SECTION 1. RESULTS OF PRIOR SUPPORT

HISTORY, GROWTH, AND NEW DIRECTIONS OF THE VCR LTER PROGRAM

The Virginia Coast Reserve (VCR) LTER is an interdisciplinary research program that addresses ecosystem state change in dynamic coastal barrier systems in response to the long-term drivers of environmental change. The VCR is part of the 1,000-kilometer barrier island-coastal bay system extending along the U.S. Atlantic Coast. It is both representative of coastal barrier systems globally and a reference for comparison with other types of land-margin ecosystems. The marine-terrestrial landscape is heterogeneous, including mainland watersheds, marshes, mudflats, bays and barrier islands (Fig 1).

Our conceptual framework for the VCR LTER has evolved over the years as our understanding of coastal barrier dynamics has increased. In **VCR I**, (1987-1992) we began with the hypothesis that large-scale events and processes, such as storms and sea-level rise, drive ecosystem dynamics. We established that the redistribution of sediment by wind, waves and currents is the main process behind these dynamics (e.g., Hayden et al. 1991; Oertel et al. 1992). We also showed that the VCR is distinguished by an extraordinarily rapid rate of landscape change, driven primarily by the frequency of storms and also by the regional extinction of foundation seagrass species in the coastal bays (e.g., Hayden et al. 1991; Young et al. 1995a, b). In **VCR II** (1992-1994), we established the non-linearity of these ecological changes, describing how gradual changes within an ecosystem are punctuated by abrupt transitions to another ecosystem state due to disturbance events (e.g., Fahrig et al. 1993; Brinson et al. 1995). This emphasis on the interaction of "press" (pervasive and subtle change) and "pulse" (sudden event or disturbance) dynamics continues to be central to our thinking. In **VCR III** (1994-2000), we developed the unifying theme that the non-linear mechanisms of state change across the marine-terrestrial landscape are controlled by the relative elevations of the land, sea and groundwater surfaces (Hayden et al. 1995). We quantified how both physical processes (storms, sea-level rise, precipitation) and biotic feedbacks (on sediment erosion/accretion and groundwater levels) influence ecosystem states and the transitions between them (e.g., Shao & Shugart 1997; Christiansen et al. 2000). The effects of these dynamic relationships influence vegetation patterns and productivity, nutrient cycling and faunal relationships in ecosystems (upland, marsh, tidal flat, coastal bay) on the landscape (e.g., Tolliver et al. 1997; Moncrief & Dueser 1998; Brinson & Christian 1999). In **VCR IV** (2000-2006), we used the geomorphic concept of hypsometry to quantify the area of the landscape in different elevations to identify ranges occupied by different ecosystems (Oertel et al. 2000). This set the stage for **VCR V** where we developed models and quantified threshold responses that trigger rapid ecosystem state change, and addressed landscape connectivity through the fluxes of sediments and organisms.

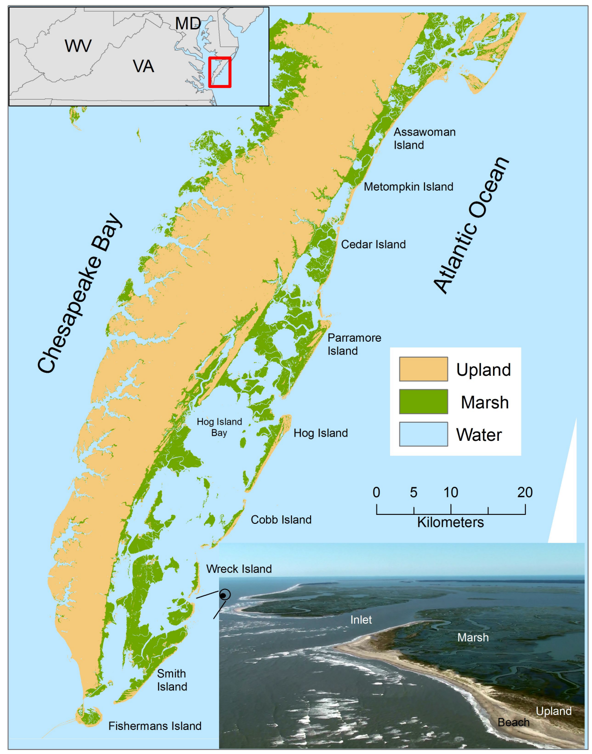


Fig. 1. Virginia Coast Reserve LTER includes an assemblage of 14 barrier islands and 9 shallow coastal bay systems, extending 110 km along the seaward margin of the Delmarva Peninsula. Intertidal marshes and mudflats occur on the mainland and barrier island borders of the system and extend into the coastal bays. Exchange with the ocean is through narrow inlets between the islands.

Throughout our history, VCR scientists have contributed to theoretical advances in understanding complex non-linear dynamics of ecosystem change. Our strength is the interdisciplinary approach we take coupling geomorphology with ecological feedbacks. In **VCR V**, we built on our long-term observations and experiments to develop quantitative models of these non-linear dynamics that show the emergence of alternative stable states, separated by thresholds, in the intertidal and subtidal parts the landscape. The mid-term site review team *"found this approach to be exciting and cutting edge. Through this research, the VCR LTER has a great opportunity to change the way we think about how ecosystems and landscapes function."* In **VCR VI**, we will extend this approach to evaluate whether the existence of alternative stable states and threshold responses to climate and other interacting drivers is a unifying theme that describes long-term change at each major ecosystem transition (e.g., mainland upland-marsh, marsh-tidal flat, tidal flat-seagrass, marsh-barrier island upland, grassland-shrubland), and we will address how the connectivity of ecosystems via fluxes of sediments and organisms influences these non-linear dynamics.

RESULTS FROM VCR V

We have produced 198 journal articles and book chapters, and 41 theses or dissertations have been completed, from January 2006 – February 2012. In addition, we have submitted a book manuscript to Oxford University Press, *Long-term Dynamics of a Coastal Barrier System*, synthesizing two decades of research at the VCR LTER. An additional $7.3 million in funding has been leveraged to help achieve our long-term research objectives. Below we describe *selected* accomplishments over the last 6 years. We have grouped our research results into the 3 themes addressed in VCR V: **1) state change, thresholds and biotic feedbacks; 2) fluxes between and within landscape units (watershed, tidal marsh, coastal bay, barrier island); and 3) landscape analysis**. We have chosen examples that both illustrate the breadth and significance of our program and set the stage for our new emphasis on the dynamics of alternative stable states in coastal barrier landscapes. We highlight in bold text the 10 most significant publications from VCR V that lay the foundation for our next phase of research. Other examples of research findings and our full list of publications can be found on our webpage (http://www.vcrlter.virginia.edu). We follow with a summary of our broader impacts, information management, and synthesis and collaborative activities.

Theme 1. State Change, Thresholds and Biotic Feedbacks

Subtidal – In shallow coastal systems, seagrasses provide important ecosystem services including stabilizing sediment, sequestering carbon (C) and nutrients, and providing habitat and an energy source for a diverse fauna. The eelgrass (*Zostera marina*) that once carpeted the seafloor of the VCR coastal bays and supported a thriving economy became locally extinct in the early 1930s as a result of disease and storm disturbance, causing a catastrophic shift to an unvegetated state. We have collaborated with colleagues at the Virginia Institute of Marine Sciences (VIMS) and The Nature Conservancy (TNC) in a large-scale ecosystem-level experiment to reverse the state change. This has resulted in >17 km^2 of restored habitat in a chronosequence of seagrass meadows 0 – 10 years since seeding. The first results of this long-term study are published in 10 papers in a special thematic issue of the journal *Marine Ecology Progress Series*. We document the recovery of key ecosystem functions related to primary productivity, C and nitrogen (N) sequestration, increased water column clarity, and sediment stabilization with a state change to seagrass dominance (Cole et al., 2012; **McGlathery et al. 2012**; Orth et al. 2012). Our long-term data indicate that at least a decade is required for these functions to be restored fully (**McGlathery et al. 2012**). The expansion of seagrass in the coastal bays has altered local hydrodynamics and switched the seafloor from an erosional environment to one that promotes deposition of suspended sediment by reducing near-bottom velocities (70-90%) and wave heights (45-70%) (**Hansen & Reidenbach 2012**).

This positive feedback of reduced sediment suspension and increased water clarity is the basis for a hydrodynamic model of vegetation-sediment-water flow interactions we developed, which shows the emergence of alternative stable states, one with clear water and a seagrass-covered bottom and the other with more turbid water and no seagrass cover (**Carr et al., 2010**). The model shows that under current conditions, bistable dynamics occur at a depth range of 1.6 – 1.8 m (mean sea level – MSL), which agrees remarkably well with the 1.6 m maximum depth limit of current restored populations determined from our long-term monitoring (**McGlathery et al. 2012**). Bare sediment is the stable state deeper than 1.8 m, and the seagrass meadow is the stable state between 0.9 and 1.6 m depth (MSL). Seagrass meadows in the bistable depth range have limited resilience on decadal time scales, particularly to high temperature events associated with climate change, which causes state change by shifting the bistable range to shallower depths, and reduces aerial coverage of meadows (Carr et al. 2012 a,b).

Intertidal – Tidal marshes occur along the mainland coast, landward edges of barrier islands and in isolated patches within coastal bays. Their spatial extent and distribution is controlled by the balance between erosion at the bay-marsh interface and transgression at the upland-marsh interface as the marsh accretes vertically in response to sea-level rise. Based on our long-term experiments and observations, we have found that VCR marshes are resistant to state change from high to low marsh in response to rising sea level over decadal time scales, and that disturbance is often necessary to overcome this resistance (Keusenkothen & Christian 2004). Disturbance also promotes fragmentation and pond formation, which in turn causes dynamic changes in food webs (Dame & Christian 2007, 2008). Our long-term record of marsh elevation indicates that some of the mainland marshes are accreting at a rate similar to that of sea-level rise (Fig. 2), but that bay marshes are more vulnerable to submergence, which has adverse effects on waterbirds (Erwin et al. 2006, 2007). We also have evidence from short-term experiments that higher temperatures associated climate change could make marshes less resilient to sea-level rise by enhancing decomposition more than production (Kirwan & Blum 2011).

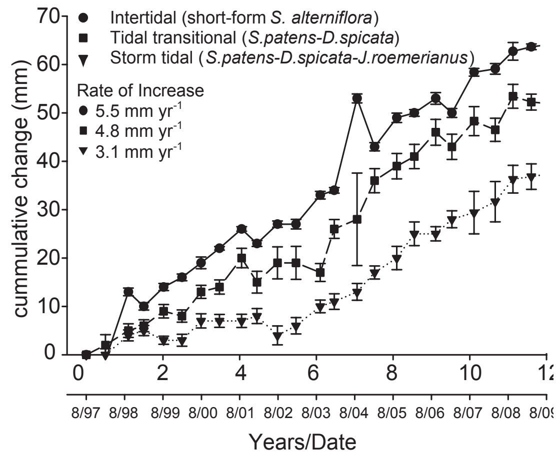


Fig. 2. Total marsh elevation change in in Phillips Creek marsh measured from SET data integrating both surface and subsurface processes.

Non-linear interactions between vegetation and the flow of water and suspended sediment also drive state change dynamics of intertidal marshes (**Brinson 2006**; Day et al. 2008; Kirwan et al. 2010; Kirwan & Blum 2011). We have developed a model that describes the strong coupling between the evolution of marshes and tidal flats, and the existence of these as alterative stable states as a function of vertical elevation (Fagherazzi et al. 2006; **Mariotti & Fagherazzi 2010**). Marsh edge erosion and sediment transport influence the dynamics of these alternative states. Our decadal scale (1957 – 2009) and detailed short-term measurements show that erosion rates vary more than an order of magnitude (0.1 m to 1.5 m per year; McLaughlin 2011). Based on a 2D model of hydrodynamics and sediment transport, we show that wave attack at the marsh boundary increases with tidal elevation until the marsh is submerged and then rapidly decreases (Fagherazzi & Wiberg 2009; Tonelli et al. 2010; Mariotti & Fagherazzi 2010). Wave energy at the marsh boundary produces a wide array of marsh edge morphologies (wave-cut gullies, terraces, overhanging root mats) that influence edge erosion rates and are related to local vegetation and sediment characteristics, and the presence of crab burrows and bivalves (Priestas & Fagherazzi 2011; McLaughlin 2011).

Barrier Islands – Long-term and landscape-scale vegetation patterns on the islands reflect non-linear dynamics and threshold responses to environmental drivers (**Young et al.** 2007, **2011**; **Zinnert et al. 2011**). We have shown that controls on plant community distribution can be explained by two key environmental parameters: distance from the shoreline (beach face) and elevation above sea level (Fig. 3; **Young et al.** 2007, **2011**). These two parameters integrate

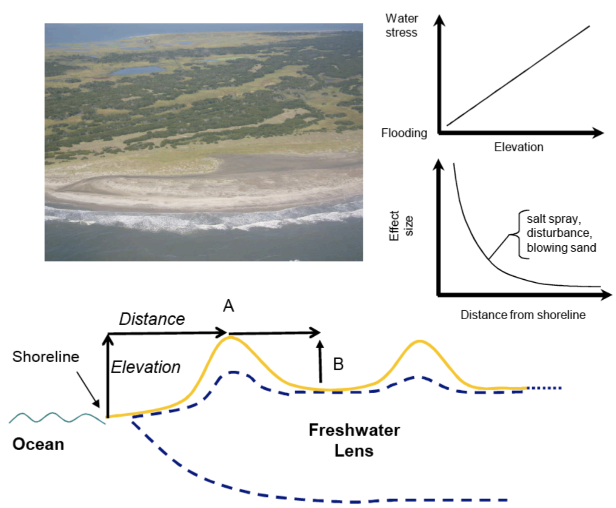


Fig. 3. Conceptual model showing the importance of landscape position for barrier island vegetation highlights distance from the ocean and elevation above sea level as main determinants of species distribution patterns.

a number of important physical and biotic variables. For example, distance from the shoreline affects exposure to sea spray, burial by windblown sand, and vulnerability to storm-related disturbance (i.e., overwash) and, as a result, the extent to which ecological succession can take place. Elevation above sea level determines disturbance vulnerability, and influences groundwater and nutrient availability. The presence of plants feeds back to influence elevation by trapping and accumulating sand, or by maintaining low elevations (see below). These relationships can be used to assess changes in species distribution with variations in island geomorphology and with climate change scenarios of accelerating sea-level rise and altered storm frequencies.

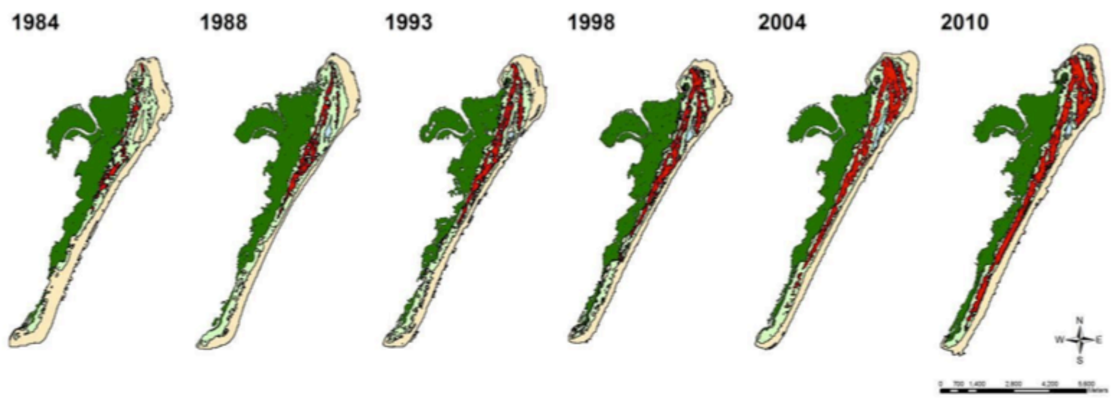


Fig. 4. Decadal changes in shrub distribution (red) on Hog Island. The >400% increase in shrub thickets over 30 years is related to decreases in minimum temperatures and precipitation and increasing atmospheric CO_2.

Over the last 30 years, we have observed a dramatic increase in shrub thickets (*Myrica* sp.; now *Morella* sp.) by >400% as shrubs encroach onto grasslands (Fig. 4; Young et al. 2007). This has also been recorded in continental arid habitats and other coastal systems (Van Auken 2000; Knapp et al. 2008; **Zinnert et al. 2011**). At the VCR, shrub expansion was not related to island area or stability (Young et al. 2007), but instead to a decrease in precipitation and increases in winter temperatures and atmospheric CO_2 concentrations (**Zinnert et al. 2011**). Analysis of recent LiDAR (Light Detection And Ranging) data showed that *Morella* has only expanded into 50% of suitable habitat (based on elevation and distance to shoreline). These shrubs may be sentinels for climate change impacts on the barrier island landscape. Long-term observations also indicate an 'upward cascade' in which predator (fox, raccoon) and small mammal populations are linked to the presence and patchiness of shrub thicket. In turn, the presence of predators on barrier islands is negatively correlated with the abundance of ground-nesting waterbirds (Erwin et al. 2011).

Theme 2. Fluxes Between and Within Landscape Units

Watershed Nutrient loading – Nutrient fluxes from watersheds and airsheds potentially influence water quality (and clarity) and the dynamics of alternative stable states in the coastal bays. Since there are no large rivers that feed into VCR bays, nutrient inputs are primarily via groundwater and atmospheric deposition. Estimates of baseflow N loading from stream monitoring in a subset of the 54 subwatersheds that drain into the VCR coastal bays and a N loading model based on watershed land use/land cover show that loading is low relative to other

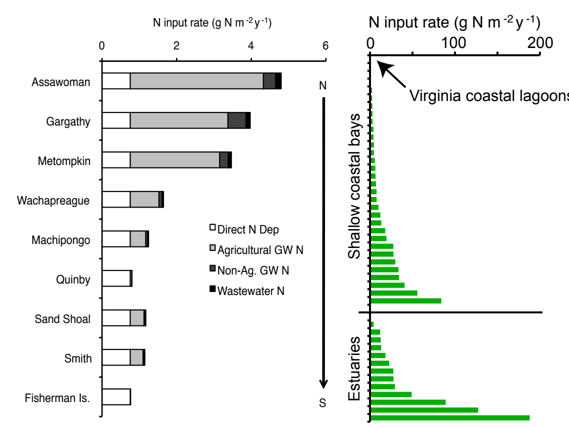


Fig. 5. Watershed loadings to VCR coastal bays determined by model based on land use and attenuation in the aquifer (left panel). Nitrogen loading to VCR coastal bays is extremely low compared to other shallow coastal ecosystems and deep estuaries (right panel; from McGlathery et al. 2007).

coastal bays, making this an excellent reference system for more eutrophic systems regionally and globally (Fig. 5; McGlathery et al. 2007; **Giordano et al. 2011**; Cole 2011). These low nutrient-loading rates are corroborated by 17 years of water quality data (Fig. 6) and shorter-term monitoring data (Moore et al., 2012) showing high water quality in the coastal bays (low inorganic N and chlorophyll concentrations). Although agricultural fertilizer is the dominant terrestrial N source to the region (Stanhope et al. 2009; **Giordano et al. 2011**; Cole et al. 2011), denitrification in the riparian zone and stream sediments is an important mechanism removing agricultural N from the shallow aquifer before it reaches the coastal bays (Gu et al. 2007; 2008a,b).

Hydrodynamics – Nutrient processing and retention, sediment redistribution, and water temperature variations are all influenced by hydrodynamics and water residence times, and may affect the dynamics of alternative stable states in the marshes and coastal bays. We recently adopted the Finite-Volume Coastal Ocean Model (FVCOM), an open-source 3D unstructured-grid model that has a number of modules, including variable forcing (tide, wind, waves), wetting-drying, sediment transport, Lagrangian particle tracking, and water quality. We have used the model to assess sediment suspension as a function of wave and tidal heights to simulate typical storm events, and have calibrated it against field measurements. The results show a significantly larger effect of wave height than tidal amplitude on sediment suspension. Residence times calculated for bays with different bathymetry and coastline geometry were spatially variable within each bay, ranging from a few hours close to the channels to 2 weeks near the mainland boundary (Fig. 7).

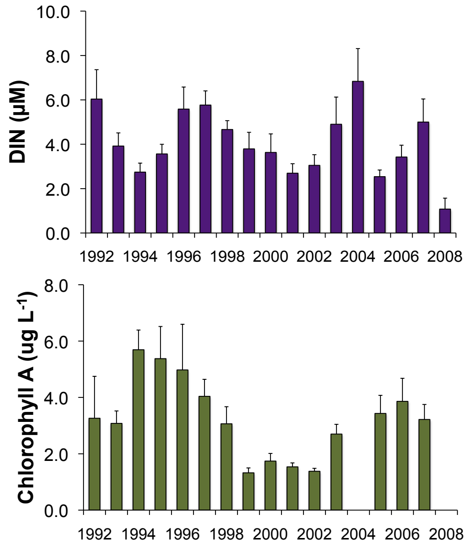


Fig. 6. Long-term data from the VCR LTER coastal bays for dissolved inorganic nitrogen and chlorophyll show consistently high water quality.

