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Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	John H Porter

Accomplishments

*** What are the major goals of the project?**

1. Evaluate the existence of alternative stable states and threshold responses to environmental drivers as a unifying dynamic across the coastal barrier landscape, by integrating coordinated long-term observations and experiments that address the mechanisms of nonlinear change with models and new experimental studies. Relate ecosystem state change to key ecosystem processes, services and trophic dynamics.

2. Address how connectivity via transport of sediments and organisms influences alternative stable state dynamics of adjacent ecosystems (e.g., seagrass and oyster connectivity to marshes, island connectivity to backbarrier marshes) and of subsidies via organism fluxes between adjacent habitats influence key ecosystem processes, services and states.

3. Use future scenarios to explore how interacting drivers affect threshold behavior and resilience of ecosystem states at different spatial scales, including climate change and changes in land use and nutrient loading. Relate ecosystem state change to key ecosystem processes, services and trophic dynamics. Engage a diverse group of stakeholders to incorporate public valuation of ecosystem services and tradeoffs into quantitative models of future scenarios.

SPECIFIC QUESTIONS ADDRESSED

1a. What are the mechanisms of non-linear state change in coastal barrier landscapes in response to environmental drivers?

1b. Are there specific thresholds for ecosystem state change and leading indicators of proximity to that threshold?

2a. To what extent does connectivity of adjacent ecosystems via sediment fluxes affect responses to environmental change?

2b. Is there evidence of subsidies via organism fluxes between adjacent habitats that influence key ecosystem processes, services and states?

3a. How will ecosystem resilience and state dynamics vary in response to climate drivers across the landscape?

3b. How will changes in land use affect subtidal and intertidal ecosystems, and how will these drivers affect the resilience of ecosystems to climate change? How are state changes related to the delivery of to key ecosystem processes, services and trophic dynamics?

3c. How do regional attitudes and motives modify future scenarios?

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:

Collection of Core Data

During 2015, we continued collection of core long-term datasets, including physical drivers (meteorology, tides, groundwater levels), marsh biomass, seagrass density, small mammal distribution and abundance, water quality of coastal bays, fish populations and changes in the elevation of coastal marshes. Highlighted below are additional activities aimed at answering our major research questions.

Mechanisms of non-linear state change

To examine transitions between upland and salt marshes, we installed groundwater wells along a transect from salt marsh to pine forest instrumented with sensors to monitor at 1-hr intervals temperature, salinity and depth to the groundwater table. In addition we measured leaf water potential of different tree species and light intensity. In an area where forest dieback occurred after hurricane Isabel, we conducted a high-resolution topographic survey to determine how microtopography, particularly small depressions, negatively affect tree survival during flooding events. We will use these data to parameterize a numerical model we have developed that combines lateral erosion of salt marshes at the bay boundary with marsh expansion into the upland forest to evaluate response under different future scenarios.

Salt marsh/tidal flat extension or retreat depends on the dynamic of the boundary between the two landforms. Erosion and collapse of the marsh edge is generally linked to wind waves (McLoughlin et al. 2015). In addition to wave energy, biotic feedbacks including vegetation characteristics, invertebrate activity and nearby oyster reefs affect

the erosion of the marsh edge. We used high-resolution field measurements in the VCR bays and cellular automata simulations to investigate the erosion of marsh boundaries by wave action.

In the coastal bays, we have added a network of temperature/light sensors that brackets the depth threshold predicted from modeling. These will identify minimum light requirements for seagrass growth and temperature thresholds in our models. We are determining the consequences of seagrass state change at population to ecosystem levels. This includes measurements of seagrass metabolism (gross primary production and respiration using the novel underwater eddy covariance approach, carbon and nitrogen cycling (including sequestration in sediments), and changes in fish and bivalve abundance and diversity.

Investigation of transitions between grassland and shrublands and their impacts on mesopredators and nesting bird populations on the barrier islands continued, with collection of physiological data (e.g., temperature) inside and outside shrub thickets, and monitoring of predator and prey populations. Additionally, landscape modeling of shrub expansion based on observed changes (via remote sensing) and LiDAR elevation data is proceeding.

We continued to test our model that simulates the growth of coastal dunes and island migration. Using this model we assessed the effect of an increasing frequency of storms and sea-level rise on dune elevation (Duran & Moore 2015, Nature). We developed a vulnerability index that captures these dynamics and can be applied to other barrier island systems.

Thresholds for state change

We coupled our long-term measurements of changes in marsh elevation to numerical models and to “marsh organ” experiments where marsh elevations are experimentally manipulated. Other work examines the role of root-zone processes in determining elevation change rates of VCR marshes, including quantification of root growth by computed tomography (CT) scans, and measurements of organic matter decay rates along a temperature gradient in multiple LTER sites.

We used a coupled hydrodynamic-vegetative growth model to identify two leading indicators of a seagrass meadow nearing the depth threshold between the vegetated and unvegetated states. Both indicators were associated with the number of leaves per shoot: “flickering”, which reflects conspicuous fluctuations from one state to the other across the threshold, and “slowing down”, which is the increased persistence of the fluctuations as a system gets close to a threshold.

Ecosystem Connectivity

We are coupling hydrodynamic modeling (FVCOM, Delft3D) with measurements of sediment characteristics in the coastal bays to address ecosystem connectivity via sediment transport. We developed a new method (Wiberg et al. 2015) for estimating the spatial distribution of sediment properties in shallow coastal bays based on limited bed sampling and knowledge of the spatial distribution of water residence times, which we have already determined (Safak et al. 2015). We used our resulting maps of seafloor properties to initialize a 2-month-long model simulation of currents, waves and suspended sediment forced with measured wind and tides during a period when in situ flow and turbidity measurements are available. We also investigated sediment flux from bays to marshes through a seasonal series of field deployments of wave gauges, current meters and turbidity sensors at an eroding marsh-edge site.

We continued our field studies of how the elevation and geometric roughness of

natural and restored intertidal oyster reefs affect larval settlement, local flow dynamics, and wave attenuation.

Subsidies

Examining links between salt marshes and coastal bays, we considered what sources of primary production support the roughly 200 million clams under cultivation at any one time in the lagoons of the VCR. Both *Spartina alterniflora* (marsh grass) and *Zostera marina* (seagrass) represent potentially important subsidies to clams from adjacent habitats. In addition, algae in both macro- and micro- forms are potentially important. We tested for the relative importance of these sources by measuring the stable isotope ratios of carbon, nitrogen and hydrogen in clams, macrophytes (marsh grass and seagrass), macroalgae, and microalgae.

State change & projected climate/land-use drivers

Linked to our work on integrating an ecogeomorphic model of barrier island evolution with an ecomorphodynamic model of salt marsh accretion, we completed a field experiment that simulates the deposition of overwash sand during storms onto adjacent marshes.

We continued our use of remote-sensing data to characterize changes in island size and land cover and are linking this information to assessments of the effects of vegetation on mammal and bird populations, which include: 1) mammal live-trapping campaigns at 21 island/marsh and 2 mainland sites to compare large, elevated, relatively stable islands with small, low-lying, geomorphologically unstable islands;2) predator surveys on the 21 islands to quantify mobility; 3) analysis of raccoon movement; 4) cost-distance analyses to determine an optimal strategy for mesopredator movement as an aid to avian habitat restoration; 5) ongoing (11 year) assessment of spring migratory shorebird populations (including federally-threatened red knot, *Calidris canutus rufa*), prey, and habitat use on the 15 main islands of the VCR; 6) modeling and data collection on how sea-level rise, shoreline change, and island geomorphology affect nesting probabilities of federally-threatened piping plover (*Charadrius melodus*); and 7) camera-based predator surveys and occupancy modeling of red fox (*Vulpes vulpes*).

Socio-ecological drivers

We continued our experiments to compare several approaches to growing the salt-tolerant biofuel crop *K. pentacarpos* in agricultural fields abandoned due to saltwater encroachment. We conducted initial germination experiments with wild seed propagated plants for seed production and seeded field plots with *K. pentcarpos* or transplanted with 1-month old seedlings and are monitored for density, plant morphology and seed production

Specific Objectives:

Mechanisms of non-linear state change

Mainland Forest/Shrub vs. Marsh. The extent of marshland is controlled by changes at its terrestrial boundary, where complex interactions determine its landward-most extent. Our objective is to document transgression of this boundary.

Marsh vs. Tidal Flat**.** Positive feedbacks between vegetation growth and sediment transport promote the development of two alternative states: salt marshes and tidal flats. Our objective is to understand the ecological and physical connectivity between these two stable systems, and the mechanisms of state change that transform salt marshes in tidal flats and vice versa.

