Marsh Plants from Images Using Deep Learning. Proceedings of the 25th International Conference on Pattern Recognition (ICPR). (DOI: 10.1109/ICPR48806.2021.9412264)

Prince, K., Cetta, A., Crotty, S.M., Denslow, N., Delfino, J. and Angelini, C. 2021. Mussels drive polychlorinated biphenyl (PCB) biomagnification in a coastal food web. Nature - Scientific Reports. 11:9180. (DOI: 10.1038/s41598-021-88684-9)

Reeves, S.E., Renzi, J.J., Fobert, E.K., Silliman, B.R., Hancock, B. and Gillies, C.L. 2020. Facilitating better outcomes: How positive species interactions can improve oyster reef restoration. Frontiers in Marine Science. (DOI: 10.3389/fmars.2020.00656)

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Renzi, J.J., He, Q. and Silliman, B.R. 2019. Harnessing positive species interactions to enhance coastal wetland restoration. Frontiers in Marine Science. (DOI: 10.3389/fevo.2019.00131)

Ritchison, B.T., Thompson, V.D., Lulewicz, I.H., Tucker, B. and Turck, J.A. 2021. Climate Change, Resilience, and the Fisher-Hunter-Gatherers of Late Holocene Georgia Coast. Quaternary International. (DOI: 10.1016/j.quaint.2020.08.030)

Seer, F., Putze, G., Pennings, S.C. and Zimmer, M. 2021. Drivers of litter mass loss and faunal composition of detritus patches change over time. Ecology and Evolution. 11:9642-9651. (DOI: 10.1002/ece3.7787)

Temmink, R.J., Christianen, M., Fivash, G.S., Angelini, C., Bostrom, C., Didderen, K., Engel, S.M., Esteban, N., Gaeckle, J.L., Gagnon, K., Govers, L.L., Infantes, E., van Katwijk, M.M., Kipson, S., Lamers, L., Lengkeek, W., Silliman, B.R., van Tussenbroek, B.I., Unsworth, R.K.F., Yaakub, S.M., Bouma, T.J. and van der Heide, T. 2020. Mimicry of emergent traits amplifies coastal restoration success. Nature Communications. (DOI: 10.1038/s41467-020-17438-4)

Vinent, O.D., Johnston, R.J., Kirwan, M., Leroux, A. and Martin, V. 2019. Coastal dynamics and adaptation to uncertain sea level rise: Optimal portfolios for salt marsh migration. Journal of

Environmental Economics and Management. 98. (DOI: 10.1016/j.jeem.2019.102262)

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Yuan, Y., Castelao, R. and He, R. 2017. Variability in along-shelf and cross-shelf circulation in the South Atlantic Bight. Continental Shelf Research. 134:52-62. (DOI: 10.1016/j.csr.2017.01.006)

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Zhang, Y., Pennings, S.C., Li, B. and Wu, J. 2019. Biotic homogenization of wetland nematode communities by exotic Spartina alterniflora in China. Ecology. 100. (DOI: 10.1002/ecy.2596)

Zhang, Y., Pennings, S.C., Liu, Z., Li, B. and Wu, J. 2021. Consistent pattern of higher lability of leaves from high latitudes for both native Phragmites australis and exotic Spartina alterniflora. Functional Ecology. 35:2084-2093. (DOI: https://doi. org/10.1111/1365-2435.13826)

Zinnert, J.C., Nippert, J.B., Rudgers, J.A., Pennings, S.C., Gonzalez, G., Alber, M., Baer, S.G., Blair, J.M., Burd, A.B., Collins, S.L., Craft, C.B., Di Iorio, D., Dodds, W.K., Groffman, P.M., Herbert, E., Hladik, C.M., Li, F., Litvak, M., Newsome, S., O'Donnell, J., Pockman, W.T., Schalles, J.F. and Young, D.R. 2021. State Changes: Insights from the U.S. Long Term Ecological Research Network. Ecosphere. (DOI: 10.1002/ecs2.3433)

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Sheldon, J.E. and Alber, M. 2019. An Examination of High Salinity Events in the Altamaha River Estuary. In: Review prepared for GA DNR-CRD.

Theses and Dissertations

Davidson, K. 2019. Trade-offs between multiple ecosystem services in UK and US salt marshes. Ph.D. Dissertation. Swansea University, Swansea, Wales, United Kingdom.

Li, F. 2017. Response and recovery of low-salinity marsh plant communities to constant and pulsed saline intrusion. Ph.D. Dissertation. University of Houston, Houston, TX, USA.

Napora, K. 2021. Refining cultural and environmental temporalities at the late Archaic-early woodland transition along the Georgia coast, UGA. Ph.D. Dissertation. University of Georgia.

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