Faunal movements and trophic dynamics on barrier islands – Migrating songbirds are important vectors of seed transfer, influencing vegetation community structure and patch dynamics of shrub thickets and grasslands (Shifflet & Young 2010). Long-term observations have shown that mammalian predators (foxes, raccoons) are highly mobile, moving from island to island based on accessibility and routes requiring the least expenditure of energy. Mammal movements and population dynamics related to vegetation structure (see above) together influence waterbird vulnerability to predation and indicate 'hotspots' where monitoring, experimental predator removal/reduction and behavioral modification (food aversion to reduce egg predation) would be most effective.

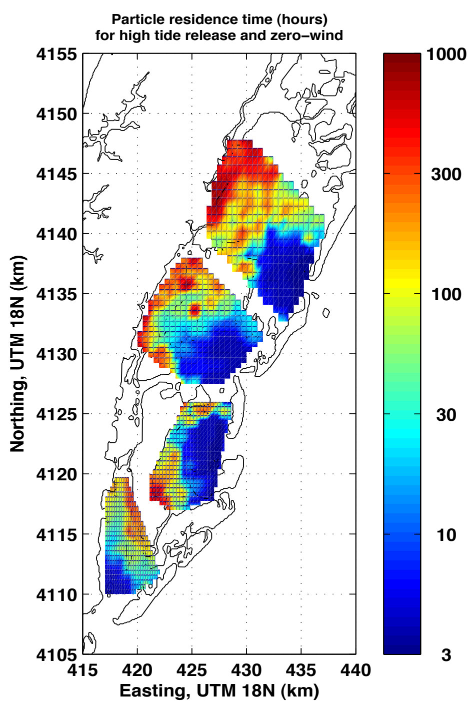


Fig. 7. Model output of water residence time for Hog Island Bay from FVCOM. Residence times within the bay are spatially variable, varying from a few hours close to the channels to 2 weeks near the mainland boundary.

Theme 3. Landscape Analysis

Landscape change analysis – Our long-term analysis of decadal-scale land use/land cover data indicate that while there have been rapid rates of ecosystem state change at the local scale, there has been little apparent change in the aggregate distribution of landscape types. For example, decadal comparisons show that there was a 43% chance that any given location the barrier island upland would shift to another ecosystem state (e.g., marsh); however, at the landscape level, no ecosystem experienced major changes in total coverage (only 7% marsh and 6% barrier island coverage lost) (dataset: knb-lter-vcr.145). This reshuffling of habitats may be typical of coastal barrier landscapes that have been impacted relatively little by human activities, where there are no, or few, barriers to movement (e.g., island overwash, marsh transgression) and little human engineering that modifies natural hydrological and geomorphic processes.

Geomorphic models of barrier island change – As sea level rises, barrier islands will respond by migrating landward across the underlying substrate to higher elevations, by disintegrating if there is no longer sufficient sand volume and relief above sea level to prevent inundation, or by drowning in place. We are using a morphological-behavior model that simulates barrier island evolution and migration as a function of sea-level rise and changes in sediment supply to understand barrier island dynamics (**Moore et al. 2010**, 2011). Our results indicate that even though migration rates will increase with current scenarios of accelerated sea-level rise, low-lying VCR islands (e.g., Metompkin) are likely to avoid disintegration or inundation due to sufficient sand and the slope of the underlying substrate.

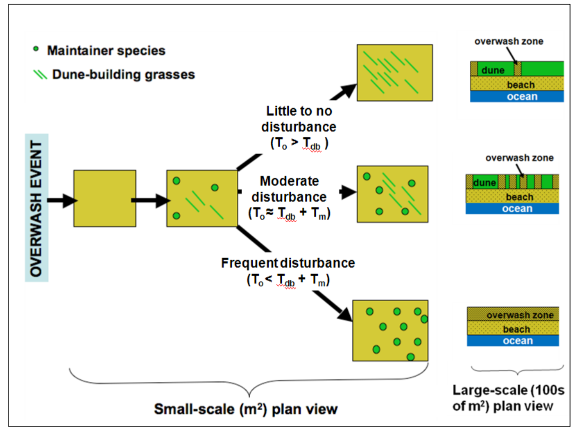


Fig. 8. Possible scenarios for ecomorphodynamically-influenced barrier evolution based on the relationship between T_o (time between overwash events), T_{DB} (time needed for dune-building grass recovery), and T_F (time added to dune recovery by the maintainer feedback), showing that the maintainer feedback may affect large-scale landscape patterns as disturbance frequency increases (i.e., T_o decreases).

Ecogeomorphic feedbacks – On the barrier islands, dune-building grasses (e.g., *Ammophila breviligulata*) aid accretion by trapping sand as they grow upward, thereby expanding the high-relief habitat in which they thrive ("dune-builder feedback"). Following overwash, this feedback can restore dunes given sufficient sand supply. However, if overwash recurs before dunes have reestablished, overwash-adapted species (e.g., *Spartina patens*) may preferentially survive, and by stabilizing the sediment so that it is unavailable for dune building, may lengthen the time needed for dune recovery and increase the vulnerability to persistent overwash ("maintainer feedback"). Over time, these feedbacks could lead to large-scale morphological changes, with 2 types of islands emerging: high-relief, less-frequently disturbed islands or low-relief, overwash-dominated islands (Fig. 8; Wolner et al. 2011).

BROADER IMPACTS AND RESULTS OF SUPPLEMENTAL SUPPORT

Education, Outreach and Diversity: The counties in which the VCR resides are among poorest counties in the state, and few of the K-12 students have ventured into the marshes or bays, or onto the islands. Thus it is significant that *every public high school student in the local county interacts with the VCR LTER program at least twice through LTER-designed classes; 64% of these students are representative of minority groups.* Each year, over 200 students are involved in our Schoolyard LTER program through classroom activities and REHS programs. Over the last 6 years, we have contributed to curriculum development at Northampton County High School, expanded our REU activities, initiated a new summer internship program for high school students (4-6 per year), and created professional development programs for area teachers (10-20 per year). Many of the undergraduate and graduate students that have been trained through the VCR program since 2006 have been involved in peer-mentoring programs. We have received supplemental funding to support research in natural resource economics on public valuation of ecosystem services (Smith and Swallow 2011), and have supported a coastal geomorphologist (M. Fenster) through an NSF Research Opportunity Award (ROA) to synthesize 40 years of barrier island shoreline data in the VCR.

Our outreach activities are focused primarily on the region in which the VCR resides, and include developing a monthly Public Seminar Series at our new site facility (Anheuser-Busch Coastal Research Center), collaborating with partners at TNC, Chesapeake Experience (teacher training), Coastal Virginia

Wildlife Observatory, and the NOAA Coastal Zone Management Program to disseminate our findings to the public, and serving as science advisors for regional planning agencies. We work with these partners and other local stakeholders in a climate-adaptation working group to assess climate change vulnerability, prioritize areas for conservation, and inform local and regional management decisions.

Information Management and Network Activities: The VCR has been an active participant in information management activities within the LTER Network. J. Porter has been a member of the Network Information System Advisory Committee since 2008 and became co-chair in 2010. He led the Controlled Vocabulary Working Group that developed lexical resources and web services, which were incorporated into the LTER Data Portal in 2011. We have hosted several international information managers from Taiwan and mainland China for training stays of up to 3 months and have participated in or co-organized a series of science and information management workshops with partners in the East Asia Pacific Region of International LTER. We have produced numerous publications on LTER information management both nationally (Porter 2010; Porter et al. 2010; Michener et al. 2011; Porter et al. 2012) and internationally (Lin et al. 2007; Lin et al. 2008; Zhu et al. 2011), and on sensor systems (Porter & Smith 2008; Porter et al. 2009; Porter et al. 2010). We provide over 150 online datasets, including 34 with durations $\geq$15 years. Data sets and access history are summarized in the Information Management section of this proposal. A number of our PIs have contributed significantly to LTER Network governance and service, including serving on the Executive (McGlathery), Education (Schwarzschild) and NISAC (Porter) committees, participating in the Ecological Reflections workshop (Schwarzschild), and serving as external advisors to 3 other LTER programs (GCE - Anderson, FCE and MCR - McGlathery) and on 5 mid-term review committees (CAP, CCE, HFR, NTL, MCR; Porter, McGlathery).

Collaborative and Synthesis Activities: Our VCR LTER research is enhanced through collaborations and synthesis activities, some of which have been funded by supplemental funds, and others by other programs or agencies. Within the LTER network, VCR PIs have collaborated with other coastal sites on eddy covariance fluxes in marshes (PIE, FCE), organic matter accumulation (PIE, GCE), marsh erosion (PIE), and with terrestrial sites on shrub expansion (JNR, SEV), and wind erosion (SEV). We have also hosted student researchers from GCE doing comparative latitudinal studies of nutrient enrichment and grazing effects on salt marshes, and have been part of the MIRADA comparison of bacterial diversity. During VCR V, we have done regional research from Maine to North Carolina, and have on-going collaborations with Padua and Parma Universities (Italy), Cordoba University (Spain), Universidad Autónoma de Baja California (Mexico), and the Taiwan Forestry Research Institute (Taiwan). A collaboration with regional partners (TNC, USGS) resulted in the acquisition of LiDAR data for the entire VCR; this provides critical data on land elevation that will greatly enhance our ability to understand ecosystem state change across the landscape.

We are committed to synthesis activities. In addition to submitting our synthesis book, we have published a number of synthesis papers in VCR V that have set the stage for the next phase of VCR research. These include reviews on nitrogen cycling and a new conceptual framework for eutrophication in shallow coastal systems (McGlathery et al. 2007; McGlathery 2008; Joye & Anderson 2008; Anderson et al. 2010; Christian et al. 2010), microbial diversity and ecosystem function (Franklin & Mills 2007a,b; Ogram et al. 2006), the consequences of sea-level rise for wetlands and waterbirds (**Brinson 2006**; **Erwin et al**. 2006, **2007**), feedbacks between ecology and geomorphology in wetlands and tidal flats (Fagherazzi et al. 2006, 2007, 2012a,b,c; Rodriquez-Iturbe et al. 2007; Day et al. 2008), linkages between geomorphology and ecosystem processes on barrier islands (Feagin et al. 2010; Nordstrom et al. 2011; Young et al. 2011), and a long-term retrospective on shrub expansion (Knapp et al. 2008; Young et al. 2007, 2011; D'Odorico et al. 2011; **Zinnert et al. 2011**).

SECTION 2. PROJECT DESCRIPTION

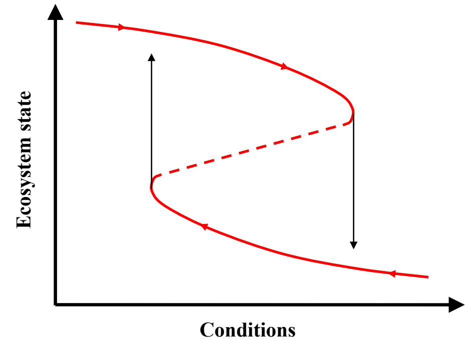
A. Introduction and Background

Coastal barrier systems are prominent features of the world's coastlines, occurring on all continents except for Antarctica, and comprising 13% of coastlines globally (Pilkey & Fraser 2003; Kennish & Paerl 2010). Like all land-margin ecosystems, they are increasingly impacted by the effects of global climate change, including sea-level rise and increased storm frequency, and by regional drivers such as land-use change from coastal development and aquaculture (Werner & McNamara 2007). The rates and intensities of these drivers are changing over time, and it is unclear how these systems will respond over the long term. Without this understanding, we cannot forecast changes in ecosystems and the key services they provide, such as storm buffering, support of commercial fisheries, carbon/nutrient sequestration and wildlife habitat. The overarching goal of the Virginia Coast Reserve (VCR) LTER program is to **understand the mechanisms underlying the response of coastal barrier systems to past, present, and future changes in environmental drivers, and to relate these to the ecosystem services these systems provide.** The coastal barrier landscape is heterogeneous, with mainland watersheds, marshes, tidal flats, shallow coastal bays, and barrier islands. Transitions between ecosystems can be abrupt with threshold responses to external drivers. Some ecosystems show inherent bistability, i.e., they have two alternative stable configurations (states) that are induced by biotic-abiotic feedbacks (Box 1). State transitions have important consequences for ecosystem services.

The VCR LTER site is an ideal system for assessing long-term environmental change in coastal barrier systems. It occurs in the most extensive stretch of coastal barriers globally, where 80% of the Atlantic and Gulf coastline comprises barrier islands and shallow bays (Allen et al. 2010). The VCR is an extremely dynamic landscape that includes an assemblage of 14 barrier islands and 9 adjacent coastal bay systems, extending 110 km along the seaward margin of the Delmarva Peninsula. This regional landscape allows us to compare systems exposed to the same climate drivers but which vary with respect to local topography, watershed land use, hydrodynamics, and water residence times. Our long-term data spanning a 66-year period from 1940 – 2006 indicate that shoreline change on the VCR barrier islands is dramatic, characterized by lateral accretion and erosion rates as high as 15 – 40 m yr^{-1} (Fig. 9). These extreme rates of

Box 1: Regime Shifts, Critical Transitions, Bistable States, and the VCR - Ecosystem regime shifts are massive changes that occur abruptly and shift systems to a new state (Fig. 9), which may not be readily reversible (Scheffer et al. 2001; Carpenter 2003; Peters et al. 2004; Walker & Meyers 2004). These changes involve critical transitions characterized by the crossing of thresholds (Scheffer 2009). Regime shifts are a problem for ecosystem management because these rapid changes are difficult to predict or anticipate (Clark et al. 2001), are often beyond the range of historical experience (Carpenter 2002; 2003), and involve thresholds that are poorly known (Groffman et al. 2006). Regional and global environmental change is likely to cause future regime shifts and worsen ongoing losses of ecosystem services with consequences for human well-being (Millennium Assessment 2005). While these changes will be evident in ecosystems throughout the world, coastal ecosystems are particularly vulnerable because of the combined effects of climate change, sea-level rise, and intensification of human use (Harley et al. 2006).

In this proposal we use the term bistability to represent the shift between two possible stable alternative configurations (states). We focus on several such bistable states on the coastal barrier landscape, including seagrass-dominated or barren coastal bay bottoms, mudflats or marshes in intertidal areas, shrubs or marshes at the mainland border, grassy or shrub-dominated islands, and high or low elevation islands. In each case, we consider a pair of end-point states (not multiple stable states). We build on our long-term data, mechanistic experiments, and modeling to progress to a quantitative understanding of the thresholds where critical transitions to the alternative state occur, drivers that move systems toward or away from critical transitions, positive feedbacks that result in the stability of the alternative state, and resilience of these states to resist change.



shoreline movement create the most dynamic coastal landscape of the U.S. Atlantic seaboard, and are on a par with the barrier islands of the Mississippi Delta (Dolan et al. 1983; Morton 2008). Historic legacies related to storm disturbance and habitat loss have shaped the present environment and set the stage for future changes. A series of severe storms convinced human inhabitants to abandon the islands in the early 1930s, and the islands now comprise the longest stretch of undeveloped coastline on the Atlantic seaboard. The storms also caused the extirpation of eelgrass already weakened by a pandemic disease and the loss of the scallop fishery that depended on the eelgrass habitat. Human population densities declined partly as a result of this economic loss, and remain the lowest of the coastal LTER sites (http://www.ecotrends.info). In 1970, the VCR was established as a reserve by The Nature Conservancy (TNC) and later was recognized as a Man and the Biosphere Reserve, creating a legacy of conservation and stewardship at the site. The relatively minor human impact on the modern-day VCR landscape makes this both a model system for understanding the dynamics of coastal barrier systems in the absence of built structures, and an important reference for more heavily impacted systems.

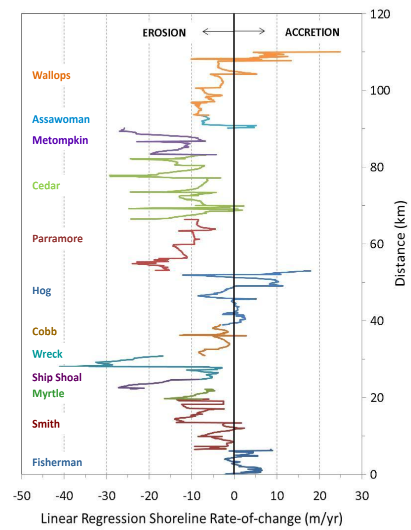


Fig. 9. Shoreline rates of change along the VCR barrier islands for the period

The underlying topography of the modern VCR landscape can be traced back to relict drainage basins of the antecedent Pleistocene land surface (Oertel et al. 1989a; Oertel 2000), and is typical of coastal barrier systems worldwide. Marshes and unvegetated tidal flats fringe the mainland and island borders of the coastal bays and also extend into the bays. The coastal bays are shallow, with <50% of the area <1 m at mean low water, and the watersheds draining into the bays are small (5-100 km^2) (Oertel 2001). The barrier islands are migrating landward as a result of sea-level rise and storms (Hayden et al. 1991; Fenster & Hayden 2007; Moore et al. 2010, 2011). For example, at the time of settlement of Hog Island's town of Broadwater in the mid-1800s, the south end of Hog Island was forested. Now it is grassland built on an overwash fan (Hayden et al. 1991), and the location formerly occupied by Broadwater is hundreds of meters offshore on the seafloor.

B. Conceptual Framework

During VCR V, we developed models describing alternative stable states in the intertidal and subtidal parts of the landscape, and have observed patterns in barrier island vegetation and island morphology that are consistent with bistable dynamics (Fagherazzi et al., 2006, 2007; Mariotti et al. 2010; Mariotti & Fagherazzi 2010; Carr et al. 2010, 2012 a,b). This has led us to **refine our working hypothesis for VCR VI to state that ecosystem changes on the coastal barrier landscape in response to long-term drivers are primarily the result of complex non-linear dynamics based on the existence of alternative stable states and threshold responses.** The dynamics of alternative stable states have been described in inland terrestrial (e.g., Noy-Meir 1975; May 1977; Walker et al. 1981; D'Odorico et al. 2011), freshwater (e.g., Scheffer et al. 2001; Heffernan 2008; Carpenter et al. 2011), hard-bottom (coral reef, rocky intertidal) and off-shore marine ecosystems (e.g., Bruno et al. 2009; Hare & Mantua 2000; Steneck et al. 2002; Bestelmeyer et al. 2011), but only recently by us (see below) and others (van der Heide et al. 2010) in soft-bottom coastal systems.

In VCR V, we described how the bifurcation of the intertidal landscape into two distinct habitats – tidal flats and salt marshes – and the presence of specific elevation ranges of these landforms with no intermediate values, indicates an abrupt transition to either stable landform (Fagherazzi et al. 2006, 2007; Defina et al. 2007). We found that the stability and elevation of the marsh platform and tidal flats is influenced by wave erosion of the marsh edge, sea-level rise, and biotic processes (Fagherazzi &Wiberg 2009; Mariotti & Fagherazzi 2010). In the subtidal part of the landscape, we described how the depth limit that separates the seagrass-vegetated state and the unvegetated state is influenced by the positive feedback of seagrass on reducing sediment suspension and improving the light environment for growth. This threshold is influenced by environmental change factors, such as sea-level rise, storms, and eutrophication (Carr et al. 2010, 2012 a,b). On the barrier islands, our long-term data show an abrupt transition from grassland to shrub thicket (Young et al. 2007). This, and previous research explaining the conversion of grassland to shrubland in more arid climates based on positive feedbacks of shrubs on their microclimate by one of our PIs (He et al. 2010; D'Odorico et al. 2011), suggests that these also may represent alternative stable states on the islands. On a larger spatial scale, island geomorphology also may be influenced by vegetation feedbacks that maintain islands in two stable configurations: 'low' islands dominated by species that are resistant to disturbance and are vulnerable to frequent overwash from storms, and 'high' islands that are less vulnerable to storms where dune-forming species trap sediment and maintain high elevation (Wolner et al. 2011). These dynamics can occur over decades to centuries and require long-term data to understand the mechanisms underlying abrupt ecosystem transitions.

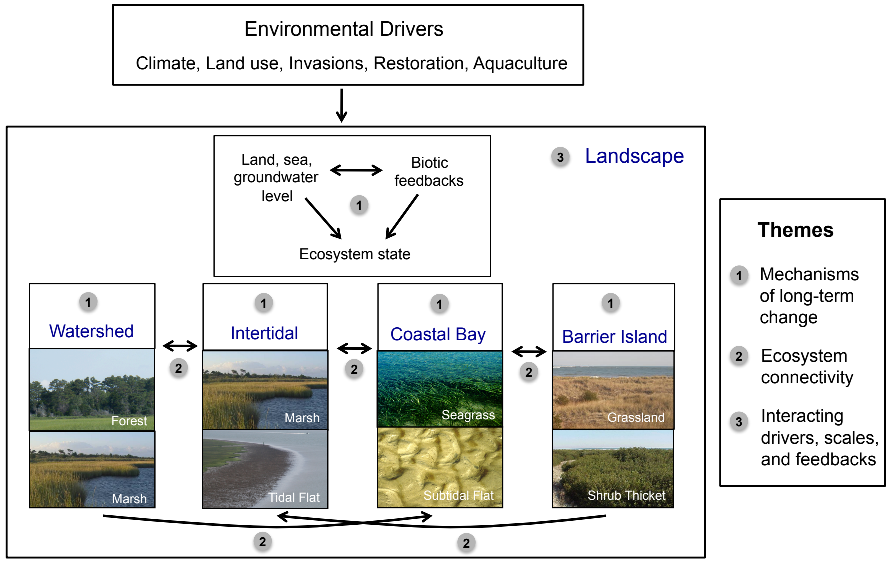


Fig. 10. Conceptual model for VCR VI showing how processes at the local level related to the relative elevations of the land, sea and groundwater surfaces, and biotic feedbacks, that modify these elevations influence the emergence of alternative stable states at each major transition on the coastal barrier landscape. Fluxes of material and organisms between ecosystems modify ecosystems, state transitions and ecological services. The interaction of environmental drivers and feedbacks influence state change dynamics at multiple scales.