Seagrass vs. Unvegetated Seafloor. To further constrain and validate the stage change

model, and to investigate the resilience of seagrass meadows, our objectives are to: 1) continue long-term monitoring of seagrass morphology and meadow characteristics, and 2) evaluate the consequences of the seagrass state change for sediment suspension, biogeochemistry and carbon sequestration.

Barrier Island Grassland vs. Shrub Thicket. Our objective is to evaluate the relative importance of temperature and water-table feedback between grassland and shrubland by investigating: 1) how shrubs modify the local microclimate, particularly in the coldest months, 2) how shrubs lower the water table, 3) the cold sensitivity of shrubs, and 4) the sensitivity of shrubs to shallow water tables using field and remote sensing (spectral/Lidar) measurements.

Barrier Island Geomorphology, “High” vs. “Low” Islands. Our objective is to develop a model of barrier-island dynamics from an existing model of dune growth that includes aeolian sediment transport and vegetation population dynamics. In model runs, forcing parameters (sea-level rise, overwash frequency, sediment-loss rates) is varied to evaluate the effect on island state (high vs. low) using migration rate as an inverse proxy (e.g., low islands have high migration rates and vice versa).

Thresholds for state change

Intertidal Marshes. The ability of marshes to maintain elevation high in the intertidal zone determines if marshland will convert to subtidal mudflats. Our objective is to understand how marsh plant growth responses to duration and frequency of tidal inundation reveal if there are leading indicators of proximity to the threshold of change.

Seagrass. To refine the growth model that estimates the maximum depth threshold of seagrass, our objective is to install a network of light and temperature sensors along the depth gradient that brackets the current threshold of the stable-bistable states predicted from the model.

Barrier Islands. Our objective is to continue monitoring fronts of shrub expansion to identify specific thresholds of change (i.e. introduction of nitrogen-fixer *Frankia* to the soils). We will identify changes in key ecosystem parameters along dune/swale transects and related these to elevation (nearness to groundwater). This will provide a basis for predictions on a larger spatial scale of state transitions with changes in elevation (erosion, accretion, sea-level rise, groundwater fluctuation).

Ecosystem Connectivity

Sediment Redistribution. Our objective is to quantify sediment fluxes from the tidal flat to the marsh at 2 sites in Hog Island Bay.

Seagrass – Marsh. Our objective is to develop a 3-point dynamic model, incorporating ecogeomorphological feedbacks between wind waves, vegetation, sediment loading and sea-level rise, to investigate how internal and external processes affect coupled marsh-mudflat systems.

Oyster – Marsh. Oysters reefs fringing marshes may impact erosion and sediment supply. Our objective is to perform *a new long-term experiment* in which we construct artificial oyster reefs and measure waves, mean currents, turbulence, suspended sediment concentrations and larval recruitment.

Island – Back-barrier Marsh. To explore couplings between barrier islands and back-barrier marshes, our objective is to merge: 1) a barrier island model, GEOMBEST, that incorporates sediment composition and supply rate to forecast barrier island evolution in response to sea-level rise and 2) a marsh transect model that predicts coupled marsh – tidal flat evolution in response to sea-level rise and

storms.

Subsidies

Cross-Habitat Macrophyte Subsidies. Our objective is to assess how the invasion of the macroalgae, *Gracilaria vermiculophylla*, affects nitrogen subsidies and trophic dynamics in adjacent marshes and mudflats.

Subsidy support and expansion of aquaculture. Our objective is to document sources of organic matter supporting clam production and changes in clam aquaculture over time, and to evaluate possible impacts of clams on biogeochemical and ecological processes.

State change & projected climate/land-use drivers

Intertidal Habitats. To determine rates of transgression, our objective is to determine historical rates of marsh expansion at the forest edge from aerial photographs.

Subtidal Habitats. Our objectives are to: 1) address how location affects habitat suitability for restoration and resilience of seagrass meadows by considering variation in physical and chemical parameters and linking these with our model of state dynamics, and 2) understand how meadow patchiness (size and configuration) affects vegetation feedbacks on sediment suspension, light attenuation, and state-change dynamics. Changes in land use will affect nutrient loading to subtidal habitats, and our objectives are to: 1) continue monitoring stream stage and nitrogen concentrations at fixed stations, 2) assess nitrate removal via denitrification from groundwater feeding streams, and 3) quantify nitrate removal from streams.

Island Habitats. To build on our 30-yr historical analysis of vegetative cover change, our objectives are 4-fold: 1) examine fine-scale changes in vegetation as a result of shoreline accretion/erosion, 2) use NDVI as a link between changes in woody cover due to hydrological patterns, 3) use LiDAR to determine the potential range of distribution based on habitat polygons, and 4) quantify changes in island shape and size and corresponding vegetative classes over 40 years using Landsat TM imagery. These remote-sensing analyses will be integrated with long-term data on species distributions and local-scale mechanisms to model bistability and vegetation change in the context of climate change scenarios of shoreline migration and sea-level rise.

Habitat/Vegetation Analysis. Our objective is to develop a temporal sequence of spatially explicit habitat descriptors for the islands based on the NOAA Coastal-Change Analysis Program (C-CAP) land cover data layers for 1984-2010. The layers contain data for 14-22 land-cover classes with 30-m pixel resolution.

Island Faunal Dynamics. Our objectives are to: 1) determine species occupancy to look for evidence of local extinctions and/or colonizations, 2) collect tissue samples for analysis of genetic relationships among populations, 3) determine species diversity to look for evidence of community-level changes over time, 4) quantify the relationship between species diversity and island attributes such as size, isolation and habitat complexity which can be used to predict future distributions relative to changes in elevation and vegetation cover driven by climate, and 5) assess effectiveness of predator removal as a strategy for conservation management for waterbirds.

Socio-ecological drivers

Our objective is to develop a survey of public valuation of ecosystem services to incorporate input from multiple stakeholder perspectives into future scenario planning related to climate and land-use change. We also are initiating a *new long-term experiment* to explore the ecological and economic benefits of an alternative biofuel

crop in agricultural fields abandoned due to sea-level rise.

Significant Results:

Mechanisms of non-linear state change

Our field data and model of lateral expansion of salt marshes shows that under relatively common circumstances, sea-level rise leads to an increase in marsh extent, because marsh encroachment in the forest is faster than marsh erosion at the bay boundary.

When we investigated the erosion of marsh boundaries by wave action using high-resolution field measurements in the VCR bays and cellular automata simulations we found: (1)when salt marshes are exposed to high-wave energy their boundaries erode uniformly, and (2) when wind waves are weak and the local marsh resistance is strong due to vegetation feedbacks, jagged marsh boundaries form (Leonardi & Fagherazzi 2015). Interestingly, despite spatial variation in marsh erosion rates in the VCR related to wave and energy and biotic feedbacks, rates were temporally consistent between 1957 and 2007 (McLaughlin et al. 2015).

In the coastal bays, genetic data show that restoration by seeding maintains high diversity in seagrass. Carbon metabolism increases 10 - 25 fold in restored meadows compared to bare sediments, though the balance between GPP and R remains similar and nitrogen processes are enhanced compared to bare sediments. Biodiversity of fish, bivalves and epifauna are also enhanced.

On the barrier islands, we have identified multiple configurations of dune-swale topography that result from local scale biogeomorphic processes (i.e sediment flux, dispersal, colonization) and influence vegetation cover type and patterns. We have found that elevation (proxy for depth to groundwater) is important in determining shrub cover, and that there is a non-linear relationship between groundwater depth and stress. Field and greenhouse experiments show that grass density affects shrub growth.

Using our model simulating growth of dunes, we found that barrier islands typically exist in “high” or “low” states and that their state is controlled by previously unrecognized dynamics: the competing, and quantifiable, effects of storm erosion, sea-level rise, and the aeolian and biological processes that drive dune recovery (Duran & Moore 2015). To validate model results we analyzed island elevation for the VCR (derived from Lidar profiles) and find evidence that island elevation in the VCR is bimodal (Duran & Moore 2015).

Thresholds for state change

Monitoring of marsh elevation suggests that mainland marshes are currently building soil elevation at a rate similar to or exceeding the rate of relative sea-level rise, but that lagoonal marshes are not. Ongoing DNA analysis of *S. alterniflora* plants suggests that genetic structure is highly variable among VCR marshes.

On the barrier islands, we determined transitions between grassland and shrubland from remote sensing imagery and initiated monitoring of shrub seedlings across a grass density gradient. We found that a threshold groundwater level influences stress response in the expanding *Morella* shrub. Seedling establishment is mediated by several factors (cover type, grass density, salinity) and is dependent on elevation. Seedlings are able to tolerate a range of densities and salinities, but have threshold levels critical for survival. Groundwater depths also influence rates of root decay, which feed back on nitrogen availability for shrub growth.