Our conceptual framework has evolved through our long-term studies, and identifies the mechanisms underlying non-linear ecosystem dynamics and the emergence of alternative stable states across the landscape as being linked to three factors: (1) the relative changes in land elevation, and in sea

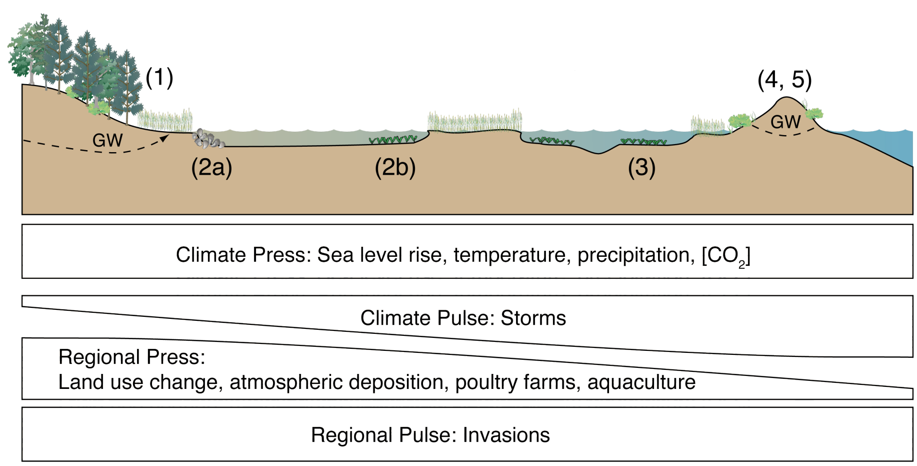


Fig. 11. Cross-section of the VCR landscape, showing the major transitions between mainland upland, intertidal marsh, tidal flat, oyster, seagrass and barrier islands where alternative stable states emerge. (1) mainland upland vs. marsh, (2) marsh vs. tidal flat, including oysters (a) and seagrass (b), (3) seagrass vs. unvegetated bottom, (4) shrub thicket vs. grassland, (5) high- vs. low-elevation island. The relative importance of specific "press" and "pulse" drivers varies across the landscape. GW – groundwater

and groundwater levels, (2) biotic feedbacks, and (3) landscape connectivity through fluxes of sediments and organisms between adjacent habitats (Fig. 10). Our framework now also includes consideration of possible future scenarios and socioeconomic connections through the provision of ecosystem services and feedbacks to human outcomes, decisions and behavior. We believe that the integration of these factors through long-term observations/experiments and modeling is a powerful and necessary approach to understanding past, present and future state change dynamics in coastal barrier systems. By developing a mechanistic understanding of non-linear dynamics and threshold responses, we also contribute to issues relevant to management and policy including landscape and restoration ecology, coupled human-natural systems, and sustainability.

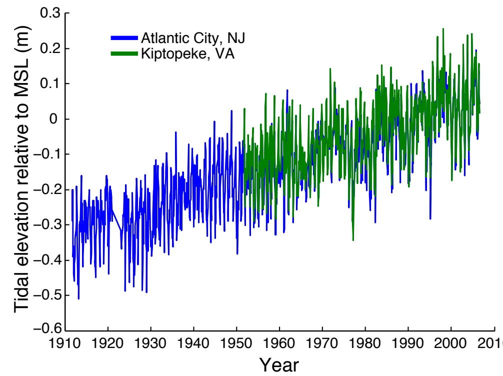


Fig. 12. Relative sea-level rise for the VCR LTER is 4.0 mm yr^{-1}.

Understanding long-term change, and anticipating its consequences, requires that we consider multiple drivers that operate at different temporal and spatial scales (Hobbie et al. 2003; Collins et al. 2010). The VCR, like most coastal systems, has been influenced by decadal to century-long changes in both chronic drivers and the frequency of sudden events or disturbances (Fig. 11).

Rising sea levels, and altered temperature and precipitation are the most pervasive drivers of chronic long-term change on coastal landscapes, including the VCR. The current relative **rise in sea level** at the VCR ranges from 3.8 to 4.0 mm yr^{-1} (Fig. 12) and is the highest among the Atlantic coast LTER sites (http://www.ecotrends.info). This is the sum of the change in elevation of the sea surface (eustatic sea-level rise) and the change in the level of the land (due to subsidence) of 2.5 to 2.9 mm yr^{-1} (Oertel et al. 1989; Emory and Aubrey 1991). The shallow seaward slope of the VCR coastal barrier landscape (<0.1%) makes this region particularly sensitive to accelerated sea-level rise (Day et al. 2008; Kirwan et al. 2011). **Temperature** effects are manifested both in long-term trends and in the variability around the mean. The frequency of high-temperature events that exceed tolerance thresholds will likely be an important driver of species change either by directly affecting physiology or indirectly by reducing resilience to other stressors (Woodward 1992; Lin et al. 2010; Carr et al. 2012b; Zinnert et al. 2011). Some species in the mid-Atlantic region are at, or near, the southern limit of their range (e.g., *Zostera marina* in coastal bays and *Morella* on the barrier islands), and other, more southerly species (e.g. *Uniola paniculata* on the islands) may expand their range with warming temperatures. Changes in **precipitation** influence the availability of freshwater and nutrients and thus vegetation patterns (Shao et al. 1995; Zinnert et al. 2011). Drought has been implicated in the die-off of mainland tidal marshes at the VCR and other sites along the Atlantic and Gulf coasts (Marsh 2007).

Most coastal systems are impacted by the intensification of human activities. The VCR is unique in that the population density and growth rate are low, and land cover is dominated by forests and crop agriculture (Stanhope et al. 2009). The high water quality of the coastal bays makes this an excellent benchmark system for documenting the impacts of land-use change regionally and globally (McGlathery et al. 2007). **Land use and nutrient loading** may change in the coming decades if the regional trend for coastal suburbanization and industrial poultry farming reaches the VCR (Giordano et al. 2011). Both **aquaculture** and **restoration** are becoming increasingly important drivers of long-term change in coastal systems (e.g., Palmer et al. 1997; Simenstad et al. 2006; Naylor et al. 2000), and consideration of this is new to VCR VI. Virginia leads the U.S. in aquaculture production of the hard clam, *Mercenaria mercenaria*, with an estimated annual dockside value varying between $20 and $30 million (Murray & Kirkley 2005; Murray & Oesterling 2010). Hard clams are raised to harvestable size throughout the VCR, and production rates are increasing. Continued natural expansion of 17 km^2 of seagrass in the VCR, and/or additional restoration, will influence water quality, nutrient cycling and trophic dynamics (McGlathery et al. 2012). Oyster reefs along the mainland margin of the VCR coastal bays also have been restored over the last two decades, after suffering significant decline due to disease, overharvest and habitat destruction. A recent estimate in 2008 documented 3.2 billion oysters in the coastal bays compared to 1.8 billion oysters in the entire Virginia portion of the Chesapeake Bay. The **invasion** and proliferation of the seaweed *Gracilaria vermiculophylla*, likely resulting from oyster trade 40 years ago, may lead to "novel" ecosystems (*sensu* Hobbs et al. 2006) with assemblages of species that have not co-occurred historically (Thomsen et al. 2005; Gulbransen et al. 2012). This has implications for habitat modification, trophic dynamics, and nutrient cycling (Thomsen et al. 2006, 2009, 2010), and may influence the success of seagrass and oyster restoration (Thomsen & McGlathery 2006).

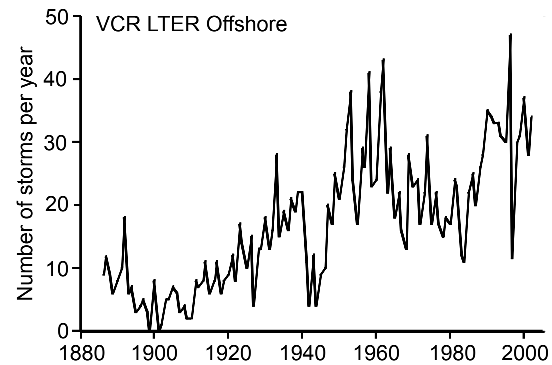


Fig. 13. Storm record for the VCR LTER. From Hayden & Hayden (2003).

Storm events are the major agents of disturbance on most coastal landscapes. Our long-term data indicate that storm frequency has changed markedly along the entire U.S. Atlantic coast over the last century (Hayden and Hayden 2003), and we are now in a period of relatively high storminess (Fig. 13). The return period for a category 1 or stronger hurricane for the VCR is expected to be 7 years, which translates into ~14% probability of being in the direct path of a hurricane each year (Hopkinson et al. 2008). Some 15 extra-tropical storms per year occur with magnitudes sufficient to move sediments and change the morphology of the islands and the associated flora and fauna (e.g., Erwin et al. 2001; Fenster and Hayden 2007; Young et al. 2011), cause erosion and accretion in the tidal marshes (Christiansen et al. 2000; Fagherazzi & Wiberg 2009), and resuspend sediments in coastal bays (Lawson et al. 2007). Ultimately, storms and sea-level rise cause the landward migration of the islands across back-barrier marshes (Hayden et al. 1980; Moore et al. 2010, 2011) and the encroachment of marshes into forests on the mainland (Brinson et al. 1995; Shao et al. 1998; Fagherazzi et al. 2012c).

C. Research Themes and Approach

Our research in VCR VI is organized into 3 synthetic and integrated themes that address alternative stable state dynamics and ecosystem processes on the coastal barrier landscape.

Theme 1. Mechanisms of long-term change. We will evaluate whether the existence of alternative stable states and threshold responses to environmental drivers is a unifying dynamic across the landscape. We will do this by integrating our coordinated long-term observations and experiments addressing the mechanisms of nonlinear change with our models and new experimental studies.

Theme 2. Ecosystem connectivity. In VCR V, we established the influence of connectivity across the landscape on ecosystem dynamics. We will build on that work and our models to 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). The impact of habitat adjacencies and fluxes on bistable dynamics remains poorly understood. We also address how subsidies influence the dynamics of ecosystem states.

Theme 3. Interacting drivers, scales, and feedbacks. We will use future scenarios to explore how interacting drivers affect threshold behavior and resilience of ecosystem states at different spatial scales. Our long-term data, synthesized in VCR V, indicates that climate (i.e., storminess, temperature, sea-level rise) is the major driver currently influencing VCR ecosystems. First, we will build on our mechanistic understanding of the dynamics of alternative stable states to forecast how ecosystem dynamics will vary with climate change scenarios. Second, we will incorporate future scenarios of land-use change and nutrient loading, as we expect in the coming decades that development will affect VCR ecosystems and their response to climate drivers. Third, we will engage a diverse group of stakeholders to incorporate public valuation of ecosystem services and tradeoffs into our quantitative models of future scenarios.

Our research relies on 4 integrated approaches: (1) long-term observations (2) long-term experiments supplemented by short-term experiments and/or process studies, (3) modeling, and (4) comparative studies. Spatially, we conduct research at three scales: within landscape units (mainland watershed, marsh and tidal flat, coastal bay, barrier island), between landscape units (e.g., marsh and bay interactions), and across the entire landscape of islands and coastal bays. Temporally, we consider scales from a fraction of a day (e.g., element cycling) to years-decades (e.g., state change) to decades-century (e.g., sea-level rise, landscape change). Our work also spans ecological scales from genetics to the landscape. Data from our observations, experiments and analyses of remote-sensing imagery are linked with models to understand the dynamics of ecosystem state transitions under current conditions, to test these dynamics by hindcasting past conditions, and to explore future scenarios of long-term change.

1) Integrated long-term observations: The collection and management of long-term data on physical, biotic, biogeochemical and landscape characteristics are central to understanding long-term changes in the coastal barrier system. Below we describe briefly the data we collect that encompass the 5 core areas of LTER research (pattern and controls of primary production, population and trophic dynamics, pattern and controls of organic matter accumulation, inorganic nutrient inputs and fluxes, and pattern and frequency of disturbance). The specific data sets are listed in the Supplemental Document, and methods are described on our website www.vcrlter.virginia.edu. These core data provide the context for understanding long-term changes and the mechanisms driving them, and are integrated into the research questions that guide our research.

Physical characteristics: We collect long-term measurements on the relative elevations of the land, sea and groundwater. We monitor a system of 38 Surface Elevation Tables (SETs) on the tidal marshes as part of an international observing system, a network of groundwater wells (now upgraded with wireless technology) in the marshes and barrier islands, and three tide gauges in the coastal bays. We have recently established a network of temperature and light sensors in the coastal bays and operate 3 meteorological stations. In VCR VI, Hayden will update the storm track and frequency record from 2001 to the present using NOAA weather map data.

Biotic characteristics of ecosystem states: We quantify how patterns of primary production and community composition for the marshes, coastal bays and barrier islands are related to long-term changes in the elevation of the land, sea, and groundwater levels, and to storm disturbance and interannual variations in precipitation and temperature. On the islands, data on small mammal abundance and distribution are collected annually and linked to vegetation distribution, and genetic analysis provides information on inter-island movements. We work with collaborators at TNC to relate waterbird colony site dynamics to vegetation and predator distribution. Starting in 2011, invertebrates and fish are monitored semi-annually in the coastal bays to relate trends to the seagrass state change, and invertebrate populations (burrowing crabs, mussels) that influence marsh edge erosion are monitored at sites where detailed process measurements are made.

Biogeochemical stocks and fluxes: Long-term measurements of sediment organic matter and nutrient cycling in the tidal marshes, barrier islands and seagrass meadows quantify trends in environmental drivers and responses to ecosystem state change. In the coastal bays, we monitor water quality and sediment parameters to track the long-term effects of changes in watershed land use and seagrass restoration on nutrient and organic matter cycling along mainland-island transects in two bays. Land-atmosphere fluxes of carbon and water fluxes over the mainland marsh are measured with an eddy covariance tower, and the inputs of atmospheric nitrogen are quantified. We monitor groundwater fluxes and baseflow nutrient concentrations in tidal creeks that drain watersheds of varying size and land use to characterize the spatial and temporal variability of nutrient loading to the coastal bays.

Landscape patterns: We maintain remote sensing GIS databases to identify the spatial distribution of ecosystem states on the VCR landscape on annual to decadal time scales based on aerial photos, LiDAR, multispectral and hyperspectral satellite imagery. In addition, there is a substantial collection of remotely sensed imagery available from our collaborators at the Naval Research Lab. This imagery and long-term observations have allowed us to scale up to landscape-level processes at the VCR and across >30 years. Our collaborators at VIMS use aerial photographs to quantify and map annual trends in coverage of restored seagrass meadows and oyster reefs. In LTER VI, we will work with them to use these photographs to also document trends in aquaculture.

2) Long-term experiments: We use long-term ecosystem-level experiments that modify ecosystem states and 'natural' experiments based on space-for-time exchange in chronosequences. *Ecosystem-level experiments:* In the seagrass restoration experiment, we quantify the reinstatement of ecosystem services by following structural and functional attributes during the shift from an unvegetated to a seagrass-dominated state (Questions 1, 2, 3). We will add a new long-term experiment seeding areas that bracket the range of stable-bistable depths in different bays. We will also add an oyster restoration experiment to assess the influence of intertidal oysters bordering mainland marshes on sediment accretion and marsh edge erosion (Question 2a). At the marsh-forest transition on the mainland, we will add a transplant experiment to assess threshold conditions for tree seedling establishment (Question 1a). On the barrier islands, we will add an experiment tracking the feedback of vegetation on elevation (Question 3a). As funding allows, we will work with our partners (TNC, USGS) to use repeated LiDAR measurements as a 'natural experiment' to test our predictions of island vulnerability to storm overwash (Question 3a). *Space-for-time experiments:* We monitor three chronosequences: 1) a series of beach ridges (dunes) and swales on Hog Island that have built seaward over the last 120 years; 2) a marsh chronosequence that has formed from a series of storm overwash events, with the oldest identified stage being at least 150 years old; and 3) a chronosequence of restored seagrass meadows that now range in age from 0 – 10 years (Question 1a). For these chronosequences, we relate vegetation state change dynamics to productivity, sediment organic matter and nutrient cycling, and animal communities.

Table 1. Quantitative models for non-linear dynamics in coastal barrier systems.

MODEL	BRIEF DESCRIPTION	INPUTS/TIME STEP	OUTPUTS
FVCOM (Chen et al., 2003; http://fvcom.smast.umassd.edu)	Open-source 2D or 3D unstructured-grid, finite-volume, free-surface coastal ocean circulation model. Accounts for momentum, mass, temperature, salinity and density. Horizontal grid comprised of unstructured triangular cells. Includes sediment model based on Community Sediment Transport Model, and includes particle tracking.	Wind speed and direction, tides at boundaries, bathymetry, sediment properties for sediment transport calculations. Time step of seconds to minutes.	Current speed & direction, wave height and period, water level, water temperature and salinity, bottom shear stress, suspended sediment concen-trations and flux
Seagrass bistability model (Carr et al. 2010, 2012a, b)	Coupled vegetation-sediment-water-flow model to examine effects of seasonal and interannual variation in density on sediment resuspension, water column turbidity, and light. Can be run over decadal time scales. Daily growth model captures belowground biomass and growth/senescence of leaves and stems.	Tidal elevation, tidal current, wind speed and direction, water temperature, PAR, bed grain size. Also initial above and belowground seagrass biomass. Time step of 1 hour.	PAR reaching the canopy, TSS, meadow characteristics (belowground biomass, aboveground biomass (leaves and stems), and shoot density.
Marsh-flat transect model (Mariotti & Fagherazzi, 2010)	1D numerical model for coupled long-term evolution of salt marshes and tidal flats. Model framework includes tidal currents, wind waves, sediment erosion, and deposition, and vegetation effects on sediment dynamics.	Tidal elevation, wind speed, sediment properties for sediment transport calculation, vegetation properties. Time step of 1 hour.	Current speed, wave height and period, bed shear stress, erosion and deposition rates, SSC, bed elevation (in time)
Marsh platform evolution model (Kirwan & Murray, 2007)	3D model of tidal marsh accretion and channel network development coupling sediment transport with productivity.	Elevation, SLR, tidal range, sediment prop-erties. Time step of 1 year.	Elevation, biomass, erosion and deposition rates.
GEOMBEST (Stolper et al., 2005; Moore et al., 2010, 2011)	2-D numerical, cross-shore, morphological-behavior model simulates evolution of barrier island morphology and stratigraphy in response to changes in SLR, sediment supply and bay sedimentation over time scales ranging from decades to millennia.	Mainland/island topo-graphy, near- and off-shore bathymetry, underlying stratigraphy, sediment supply rates, SLR, shoreface depth and erosion rate, bay sedimentation rate. Time step 10-100 years.	Cross-sectional barrier island/offshore strati-graphy and morphology (bathymetry/topography) barrier island volume; barrier island migration rate.

3) Models: Models are critical to our research, and the site review team recognized our strength in quantitative modeling of geomorphic process and biotic feedbacks. Based on our >20 years of observational and experimental data, we have conceptual models of ecosystem state change for the major transitions on the landscape. We now have developed, or are developing, quantitative models that include specific mechanisms for each of these transitions. The models play a central role in planning our research helping in the formulation of a conceptual framework for the interpretation of experimental results and the formulation of new research questions, and in forecasting future change. They are used to guide data collection, and observations and experiments are used to test and modify the models. A brief description of our existing models is included in Table 1.

4) Comparative work: We are taking advantage of unique opportunities for comparative work to advance our understanding of fundamental ecological process in both terrestrial and coastal systems. The most notable are: (a) The *network of LTER eddy covariance flux towers* in the intertidal zone at the VCR, FCE, GCE, and PIE sites provides an unparalleled opportunity to understand the role of intertidal systems in global and regional carbon budgets. We plan to continue our collaboration through studies on the magnitude and controls of net ecosystem exchange (NEE) in response to interannual variation in sea-level rise and storms. This information is also important in understanding how variation in NEE influences adjacent benthic communities through lateral transport of carbon. (b) Comparative measurements of marsh primary production and mean sea level at LTER (PIE, VCR) and other Atlantic coast sites have been used to *develop models that describe a tipping point for marsh submergence as sea-level rises* that is determined by local sediment supply and marsh grass growth (Kirwan et al. 2010). We will continue to make comparative measurements of sediment accretion, marsh growth responses to experimental manipulations of marsh elevation, and sediment supply to improve the model and its generality. (c) Our ideas about *bistable dynamics as it applies to grassland vs. shrub thickets* on the barrier islands have grown in part out of work on vegetation feedbacks on microclimate by our PIs (D'Odorico, Fuentes, Hayden) in the shrub-dominated ecosystems of the SEV site. We expect that continued comparative work with both SEV and JRN will provide new insights on alternative stable state dynamics and shrub encroachment in grassland/shrub ecosystems. (d) We are initiating comparative studies with SBC to address the *importance of subsidies* of subtidal marine macrophytes to adjacent intertidal ecosystems. This transfer of organic matter may apply generally across many coastal regions.

We use innovative technology to address our questions. We established an eddy covariance flux tower on a mainland marsh in 2007, and our PI Fuentes (Kathilankal et al. 2008a,b) has helped the other Atlantic Coast marine sites (FCE, GCE, PIE) establish similar flux towers. Two other PIs are leaders in developing *in situ* sensor technology for marine applications: Reidenbach modified the particle imagery velocimetry technology to measure *in situ* velocity and turbulence in seagrass meadows and over oyster reefs (Reidenbach et al. 2010); Berg developed the eddy covariance method for measuring underwater benthic fluxes to estimate metabolism, which is also being used in the seagrass and oyster ecosystems (Berg et al. 2003, 2007). We use webcams to monitor marsh edge erosion and waterbird nest sites, and are establishing more to quantify habitat use by mammals on the barrier islands. We also have led pioneering work in developing distributed sensors and wireless technology for long-term data collection (Porter & Smith 2008; Porter et al. 2009, 2010, 2012). These spatially-distributed, temporally-intensive physical data (e.g., temperature, light, groundwater level) are crucial to developing our models.

C. Research Questions

The research themes and questions are integrated in our conceptual framework through hypothesized nonlinear dynamics and interactions across the landscape/seascape of the VCR (Figs. 10, 11). For each question, we describe our rationale and our ongoing and proposed research activities.

Theme 1: Mechanisms of long-term change

Question 1a: What are the mechanisms of non-linear state change in coastal barrier landscapes in response to environmental drivers? Our research to date indicates that non-linear state transitions occur across the terrestrial and marine portions of the VCR landscape. We will build on our work in VCR V to address how these changes can be described as a shift between alternative stable states at all the major ecosystem transitions (e.g., mainland upland-marsh, marsh-tidal flat, tidal flat-seagrass, marsh-barrier island, grassland-shrubland; Fig. 12). Throughout, we use a modeling framework to guide our research, and integrate this with long-term observations and experiments, and short-term process measurements.

Mainland forest/shrub vs. marsh (PI Leads – Wiberg, Fagherazzi, Kirwan, Blum): Nearly 20 years ago, VCR PIs developed a conceptual model of the transition from terrestrial forest to salt marsh as a function of sea-level rise, land slope and sediment supply (Brinson et al. 1995) that has guided work on this problem in a variety of settings (e.g., Williams et al. 1999; Doyle et al. 2010; Hoeppner and Rose 2011). Subsequent studies on the Gulf and mid-Atlantic coasts (e.g., Williams et al. 1999; Kirwan et al 2007) suggest that two thresholds control the transition. The first is the failure of seedlings to regenerate while mature trees continue to grow. The second is a disturbance threshold (e.g., wind, fire) leading to mortality of mature trees. Together, these lead to a step-wise retreat of the forest edge. The loss of regeneration can potentially be due to flooding (water logging), groundwater salinity, soil redox conditions, sulfide toxicity, or erosion related to storm surge and sea level (Brinson et al. 1995). We hypothesize that the transition zone between healthy, regenerating upland forest and treeless high marsh is a bistable region where, at a given elevation, either high marsh or mature, but non-regenerating, forest can be present (Fig. 14). Shading by mature trees inhibits establishment of marsh grasses, and increases in near-surface soil saturation and pore-water salinity in marsh-grass stands inhibit tree seedling establishment. Disturbance can switch the system to the marsh stable state by killing adult trees, reducing evapotranspiration, and increasing soil saturation. If periods are long enough between storm surges, shrublands, and eventually forests, could again develop on the upland fringe of marshes.

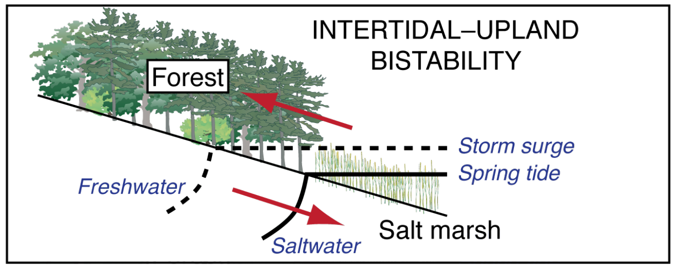


Fig. 14. Conceptual model for alternative stable states at the mainland-marsh interface.

We will establish two sets of transects at the boundary between salt marshes and the upland. One will be at a location affected by Hurricane Isabel in 2003, which triggered a large-scale tree die off. The other will reestablish a set of transects established 20 years ago (Hmieleski 1994) that cross the high marsh – forest transition. For all transects, we will conduct annual surveys of topography and vegetation zonation, monitor a series of wells for long-term variations in water-table levels, temperature and salinity, and measure productivity and soil geochemistry. A *new long-term experiment* transplanting seedlings along the transects will provide data on threshold conditions for regeneration. The field surveys will be integrated with an analysis of remote sensing images that include 50 years of aerial photographs, 30 years of LANDSAT images, and high resolution IKONOS imagery to determine changes in the upland boundary. These data will be used to parameterize and test numerical models, including modified versions of the SLOPE model (Doyle et al. 2010) and a terrestrial forest gap model (Shugart 1998). Feedbacks between ecological and hydro-geomorphological processes will be included, such as transpirative controls on water-table elevation and pore-water salinity, and organic-matter control on surface elevation.

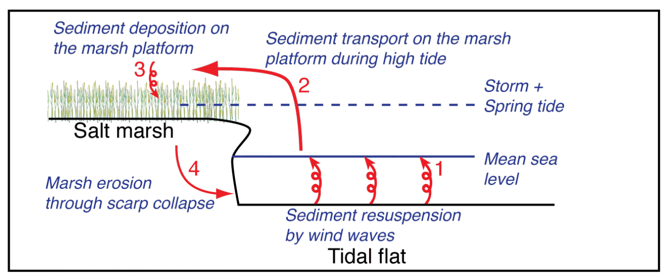


Fig. 15. Non-linear feedbacks between vegetation, sediment redistribution, and landforms in intertidal areas. The arrows represent sediment fluxes: 1) resuspension, 2) transport from subtidal to marsh platform, 3) deposition, and 4) erosion of marsh edge.

Marsh vs. tidal flat (PI Leads - Fagherazzi, Wiberg): At the marsh-coastal bay interface, the dynamics of the boundary between the two alternative stable states – broad, expansive marshes and unvegetated tidal flats – are important in determining salt marsh/tidal flat extension or degradation (Fig. 15; Fagherazzi et al. 2006; Mariotti & Fagherazzi 2010). Erosion and collapse of the marsh edge are generally linked to wind waves, and are expected to increase under increased storminess and sea-level rise (Moeller 1996, 2006; van de Koppel et al. 2005; Mariotti et al. 2010). However, our decadal time-series and detailed short-term measurements of marsh-edge erosion and modeling of wave power effects on erosion indicate that complex relationships between edge characteristics (plant biomass, sediment grain size, crab burrow volume, scarp height, planimetric shape) and wave power determine the spatial variation in marsh edge morphology and erosion rates (Mariotti et al. 2010; McLoughlin 2011; Priestas & Fagherazzi 2011).

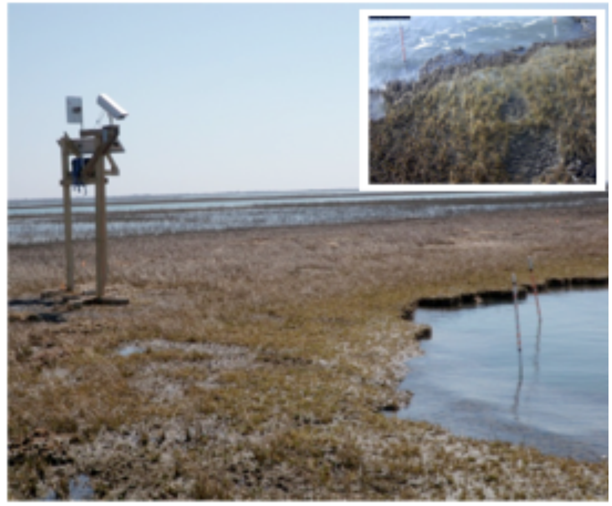


Fig. 16. Webcam recording marsh edge erosion. Inset shows image of waves impacting the marsh edge taken by the webcam. The edge at this site has eroded to the point where it is now barely in view of the camera.

We propose to continue monitoring two of our long-term study sites, one that is eroding and another that is prograding, to increase our observational dataset and to refine our model of the bistable dynamics of the marsh–tidal flat system (Mariotti and Fagherazzi 2010). We have 10 SETs that we will continue to monitor at the sites to measure changes in vertical elevation. We will determine boundary retreat (cm/yr - m/yr) using ground surveys and aerial photos. We will also deploy a set of high-resolution instruments to measure waves, scarp erosion, sediment fluxes, and tidal currents. We currently have a webcam monitoring the boundary at the erosional site (Fig. 16), and will set up a similar camera at the prograding site to provide information on the processes responsible for the mechanical removal of the vegetation mat by waves (root scalping). We will also use invertebrate exclosures to determine the roles of vegetation roots and crab burrows in determining scarp stability and morphology.

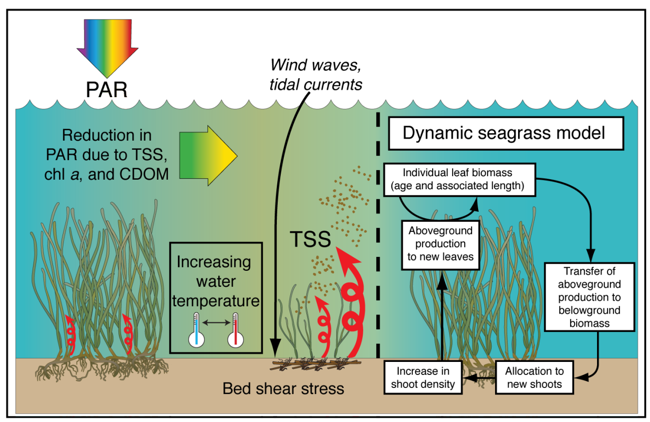


Fig. 17. Coupled hydrodynamic-vegetation-growth model based on the positive feedback of seagrass vegetation on sediment suspension and light availability leads to emergence of alternative stable states in the coastal bays.

Seagrass vs. unvegetated seafloor (PI Leads – D'Odorico, McGlathery): In the coastal bays, the large-scale restoration experiment provides an ideal setting in which to characterize how the positive feedback of seagrass presence on sediment suspension and light availability influences the emergence of alternative stable states (Fig. 17; Carr et al. 2010; Hansen & Reidenbach 2012; McGlathery et al. 2012). Our model results thus far indicate that the strength of this feedback depends strongly on seagrass morphology and density (Carr et al. 2010; Carr et al. 2012a,b). In order to further constrain and validate the model, and investigate the resilience of seagrass meadows to changing environmental conditions over annual and decadal time scales, we need more information on variation in seagrass morphology and meadow characteristics, and temperature trends.

We will continue our annual measurements of peak seagrass shoot density, shoot recruitment, leaf mortality, leaf length and width, above-to-below ground biomass ratios, and growth rates in the seagrass chronosequence. We will also increase our sampling frequency to seasonal time scales at selected sites. In addition, the presence and number of flowering shoots and seed production will be measured along gradients of light availability and water temperature in order to provide insight on meadow morphologic response to changing environmental conditions. We have recently installed a network of temperature and light sensors along the depth gradient (0.5 – 2.0 m MSL) in our long-term experiment that brackets the current threshold of the stable-bistable states predicted from the models. These measurements will also be used to inform the model with respect to the minimum light requirements for seagrass growth and the maximum summer temperatures for seagrass survival. We will modify the model to incorporate shoot recruitment from seeds, and biomass allocation to flowering shoots and seed production.

Barrier Island Grassland vs. Shrub Thicket (PI Leads – Young, D'Odorico): Our long-term study of the dune-swale chronosequence on one of the barrier islands, Hog Island, has revealed that newly formed swales may either remain as a grass-dominated system or shift to *Morella* sp. shrub thicket as a new stable state if the N-fixing actinomycete, *Frankia* sp., is present. Once grassland is converted to shrub thicket, there are significant alterations in microclimate (He et al. 2010), especially temperature, that may feed back positively to favor shrubs at the expense of grasses (Fig. 18). Shrubs are also known for being sensitive to water table depth and water-logging conditions (Tolliver et al. 1997; Naumann et al. 2008). In the past few years, shrub expansion has been favored by the decrease in precipitation, which has lowered the water table in low-elevation swales and reduced soil anoxia (Zinnert et al. 2011). Shrubs have high evapotranspiration (ET) rates and, in turn, increase the depth to the water table. If shrubs were removed, the water table would rise in swales and there would be a quick return to a system dominated by grasses. Thus, this system may exhibit two alternative stable states (shrub thicket and grass-dominated swale) emerging from the interaction of vegetation with water table dynamics (Ridolfi et al. 2006; Runyan and D'Odorico 2010; D'Odorico et al. 2011).

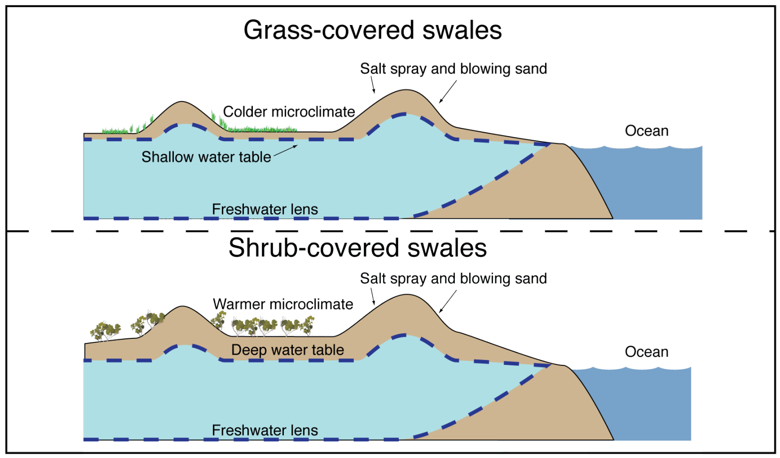


Fig. 18. Feedbacks of shrubs on the local microclimate may lead to the emergence of alternative stable states and the encroachment of shrub thickets onto grasslands.

We will evaluate the relative importance of these feedback mechanisms by experimentally investigating: 1) the ability of shrubs to modify their local microclimate, particularly in the coldest months of the year; 2) the ability of shrubs to lower the water table; 3) the cold sensitivity of shrubs; and 4) the sensitivity of shrubs to shallow water tables. Using an existing LiDAR data set and our comprehensive hyperspectral and aerial photo imagery for the barrier islands, we will relate shrub expansion to microtopography for all islands. Remote sensing indices such as the normalized vegetation index (NDVI) can be used as an indicator of groundwater

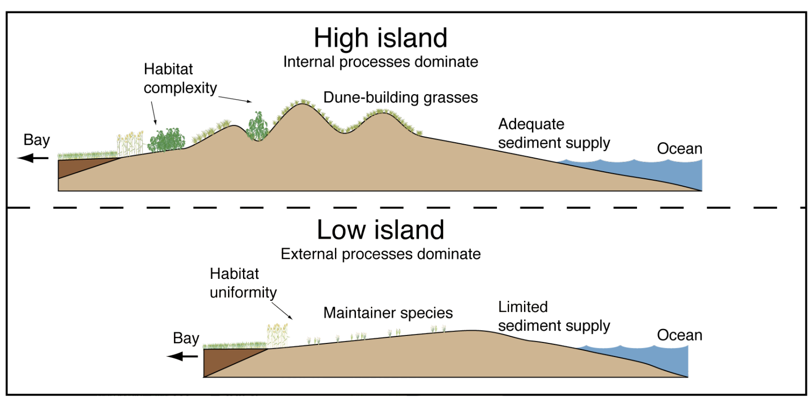


Fig. 19. Ecogeomorphic feedbacks of vegetation on sediment accumulation and island elevation may lead to the development of "high" and "low" islands as alternative stable states.

availability in dry years. In addition, we will use ground-penetrating radar and a network of wells to compare the seasonal dynamics of the soil freshwater lens on a high relief island with extensive shrub thickets (Hog Island) with that on a low relief island with few shrubs (Metompkin Island). We will supplement these large-scale and long-term data with at least 3 years of data on micro-scale climate measurements to capture variation in precipitation and temperature related to storm events and drought periods. Arrays (n=10) of temperature sensors (Hobo packs) will be deployed at the soil surface in grass-covered and shrub-thicketed swales to assess spatial and seasonal variations. Temperature data will be supplemented with coordinated measurements of stomatal conductance, stem hydraulic conductivity, ET, and net CO_2 assimilation using portable gas exchange systems (Kathinlankal et al. 2011). These data will be used to further develop an earlier VCR model of shrub ET (Shao et al. 1995), emphasizing the feedbacks between ET and available freshwater during the summer months. The data will also be integrated into a rules-based model that simulates shrub thicket expansion in response to changes in sea-level rise and shoreline migration (Question 3a).

Barrier Island Geomorphology, "High" vs. "Low" Islands (PI Leads: Moore, Young): On a larger spatial scale, our conceptual framework for the evolution of barrier island systems generally classifies islands as being in one of two states (Fig. 19). "Low" islands have little relief above sea level and are vulnerable to storms and sea-level rise. They migrate rapidly landward and are generally low in ecological diversity and productivity. In contrast, "high" islands are less vulnerable to storms, tend to be dominated by internal processes (e.g., sediment trapping by vegetation), require long time periods to respond to changes in forcing, migrate slowly, and have more complex topography and vegetation community structure. The height and width of a barrier island are both outcomes and drivers of dynamics. For example, in VCR V we identified the "maintainer feedback", whereby islands that are more frequently disturbed by storm-induced overwash events (e.g., 2-4 years) are more likely to be dominated by the grass *Spartina patens* over *Ammophila breviligulata* (a dune-builder). This delays the establishment of dunes and increases the likelihood of future overwash (Wolner et al. 2011). We hypothesize that due to these feedbacks (Fig. 20), large-scale barrier island evolution on decadal to century time scales exhibits bistable dynamics such that: 1) intermediate island states are unstable, 2) there exists a range of conditions under which an island may exist in either the low or high state, and 3) there are thresholds near which small changes in forcing cause a major transition to the alternative state.

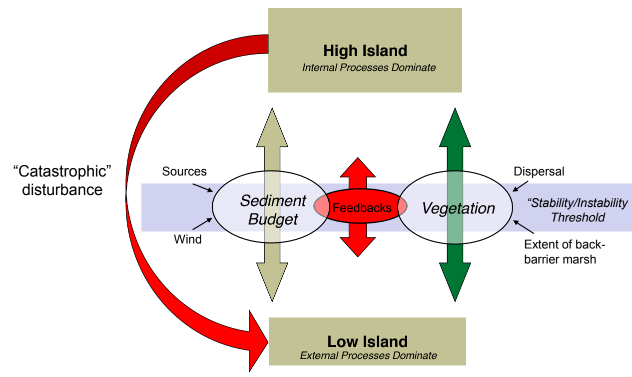


Fig. 20. Ecogeomorphic framework for barrier island evolution, showing feedbacks between vegetation and sediment supply, which over time result in the development of two large-scale morphologies with either high-relief, less frequently disturbed islands or low-relief overwash-dominated islands.

We propose to develop a model of barrier island dynamics using long-term observations of island migration rates, island morphology and vegetative species composition within the VCR. This will be developed from an existing model of dune growth that includes aeolian sediment transport and vegetation population dynamics (e.g., plant growth rate as a function of erosion and accretion), as well as interactions among the two (Duran & Hermann 2006). We will vary forcing parameters (e.g., sea-level rise, overwash frequency, sediment-loss rates) in a series of model runs on decadal-century time scales to evaluate how island state (high vs. low) varies as a function of forcing using migration rate as an inverse proxy for island state (e.g., low islands have high migration rates and vice versa). This process-based modeling will be used to assess whether bistable dynamics emerge (e.g, high vs. low islands), and if they do, to identify threshold responses.

Question 1b. Are there specific thresholds for ecosystem state change and leading indicators of proximity to that threshold? Our models and data for ecosystem state change include threshold responses to environmental drivers. These abrupt ecosystem state changes may or may not be associated with early warning signs (Scheffer et al. 2009; Hastings & Wysham 2010; Bestelmeyer et al. 2011). We propose to determine the thresholds existing between alternative states using long-term data sets and manipulative experiments. In addition, we build on our results for seagrass ecosystems (Carr et al. 2012b) to further quantify the parameters identified as leading indicators of state change.