The long-term monitoring of the seagrass experiment shows a depth limit of 1.6 MSL that agrees with results of coupled vegetation growth - hydrodynamic model. Shoot transplant experiments along a depth gradient in a second bay show the same agreement.

Ecosystem Connectivity

Modeled suspended sediment concentrations (SSC) in the coastal bays based on residence time and sediment characteristics provides information on light availability for benthic production and sediment availability for marsh accretion. Lower SSC in sandier regions of the bays, near barrier islands and inlets, resulted in higher benthic light availability but lower sediment supply for deposition on back-barrier marshes. Higher SSC in more landward, muddier regions resulted in greater light attenuation and sediment availability for deposition on mainland fringing marshes (Wiberg et al. 2015).

Natural and restored intertidal oyster reefs were effective at reducing wave energy for intermediate water depths but were much less effective for deeper water (high tide and storm surge). This suggests a fringing reef might provide some benefit in reducing edge erosion for marshes with elevations close to mean sea level, such as are relatively common along the mainland, but less likely to be benefitmarshes located higher in the tidal frame.

Subsidies

In our studies of the connections between coastal bays and adjoining marshes, we found that clam aquaculture is increasing in the VCR at the rate of 250 new beds (=15,000 m2 coverage) per year and habitat analysis indicates the potential of aquaculture to occupy substantial bottom area. Flux rate measurements and budgetary analysis indicate clam aquaculture accelerates carbon and nutrient cycling particularly the production of dissolved inorganic carbon and ammonium. Bivalve beds also enhance nitrate reduction and increase sediment organic matter as well as pore water sulfide. These studies indicate aquaculture has impacts at least on the immediate surrounding environment.

State change & projected climate/land-use drivers

Our experimental manipulation of simulated sand overwash on marshes showed that relatively thin additions of overwash sand (5-10 cm) stimulated marsh productivity via root growth, whereas thick additions representative of large events (>15 cm) led to vegetation mortality. These results support the model-derived finding that marsh vulnerability to sea-level rise is potentially reduced by overwash from storms. However, changes in storm climate and barrier island morphology (i.e. dune height) that influence the size of overwash events is an important consideration.

The numerical model we developed to explore the coupling between marsh edge erosion and upland transgression indicates that moderate sea-level acceleration will actually lead to net marsh expansion, although faster accelerations lead to net marsh loss.

A seagrass transplant experiment in a northern coastal bay shows the negative feedback of high sediment organic matter, hydrogen sulfide and ammonium, and low oxygen on seedling survival.

The coupled bay-marsh state change model indicates that the presence of seagrass has a positive effect on marshes by attenuating waves and reducing marsh edge erosion in bays with low fetch.

Nitrogen fertilization of dune-building grasses increases stem density and has a

positive effect on the vegetation feedback on dune building and post-storm recovery.

On the barrier islands, woody vegetation increased 40% from 1984 to 2011. Conversion rates from grassland and shrubland were nonlinear and resulted in three patterns of barrier island change: resistant “high islands”, eroding “low islands”, and islands in transition.

The distribution of raccoons on the islands has expanded over the past 30+ years, with islands near the mainland having greater recolonization. The minimum costs of immigration to specific islands vary >3 orders of magnitude, making some islands better targets for predator removal to aid recovery of shorebirds.

Socio-ecological drivers

The economic valuation showed that 1) residents prefer a 'living shorelines' approach to sea walls for protecting shorelines, but most respondents chose 'no-action', 2) residents who were more 'conservation-minded', and those who claim membership in a concerned citizen’s group, were more likely to choose a management plan than to take 'no action', 3) a person’s desire to preserve historic culture (“keep things the way they are”) was an indicator of likelihood to choose 'no action', and 4) wildlife preservation, shoreline protection, and marsh persistence were the most valued ecosystem services.

Key outcomes or Other achievements:

VCR scientists have published 116 journal articles and 13 book chapters during the first half of this funding cycle. Notable publications include 3 papers published in Nature (Fourqurean, McGlathery et al. 2012 - seagrass blue carbon storage; Kirwan & Megonigal 2013 - marsh resilience to sea-level rise and human impacts; Duran & Moore 2014 - barrier island bistability), and one in Science (Temmerman & Kirwan 2015 - cost-efficient nature-based solutions to sustain coastal communities). A complete list of publications can be found at http://www.vcrlter.virginia.edu/home1/biblio.

Key accomplishments during the first half of the project period include testing of the multiple stable state models for the subtidal and intertidal parts of the landscape with long-term observations and experiments; development and testing of models with long-term data that show emergence of bistability of barrier islands; empirical support of biotic feedback mechanisms that could lead to multiple stable states of island vegetation; coupling of non-linear dynamics of adjacent ecosystems; and research on scenarios of change and coastal resilience.

Mechanisms of state change & ecological consequences

<u>Seagrass</u>

Long-term data from restoration experiment supports model results of depth threshold for state change; potential for state change at landscape scale depends on water quality and sediment characteristics.Seagrass state change has ecological consequences: enhances metabolism, carbon and nitrogen sequestration, promotes biodiversity, and enhances water quality.

Coupled models predict that seagrass presence does not limit sediment supply for marsh accretion.

Islands

Simulation results suggest that plant zonation (i.e., the distance from the shoreline that dune-building vegetation can grow) determines maximum dune size and that sand supply determines how long it takes for dunes to form following a storm.

Barrier Islands

Barrier islands tend to exist predominantly in 2 states: “Low” islands - dunes absent, narrow, prone to overwash, migrate rapidly, low biodiversity; “High” islands (or parts of islands) - dunes present, migrate slowly (if at all), high biodiversity. Increasing storm frequency and rising sea level may trigger thus rapid shifts from high to low state with ecological consequences; plant-mediated feedbacks affect island response.

Grassland/shrubland transitions on barrier islands are nonlinear and determined by landscape position; fresh groundwater availability is the primary driver. Increased nitrogen enhances biomass/cover and may provide a positive feedback on shrub expansion.

The link between geomorphology and vegetation has trophic-level ecological consequences affecting mammals and nesting shorebirds.

Tidal Marshes

Marshes tend to be stable in vertical dimension (i.e. build elevation with sea level rise), but with thresholds and warning signals. Threshold rate of sea-level rise between regions increases with sediment concentration and tidal range.

Marshes are inherently unstable at seaward and landward boundaries (erosion + migration). Physical and biological processes dictate the heterogeneity of marsh boundaries, and this heterogeneity drives non-uniform marsh erosion and state change between tidal flats and salt marshes. We can forecast the state change from marsh boundary variability.

The fate of marshes cannot be assessed without consideration of adjacent ecosystems (bays, uplands, barrier islands). If enough adjacent land to accommodate severe loss of existing marsh, expansion is possible. Marsh response to sea-level rise depends on human response - the interaction between sea-level rise and human impacts is more important than the rate of sea-level rise itself

Ecosystem Connectivity

Accumulations of invasive macroalga, *Gracilaria vermiculophylla*, alters the “state” of mudflats, provide nitrogen subsidies to marsh grass and epifauna, and subsidizing birds by enhancing invertebrate populations. This macroalga also harbors bacterial pathogens that cause seafood poisoning and wound infections, which may threaten regional aquaculture operations.

Sources of primary production supporting the burgeoning clam aquaculture in the VCR are benthic microalgae and macroalgae from adjacent tidal flats. Clam aquaculture has the potential to expand significantly in the VCR, potentially competing with restored seagrass and stimulating carbon and nitrogen cycling.

Restored oyster reefs attenuate wave energy at intermediate water depths but are significantly less effective for deeper water conditions that allow for the development of larger waves. Reefs remove sediment from the water column at moderate flow speeds but can contribute sediment to the water column as flow speeds large enough to resuspend sediment from the reef structure.

Coupled nonlinear dynamics of adjacent systems

In systems with large fetch, like the VCR, seagrass meadows positively affect marshes by maintaining shallower tidal flat depths and reducing wave energy acting on the marsh boundary.

When a tidal flat is small and already prone to drowning with sea-level rise, seagrass can starve a marsh of sediment and accelerate drowning of a marsh. Increased sediment suspension from marsh erosion decreases light availability and has a negative feedback on seagrass ecosystems.

On barrier islands, storm overwash is the key mechanism linking marshes and barrier islands, and is important for maintaining narrow back-barrier marshes. Frequent, low magnitude deposition stimulates productivity and alleviates flooding stress; thick overwash causes mortality. The presence of back-barrier marshes reduces island migration rate by about 30%.

Interacting drivers, future scenarios and resilience

The barrier island response to climate change depends on: plant species composition (biotic feedbacks), overwash and barrier/marsh couplings. Barrier island vulnerability to storm overwash depends on the likelihood that dunes will re-establish prior to the next storm event. Range expansion of the southern dune-building grass could cause dunes to become discontinuous and hummocky. These changes increase vulnerability to overwash and island migration rates, with consequences for beach area, island vegetation, and habitat availability for predators and shorebird prey.

The spatial extent of marshes under future scenarios of climate and land-use change is controlled by the balance between state changes at its boundaries (erosion at the lagoon-marsh interface and transgression of marsh into higher elevations at the forest-marsh interface). Erosion of marsh edges can occur in the absence of storms, and over the long term is determined more by mean climate variables than storm events. Marsh loss is inevitable unless erosion at the seaward edge is compensated by expansion of marshes into adjacent uplands, which can only occur in the absence of anthropogenic structures. Moderate sea-level acceleration will actually lead to net marsh expansion, although faster accelerations lead to net marsh loss.

Seagrass meadows are relatively resilient to scenarios of sea-level rise as long as there is opportunity for coastal bays to transgress landward. Climate change (increased temperatures and storminess) and increased nutrient loading from land-use change could cause meadows in deeper waters to cross a threshold to the unvegetated state. This would reduce the spatial cover of extant restored seagrass meadows and possible limit their expansion.

Environmental economic assessment of county-level adaptation options to alternative future scenarios show that most consistently valued coastal ecosystem services are wildlife preservation, salt marsh accretion, and shoreline protection. Planting native marsh halophytes in fields no longer able to support traditional crops may be an effective adaptation strategy to sea-level rise that provides ecologic and economic benefits.

*** What opportunities for training and professional development has the project provided?**

14 graduate students, 4 post-docs and 11 undergraduate students were trained this year through the VCR LTER program.

VCR has a formal 'tiered' mentoring program that involves faculty, graduate students, undergraduate students and high school students working together as a team on specific research projects. Ongoing K12 activities include: Coastal Bay Ecology and Fall Migration Workshops on the Eastern Shore, professional development workshops for area K12 teachers; Oyster Gardening Program that provides training and curriculum materials for local teachers along with classroom materials and field trips run in partnership with VA Oyster Reef Keepers; Summer Science Internships for local high school students through our Research Experience for High School Students (REHS) program made possible by leveraging SLTER Funds with additional support from TNC; and our Water Cycle/Nutrient dynamics field trip at the VCR run on request for class groups from across Virginia.

Teachers from the Kiptopeke and Occohannock Elementary Schools Talented and Gifted Program (TAG) have received instructional training and supplies to participate in the Oyster Gardening Program. TAG groups at both schools grew and monitored batches of baby oysters during the school year. In 2015, 28 of these students participated in a half-day water quality and coastal habitat field trip on the Eastern Shore.

VCR researchers and staff work with the science faculty at Northampton High School, giving guest lectures and assisting with curriculum development. Every one of the 200 high school student in the county is exposed to VCR research at least once in their high school career; over 50% of these students are from traditionally underrepresented groups. We held two Art and Ecology workshops (Plein Aire Painting and Observational Drawing) that provided training for ~45 teachers. Artwork and essays generated from the workshops were displayed in public exhibitions at the Barrier Islands Center Museum on the Eastern Shore and in the Science and Engineering library at the University of Virginia.

VCR researchers are part of a collaborative team led by colleagues at the GCE LTER teaching a on-line distributed graduate course entitled "Sea level rise and saline intrusion into coastal habitats" that involves 14 institutions, and over 100 students and 15 researchers.

*** How have the results been disseminated to communities of interest?**

The VCR holds a monthly public seminar series at the Anheuser-Busch Coastal Research Center, which is attended by 2050 local residents and planners. VCR PIs and graduate students from UVA and our partner institutions provide lectures to school and public groups in their areas.

The VCR Citizen Science Program includes collaborations with the VA Oyster Reef Keepers and the VA Master Naturalists. The VCR lab is a demonstration site for local vegetation.

The VCR disseminates research findings and data through the VCR LTER website (www.vcrlter.virginia.edu). Use of the website continues to increase, with 21,704 page views in 6,491 sessions by 4,174 users during the period 2014-10-01 through 2015-09-30. During that same period, VCR/LTER data files were downloaded 8,872 times from the LTER Data Portal.

Several VCR investigators and Schwarzschild serve on the Eastern Shore's Climate Adaptation Working Group and are partners with The Nature Conservancy (TNC) on the Department of Interior (DOI) funded Coastal Resilience grant. Activities supported by leveraged funding from a NSF Coastal SEES project and the DOI Coastal Resilience project engage regional stakeholders and policy makers in visioning scenarios of climate change and in understanding the impacts of specific adaptation actions on wetland vulnerability and coastal resilience. Schwarzschild is as a science advisor to the Accomack-Northampton County Planning District Commission's Hazard Mitigation Plan update and has been elected to their Resource Conservation and Development Committee. In 2014 we signed an MOU with the NASA Wallops Island Flight facility and partners from TNC, Virginia Institute of Marine Sciences, University of Maryland, University of Delaware, Old Dominion University and The Chincoteague Bay Field Station to form the Mid-Atlantic Climate Research Institute. In 2015, the ABCRC hosted a visiting group from Panama to train researchers on methods to monitor carbon flux in coastal ecosystems using eddy covariance and a delegation from Ghana investigating the challenges of conserving barrier island-lagoon ecosystems facing climate change and sea-level rise.

The experimental work on planting salt-tolerant *K. pentacarpos* as an adaptation strategy for farmers to sea-level rise and is being done as a demonstration project with TNC and colleagues at the University of Delaware. We have presented our work at the Virginia Tech Agricultural Experiment Station Field Days and our research was the topic of a feature article in The Delmarva Farmer, an American Farm publication. We plan to expand the demonstration projects in collaboration with Agricultural Extension Agents to engage more local farmers known to have abandoned fields adjacent to encroaching salt marshes.

The VCR is a site in the NOAA Sentinel Site Program for the Chesapeake Bay Sentinel Site Cooperative.

*** What do you plan to do during the next reporting period to accomplish the goals?**

Mechanisms of non-linear state change

At the marsh-upland boundary, we will continue to analyze high-resolution data of water levels and salinity and relate these to vegetation productivity and regeneration, and light availability. This will be done (1) along the marsh-to-forest transition

and (2) in a topographic depression where tree dieback occurred and a nearby convexity were trees survived hurricane Isabel. We are also collecting topographic data at locations where tree dieback occurred throughout the VCR to scale-up our results to the entire marsh-forest boundary.

In the coastal bays, we will quantify the number of flowering shoots and seed production along gradients of light availability and water temperature and will modify the seagrass bistability model to incorporate shoot recruitment from seeds, and biomass allocation to flowering shoots and seed production. We will continue our analysis of ecological implications of state change on carbon and nitrogen cycling, and faunal biodiversity.

On the barrier islands, we will continue measurements of environmental and biotic factors in the grassland/shrubland transition zone and continue measurements of plant response to nitrogen additions. We will experimentally test effects of grass density on shrub establishment in the field, and we will continue automating the transition matrices of land-cover change to capture changes for each of the time steps for which we have data. We are particularly interested in the trajectories and transition probabilities for upland areas. We will focus on transitions between sand, grassland, shrubland, and forest as these have particularly significant implications for the occurrence of small mammals species, mammalian predators and shorebirds.

The coastal dune model currently includes a generic dune grass having characteristics similar to those of *Ammophila breviligulata*. We are in the process of adding additional grasses to the model (representative of *Spartina patens* and *Uniola paniculata*) to consider the role of inter-species competition on dune formation, dune morphology and island/habitat evolution.

Thresholds for state change

In our examination of salt marsh elevation, we will compare vegetation growth patterns measured in the marsh organs to trends in our long-term biomass data to determine whether the lack of sensitivity to flooding frequency is generalizable or site specific. Marsh organ experiments have been conducted for 2 years, and we do not anticipate any new organ experiments; instead we will continue to monitor growth along natural elevation gradients.

In the coastal bays, we will continue to monitor experimental seagrass addition plots over several years to evaluate the dependency of recovery rate and plant morphological characteristics on water depth. We hypothesize that plots in deeper water would recover more slowly or not recover at all. This study will allow us to identify the critical water depth threshold and evaluate the possible occurrence of a critical slowing down phenomenon, whereby the response to a perturbation becomes slower as the critical threshold is approached.

On the barrier islands we will continue monitoring seed rain data, species composition/cover and other environmental variables to further refine the dispersal curve and identify threshold levels of water availability, salinity, grass density, and composition that determine seedling establishment.

Ecosystem Connectivity

For the aquaculture studies in the coastal bays, we will continue to monitor trends in clam production using aerial photos taken annually. Studies of nutrient cycling related to aquaculture will also be continued. We will further explore the potential for impacts and subsidies, particularly the effects of enhanced nutrient fluxes in these oligotrophic bays.