Intertidal marshes (PI Leads – Kirwan, Blum): We will experimentally manipulate marsh elevations in a new experiment using "marsh organs" (Fig. 21; Morris 2007; Kirwin et al. 2012) and measure the response of *Spartina alterniflora* productivity to disturbance (removal of aboveground biomass). We will build platforms that each expose 36 replicate mesocosms to a variety of elevations between mean sea level and mean high tide. While we expect that productivity will be highest at moderate elevations and lower at extremely high and low elevations based on the results of Morris et al. (2002), it is not known how elevation impacts recovery from disturbance. Recovery time is related to ecosystem resilience. We hypothesize that the rate of vegetation recovery will decrease at progressively lower elevations, even as productivity in non-disturbed mesocosms continues to increase. To test this, we will clip all vegetation in some of the mesocosms midway through the growing season, and measure the time it takes for vegetation to grow back to its pre-disturbance state. We anticipate that at high elevations, moderately productive vegetation will survive the disturbance but recover slowly (stable vegetated state). Conversely, we anticipate that at low elevations, moderately productive vegetation will not survive the disturbance (transition to stable unvegetated state). The experiment will help us identify the bistability elevation range for *S. alterniflora* marshes; we can use the information on the elevation threshold that triggers state change to determine how close the system is to the tipping point of submergence. We will compare the marsh 'organ' results to long-term trends in productivity (measured as end-of-year biomass) from various locations at comparable elevations.

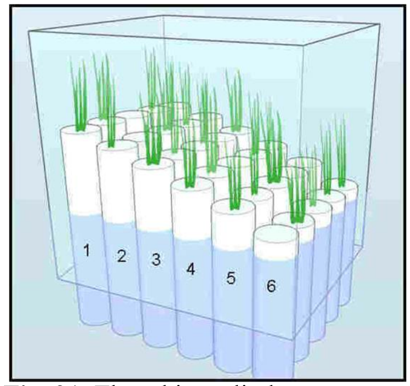


Fig. 21. The white cylinders are submerged at different depths in the water. The plants submerged deepest (row 6) experience the highest sea levels. The plants elevated highest (row 1) experience the lowest sea levels. (Credit: Adam Langley/SERC).

Seagrasses (PI Leads – D'Odorico, McGlathery): Through our long-term monitoring and modeling of the seagrass state change, we have identified the maximum depth threshold (1.6 m MSL) for stable seagrass populations (Carr et al. 2012a,b; McGlathery et al. 2012). The coupled hydrodynamic-vegetative growth model identified two leading indicators of a meadow nearing the depth threshold between the vegetated and unvegetated states in decadal scenarios of sea-level rise and temperature increases. 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 (*sensu* Scheffer et al. 2009; Fig. 22; Carr et al. 2012 a, b). The model currently estimates year-end distributions of seagrass parameters, and leading indicators are determined from changes across years on a 50-year time frame. We will refine the parameterization of the model by making monthly measurements from May – October of shoot density, leaves per shoot, leaf width, and above- to below-ground biomass ratios. In addition, we will use the temperature and light measurements across the depth

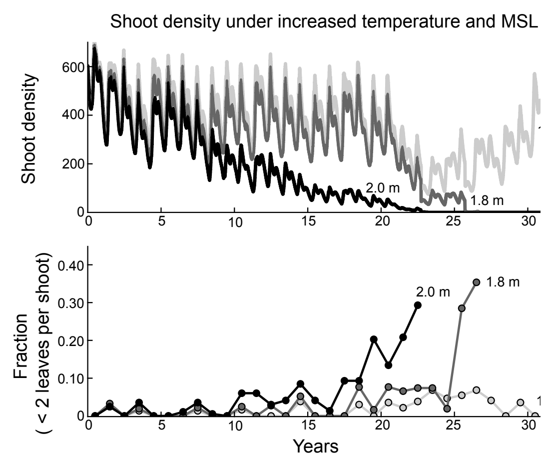


Fig. 22. A) *Zostera marina* shoot densities for meadows initiated at 1.5, 1.8 and 2.0 m MSL under increased temperature and sea level. B) The appearance of flickering and slowing down prior to loss for the meadows initiated at 1.8 and 2.0 m MSL. Flickering, slowing down, but then recovery of the meadow initiated at 1.5 m MSL.

range of the stable/bistable transition to refine the growth model that estimates the maximum depth threshold.

Barrier Islands (PI Leads – Young, Day): Analyses of remote sensing imagery (Zinnert et al. 2011) have identified "fronts of change" from stable grassland to stable shrub thicket in barrier island swales. The switch to the alternative stable state occurs after the actinomycete, *Frankia* sp., has dispersed into the grassland soils (Wijnholds and Young 2000). Continued monitoring of the fronts of change will identify thresholds (i.e. *Frankia* introduction to the soils) on the VCR islands. We will instrument these transitions with sensor arrays consisting of "Hobo" packs to measure soil temperature and data loggers with quantum sensors to measure light. In addition, we will measure shrub dispersal and seedling establishment patterns, shrub and grass species composition, densities and productivity, elevation and proximity to the freshwater lens in replicate 5x5m plots. We will focus initially on the northern and southern portions of Hog Island. Shrub expansion is related to island accretion on the northern third of the island, whereas expansion on the southern end is occurring in a relatively stable portion of the landscape. This comparative approach will permit the separation of environmental changes associated with landscape position effects (Young et. al. 2011) from possible climate change influences. In addition, environmental changes associated with a shift from grassland to shrub thicket, especially at the threshold of *Frankia* establishment, will be quantified. Results will be used to parameterize the rules-based model for shrub expansion (Question 3a). Additional fieldwork will focus on other islands (e.g. Metompkin and Smith Islands) where shrub expansion patterns have been identified through remote sensing.

Theme 2: Ecosystem connectivity

Question 2a. To what extent does connectivity of adjacent ecosystems via sediment fluxes affect responses to environmental change? Quantifying linkages among ecosystems is critical to developing an understanding of patterns and dynamics on a heterogeneous landscape (e.g., Peters et al. 2004, 2008; Bostrom et al. 2011), though the effect of habitat adjacencies and fluxes on bistable dynamics is not well understood. In coastal barrier landscapes, sediment redistribution alters the vertical elevation of ecosystems, e.g., sediment accretion on tidal marshes, overwash on barrier islands. We propose to address whether the flux of sediments between ecosystems (e.g., subtidal-intertidal, barrier island-marsh) influences the emergence of alternative stable states. For the intertidal marshes in the VCR, two interactions exist that are spatially distinct: seagrass connections to marshes on the barrier islands and in the coastal bays, and oyster connections to mainland marshes.

Sediment redistribution (PI Leads – Wiberg, Fagherazzi): Previous work at the VCR-LTER has documented the relatively widespread erosion of marsh edges fronting the shallow bays (McLoughlin 2011), and increases in marsh surface elevation in many locations that are commensurate with rates of sea-level rise in the VCR. This raises important questions concerning the fate of sediment eroded from the marsh edge and the source of sediment depositing on the marsh platforms. If marsh-edge erosion feeds deposition on adjacent marsh surfaces, can the increased erosion rates expected to accompany sea-level rise (e.g., Mariotti et al. 2010) supply the sediment needed for marshes to accrete at a rate that maintains their elevation with respect to sea level? Will successful restoration of seagrass in the lagoons promote marsh loss by reducing the overall supply of sediment or promote marsh stability by reducing the wave energy attacking the marsh edge? (Fringing oyster reefs near marsh edges could play similar roles.) If sediment eroded from marsh edges is transported into the bays rather than back onto the marsh platforms, will the resulting increase in turbidity significantly affect light availability for seagrass?

Answering these questions requires a more comprehensive picture of sediment transport and deposition in the VCR bays than we currently have. Previous field measurements and modeling have examined the potential for sediment resuspension and light attenuation in Hog Island Bay (Lawson et al 2007), but did not account for sediment redistribution or consider other bays in the system. In VCR V, we used the FVCOM model (Table 1) to quantify residence times for sediment, water and nutrients. In VCR VI, we will expand our system-wide hydrodynamic modeling to include sediment suspension and redistribution using FVCOM and Delft3D, which couples hydrodynamics and morphodynamics (Lesser et al. 2004). Continuing field measurements of flow and suspended sediment concentrations in seagrass beds, over oyster reefs and in bare sediment regions of the bays will allow us to test the model and to incorporate effects of seagrass meadows and oyster reefs on wave attenuation, circulation, and bed stabilization (see below). We will also investigate the use of natural (e.g., Jaffe et al. 2006) or deliberate (e.g., Spencer et al. 2011) tracers to track the fate of sediment eroded from the marsh edge. The Delft3D model, which has been extensively applied to coastal environments, will allow us to investigate longer-term trends in marsh erosion and accretion, sediment redistribution, and resulting changes in patterns of circulation and sediment transport. As a test of this model, we will attempt to hindcast the dramatic rates of salt-marsh extension observed on Mockhorn Island (Erwin et al. 2004) and forecast the effects of the planned fringing oyster reef experiment on marsh edge erosion (see below).

Seagrass – Marsh (PI Leads – D'Odorico, Fagherazzi, Reidenbach, Wiberg): Our understanding of the mechanisms promoting the existence of salt marshes and tidal flats as alternative states in a bistable landscape does not account for the role of seagrasses and their effects on wave energy, bed scouring and sediment resuspension. These effects will influence the wave energy impacting the adjacent marsh boundary and the supply of sediments for marsh accretion in response to sea-level rise (Fig. 23). Based on our current modeling work and the success and scale of the seagrass restoration in the VCR, we have a unique opportunity to explore how the adjacency of seagrass and salt marsh ecosystems may impact bistable dynamics of each through the flux of sediments and the attenuation of wave energy.

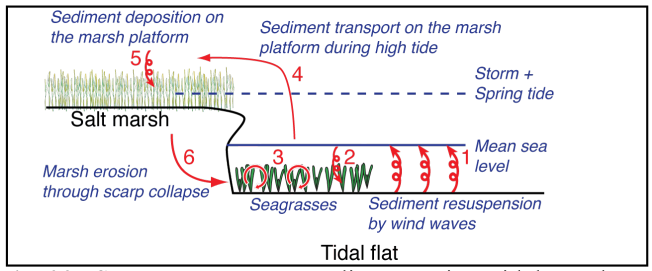


Fig. 23. Seagrass ecosystems adjacent to intertidal marshes may reduce sediment availability for marsh accretion and buffer wave energy, and modify bistable dynamics in these systems. Arrows represent sediment fluxes: 1) resuspension, 2) sedimentation, 3) retention, 4) transport to marsh platform, 5) deposition, and 6) erosion of marsh edge.

At several sites where seagrass meadows are located adjacent to marshes, we will measure total suspended solids (TSS) using optical backscatter sensors, wave heights using submerged pressure sensors, and marsh edge erosion using erosion pins and surveys for short-term measurements and aerial photography for longer-term estimates. We will merge the alternative stable state models presented in Mariotti and Fagherazzi (2010) and Carr et al. (2010) to determine the influence of seagrass meadows on sediment input and wave energy at the marsh edge and how this affects the resilience of salt marshes to sea-level rise and storms. To accomplish this, we will expand the coupled hydrodynamic-seagrass model to incorporate lateral expansion of the meadow, and deepening and incision of the seabed by sediment scour, with scour rates dependent on seagrass density. The effects of the seagrass meadow on suspended sediment will affect the sediment supply parameter in the marsh model. The coupled model will be run for varied environmental and climatic drivers, and model predictions will be compared with field data.

Oyster – Marsh (PI Leads – Reidenbach, Wiberg): In the VCR and similar coastal bay systems, oyster reefs form primarily in intertidal regions and are found fringing mainland marshes or along tidal channel banks. Our initial measurements of local hydrodynamics and sediment dynamics along restored oyster reefs indicate that the combined influence of filtration by the oyster reef community and local hydrodynamics has a strong, non-linear effect on sediment deposition and suspension (Whitman 2011). At low velocities, increased sediment uptake is positively correlated with increasing water velocity due to enhanced turbulent mixing, which makes more of the water column available for filtration. At intermediate water column velocities, maximum uptake rates are reached. At high velocities, hydrodynamically controlled sediment suspension is greater than that of uptake by bivalve filtration, resulting in an efflux and net transport of sediment away from the reef.

We propose to expand on this work with a *new long-term ecosystem-level experiment* to determine how oyster reefs fringing marsh edges impact erosion and sediment supply to the marshes (Fig. 24). This experiment will be coordinated with TNC, which has received separate funding for the restoration. We will construct at least 1.5 acres of replicate artificial reefs composed of shell material adjacent to a mainland marsh. Waves, mean currents, turbulence, and suspended sediment concentrations will be measured across the constructed reefs and along adjacent exposed marsh edges using wave gauges, optical backscatter sensors, and acoustic Doppler profilers. Dissipation of wave energy across the constructed reefs and sediment supply to the marsh will be compared to adjacent exposed marsh regions. Rates of accretion/erosion of the marsh edge will be measured with erosion pins and aerial photography to quantify the impacts of constructed reefs on lateral expansion/contraction of the marsh. Measurements of sediment accretion made with SETs on the marsh surface will be used to quantify the impact of these breakwaters on marsh elevation.

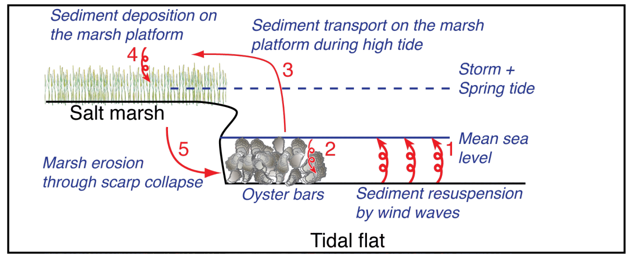


Fig. 24. Oyster bars adjacent to intertidal marshes may reduce the sediment supply and wave energy hitting the marsh boundary, and influence state change dynamics. Arrows represent sediment fluxes: 1) resuspension, 2) sedimentation, 3) transport to marsh platform, 4) deposition, and 5) marsh edge erosion.

Island – back-barrier marsh (PI Leads – Moore, Fagherazzi, Kirwan): The adjacency of back-barrier marshes to barrier islands may influence both barrier island migration and marsh accretion in response to sea-level rise. Barrier islands provide sediment inputs to back-barrier marshes via overwash during storms (Walsh 1998), and this can facilitate a marsh building vertically and surviving faster rates of sea-level rise. At the same time, back-barrier marshes provide a critical nucleation point allowing the collection and maintenance of barrier island sand and a platform across which islands can migrate (Fig. 25). A barrier island that migrates over a marsh platform requires less sand from the shoreface and along-shore sources to keep pace with sea-level rise. Thus, the coupling between barrier island and marsh processes may be critical in determining how an island-marsh system evolves and which state is stable (i.e., high or low; Question 1b) as forcing conditions change (e.g., sea-level rise rate, storm intensities).

We will explore these decade-century scale couplings by merging 3 ecomorphodynamic models that our PIs have developed (Table 1): 1) GEOMBEST incorporates sediment composition and supply rate to forecast barrier island evolution in response to sea-level rise (Moore et al. 2010, 2011); 2) A marsh plan-form model couples sediment transport and plant productivity to produce a 3D representation of tidal marsh accretion and channel network development (Kirwan & Murray 2007); 3) A marsh transect model predicts coupled salt marsh – tidal flat model evolution in response to sea-level rise and storms (Question 1b; Mariotti & Fagherazzi 2010). We will first incorporate storm-driven sedimentation to the marsh plan-form model to address how overwash frequency affects marsh accretion rates. We will then merge the marsh accretion component of the plan-form marsh model with the barrier island model. This will allow us to assess the effects of sea-level rise and changes in storm intensity on marsh-island coevolution and the effects on island volume and migration rate, and on marsh area and accretion. Finally, we will incorporate marsh-edge erosion by merging the marsh-edge erosion component from the marsh transect model with the other two models. We will compare long-term data sets of overwash frequency, historical barrier island shoreline change, and marsh width and edge erosion in the VCR to patterns that arise in our model runs. These comparisons will inform model development, but also potentially lead to new interpretations of existing data. For example, our holistic modeling may also offer new insight into chronosequences of marsh development on overwash fans of different ages (Osgood and Zieman 1993), and the factors controlling the productivity of intertidal marshes (Question 1b; Kirwan et al., 2012).


Fig. 25. Recent beach erosion reveals marsh peats under barrier island sands illustrating barrier island “roll-over” in response to storms and rising sea level.

Question 2b. Is there evidence of subsidies via organism fluxes between adjacent habitats that influence key ecosystem processes, services and states? In addition to sediment, fluxes of organisms between adjacent ecosystems can affect trophic dynamics, nutrient cycling, and possibly ecosystem states.

Recent studies emphasize cross-ecosystem linkages between land and sea, particularly the importance of organisms as vectors and regulators of these transfers (Garcia et al. 2011; Mellbrand et al. 2011; Dugan et al. 2011). Here, we focus on exchange between subtidal and intertidal communities. We view the question of subsidies in the context of long-term changes underway in the VCR and ask how an invasive species and an aqua-cultured species influence, and are influenced by, cross-ecosystem subsidies. We also address how these species interact with recovering seagrasses as the state change occurs in the VCR.

Cross-Habitat Macrophyte Subsidies: (PI Lead – McGlathery): Two important changes in the subtidal zone may affect adjacent marshes and tidal flats in the coming decades: the large-scale seagrass restoration (Question 2a) and the invasion of the seaweed *Gracilaria vermiculophylla*. Seagrass meadows are linked to the larger seascape via passive drift of detritus and the foraging patterns of consumers (Heck et al. 2008). Likewise, macroalgae can move between habitats as live or detrital material, potentially altering habitat structure, species composition and ecosystems functions of neighboring habitats (Ruesink et al. 2006; Grosholz & Ruiz 2009), having both positive and negative effects on native species (Rodriguez 2006; Thomsen et al. 2009, 2010). We have recently identified *G. vermiculophylla* as a widespread invasive species of Asian origin in the VCR coastal bays (Thomsen et al. 2005; 2006, 2010), and it has proliferated in the coastal bays and in the intertidal flats, marshes and oyster reefs (Thomsen & McGlathery 2006; Thomsen et al. 2009; Gulbransen et al. 2012). We propose to address how these changes may impact nutrient cycling, productivity, and trophic dynamics in intertidal habitats. We will quantify macroalgal and seagrass biomass in intertidal flats and marshes and use N-15 isotope tracer experiments to investigate nutrient subsidies to sediments, vegetation (salt marsh, benthic microalgae), and higher trophic levels (invertebrates). These data will be related to patterns of primary production and invertebrate abundance and diversity. In addition, we will assess the 'upward cascade' of habitat subsidies of subtidal macrophytes to invertebrates and shorebird populations that feed on them in the intertidal zone (Dugan et al. 2003). This is part of a coordinated cross-site comparison with colleagues at SBC LTER who are addressing macrophyte (kelp) subsidies to adjacent beach habitats.

Subsidy Support and Expansion of Clam Aquaculture: (PI Leads – Pace, Anderson, Reidenbach): Resources to support clam aquaculture, which provide ecosystem services through the provision of food and via their filter feeding activities, may derive from phytoplankton, benthic microalgae, macroalgae, seagrass, marsh grass, and/or terrestrial organic matter. We are using stable isotopes of carbon (C-13), nitrogen (N-15), and hydrogen (H-2), and a Bayesian isotope-mixing model (Solomon et al. 2011) to identify the organic matter sources supporting clam growth. Our results indicate that benthic micro- and macroalgae are the main resources for clams, and that macrophytes (marsh and seagrass) are of little significance (Fig. 26). We will build on these studies by developing a model of clam growth in the aquaculture beds based on measured temperature variation and food as supplied by resuspended organic matter including benthic algae (Cardosa et al. 2006; Hoffman 2006). We hypothesize that the capability of a site to support clam production (at economically useful rates) is driven by subsidies of benthic micro- and macroalgae from adjacent intertidal or subtidal habitats, and that clams will benefit from suspended organic matter up to a threshold. Sediment suspension and transport will be examined using the FVCOM and Delft3D hydrodynamic models (see Question 2a). We will use the growth model to examine the potential impact of high temperatures on production and of variation in resource supply to beds in different locations under varying conditions, including projected warming and storm trends.

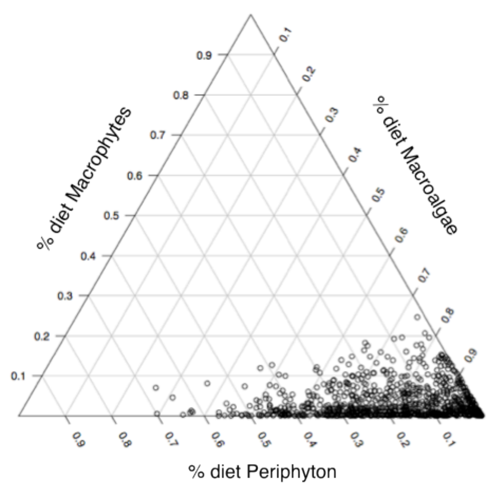


Fig. 26. Results of Bayesian model for sources of organic matter to clam diets. Points represent possible outcomes that incorporate uncertainty in sources, trophic fractionation (for nitrogen), environmental water use (for deuterium), and variation in isotopic composition of clams.

Long-term expansion of clam beds may influence water and sediment quality and potentially compete with seagrasses. Clam aquaculture generally requires sandy sediment and depths from barely subtidal to approximately 1.1 m at MSL, which overlaps the depth range suitable for seagrass habitat (0.9 – 1.6 m MSL). The interactions of these species will likely increase over the coming decades and possibly result in a conflict between the ecological benefits of seagrasses and the economic benefits of clam harvest (Question 3c). Both habitats are important in sequestering C and N. For seagrass, retention of C and N in plant tissues is ephemeral, but seagrass meadows accumulate and store C in the sediments (McGlathery et al. 2007, 2012). For clams, some of the C and N taken up by clams is removed from the system as the clams are harvested. Of the N taken up, about half is released to the sediment as biodeposits (feces and pseudofeces) (Condon 2005; Hofmann et al. 2006), although the fate of this organic N is largely unknown (Nizzoli et al. 2006). We propose to use aerial surveys to document current trends of aquaculture and field studies to measure the effects of clams on nutrient cycling and water quality. Clam aquaculture beds are easily recognized on aerial photographs by the predator-exclusion nets that are used to protect the beds. We will quantify rates of N cycling (mineralization, nitrification, denitrification, anammox) and compare these to similar data for seagrass meadows and bare sediments, to determine the differences in N processing and burial. We are currently quantifying C burial in seagrass meadows and bare sediments (McGlathery et al. 2012), and will make similar measurements in sediments underlying clam beds to assess the role of these different shallow benthic habitats in C sequestration. These studies build on our 15-year database on nutrient cycling processes in the VCR coastal bays (e.g., Anderson et al. 2001, 2010; McGlathery et al. 2007; Tyler et al. 2003) prior to the expansion of aquaculture and seagrass. Finally, we will measure the same suite of parameters as for the oyster reefs (waves, mean currents, turbulence, TSS) to determine clam bed effects on water clarity.

Theme 3: Interacting drivers, scales and feedbacks

Question 3a. How will ecosystem resilience and state dynamics vary in response to climate drivers across the landscape? We will develop a range of realistic future scenarios of climate change for the region to assess ecosystem responses over a 50-100 year time frame. For sea-level rise, we will use our current estimate (4 mm yr^{-1}) and an accelerated rate of 6.5 mm yr^{-1} (IPCC 2007). Precipitation and storm scenarios will include current conditions and those representing the 10 wettest and driest years, and the 10 years with the highest and lowest storm frequencies, over the last 50 years. For the ocean temperatures used in the seagrass models, we will use an increase of 2.2 ^{o}C over 50 years (Najjar et al. 2000), and will overlay this trend with past records of high temperature events above the mean (Carr et al. 2012).

Changes in Intertidal Habitats (PI Leads – Kirwan, Fagherazzi, Blum, Wiberg): In previous sections, we proposed a number of experiments to describe the processes that determine whether intertidal elevations are dominated by a vegetated marsh state or an unvegetated tidal flat state (e.g. the controls of edge erosion, the influence of flooding on interior marsh productivity). However, the value of ecosystem services associated with intertidal wetlands in future scenarios of climate change depends not only on their presence or absence, but also on their size and spatial configuration (Peterson & Turner 1994; Barbier et al. 2008). We will address the following two issues:

1) Lateral erosion/transgression along marsh boundaries – The spatial extent of marshes is controlled by the balance between lateral erosion at the lagoon-marsh interface, and lateral transgression of marsh into higher elevations at the forest-marsh interface as marshes accrete vertically with sea-level rise (Brinson et al. 1995). Historic data from aerial photographs covering 50 years suggest that rates of marsh erosion and transgression at the VCR have been similar, resulting in a stable marsh area (Knowlton 1971; Kastler & Wiberg 1996). Our numerical model indicates that marsh edge erosion is a positive function of the sea-level rise rate (Mariotti & Fagherazzi 2010), and conceptually, we believe that this would also be true for rates of marsh transgression into low-lying forests. To determine relative rates of marsh erosion and transgression, we will incorporate historical observations of marsh expansion at the forest edge based on aerial photographs and our process-based understanding of these dynamics (Question 1a) into our model of marsh edge erosion. This model will explore a range of conditions (rates of sea-level rise, wind-wave climate, elevation and slope of marsh-forest margin) that lead to either expansion or contraction of marsh area, and will forecast changes in marsh width at different parts of regional landscape where these parameters vary.

2) Vertical elevation changes in interior marsh – Marsh vulnerability depends largely on its ability to maintain an elevation high in the intertidal zone. In Question 1b, we proposed elevation platform experiments that determine minimum, maximum, and optimum elevations for vegetation growth. It has been proposed that *Spartina alterniflora* marshes tend to be stable when their elevations are higher than optimum for aboveground growth, and unstable when their elevations are lower than optimum (e.g. Morris et al. 2002). Here, we propose to use LiDAR and GPS surveys to map the spatial distribution of marshes that are higher and lower than optimum in an effort to illustrate which marshes are likely to be unstable today and in the near future. We then propose to map the maximum rate of sea-level rise that a marsh can survive based on the linear relationship between threshold sea-level rise rate and sediment availability that has been observed in a number of numerical models (Kirwan et al. 2010). We will extrapolate this relationship into a spatial domain using suspended sediment concentrations derived from long-term field monitoring and from the FVCOM model (Question 2a). This map will show the rate of sea-level rise that leads to state change at points throughout the VCR, and will offer a spatial representation of which marshes are likely to be most vulnerable, and the size and configuration of marshes that should survive the next century of sea-level rise at different projected rates.

Changes in the Subtidal Habitats (PI Leads – McGlathery, D'Odorico, Wiberg Schwarzschild): Our model for bistable dynamics of a seagrass meadow indicates that seagrasses are not particularly sensitive to projected rates of sea-level rise, as long as the subtidal realm can transgress landward, but that high-temperature events could cause a change to an unvegetated state in deeper waters (Carr et al. 2012a,b). This occurs because high temperatures alter the C balance of plants and increase the minimum light requirements for growth and survival (Moore et al. 2012). The model currently does not include ways in which sediment characteristics that are also known to influence plant C balance (e.g., high organic matter) affect the threshold depth for a stable seagrass system. It also does not include how patchiness at the landscape scale influences the feedback on sediment suspension and light availability. Both considerations are important to understanding the resilience of seagrass meadows to climate change.

Location effects – We will address how location affects habitat suitability and resilience of seagrass meadows by considering variation in physical and chemical characteristics of the environment, and linking these with our model of alternative state dynamics. Sediment organic matter will be measured in 3 bays that vary with respect to size, depth, and water residence time. We will set up *a new long-term experiment* in which we will seed areas that bracket the range of stable/bistable depths predicted by the model and we will monitor the establishment and survival of seedlings over time. These data will be related to light and temperature measurements to assess minimum light requirements for survival of the seagrass in sediments of varying organic content. We will use this information to modify the minimum light requirements in our hydrodynamic-growth model, and to forecast the resilience of seagrass to future scenarios of climate (sea-level rise, storms, temperature) and to increased nutrient loading related to land-use change (Question 3b).

Landscape effects – The effect of meadow patchiness (size and configuration) on the feedbacks to sediment suspension and light attenuation is necessary to understand bistable dynamics at a scale larger than a single meadow (Luhar et al. 2008; van der Heide 2010). This process is complicated by the variability of water depth, and wave and tidal current forcing in space and time. Our collaborators at VIMS are generating a database on patch size and structure from 10 years of annual aerial photographs. We will use these data to constrain a spatially-explicit sediment dynamics model that we have recently developed for a heterogeneous subtidal landscape comprising bare areas and seagrass meadows. We will enhance the model by integrating a spatially-explicit model of seagrass growth (expansion due to rhizome branching and seedling establishment; see Question 1a). This

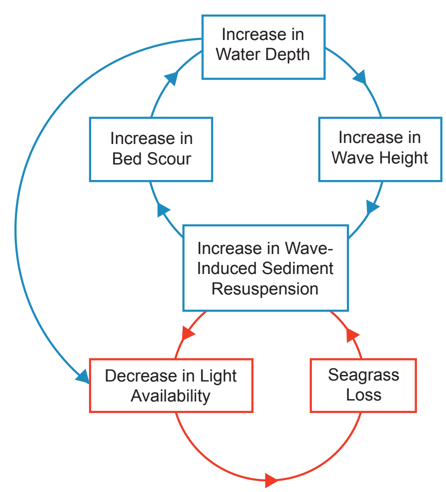


Fig. 27. Abiotic (blue) and biotic (red) feedbacks on subtidal flat dynamics. The feedback of seagrass meadows could stabilize the seabed at relatively shallow depths.

coupled model will be used to investigate: 1) the water depth ranges that are suitable for seagrass growth with different seagrass patch configurations; 2) the bistable range of water depths in which seagrass cover and bare sediment conditions are possible stable states; and 3) bathymetric changes due to redistribution of sediment and enhanced scouring in bare sediment areas (Fig. 27). Given the sensitivity of seagrass to light availability, it is crucial to investigate how suspended sediment and light vary with the size of gaps opened by disturbances (storms, temperature) that could increase in intensity and/or frequency as climate changes.

Changes in Island Habitats (PI Leads – Young, Moore, Dueser, Porter, Moncrief): On the islands, rising sea level, changes in storm intensity, and expansion of the geographic ranges of vegetation with climate warming will likely influence island vulnerability to overwash. This has implications for the vegetation feedback described in Question 1a that maintains "high" vs. "low" islands. In addition, the current dominant dune-building grass of the VCR barrier islands may switch from *Ammophila breviligulata* (C-3 or cool season) to *Uniola paniculata* (C-4 or warm season) in response to alterations in precipitation and temperature. This latter shift could cause the continuous, linear dunes of the VCR to become discontinuous and hummocky (with intervening overwash-prone low areas) due to the differing growth patterns of the two grasses and the resulting change in ecogeomorphic feedbacks (Godfrey et al. 1979; Stallins & Parker 2003). This transition is already beginning: *Uniola* was only observed on the southernmost barrier island in 1996, and now populations have been found in the middle of the island chain. Changes in vegetative feedbacks and dune morphology could lead to more widespread overwash during storms, and could possibly increase island migration rates and facilitate conversion from high to low islands, which would have important consequences for beach area, island vegetation, habitat heterogeneity and availability for predators and shorebirds.

Island vulnerability to overwash – We propose both long-term monitoring and experiments (decadal) to better understand the mechanisms behind the vegetation feedback on sediment elevation. We will plant replicate experimental plots (10m x 10m) of *Spartina patens* (overwash-adapted) and *A. breviligulata* (dune-building) following an overwash event and track differences in vegetation distribution and local changes in island elevation. The number of plots per overwash will depend on the overwash fan size. Replicate overwash fans will be located in areas with similar intermediate beach width (as a proxy for potential sediment supply and overwash frequency). In addition, we will initiate long-term aerial and ground surveys (at selected sites) of *S. patens* and the 2 dune-building grasses (*A. breviligulata* and *U. paniculata*) to determine the extent and rate of movement of their distributions over time. 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. This model will combine overwash probability calculated for a storm of a given size (using LiDAR data and wave data), storm occurrence probabilities (determined from long-term observations) and dune growth rates (based on monitoring and experiments described in Question 1a) to assess how changes in forcing (e.g., sea-level rise, storm intensity, vegetation composition) are likely to alter barrier island vulnerability to overwash. As funding allows, we will use repeated LiDAR measurements for specific areas to test our model predictions of overwash probability.

Island vegetation - Reflectance (NDVI) and LiDAR imagery provide rapid assessment of geomorphologic processes and vegetation change over large spatial scales. We will build on our analysis of 30 years of change for vegetative cover on Hog Island (Zinnert et al. 2011) to quantify historical change across the entire VCR island chain. We will examine fine-scale changes in vegetation cover as a result of shoreline accretion and erosion (Questions 1b), use NDVI as a link between changes in woody cover due to hydrological patterns (e.g bistability of grassland vs. shrub thicket), and use LiDAR to determine the potential range of distribution based on habitat polygons (Young et al. 2011). We will also quantify changes in island shape and size and corresponding vegetative classes over 40 years using Landsat TM imagery. To explore future climate change scenarios of shoreline migration and sea-level rise we will integrate these remote-sensing analyses with long-term data on species distributions and local-scale mechanisms to model bistability and vegetation change. We are developing a rules-based cellular automata model that simulates shrub thicket dynamics within the context of bistability at several spatial scales: swale, cross-island, island, and island chain. We will use the model to predict shrub expansion (or contraction) in response to increases in sea level and to changes in storm frequency, associated variations in shoreline migration, and availability of groundwater from the freshwater lens.

The model currently incorporates the habitat polygon for *Morella* and will be extended to include polygons for other species (e.g. *A. breviligulata* vs *U. paniculata*) (Question 1a).

"Upward cascade" of vegetation state change on predator and bird populations – We will link the landscape modeling of island vegetation to faunal distributions and to analyses of the effects of manipulations (removals) of mesopredators (raccoons, foxes). At the whole-island level, observations of vertebrates will be related to island properties (e.g., island area, elevation, area of woody vegetation) to identify threshold levels of habitat needed to support populations of particular species. Our expectation is that the threshold island area associated with local extinction of a species will be lower than the threshold area required for successful immigration of that same species. We will integrate vertebrate distribution data from existing long-term small mammal trapping efforts (Dueser & Porter 1986) with a network of new camera traps and tracking stations to monitor the frequency of occurrence of larger animals (e.g., foxes, raccoons, rabbits) associated with vegetation cover. Analysis of long-term data on locations of small mammals (using a 22-year record of small mammal captures and vegetation on Hog island) relative to vegetation, elevation and hyperspectral land cover data will allow us to predict where small mammals may be found on future landscapes based on habitat availability.

Question 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? **(PI Leads – McGlathery, Mills, Blum, Kirwan, D'Odorico):** We will incorporate the effects of changing land use and associated increases in nutrient loading into our forecasting of ecological change in response to climate drivers. We will use our watershed model of N loading based on land use (Giordano et al. 2011; Cole 2011), linked to stream attenuation of nutrients (Gu et al. 2007, 2008a, b) to create realistic future scenarios of land-use change on N loading to the coastal bays. We have documented a regional gradient in N loading in mid-Atlantic coastal bays driven by differences in land use, with generally higher rates in the northern bays where agriculture and residential/commercial development is more extensive than in the VCR (McGlathery et al. 2007; Anderson et al. 2010; Cole 2011). Future scenarios using the watershed N loading model indicate that realistic increases in agriculture (poultry farming, switch from traditional row crop to tomato plasticulture) and residential development could lead to up to a 7-fold increase in annual N loads, typical of the more heavily impacted northern bays (Giordano et al. 2011). Changes in nutrient availability will likely affect dynamics of seagrass meadows, intertidal marshes, and their interactions.

For seagrass, eutrophication scenarios are expected to increase light attenuation by enhancing algal growth in the water column and on seagrass blades (McGlathery et al. 2007). This would shift the bistable range of seagrasses towards shallower water depths (Carr et al. 2010), which is consistent with large-scale surveys relating the depth distribution of eelgrass to N loading (Nielsen et al. 2002). We propose to link our measurements and models of N loading with changing land use to the water quality response in the coastal bays (dissolved N and chlorophyll; Boynton et al. 1996; Giordano et al. 2011) and feedbacks on light attenuation. These effects will be incorporated into the alternative stable state model for seagrasses (Question 1a) to identify how future land use changes could influence the resilience of restored seagrass meadows to increased temperatures associated with climate change (Question 3a).

For intertidal marshes, previous work at the VCR and elsewhere indicates that N fertilization tends to increase aboveground productivity and soil metabolism and may decrease root and rhizome biomass (Morris et al., 2002; Darby & Turner 2008; Turner 2011). In frequently flooded portions of the marsh, we hypothesize that enhanced aboveground growth of vegetation will trap available sediment and increase marsh accretion rates. In infrequently flooded portions of the marsh that rely on organic accretion, we hypothesize that enhanced aboveground growth will lead to little change in elevation and that N loading will lead to reduced organic accretion by enhancing decomposition more than production, and increased vulnerability to sea-level rise. We will test these hypotheses by fertilizing replicate plots based on the N loading scenarios outlined in Giordano et al. (2011) and measuring plant growth, sediment elevation (using SETs), above- and belowground biomass and sediment shear strength. These experiments will be integrated with our numerical models of marsh-edge erosion and the development of alternative stable states to consider the effect of N loading on root-to-shoot ratios and resistance to erosion (Questions 1a, 3a). We expect that a decrease in root production will reduce the shear strength of the marsh sediment and increase the rate of erosion, but that an increase in aboveground growth will increase the elevation of the remaining marsh platform.

***Question 3c. How do regional attitudes and motives modify future scenarios?* (PI Leads – Swallow, McGlathery, Blum):** Stakeholders differ in their vision of the future and in their understanding of the forces that determine trends and trajectories of change. For example, sudden shifts in an ecosystem state may change public perception and understanding of the way that systems need to be managed to enhance resilience. This, in turn, may feedback to alter the policies and institutions that carry out that management (Groffman et al. 2006). Engaging a diverse group of stakeholders (i.e., resource managers, policy makers, public citizens) with academics in creating realistic alternative future scenarios is an effective approach that leads to a shared understanding of key processes and uncertainties (Carpenter et al. 2009; Chapin et al. 2011), and is especially well-suited to long-term programs such as LTER (Peterson et al. 2003).

We will build on our strong collaborations with TNC and the Eastern Shore Climate Adaptation Working Group, and also on our previous results from supplemental funding on the public valuation of ecosystem services (Smith & Swallow 2011; Smith 2012) to incorporate input from multiple stakeholder perspectives into future scenarios of climate and land-use change. We will do this following the approach described by Peterson et al. (2003) using the Millennium Ecosystem Assessment conceptual framework (Millennium Assessment 2005) that incorporates both qualitative and quantitative input. Plausible future scenarios (decadal to century time scale) will be developed through organized working groups to get stakeholder input on: 1) potential development related to population increases, 2) technological advances (e.g., agricultural practices that could modify nutrient loading), 3) introduction of poultry farms, 4) enhancing resilience to climate change through living shorelines, 5) planting salt-tolerant crops, 6) expansion of aquaculture, and 7) sustaining habitats through conservation and restoration.

Considering multiple factors may involve tradeoffs, for example between seagrass restoration and clam aquaculture (see Question 1b). Also, rising sea level threatens agricultural fields bordered by marshes, and farmers face a choice between abandoning farmland, hardening the shoreline to delay submergence, or adopting adaptation strategies such as planting salt-tolerant crops like salt marsh mallow (*Kosteletzkya pentacarpos*). In VCR VI, we will initiate a *new long-term experiment* in collaboration with TNC to explore the ecological and economic benefits of *K. pentacarpos* (an alternative biofuel crop) in abandoned agricultural fields (e.g., nutrient and C sequestration, exclusion of invasive species).

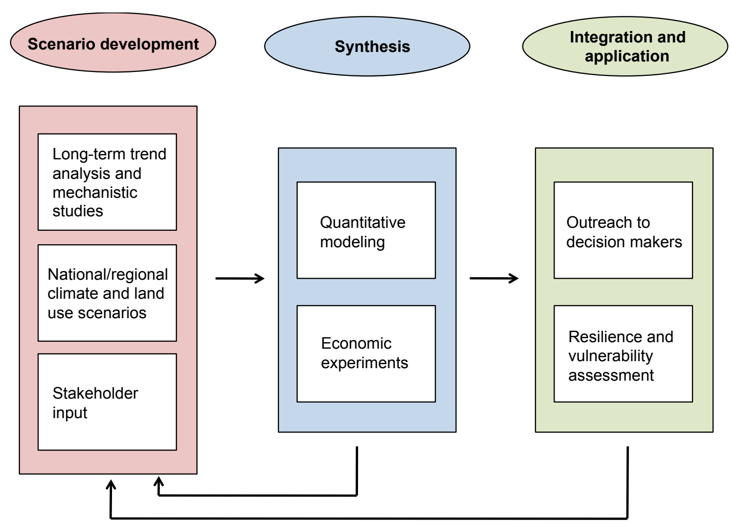


Fig. 29. Schematic of development of future scenarios of environmental change, integration of scenarios into modeling and experiments, and integration of outcomes into outreach and resilience/vulnerability assessments. Feedbacks from application and synthesis modify further scenario development.

We will integrate future scenarios with our quantitative models on ecosystem state change (modifying drivers) and with economic experiments that assess public valuation of ecosystem services. The latter builds on work done by Smith and Swallow (2011) and Smith (2012) using "willingness to pay" techniques to estimate preferences and value of public goods associated with restoration of specific habitats. Their approach used public auction methods to translate willingness to pay into actual revenues for restoration activities. This will complement TNC's public polling program to determine the drivers and motivations for local citizen's behaviors and decisions regarding environmental change risks. The ultimate goal is for integrated outcomes of the future scenario development and modeling to be incorporated into outreach, decision-making and resilience/vulnerability assessments (Fig. 29).

D. Synthesis and Significance

The proposed research addresses important ecological questions of global importance. Place-based studies that combine field observations, experiments and modeling are needed to advance our understanding of global environmental change. Our proposal builds on 24 years of data to understand these changes in coastal barrier ecosystems, which are prominent on all continents except Antarctica. We address key issues including climate change, land-use change, coupled human-natural systems, altered hydrological and biogeochemical cycles, the introduction of exotic species, and forecasting landscape change (NRC 2003; Millennium Assessment 2005). One of the strengths of the VCR is the close collaboration of physical scientists with biogeochemists and ecologists, and the understanding we are developing of nonlinear dynamics and the existence of alternative stable states can be applied to similar coastal landscapes.