Relative to modeling of suspended sediment concentration, priorities for the next 3 years are to: 1) Incorporate modeling results and bay-marsh flux measurements into a longer-time-scale, spatial model of marsh evolution in the VCR; 2) Incorporate the effects of seagrass meadows on flow and turbidity into our Delft3D simulations; and 3) Test the new method for quantifying bed properties in another system, e.g., PIE LTER, where the necessary inputs are available.

The Nature Conservancy constructed several additional artificial oyster reefs during 2013 and 2014 to serve as a focus of new long-term experiment. Waves, mean currents, turbulence, and suspended sediment concentrations will continue to be measured across these constructed reefs and at nearby control sites. Additional reefs over a range of ages (from 1 to 50 years) will be monitored to determine how wave attenuation is affected by reef morphology, water depth, incident wave height, and wind speed. Rates of accretion/erosion of the marsh edge will be monitored using aerial photography and surveying.

Subsidies

In our examination of subsidies in the coastal bays, we will test if macroalgal mats, by attracting invertebrates like amphipods, promote movement of *Vibrio* pathogens through bird foraging on amphipods. We will test for the abundance of the two *Vibrio* species in mats, amphipods, oysters, and bird feces on mudflats with high and low macroalgal densities and will also conduct experimental manipulations of *G. vermiculophylla* to test for its effects on pathogen abundance. For the aquaculture studies, we will continue to monitor trends in clam production using aerial photos taken annually. Studies of nutrient cycling related to aquaculture will also be continued. We will further explore the potential for impacts and subsidies, particularly the effects of enhanced nutrient fluxes in these oligotrophic bays.

State change & projected climate/land-use drivers

We are currently adding marsh edge erosion by waves into our coupled model of barrier island-marsh evolution. This work will be based on relatively simple relationships between erosion rate and wave power (McLoughlin et al. 2015), including the influence of tidal-flat fetch and depth on wave characteristics. The new model will consider connectivity between barrier islands, marshes, and tidal flats, and the impact of these couplings on system response to sea-level rise and storms.

We will continue to monitor the dune grass transplantation experiment, the post-fertilized dune plots and the expansion of *Uniola*. To address the affects of shrub expansion on island fauna, we will 1) continue to relate long-term data on vegetation change, mammal predators and shorebird populations; 2) continue analysis of how climate-driven geomorphology changes affect migratory and nesting shorebird abundance, habitat selection and prey availability; 3) add camera trapping efforts on mammals on several VCR islands; and 4) conduct additional trapping to assess changes in small mammal populations.

Using the vulnerability index developed by Duran and Moore (2015) we will also model barrier island vulnerability to overwash as a function of the likelihood that dunes will re-establish prior to the next storm event.

Socio-ecological drivers

In our studies of attitudes of the populace of the Eastern Shore, a second survey is being developed to consider choices from the perspective of the public's willingness to ask owners of on-coast properties to change their planned responses to sea-level rise.

We will continue our recently established (2012) long-term experiment designed to explore the ecological and economic benefits of *K. pentcarpos* in abandoned agricultural fields (e.g., nutrient and C sequestration, exclusion of invasive species). Specifically we will examine explore the ecological and economic benefits of *K. pentcarpos.*

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers

Berg, P and Reimers, CE and Rosman, JH and Huettel, M and Delgard, ML and Reidenbach, MA and Özkan-Haller, T (2015). Technical Note: Time lag correction of aquatic eddy covariance data measured in the presence of waves. *Biogeosciences Discussions*. 12 8395-8427. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.5194/bgd-12-8395-2015

Emery, Kyle A. and Wilkinson, Grace M. and Camacho-Ibar, Victor F. and Pace, Michael L. and McGlathery, Karen J. and Sandoval-Gil, Jose M. and Hernández-López, Julieta (2015). Resource use of an aquacultured oyster (Crassostrea gigas) in the reverse estuary Bahía San Quintín, Baja California, México. *Estuaries and Coasts*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: DOI 10.1007/s12237-015-0021-9

Feagin, Rusty A and Figlus, Jens and Zinnert, Julie C and Sigren, Jake and Martínez, Marisa L and Silva, Rodolfo and Smith, William K and Cox, Daniel and Young, Donald R and Carter, Gregory (2015). Going with the flow or against the grain? The promise of vegetation for protecting beaches, dunes, and barrier islands from erosion. *Frontiers in Ecology and the Environment*. 13 (4), 203-210. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed =

Yes ; DOI: doi:10.1890/140218

Graziani, D. and Day, F.P. (2015). Thresholds of change in decomposition rates along a dune/swale transect on a Virginia barrier island. *Journal of Coastal Research*. 31 (1), 148-154. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.2112/JCOASTRES-D-13-00102.1

Hayn, M. and Howarth, R.W. and Marino, R. and Ganju, N. and Berg, P. and Foreman, K.H. and Giblin, A.E. and McGlathery, K.J. (2015). Exchange of nitrogen and phosphorus between a shallow seagrass-dominated lagoon and coastal waters. *Estuaries and Coasts*. 37 (1), 63-73. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1007/s12237-013-9699-8

Howarth, R.W. and Hayn, M. and Marino, R.M. and Ganju, N. and Foreman, K.H. and Berg, P. and Giblin, A.E. and McGlathery, K.J. and Walker, J.D. (2014). Metabolism of a nitrogen-enriched coastal marine lagoon during summertime. *Biogeochemistry*. 118 (1-3), 1-20. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 0.1077/s10533-013-9901-x

Huddleston, Samuel H. and Porter, John H. and Brown, Donald E. (2015). Improving forecasts for noisy geographic time series. *Journal of Business Research*. 68 (8), 1810-1818. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: http://dx.doi.org/10.1016/j.jbusres.2015.03.040

Koopmans, Dirk J and Berg, Peter (2015). Stream oxygen flux and metabolism determined with the open water and aquatic eddy covariance techniques. *Limnology and Oceanography*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/lno.10103

Leonardi, N. and Fagherazzi, S. (2015). Local variability in erosional resistance affects large scale morphodynamic response of salt marshes to wind waves. *Geophys. Res. Letters*. 42 . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: doi:10.1002/2015GL064730

Leonardi, Nicoletta and Fagherazzi, Sergio (2014). How waves shape salt marshes. *Geology*. 42 (10), 887-890. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1130/G35751.1

Leonardi, Nicoletta and Kolker, Alexander S and Fagherazzi, Sergio (2015). Interplay between river discharge and tides in a delta distributary. *Advances in Water Resources*. 80 69-78. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.advwatres.2015.03.005

Mariotti, G and Valentine, K and Fagherazzi, S (2015). Time-dependent behavior of a placed bed of cohesive sediment subjected to erosion and deposition cycles. *Ocean Dynamics*. 65 (2), 287-294. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1007/s10236-014-0798-2

Murphy, A.E. and Anderson, I.C. and Luckenbach., M. W. (2015). Enhanced nutrient regeneration at commercial hard clam (Mercenaria mercenaria) beds and the role of macroalgae. *Marine Ecology Progress Series*. 530 135-151. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1007/s10236-014-0798-2

Porter, John H. and Dueser, Raymond D. and Moncrief, Nancy D. (2015). Cost-Distance Analysis of Mesopredators as a Tool for Avian Habitat Restoration on a Naturally Fragmented Landscape. *Journal of Wildlife Management*. 79 (2), 220-234. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/jwmg.829

Safak, I. and Wiberg, P. L. and Richardson, D. L. and Kurum, M. O. (2015). Controls on residence time and exchange in a system of shallow coastal bays. *Continental Shelf Research*. 97 (0), 7-20. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: http://dx.doi.org/10.1016/j.csr.2015.01.009

Temmerman, Stijn and Kirwan, Matthew L (2015). Building land with a rising sea. *Science*. 349 (6248), 588-589. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1126/science.aac8312

Vinent, Orencio Durán and Moore, Laura J (2014). Barrier island bistability induced by biophysical interactions. *Nature Climate Change*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1038/nclimate2474

Wiberg, Patricia L and Carr, Joel A and Safak, Ilgar and Anutaliya, Arachaporn (2015). Quantifying the distribution and influence of non-uniform bed properties in shallow coastal bays. *Limnology and Oceanography: Methods*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; DOI: doi: 10.1002/lom3.10063

Licenses

Other Conference Presentations / Papers

Other Products
Databases.

The VCR/LTER shares 195 online datasets with an aggregate volume of approximately 250 GB. These are published via the VCR/LTER web site (http://www.vcrlter.virginia.edu), the LTER Data Portal (http://portal.lternet.edu), and the DataOne Search data portal.

The datasets are frequently downloaded for use by researchers and students. 231 of the data files associated with online datasets (some datasets include multiple data files) were downloaded a total of 9,282 times (8,782 times from the LTER Data Portal and 500 times from the VCR LTER web site) during the period 2014-10-01 to 2015-09-30.