The relevance of our research extends beyond coastal barrier systems. We ask fundamental questions related to non-linear dynamics in marine and terrestrial ecosystems, the emergence of bistable dynamics and leading indicators of threshold responses to change, linking landscape heterogeneity with resilience to state change, biotic feedbacks on geomorphology and nutrient cycling, and trophic cascades. We do this by combining long-term empirical data from observations and experiments with numerical models, and we use novel technologies developed by our PIs to quantify processes.

Through our long-term and close collaboration with TNC, we have provided the scientific foundation for decisions related to stewardship and sustainability of the coastal barrier system. We meet with TNC quarterly, and work with them to inform and engage regional stakeholders. Examples of how LTER research has influenced regional policy include: 1) Explicit consideration of sea-level rise and land-use effects on water quality in county Comprehensive Plans and the regional Hazard Mitigation Plan; 2) The 2010 passage of comprehensive shoreline management legislation by the Virginia General Assembly that promotes living shorelines; 3) Inclusion of management alternatives that account for sea-level rise in the Comprehensive Conservation Plan for the USFWS's Chincoteague National Wildlife Refuge; and 4) The decision by NASA's Wallops Island Flight Facility to use sand replenishment rather than construct a 500-ft groin to mitigate shoreline erosion to protect launch facilities.

We also have close ties with regional academic collaborators on seagrass restoration (R. Orth, VIMS), scallop restoration and fisheries (M. Luckenbach, VIMS), and ocean acidification (R. Zimmerman, Old Dominion University). This leverages our LTER research and broadens our understanding of coastal barrier systems. Within the LTER Network, the four Atlantic Coast marine sites (PIE, VCR, GCE, FCE) plan to meet annually to advance cross-site synthesis and collaborations. Meetings will rotate among the sites, and will be held in conjunction with annual site meetings. PIs will attend the annual meeting of the host site, and then meet on the following day(s) to address cross-site topics such as: 1) drivers of wetland accretion, 2) role of lateral flux in the carbon budget of coastal wetlands, 3) controls of coastal plant productivity, and 4) coastal food webs. In addition, we place our work in a broader context through collaborations with other marine (SBC) and terrestrial (SEV) sites.

SECTION 3. EDUCATION AND OUTREACH

The VCR LTER program has a high impact on the local community, one of the poorest counties in the state; this was noted by the midterm site-review team. Our SLTER activities have been centered at the high school level; the majority of these students have had little exposure to coastal issues. *More than half of these students are from traditionally under-represented groups, and through LTER-related classes, every one of the 200 students is exposed to LTER science at least twice during their high-school career.* With VCR VI, we plan to extend our activities to the primary schools and expand our interactions with the local high school. As our outreach plan details below, we address site-level and network-level needs, as well as communication to a larger audience through our partnerships and collaborations.

Primary/Secondary Outreach/Education – Our SLTER program contributes significantly to the public high school science education budget. Resources are used to support 5 of the 6 science courses offered (Earth Science, Chemistry, Physics, Environmental Science, Marine Biology), involving approximately 200 students each year. During VCR V, we provided water quality monitoring equipment, a digital weather station, GPS units, and computers loaded with GIS software. In 2007, we initiated our Research Experience for High School Students (REHS) program which partners 4 local high school students with VCR graduate students to conduct field based research projects each summer. All of the 16 students who have participated in this program have been accepted to colleges or universities, 6 have matriculated to UVA, and one is currently working as a lab assistant for Lead PI McGlathery. During VCR VI we will continue these activities, and build new partnerships with local elementary schools through the initiation of an Oyster Gardening program and development of Schoolyard field guides.

Teacher Outreach/Education – The VCR-SLTER program provides professional development and training programs for all public school science teachers in Northampton County. These training programs are open to educators from across the state and consistently involve 20-25 additional educators each year. Activities range from formal graduate-level classes ("Environmental Science on the Eastern Shore of Virginia") led by UVA faculty, to field-based experiential training workshops conducted with our partner Chesapeake Experience (www.chesapeakeexperience.org), a 501C3 organization. As part of VCR VI, we are developing a program for public school art teachers that will couple instruction in painting with lessons on marsh ecology and local environmental issues.

Undergraduate and Graduate Outreach/Education – In VCR VI, we will continue to support 2-4 REU students each year for 10-weeks of summer field-based research. We have a formal peer-mentoring program where we partner undergraduate researchers with graduate students and faculty supervisors. Many of these students continue to work on LTER research through the academic year and complete theses, and many have been successful in obtaining their own research funding. In addition, the new VCR laboratory hosts academic class field trips from 5 universities (~150 students annually). Graduate students hold a peer-mentoring workshop during our annual ASM that helps build collaborations.

Network-Level and Synergistic Activities – Our site director and education coordinator will continue his role as a member of the LTER Education Executive Committee and co-chair of the Higher Education Working Group in VCR VI. The four Atlantic coastal sites (PIE, VCR, GCE, FCE) will collaborate to teach a cross-disciplinary graduate course during years 3 and 6 of our proposal cycles. The course will be taught by video-conferencing and will be offered to students at each of our participating institutions. It will feature readings and lectures from PIs at the 4 sites and will provide experience in accessing and analyzing LTER data. The goal will be to expose graduate students to the breadth of coastal research, and to provide tools that will allow them to function comfortably in a highly interdisciplinary research environment. In addition, we co-hosted an artist-in-residence program with the UVA Kluge-Ruhe Aboriginal Art Collections, and ran a workshop with participants from the Departments of English, Art, Music, Landscape Architecture, and Biology to plan a place-based art/humanities – science collaboration program at UVA's 3 field stations. To build on these successes, during VCR VI we will initiate an "Artist and Writer in Residency Program" at the VCR and have plans for cross-disciplinary classes in Nature Photography and Biological Illustration that will include students from Environmental Sciences and the Art Department at UVA.

Public Outreach/Education – We will continue to build on our strong partnership with TNC, the Barrier Islands Center Museum and other local agencies to disseminate our findings to stakeholders. Ongoing outreach activities include: 1) a monthly science seminar series; 2) membership in the Eastern Shore Climate Adaptation Working group, a partnership between TNC, local, regional and federal agencies; 3) and a regional committee formed to examine current zoning regulations and the potential economic and ecological impacts of developing commercial poultry production.

For VCR VI, we are developing new outreach programs that involve stakeholders in decision making in the context of future scenarios. The first is a 2-week, graduate-level course for public school science teachers, regional planning officers, and elected officials entitled "Watershed Conservation and Sustainability" to be co-instructed by VCR LTER PIs and built around the Chesapeake Bay Game, a multi-player simulation modeling game developed at UVA (http://www.virginia.edu/baygame/). The Bay Game allows participants to take on the roles of stakeholders, resource managers, farmers, and watermen. The decisions and choices players make result in data-driven simulations of water quality, benthic productivity and fisheries yields, and provide feedback on management and sustainable use decisions. The second new program is to calibrate a Nitrogen Footprint calculator developed by PI Galloway for the Eastern Shore of Virginia (http://n-print.org/). Once calibrated to regional conditions, this calculator will be a powerful tool providing information on the impacts that land and resource use have on N loading to the coastal bays. Finally, we work with UVA's Institute for Environmental Negotiation on "listening sessions" to assess local citizen responses to climate change issues (http://ien.arch.virginia.edu/projects-current/virginia-sea-level-rise). The LTER initiatives have received enthusiastic support from the UVA Vice President for Research as they dovetail well with a new sustainability initiative at UVA.

SECTION 4. RESPONSE TO MID-TERM EVALUATION

The mid-term review was uniformly positive and supportive of the direction the VCR is taking across all 5 of the LTER (and NSF) review criteria. In the review team's words: "Strengths of the program include new and interesting ideas on thresholds and multiple stable states in the barrier islands-lagoon-mainland landscape/seascape, strong leadership and staff, effective partnerships with conservation organizations and various academic institutions, a variety of education and outreach activities, and innovative use of technology for data collection and sharing." We have embraced the recommendation of the review team to focus the VCR VI proposal on quantifying the features and fluxes of the VCR into a comprehensive theory of coastal barrier landscape/seascape systems.

The review team found our approach to addressing ecosystem state change and its consequences – by considering how the relative position of the land, sea, and groundwater surfaces and ecological feedbacks lead to non-linear dynamics and the emergence of alternative stable states – to be exciting and cutting edge. We have developed these ideas in the proposal by further quantifying the physical dynamics, biotic feedbacks, and thresholds that can lead to alternative ecosystem states across the marine and terrestrial landscape, addressing how fluxes between adjacent habitats influence bistable dynamics, exploring possible leading indicators of state change, and using quantitative models to assess future scenarios of climate and land-use change. The review team also made specific suggestions that we have also incorporated into the proposal:

1) The models are taking a central role in planning the research; they are used to guide data collection, and observations and experiments are used to test and modify the models. This is an iterative process. We have had two model-data workshops as suggested by the site review team to focus discussion and integrate modeling efforts and goals, and we will continue this on an annual basis.

2) We have the LiDAR data in hand and are using these to test our ideas at the landscape scale on the importance of elevation on ecosystem states, and the vulnerability of islands to disturbance by storm overwash. We liked the review team's idea to use repeated LiDAR data to test our ideas of island vulnerability to overwash and have incorporated this into our research plan as a long-term 'experiment'.

3) In addition to the 'super-experiment' of creating large-scale seagrass state change, we have designed 5 other ecosystem-level experiments that: a) address how oyster reefs that once lined the mainland marshes influence marsh erosion and bistable dynamics at the marsh-tidal flat interface; b) address ecogeomorphic feedbacks of vegetation that influence island elevation; c) determine the elevation threshold that triggers state change from *S. alterniflora* marsh to tidal flat; d) address thresholds for forest regeneration, and e) benefits of planting salt-tolerant crops at the mainland upland-marsh transition.

4) We have done the retrospective analysis recommended by the review team, and this appears as both our refined conceptual model (Fig. 1), and a description of the major findings of VCR LTER science that have led to the progression of theory of state change in coastal barrier systems (see Prior Results).

5) The site review team liked the integration of natural resource economics into our research, and encouraged us to retain this function. We have done this by incorporating feedbacks of public valuation of ecosystem services on decisions related to stewardship and sustainability into our development of future scenarios. This also builds on our long-term partnership with TNC and other regional stakeholders.

6) We have redesigned our web page to make it easier to access information and data.

With this next phase of VCR LTER research, we will be in a position to provide a unified picture of alternative (bistable) state dynamics across the coastal barrier landscape. The research proposed will further our understanding of the mechanisms of state transitions and threshold dynamics, and how the coupling between adjacent ecosystems influences the emergence of alternative states for all the major ecosystem transitions on the landscape. This will greatly enhance our ability to quantify non-linear dynamics in coastal barrier systems and anticipate the consequences for ecosystem services in response to future scenarios of environmental change.

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SUPPLEMENTAL DOCUMENT 1. SITE MANAGEMENT

Governance and Administration – The governance and administration of the VCR LTER is hierarchical, with a Lead PI, Executive Committee, Research Oversight Committee, and Committee-of-the-Whole (Fig. 1). Overall direction of the program is provided by the Lead PI K. McGlathery. She has been involved in the VCR LTER program for 16 years, and took over as Lead PI in summer 2004. McGlathery is the corresponding PI for interactions with NSF, the LTER Network Office and LTER Science Council, and regional partners. The Executive Committee, consisting of the Lead PI and 3 other signatory PIs have the primary decision-making responsibilities for the project, with the Lead PI having the final say on issues. The Lead PI is responsible for project communication, including timely annual reports to the NSF, facilitating annual scientific meetings, inter-site and international activities, and long-term research planning sessions. The 3 signatory PIs include P. Wiberg, J. Porter, and M. Reidenbach. Wiberg is a physical oceanographer specializing in sediment transport processes and has been involved in the LTER program for over 15 years. Porter is full-time on the VCR LTER program as the Information Manager and formerly served as Lead PI (1998-2000); he has been involved in the program since its inception. Reidenbach is a physical hydrologist whose work focuses on the interaction between hydrodynamics and benthic organisms; he has been involved with the VCR LTER program for 5 years and is expected to take over the leadership of the VCR LTER at the end of the next funding cycle (see below). The Research Oversight Committee consists of the Executive Committee and PIs who serve as group leaders for specific research areas (Table 1). This committee works together with the Lead PI and Executive Committee to coordinate efforts to plan research activities, prepare annual reports and renewal proposals. All PIs, Senior Scientists, students and staff participate in "Committee-of-the-Whole" discussions on the research agenda and outreach.

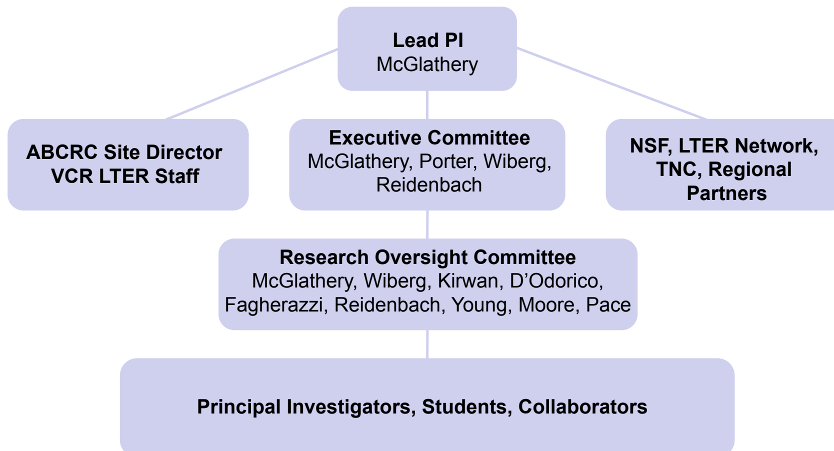

Fig. 1. Organizational structure of the VCR LTER program. The Executive Committee has primary decision-making responsibilities, with the Lead PI having the final say on all issues. The Research Oversight Committee works with the Lead PI and Executive Committee to coordinate and plan research activities, prepare annual reports and renewal proposals. The Lead PI is the liaison to agencies and partners, and supervises the Site Director and Research Staff.

Table 1. Group leaders for key research areas who serve on the VCR Research Oversight Committee

Research Area	Group Leader(s)
Marshes	Kirwan
Watersheds/Coastal bays	McGlathery
Islands	Young
Geomorphology	Moore
Hydrodynamics	Wiberg, Reidenbach
Bistability modeling	D'Odorico, Fagherazzi
Subsidies	Pace

The VCR LTER research staff is based at the field site, at the newAnheuser Busch Coastal Research Center (ABCRC) in Oyster, VA. A Ph.D.-level site manager (A. Schwarzschild), 3 full-time research staff (2 at M.S level), and a part-time fiscal technician support research activities and project management at the site. Schwarzschild has the day-to-day responsibility of coordinating the staff activities; all report to the Lead PI who has final say on research priorities.

Continuity, New Investigators, and Succession Planning – Some veteran PIs have retired or have moved to a less-active Senior Scientist status, and we deeply regret the loss of our long-time PI and friend, Mark Brinson, due to an untimely death in 2011. In VCR V we added several new PIs to the program based on perceived research needs related to these PI changes and to the evolution of the program. *Sergio Fagharazzi* (Boston University) is a modeler of coastal bay hydrodynamics and geomorphodynamics of the marsh-lagoon interface. *Paolo D'Odorico* (UVA) is a hydrologist with special interests in stochastic modeling of alternative stable state dynamics. *Matthew Kirwan* is a coastal geomorphologist who focuses on landscape responses to climate change, emphasizing interactions between vegetation, sediment transport, and carbon cycling. *Laura Moore* (UNC) is a coastal geomorphologist who specializes in morphodynamics of barrier islands. *Matthew Reidenbach* (UVA) is a physical hydrologist who studies fine-scale flow, and sediment and nutrient transport in benthic systems, including seagrasses and oyster reefs. *Michael Pace* (UVA) is an aquatic ecosystem ecologist who focuses on trophic dynamics. *Peter Berg* (UVA) specializes in modeling biogeochemical processes and brings the novel eddy correlation technique for measuring benthic metabolism to the VCR. *Todd Scanlon* (UVA) is a catchment hydrologist who specializes in land-atmosphere interactions. And *Charles Bachmann* is a hyperspectral remote-sensing expert who works at the Remote Sensing Division of the Naval Research Laboratory. All have active research programs and most advise graduate students at the VCR. In addition, using NSF supplemental funds, we have developed collaborations with two other researchers. *Stephen Swallow* is a natural resource economist (UConn) whose research addresses the link between the public valuation of ecosystem services and decision-making, and *Michael Fenster* is a coastal geomorphologist at Randolph Macon College and has been funded through several ROA supplements.

We are planning ahead for a change in site leadership during the next funding cycle. The VCR program benefitted greatly from the planned site leadership change between Hayden and McGlathery, and we will use the same model for the future. We have identified the PI (Reidenbach) who will likely serve as the next lead PI, and he has been included as a signatory PI on this renewal proposal. As a signatory PI, he will take on progressively more responsibilities of program management so that during the next funding cycle (VCR VII) he can ultimately assume the leadership role.

The VCR LTER and the University of Virginia are committed to involving a diversity of scientists in our program. Currently, 30% of our PIs (and Senior Scientists), including the Lead PI and one of the 3 other signatory PIs, are women or from other traditionally underrepresented groups. As retirements open up new faculty positions in the Department of Environmental Sciences at UVA in coastal sciences, we will work with our Office of Equal Opportunity Programs (EOP) to identify advertising opportunities that will reach women, racial minorities, veterans and persons with disabilities. We will also network with colleagues at peer institutions for leads on qualified applicants from these traditionally underrepresented groups. We work with the EOP in advertising for staff positions at the VCR LTER.

Communication and Integration of non-LTER Scientists - During the academic year, the Executive Committee meets at least monthly to deal with research planning, general administrative issues, advice and consent regarding policies and procedures, and to respond to NSF initiatives and Network and inter-site activities. McGlathery meets weekly with the VCR site manager and the research/fiscal staff at the VCR ABCRC lab on the eastern shore via videoconference to review and plan research activities.

The Internet is used widely within the project to coordinate activities and to exchange information. A web calendar is used to log all research activities and to coordinate needs for boats, laboratory space and housing. An email forwarding system (linked to the personnel database) facilitates inter-investigator communication. WWW forms are used extensively to facilitate submission and retrieval of datasets, bibliographic entries, project reports and plans. We routinely have videoconference meetings of VCR investigators from multiple sites.

We have an annual "All Scientists" meeting (ASM) for VCR researchers, which we now hold at the VCR site. In addition to VCR LTER PIs, students, and staff, we invite our collaborators from The Nature Conservancy and other affiliated institutions. At the meeting, PIs, collaborators and students give formal presentations (talks or posters) of research findings, and we have smaller group workshops to address specific research issues and plan upcoming research activities. This meeting is an important venue to engage non-LTER funded scientists in discussing and planning collaborative research activities.

Typically more than 60 researchers and practitioners attend the annual ASM. Each year we will invite a colleague to attend the ASM who is not an LTER collaborator to provide an outside perspective on our research goals and progress. The annual meetings of the Lead (or representative) PIs of 4 Atlantic Coast sites (PIE, VCR, GCE, FCE) will rotate among the sites, and will be held conjuction with the site ASM.

In addition, smaller groups of PIs and collaborators meet informally throughout the year to work on collaborative research projects. We have established several key collaborations with regional non-LTER investigators whose work complements and leverages LTER science. We have partnered with *R. Orth*, from the Virginia Institute of Marine Sciences (VIMS), over the last 10 years in the seagrass state change work. His expertise in restoration by seeding has been instrumental to the success of the program, and we continue to work with him on new restoration efforts and on following the expansion of restored meadows in the VCR coastal bays. We also collaborate with *M. Luckenbach*, the director of the nearby VIMS Wachapreague field station. His expertise is in fisheries and aquaculture, and our collaboration is important to understanding the trophic consequences of state change in the coastal bays. Luckenbach is spearheading a scallop restoration program in the restored seagrass meadows; returning the scallop fishery back to this region would be a remarkable achievement. We are collaborating with *R. Zimmerman* at Old Dominion University who has NSF funding to address the effects of ocean acidification on seagrass. His results will be incorporated into our models of seagrass resilence to future scenarios of climate change. Through these collaborations we can broaden the scope of the research in the VCR without having to support all research through LTER funds. We are also reaching out to new collaborators who may be recruited as new PIs on the project, including *S. Karpantry* (Virginia Tech) who is looking at the effects of storms and island overwash on migratory birds, and *R. Fulweiler* (Boston University) who is interested in working on nitrogen and sulfur biogeochemistry in coastal marshes. We have partnered with TNC to obtain LiDAR for the VCR, and are collaborating with *J. Anderson* of the U.S. Army Corp of Engineers on the use of the LiDAR data to quantify vegetation structure on the barrier islands.

Fig. 2. Participants in the 2011 VCR All Scientists Meeting in Oyster, VA.