Other Publications

Patents

Technologies or Techniques

The VCR/LTER provides a web service that automates generation of statistical programs based on Ecological Metadata Languagebased metadata. Given the identity of a specific dataset in a repository or any webaccessible EML metadata the web service will create R, Matlab (courtesy of GCE LTER), SAS or SPSS programs. The web service is described at http://www.vcrlter.virginia.edu/data/eml2/PASTAprogHelp.html, with detailed information at: http://www.vcrlter.virginia.edu /data/eml2/PASTAprogWebService.pdf. There is also a webportal for statistical code generation at: http://www.vcrlter.virginia.edu/data/eml2/eml2stat.html. During 2014 the web service was incorporated into the LTER Data Portal so that links which use the service are available for data from all LTER sites in the "Code Generation" section of each data package that includes one or more data tables.

The VCR LTER also shares with other LTER sites tools for summarizing the upload status of datasets into PASTA and tallying downloads from PASTA (https://github.com/lter/VCR)

Thesis/Dissertations
Timmerman, Ross. *Biophysical Controls on Sediment Suspension in a Shallow Coastal Bay*. (2014). University of Virginia. Acknowledgement of Federal Support = Yes

Sedghi, Nathan M.. *Blue carbon in coastal freshwater/brackish marshes on the barrier islands of Virginia: Belowground carbon dynamics*. (2015). Old Dominion University. Acknowledgement of Federal Support = Yes

Adams, Emily C.. *Blue carbon in freshwater / brackish marshes on the barrier islands of Virginia: Aboveground net primary productivity and carbon pools*. (2015). Old Dominion University. Acknowledgement of Federal Support = Yes

Emery, Kyle A.. *Coastal bivalve aquaculture carbon cycling, spatial distribution and resource use in Virginia, USA and Baja California, Mexico.*. (2015). University of Virginia. Acknowledgement of Federal Support = Yes

Walker, Janet. *Genetic Diversity and Spatial Structure of Spartina alterniflora at Four Spatial Scales*. (2015). University of Virginia. Acknowledgement of Federal Support = Yes

Ethridge, Sherer B.. *Hydrogeomorphology and horizontal movement of Juncus roemerianus*. (2015). East Carolina University. Acknowledgement of Federal Support = Yes

Dows, Benjamin. *Roles of seed dispersal and environmental filters in establishment of the dominant shrubs: Morella cerifera and M. pensylvanica, on an Atlantic barrier island*. (2014). Virginia Commonwealth University. Acknowledgement

of Federal Support = Yes

Burns, Talia N. Dibbell. *Spartina alterniflora Responses to Flooding in Two Salt Marshes on the Eastern Shore of Virginia*. (2015). University of Virginia. Acknowledgement of Federal Support = Yes

Duvall, Melissa S.. *The Effects of Waves and Tidal Inundation on Sediment Deposition and Flux across a Bay-Marsh Boundary*. (2014). University of Virginia. Acknowledgement of Federal Support = Yes

Websites
Virginia Coast Reserve Long-Term Ecological Research
http://www.vcrlter.virginia.edu

Main web site for the Virginia Coast Reserve LongTerm Ecological Research project. Includes links to personnel, data, research summaries, student theses, online maps and planning resources for fieldwork. During the period Oct 1, 2014 to Sep 30, 2015 the primary site had 4,174 users and 21,704 page views. 37% of visitors used the site more than once. Users were primarily from the US (78%), with additional users from Russia (2%), Poland, UK, and China (1% each).

Participants/Organizations

Research Experience for Undergraduates (REU) funding

Form of REU funding support: REU supplement

How many REU applications were received during this reporting period? 7

How many REU applicants were selected and agreed to participate during this reporting period? 5

REU Comments:

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
McGlathery, Karen	PD/PI	4
Porter, John	Co PD/PI	9
Reidenbach, Matthew	Co PD/PI	3
Wiberg, Patricia	Co PD/PI	3
Anderson, Iris	Co-Investigator	1
Bachmann, Charles	Co-Investigator	1
Berg, Peter	Co-Investigator	2
Blum, Linda	Co-Investigator	5
Christian, Robert	Co-Investigator	1
D'Odorico, Paolo	Co-Investigator	1
Day, Frank	Co-Investigator	3

Name	Most Senior Project Role	Nearest Person Month Worked
Dueser, Raymond	Co-Investigator	3
Fagherazzi, Sergio	Co-Investigator	2
Fenster, Michael	Co-Investigator	2
Fuentes, Jose	Co-Investigator	1
Galloway, James	Co-Investigator	1
Hayden, Bruce	Co-Investigator	1
Karpanty, Sarah	Co-Investigator	2
Kirwan, Matt	Co-Investigator	2
Lawson, Sarah	Co-Investigator	1
Macko, Stephen	Co-Investigator	1
Mills, Aaron	Co-Investigator	2
Moncrief, Nancy	Co-Investigator	1
Moore, Laura	Co-Investigator	2
Pace, Michael	Co-Investigator	1
Schwarzschild, Arthur	Co-Investigator	12
Smith, David	Co-Investigator	1
Swallow, Stephen	Co-Investigator	1
Young, Donald	Co-Investigator	2
Zinnert, Julie	Co-Investigator	2
Carr, Joel	Postdoctoral (scholar, fellow or other postdoctoral position)	4
Delgard, Marie Lise	Postdoctoral (scholar, fellow or other postdoctoral position)	4
Goldstein, Evan	Postdoctoral (scholar, fellow or other postdoctoral position)	2

Name	Most Senior Project Role	Nearest Person Month Worked
Smyth, Ashley	Postdoctoral (scholar, fellow or other postdoctoral position)	6
Boyd, David	Technician	12
Buck, Christopher	Technician	8
Luckenbach, Patrick	Technician	3
Maben, John	Technician	1
Trachta, Charles	Technician	4
Neafsey, Ernest	Staff Scientist (doctoral level)	4
Adams, Emily	Graduate Student (research assistant)	2
Besterman, Alice	Graduate Student (research assistant)	6
deVries, Elsemarie	Graduate Student (research assistant)	4
Emery, Kyle	Graduate Student (research assistant)	6
Kearney, William	Graduate Student (research assistant)	4
Lauzon, Rebecca	Graduate Student (research assistant)	4
Lunstrum, Abby	Graduate Student (research assistant)	4
Murphy, Elizabeth	Graduate Student (research assistant)	4
Oreska, Matthew	Graduate Student (research assistant)	4
Ruiz-Plancarte, Jesus	Graduate Student (research assistant)	4
Sedghi, Nathan	Graduate Student (research assistant)	2
Smith, Matt	Graduate Student (research assistant)	3
Volaric, Martin	Graduate Student (research assistant)	4
Yue, Ian	Graduate Student (research assistant)	4
Schieder, Nathalie	Non-Student Research Assistant	3

Name	Most Senior Project Role	Nearest Person Month Worked
Claspsaddle, Madison	Undergraduate Student	1
Deaton, Charles	Undergraduate Student	2
Givens, Kiera	Undergraduate Student	3
Hill, Tyler	Undergraduate Student	2
Walker, Janet	Undergraduate Student	2
Warner, Nicholas	Undergraduate Student	3
Bartenfelder, Amy	Research Experience for Undergraduates (REU) Participant	3
Braun, Andrew	Research Experience for Undergraduates (REU) Participant	3
Hahne, Sara	Research Experience for Undergraduates (REU) Participant	3
Price, Taylor	Research Experience for Undergraduates (REU) Participant	3
Spady, Katie	Research Experience for Undergraduates (REU) Participant	5
Cook, Allice	Other	1
Sorabella, Laurie	Other	1

Full details of individuals who have worked on the project:

Karen McGlathery
Email: kjm4k@virginia.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 4

Contribution to the Project: Project leader, seagrass research

Funding Support: NSF

International Collaboration: Yes, Denmark, France, Mexico
International Travel: No

John H Porter
Email: jhp7e@virginia.edu

Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 9

Contribution to the Project: Information management, landscape, population and community ecology research

Funding Support: NSF

International Collaboration: Yes, China, Taiwan
International Travel: Yes, Taiwan - 0 years, 0 months, 12 days; China - 0 years, 0 months, 8 days

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Matthew A Reidenbach
Email: reidenbach@virginia.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 3

Contribution to the Project: Research on oyster reef establishment and consequences

Funding Support: NSF

International Collaboration: No
International Travel: No

Patricia L Wiberg
Email: pw3c@virginia.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 3

Contribution to the Project: Studies of sediment dynamics and water movements

Funding Support: UVA, NSF

International Collaboration: No
International Travel: No

Iris Anderson
Email: iris@vims.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Studies of nitrogen and phosphorus cycling and clam aquaculture

Funding Support: SeaGrant, VIMS

International Collaboration: Yes, Italy
International Travel: No

Charles Bachmann
Email: bachmann@cis.rit.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Use of hyperspectral remote sensing

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Funding Support: Office of Naval Research

International Collaboration: No
International Travel: No

Peter Berg
Email: pb8n@virginia.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 2

Contribution to the Project: Aquatic flux measurements

Funding Support: NSF, UVA Dean's office

International Collaboration: No
International Travel: No

Linda Blum
Email: lkb2e@virginia.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 5

Contribution to the Project: Study of linkages between ecological and geomorphological process in salt marshes focused primarily on soil organic matter accumulation and thus plant belowground production and decomposition

Funding Support: UVA

International Collaboration: No
International Travel: No

Robert R Christian
Email: CHRISTIANR@ecu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Network analysis, studies of marsh macrophytes

Funding Support: Personal

International Collaboration: Yes, Italy
International Travel: No

Paolo D'Odorico
Email: pd6v@virginia.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Modeling of coastal lagoons

Funding Support: UVA

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Chesapeake Experience	Other Nonprofits	York County, VA
Dickinson College	Academic Institution	Carlisle, PA
Northampton County Public Schools	School or School Systems	Eastville, VA
Old Dominion University	Academic Institution	Norfolk, VA
Smithsonian Environmental Research Center	State or Local Government	Edgewater, MD
The Nature Conservancy	Other Nonprofits	Nassawadox, VA
University of Bremen	Academic Institution	Germany
Virginia Institute of Marine Sciences	Academic Institution	Gloucester Point, VA

Full details of organizations that have been involved as partners:

Chesapeake Experience

Organization Type: Other Nonprofits
Organization Location: York County, VA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: We collaborate on joint educational programs for K-12 and public groups.

Dickinson College

Organization Type: Academic Institution
Organization Location: Carlisle, PA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: Thomas Arnold collaborates on carbon flux studies

Northampton County Public Schools

Organization Type: School or School Systems
Organization Location: Eastville, VA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: We collaborate with the Northampton Public School system on Schoolyard LTER activities for K-12 students.

Old Dominion University

Organization Type: Academic Institution
Organization Location: Norfolk, VA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: Richard Zimmerman collaborated on development of bathymetric data layers

Smithsonian Environmental Research Center

Organization Type: State or Local Government
Organization Location: Edgewater, MD

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: Whitman Miller collaborates on carbon flux studies

The Nature Conservancy

Organization Type: Other Nonprofits
Organization Location: Nassawadox, VA

Partner's Contribution to the Project:
Facilities

More Detail on Partner and Contribution: The Virginia Coast Reserve of The Nature Conservancy (TNC) is our primary research site. TNC allows us access to the islands for our research.

University of Bremen

Organization Type: Academic Institution
Organization Location: Germany

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: L. Moore has collaborated with Orencio Duran Vinent

Virginia Institute of Marine Sciences

Organization Type: Academic Institution
Organization Location: Gloucester Point, VA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: Collaborate with Robert J. Orth on seagrass restoration and Mark Luckenbach on invertebrate population montoring

What other collaborators or contacts have been involved?
Nothing to report

Impacts

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

We have continued to contribute to the understanding of coastal systems through our observations, experiments and modeling of the effects of climate (sea-level rise, storms) and land use (cultural eutrophication) on barrier islands, marshes and lagoons. This involves developing detailed understanding of sediment, biogeochemical and organism fluxes, controls on plant production and distribution and abundance of plant and faunal species, including community interactions and trophic dynamics.

WATERSHEDS AND LAGOONS

Coastal eutrophication has been recognized as an increasing global problem. Symptoms of eutrophication include blooms of phytoplankton, which when they decompose may reduce available oxygen in the water; blooms of harmful algae that are toxic to fish, shellfish, and occasionally humans; blooms of macroalgae that cause die-backs of seagrasses which are vital to maintaining populations of many fish and crabs; and increasing anoxia. Eutrophication generally results from export of excess nutrients from land, in particular nitrogen. Sources of nitrogen include agriculture, septic tanks, waste-water treatment plants, industry, and atmospheric deposition of nitrogen derived from automobiles, power plants, and other industrial sources. Nitrogen from these sources is most often transported to coastal waters in shallow groundwater and in surface water runoff.

Our modeling and process studies have indicated that the VCR lagoons receive relatively low inputs of nitrogen from the coastal watersheds compared to more eutrophic lagoons in the mid-Atlantic. This is true in part because population densities are relatively low in the VCR watersheds and there is little point-source agriculture (e.g., chicken farms). Much of the fertilizer nutrients that enter the groundwater is removed by an intact riparian zone and by stream sediments, both of which are active sites of denitrificaiton. Nitrogen that enters the lagoon is rapidly removed by both benthic macro- and microalgae. As a result, there is little flux of nutrients from the sediment to the water column and phytoplankton concentrations are typically low. Blooms of macroalgae that occur in early summer typically crash during mid-summer, releasing much of the nitrogen as dissolved inorganic and organic nitrogen. The sediments act to rapidly remove the nitrogen released to the water column by a combination of mechanisms including immobilization by benthic microalgae and coupled nitrification - denitrification. Our recent research has shown that nitrogen is retained in the sediments for a longer time than would be expected by turnover of plant biomass because nitrogen 'shuttles' back and forth between bacterial and benthic microalgal pools.

Our conclusions regarding the importance of macroalgae in influencing the dynamics of nutrient movements within the lagoon helps to explain the role of the lagoon as an active mediator between mainland nutrient sources (e.g., agricultural fields) and the coastal ocean. The recent discovery that the dominant macroalga in the lagoon is an exotic (rather than its native congener), will be important to understanding long-term changes in the lagoon's characteristics. We have shown the importance of this invasive macroalgae in subisidizing nutrients and habitat in intertidal marshes and mudflats.

Shallow bays in the VCR and elsewhere along the US Atlantic coast experienced a dramatic state change in the 1930's when a single storm decimated seagrass populations already decimated by disease. Until recently, VCR lagoons persisted in an alternate, algal-dominated state. Recent field work and modeling showed that high turbidity events in the VCR were episodic and wind driven and we estimated that average light availability over 65-87% of the lagoon bottom is suitable for seagrass recolonization (Lawson et al., 2007). Beginning in 2007, in collaboration with Robert Orth from the Virginia Institute of Marine Science, we began to restore seagrass in a 509 acre 'set aside' we have obtained from the Virginia Marine Resources Commission in our primary lagoon study site, Hog Island Bay. The set-aside was renewed in 2010.

Surface Elevation Tables (SETs) are used at numerous VCR/LTER research sites to quantify changes in sedimentation and subsidence that ultimately will determine the fate of marshes in the face of sea level rise. These baseline measurements at different marshes are then used in association with process-based studies focusing on the processes such as transport of material through tidal flooding, burial of organic matter and its decomposition, marsh plant production (both above and below

ground) and the feedbacks on sedimentation rates, bioturbation by crabs, and even herbivory by insects to develop models aimed at predicting changes in marshes over the coming decades. Our results indicate that the on mainland marshes, the rate of accretion is generally keeping pace with sea level rise, and that specific rates are position dependent, with the upper marsh receiving less input. Results in the lagoon marshes suggest that sea-level rise may be exceeding the ability of the marshes to keep up.

BARRIER ISLANDS

Within the realm of coastal sciences, our work continues to show that barrier island plant communities are sensitive to climate change. These may serve as sentinels to climate change due to a rapid response to shoreline migration and storm related disturbances. The results our work to date have increased our understanding of dynamic vegetation changes and their causes in coastal barrier island ecosystems. We have established that landscape position is they key factor controlling the pattern of plant community development and production on the islands, with distance from the shore (and susceptibility to salt spray and overwash disturbance) and elevation (and distance to the groundwater) as the important factors defining landscape position. New cross site and cross species analyses are linking meteorological and climatological drivers to plant production. This analysis is revealing complex patterns showing that all species and sites do not respond similarly to meteorological drivers.

The conversion of grasslands to shrubs has significant cascading effects on trophic dynamics. We have shown that increased shrub cover provides refuge for mammalian predators that impact migratory waterbird populations. VCR scientists are working with regional managment agencies on novel predator management techniques.

The data compiled so far have enabled tests of previously recently developed untested conceptual models. Additionally, the data are contributing to a long-term predictive model of barrier island morphodynamics. These data will provide climate change assessments along one of the longest natural, mixed-energy barrier island systems in the world. We have coined the term 'maintainer feedback' to apply to processes that maintain low elevations (in contrast to the more typically considered 'dune-builder feedback,' which leads to increases in island elevation). Our work on the maintainer feedback has improved our understanding of the role of combined physical and vegetative processes in barrier island evolution. We have found evidence to suggest that this feedback, working in conjunction with physical processes alone, has the potential to accelerate large-scale shifts from dune-dominated to overwash-dominated barrier morphologies with climate change-induced increases in storm intensity and sea-level rise.

What is the impact on other disciplines?

The studies conducted by the VCR/LTER are inherently interdisciplinary or multidisciplinary. Our studies are being performed by an interdisciplinary team of ecologists, hydrologists, biologists, and physical oceanographers. When such collaborations take place, it is not unusual that each each group of scientists will gain greater insight into problems that may not be recognized within their own discipline.

Research on ecological information management has included computer scientists. The challenges posed by ecological data provide opportunities for innovation in computer science. Our work with development of wireless sensor networks, and processing of the massive data flows they can generate, contributes to better defining the cyberinfrastructure challenges that will confront us in coming decades.

What is the impact on the development of human resources?

As can be seen from the number of graduate and undergraduate students listed on our participant list, this project provides abundant opportunities for training. Moreover, the inter- and multi-disciplinary nature of the research teaches the students how to operate in a collaborative environment. Each year, the VCR LTER supports approximately 25 graduate students who conduct their M.S. and Ph.D. projects at the VCR site and approximately 15 undergraduate students work each year as research assistants in the field and laboratory.

Our SLTER program, and related activities, have helped introduce scientific concepts to K-12 students. All high school students take an LTER-based course before they graduate, and some take more than one course. More than half of these students are from traditionally underrepresented groups.

Day was a member of a diversity working group that received funding from the LTER office and met in Albuquerque to address LTER related diversity issues. That group has now been appointed as an LTER standing committee, and he has

developed a diversity plan for the VCR LTER site.

What is the impact on physical resources that form infrastructure?

The VCR/LTER is the principal user of the Anheuser-Busch Coastal Research Center (ABCRC) of the University of Virginia and provides, through user fees, resources that allow the center to support a substantial housing, lab and boat infrastructure. The ABCRC provides facilities for a number of smaller, more limited projects and educational programs.

Reidenbach has developed an underwater laser-based velocity measuring system. Particle image velocimetry (PIV) has been used for a number of years in laboratories to measure velocity and turbulence over an area ranging from square millimeters to square meters. This system uses a laser and optics to create a laser light sheet. This light illuminates suspended particles in the flow and, using a digital camera, particle motion is recorded. With the recent development of laser diodes, powerful yet energy efficient lasers can be placed in water tight housings and submersed underwater. The system developed uses a 250 mW laser with a wavelength of 532 nm (green light). A waterproof housing has been designed to hold both the laser and optics used to spread the beam into a narrow, yet wide sheet. The housing is sealed and the laser is pulsed on and off using a magnetic switch controlled from outside the housing. Imaging of the illuminated particles is done using a high definition camcorder (Sony HDR-HC7) that can obtain images up to 60 frames per second. Both the laser and camera are attached to a rigid frame and can be deployed in the coastal ocean where suspended sediment particles are tracked.

What is the impact on institutional resources that form infrastructure?

LTER researchers form the core of a monthly seminar series offered at the the Anheuser-Busch Coastal Research Center (ABCRC) of the University of Virginia. Additionally, ecological science programs in the Northampton County High School are highly dependent on resources and facilities provided through our SLTER program.

What is the impact on information resources that form infrastructure?

This project provides a wide array of information resources to the larger scientific community through our formal datasets, which are available via our site data catalog (http://www.vcrlter.virginia.edu/cgi-bin/browseData.cgi), LTER Network, and affiliated data centers (e.g., KNB, DataOne). Data from VCR/LTER tide station is also served by NOAA (http://water.weather.gov/ahps2/hydrograph.php?wfo=akq&gage=cchv2).

Since November 1, 2012, VCR/LTER data files have been downloaded at least 18,932 times. The rate of use is increasing with nearly half (9,282) the data files downloaded during the last year. Of the 539 downloads where the user was identified, 200 (37%) were by users external to the VCR/LTER project. The majority of external downloads were for research (82%), with 18% for education (e.g., student class projects).

As noted below, we provide code generation web services that are used in the LTER Data Portal to generate statistical programs for using LTER data.

Additionally, on our website (http://www.vcrlter.virginia.edu) we provide access to maps, photographs, documents, publication lists and research descriptions.

What is the impact on technology transfer?

The VCR/LTER organized and hosted a workshop in 2013 that enhanced the LTER Controlled Vocabulary, a tool that is used to improve data discoverability. The LTER Controlled Vocabulary has been integrated into other systems, such as the European LTER ENVTHES project.

The PASTAprog web service, which creates customized statistical programs for datasets documented in Ecological Metadata Language, is used to write approximately 10 programs each day that allow users to more easily use LTER datasets from all sites.

What is the impact on society beyond science and technology?

The high historic rate of sea-level rise (~4mm/yr) within the Virginia Coast Reserve make it a bellweather site for assessing the probable impacts of global sea-level changes. Our results concerning the response of salt marshes, upland and lagoon

systems can provide insights that extend to other systems that are only now beginning to experience heightened sea level. VCR researchers work with regional planners and decision-makers in the Mid-Atlantic Climate Adaptation Working Group. In addition, VCR researchers are working The Nature Conservancy to develop a web-based decision tool for coastal resilience that includes natural and social science data to visualize future scenarios of climate change and sea-level rise.

The VCR LTER (UVA) has joined a consortium of institutions in the Mid-Atlantic, including NASA - Wallops Island, University of Delaware, University of Maryland, and the Virginia Institute of Marine Sciences to establish the Mid-Atlantic Coastal Resilience Institute, with the purpose of colloborating with respect to data, models and tools to address coastal reslience in response to climate change.

Work that we are currently doing at the VCR is of much interest to the Department of Environmental Quality of the State of Virginia, and in particular to the Water Conservation Districts located on the Eastern Shore. The major source of nitrogen to VCR coastal lagoons is agriculture. Proper management of agricultural activities and fertilization practices requires an improved understanding of nitrogen losses to the coastal lagoons via groundwater and surface water runoff.

We work closely with colleagues at the Virginia Institute of Marine Sciences and The Nature Conservancy to address issues relevant to sustainable restoration of seagrass and oysters in the VCR and in the mid-Atlantic region in general. Our models on bistable dynamics of seagrass meadows and the dependence on water depth provides useful information on regions within the VCR coastal bays that could potentially support seagrass habitats. We also are providing information on how the maximum depth limit for sustainable seagrass meadows could vary as a function of sediment conditions (organic content, grain size, hydrogen sulfide) and this helps managers identify areas that are most likely to support seagrass habitats over the long term. In addition, our work on hydrodynamic influences on oyster feeding and larval settlement is useful to practitioners in understanding how currents and exposure affect oyster growth and the persistence of oyster reefs.

Recent VCR research is the first the importance of restored seagrass meadows in sequestering carbon and highlighted the role of habitat restoration in mitigation of rising atmospheric CO2 levels. Because the scale and success of seagrass restoration, VCR scientists have been chosen to write the international protocol for the Verified Carbon Standards program on to assign carbon credits on international trade markets for seagrass restoration.

In collaboration with the TNC, we have done a retrospective analysis of long-term trends in erosion and accretion of mainland marshes throughout the VCR from the 1950's to the present. This is coupled with information on the presence of oyster reefs as a potential buffer to marsh erosion. Patterns of erosion were also overlain on maps of TNC-conserved lands to identify potential areas to study climate adaptation and the potential for marshes to transgress onto the mainland with predicted scenarios of climate change and sea-level rise.

Knowledge of the relationship between land use, nutrient contamination of groundwater, groundwater export of nutrients to coastal lagoons, and the fate of nutrients within lagoons will be of benefit to state and federal agencies charged with managing coastal resources. This knowledge will be especially important given the ongoing return of seagrasses to large areas of the coastal bays, from which they have been absent for over 70 years. The VCR lagoons are also a model system to understand the important role of plants in mediating nutrient export from coastal watersheds to the open ocean.

Changes/Problems

Changes in approach and reason for change

We will build on the work of Wiberg and Fagherazzi to develop a sediment budget for the VCR lagoons. This was recommended by the mid-term site review team and is important to understanding landscape-level responses to sea-level rise and storms.

Also based on recommendations of the mid-term review team, we will synthesize data on carbon pools and fluxes to work on a carbon budget, both for individual subsystems, and ultimately for the VCR as a whole.

Actual or Anticipated problems or delays and actions or plans to resolve them

Nothing to report.

Changes that have a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects
Nothing to report.

Significant changes in use or care of vertebrate animals
Nothing to report.

Significant changes in use or care of biohazards
Nothing to report.