Budgeting and Accountability – UVA PIs are supported primarily through graduate student funding, including stipend, tuition, health, and also travel to the field site of the PI and student, and research supplies. For UVA graduate students, the VCR LTER matches the Department of Environmental Sciences contribution to cover the expenses of attending a research conference to present their work. UVA PIs request student support from the Lead PI, and funds are allocated based on need and research priorities. A small number of undergraduates are also supported during the academic year to work in individual investigator's labs. Subcontracting PIs are allocated funds based on their participation in core research activities. At the time of the 3-year review, allocation of funds to subcontracting PIs will be evaluated, and adjustments will be made if needed, depending on research productivity and priorities for the 2nd half of the grant cycle. All PIs and their graduate students are required to submit annual reports documenting research activities, findings, publications, and datasets. All funding decisions are made by the Lead PI, in consultation with the Executive Committee. The LTER core grant covers the lab, housing and boat expenses of all PIs and Senior Scientists.

New Field Station - The VCR LTER program had a new home as of August 2006 at the University of Virginia's Anheuser Busch Coastal Research Center in Oyster, Virginia. The Center is located on 42 acres on Oyster Harbor, with boat access to the coastal ecosystems of the VCR. The new facility has greatly enhanced our work. In the year following the opening of the ABCRC, the number of user nights at the field site nearly doubled and has stayed at that high level to the present.

SUPPLEMENTAL DOCUMENT 2. DATA MANAGEMENT PLAN

The Information Management activities at the Virginia Coast Reserve Long-Term Ecological Research (VCR/LTER) Project have as their goal **to promote advances in ecological science by providing the information resources needed by VCR/LTER researchers and through making those resources available to the rest of the ecological research community.** To this end the VCR/LTER Information Management Policy is conformant to the LTER-wide Data Access Policy, requiring that, except when specifically justified (e.g., Type II data), data is made publically available within two years of collection or creation.

Principles: Five principles underlie the VCR/LTER Information Management System. These principles motivate how the system has, and will be, developed.

- **Data and the scientists who collect them are inextricably linked.** Thus we try to develop systems that facilitate interaction of scientists with their data, including interactive web forms for metadata entry and editing, thus allowing each researcher to instantly correct errors in the metadata. We provide tools to help researchers enter data and perform quality assurance analyses.
- **Data resources are needed at a wide array of locations and the information required by researchers takes many forms.** The VCR/LTER research community is widely distributed at numerous institutions. We therefore focus on developing and using web and network-based resources that are accessible to each of them and, similarly, to the larger research community.

  We take a broad view of what constitutes "data" that goes well beyond columns of numbers to include video, images, documents, bibliographic and personnel information. We try to populate our web site with everything a researcher might need to know about our site.
- **Automating routine tasks helps improve both productivity and data quality.** We make extensive use of wireless networks in our remote study sites to automatically stream data into workflows that perform quality control and assurance activities, produce graphical products for the web and update datasets for download. For our long-term manually collected data we have developed specialized data input tools and associated workflows.
- **Some data are particularly valuable.** Extra resources are devoted towards data that are considered most important. VCR/LTER data that are long term, are spatially extensive, of wide use, costly to obtain or identified as important by investigators receive special attention, including development of specialized workflows and tools.
- **Many hands make light work**. We are eager participants in many LTER Network-wide initiatives aimed at developing standards, tools, web services, and protocols that benefit both the VCR/LTER and the LTER network as a whole. We make extensive use of the LTER Data Access Server for providing our data, allowing a single login to work across datasets from multiple LTER sites. We recently pooled supplement funds with other LTER sites to help connect the Drupal Content Management system with Ecological Metadata Language and are active participants in many of the LTER Information Management (IM) working groups (e.g., Controlled Vocabulary, Web services and GIS).

Deliverables: We believe information management is not an add-on to the scientific enterprise, but rather an integral part of it. Many of the major discoveries of tomorrow will be inextricably linked to the information resources being developed today. To promote this viewpoint we have been active in publishing papers on information management in a wide variety of venues including 9 in peer-reviewed journals (5 domestic, 4 international), 6 in peer-reviewed proceedings and over a dozen in newsletters (e.g., Databits, LTER Network News) since 2006.

As deliverables, the VCR/LTER provides 120+ GB of data in nearly 160 separate datasets, 34 of which have a duration ≥ 15 years. Through the use of Ecological Metadata Language (EML) 2.1 (level 5) metadata, our data can be discovered using the LTER Data Portal and other associated cataloging systems, as well as the VCR/LTER Data Catalog. Not surprisingly most of the data use since 2006 has been by researchers associated with the VCR/LTER, although outside users account for 44% of the dataset use where the source can be ascribed (Table 1). 90% of educational uses (e.g., data downloaded for use in class projects) are external to the VCR/LTER.

Table 1: Formal downloads of VCR/LTER datasets from November 2006 through February 2012. The LTER Data Access Server (DAS) does not always provide sufficient information to allow determination of requestor status or proposed use and these are labeled "Unknown". Not included are informal downloads of online tables, graphs etc. which were not tallied.

	Research	**Education**	**Unknown**	**Total**
VCR/LTER Associated	399	21		420
Non-VCR/LTER	136	192		328
Unknown (DAS)			608	608
Total	535	213	608	**1356**

Proposed Information Management Systems and Metadata Standards: We plan to build on our existing Information Management Systems and use Ecological Metadata Language (EML) metadata to fully comply with LTER Network goals for data accessibility. Since 2004 we have provided full attribute-level (level 5) EML metadata for each of our online datasets. Metadata is automatically updated from our metadata database several times each day. All EML metadata was updated in 2010 to version 2.10. Our web site and information management practices fully conform with the "Review Criteria for LTER Information Management Systems V1.1" (2009) and meet almost all of the recently introduced "EML Best Practices for LTER Sites Version 2" (2011). As discussed below we are actively engaged in improving the taxonomic and unit elements of our EML metadata to be in full compliance with the new EML Best Practices.

During the 2006-2011 funding cycle, in addition to adding new datasets and updating long-term datasets, we have made a number of improvements to the system. These included: 1) moving the web and database services from an aging Sun Unix computer to virtual Linux machines, 2) a transition of our web page to use the Drupal Content Management System and an accompanying redesign of the VCR/LTER web structure (Fig. 1), 3) upgrade of EML to version 2.1, 4) transition to use of LTER-standard keywords and improvement of metadata editors to provide drop-down lists and automatically suggest LTER-standard keywords, 5) testing of all tabular datasets to assure that data types and ranges correspond to the metadata, and 6) expanding our field wireless network to add a network of ground-water wells and development of workflows to support them.

Milestones: During the proposed funding cycle we plan to build on the existing system (Table 2) by adding additional datasets and continuing to improve the quality of our data and metadata. Specific milestones include: 1) develop workflows for doing more sophisticated error checking on datasets (Fig. 2), 2) implement new web-service-based tools for improving the taxonomic and units elements of our EML metadata, 3) move completely to use of the LTER Data Access Server for the delivery of datasets to improve accessibility for the LTER Network Office's PASTA system, and 4) continue improvement of interfaces to make them more "researcher friendly" through improvement of data browse capabilities. Additionally, we are particularly eager to cooperate with other LTER sites in the development of "value-added" datasets, data products and workflows using the PASTA framework. A list of past milestones is included at the end of "An Introduction to VCR/LTER Information Management Systems."

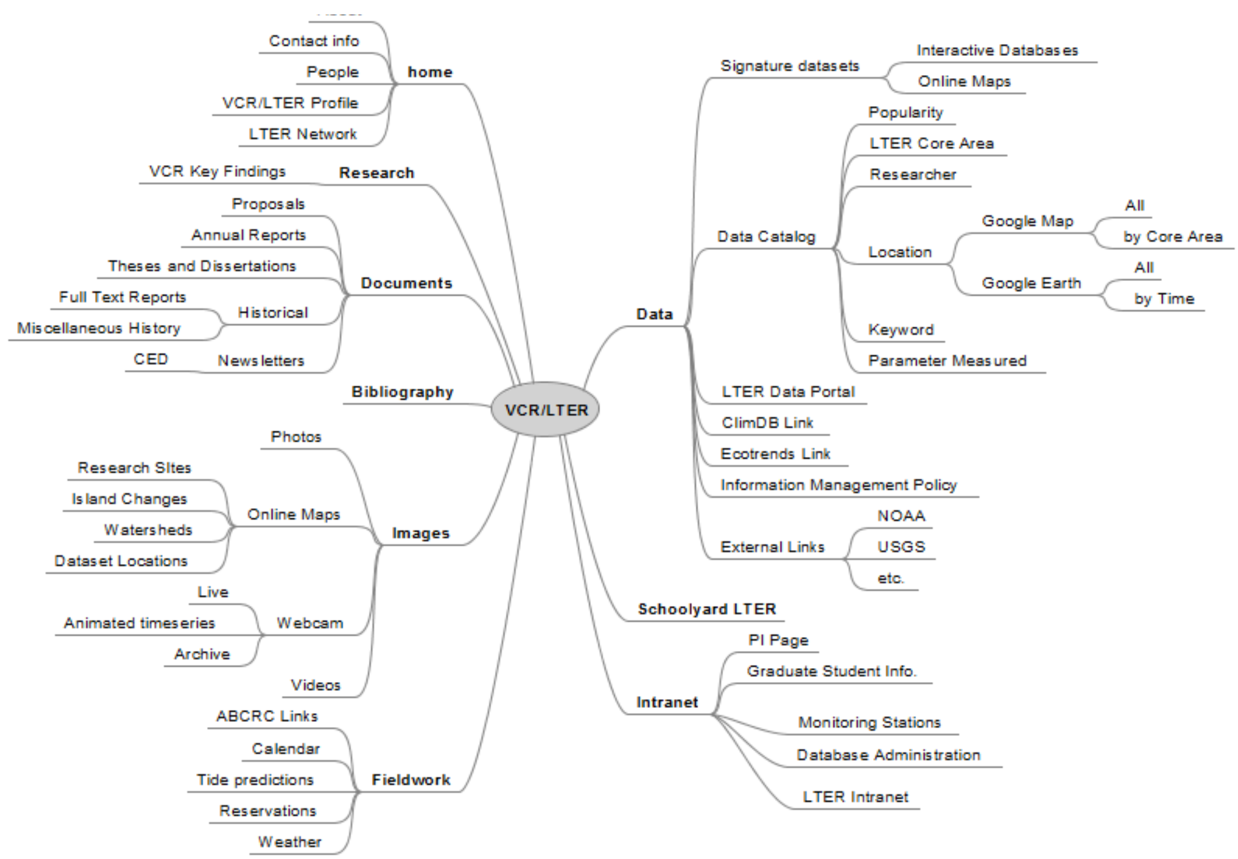

Fig. 1. Map of the VCR/LTER Web Site showing the rich array of information resources it provides. The Data Catalog provides a number of ways for browsing for datasets, including Google Earth.

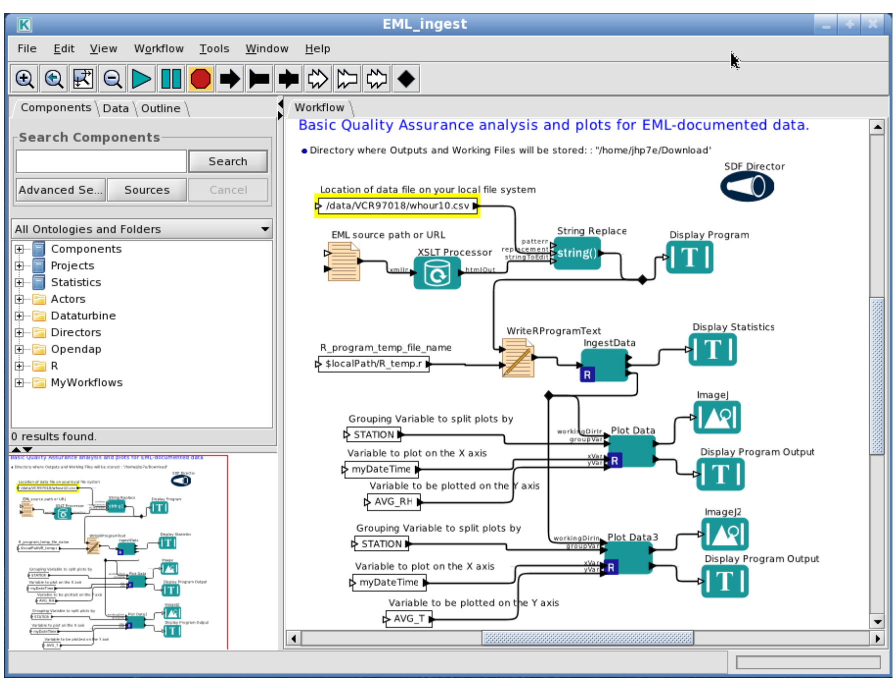

Fig. 2. Sample Kepler workflow for performing quality assurance analysis on EML-documented data.

Table 2: The software and hardware used by the VCR/LTER Information Management System. For more details see: http://www.vcrlter.virginia.edu/elecvol/ecoinformatics/VCR_IM_Description_12.pdf

Software	Primarily Linux-Apache-MySQL-PHP (LAMP), PERL, R, SAS, SPSS, ArcGIS, MapServer , VMWare for servers and PC and Mac for desktop analyses
Databases	MySQL (web page, EML generation), mSQL (web metadata editor) and Access (specialized data input applications)
Web	Drupal Content Management System running under an Apache Web Server
Hardware	Fedora and Ubuntu Linux virtual servers running on two physical servers with an aggregate of 8.5 TB of disk and 18 GB of RAM. Each virtual machine serves a specialized function (e.g., database, web server, web mapping, etc.)
Backups	Daily, weekly and monthly Linux dumps to network appliances in a different building. Servers are physically separated in different buildings to allow some large files to be mirrored between servers. Separate USB disks are used to provide periodic off-grounds backups. The Lead PI of the VCR/LTER has a copy of all critical passwords and a periodically-updated system description in the event the Information Manager becomes incapacitated.
Metadata	EML 2.10 level 5 metadata is generated by a PERL script operating on mSQL and MySQL databases. Editing uses a web-based form system using mSQL/EMBER, with data mirrored to MySQL.
Data	To maximize archival capabilities datasets are maintained as files, typically text files, although some specialized files (e.g., models in spreadsheets, GIS data) are stored in binary formats.

Data Management and the Design of Research Projects: To better integrate information management into the full research enterprise, the VCR/LTER employs a Ph.D-level Information Manager with extensive experience in experimental design, statistics and geographical information systems. As needed undergraduate and graduate research assistants are used to work on particular datasets and tasks under his supervision. The information management staff are available to all VCR/LTER investigators, staff and students for consultation and are frequently consulted regarding experimental design, data handling and analytical procedures and preparation of data for archival storage.

To assure that researchers contribute their data to the VCR/LTER databases, the site executive committee periodically meets to review progress on submission of data and contacts investigators regarding data. Per the Information Management Policy contribution of data is expected of all VCR/LTER investigators and failure to do so may constitute grounds for disassociating the investigator from the project. Specific responsibilities are also spelled out in the VCR LTER Information Management Plan. We have also increasingly moved, where possible, to the use of automated sensors that use our wireless network to automatically transfer data for ingestion and posting on the web in near real time (Fig. 3). Graduate student data constitute a special challenge because, especially for short-term experiments aimed at understanding specific processes, the data may not be of sufficient duration or apparent value (beyond the specific use) to justify major efforts at preparation of the data for archival storage in a formal dataset. We therefore strongly encourage graduate students to include "data appendices" in their theses and dissertations . Thus the thesis includes both the metadata and data in a human-readable form. In the cases where data collection will continue beyond a single graduate student, or the data are of sufficient quality and importance to justify it, a formal dataset with appropriate workflows are developed.

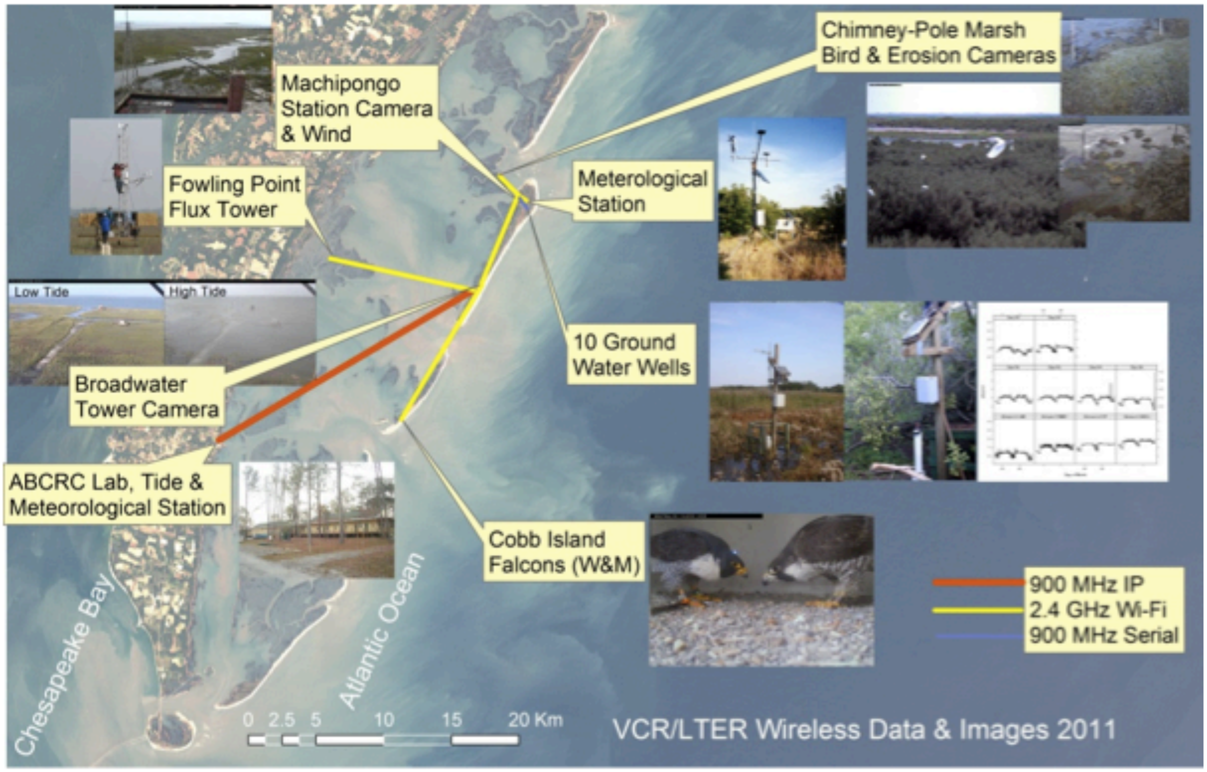

Fig. 3. The VCR/LTER Wireless Network extends from the ABCRC laboratory to our main island research areas and connects a wide variety of instrumentation, including data loggers and cameras. Workflows are used to automate processing of data to provide near real-time online access.

Activities in the LTER Network and Beyond: We have been, and plan to be during the proposed research, very active in the LTER Network. The VCR/LTER Information Manager currently serves as the co-chair of the LTER Network Information System Advisory Committee (NISAC), chair of the Controlled Vocabulary Working Group (which recently created a polytaxonomy of LTER keywords that is now used to augment searches at the LTER Network Data Portal), and is an active member of several other working groups (Web Services, GIS, IM Curriculum Development). He has also been active in helping to teach information management best practices, including two for-credit courses at UVA and co-teaching of a Summer Institute at the University of New Mexico. We have also been actively engaged with International LTER partners, particularly in the East-Asia-Pacific region. Activities have included training workshops and science workshops that focus advanced information management technologies on scientific research problems. Outside of LTER, the VCR/LTER Information Manager is the past chair of the Global Change Master Directory User Working Group and the Oak Ridge National Laboratory Distributed Active Archive Center User Working Group.

SUPPLEMENTAL DOCUMENT 3. VCR LTER DATA SETS

All datasets are available via the VCR/LTER data catalog and the LTER Network Data Catalog. Datasets are ordered by number of uses so many of the newer datasets (that have had fewer opportunities to be used) are near the bottom. The LTER core area for each data set is identified as follows: PP – patterns and controls of primary prouction; PTD – population and trophic dynamics; OM – patterns and controls of organic matter accumulation; IN – inorganic nutrient inputs and fluxes; and DIS – pattern and frequency of disturbance.

1. VCR97018: **Hourly Meteorological Data for the Virginia Coast Reserve LTER**
   Author(s): John H. Porter, David O. Krovetz, William K. Nuttle, James Spitler, Core Areas: DIS Uses: 289

2. VCR99062: **Long Term Mammal Data from Powdermill Biological Station**
   Author(s): Joseph F. Merritt, Core Areas: PTD Uses: 67

3. VCR97038: **Hog Island Small-Mammal Trapping**
   Author(s): John H. Porter, Raymond D. Dueser, Core Areas: PTD Uses: 67

4. BPH8801A: **LTER hurricane record for the Virginia Coast Reserve.**
   Author(s): Bruce P. Hayden, Core Areas: DIS Uses: 64

5. RDD6B7501A: **Survey of island small mammals - trapping data. 1975-1977**
   Author(s): Raymond D. Dueser , Susan A. McCuskey, Gregory S. Hogue, John H Porter , Core Areas: PTD Uses: 62

6. VCR03095: **Georeferencing organic matter measurements on the VCR/LTER 1998**
   Author(s): Heather Kerkering, Core Areas: OM Uses: 53

7. ALM7D8802A: **Temporal and spatial distribution of microbial biomass, growth and activity. 1988-90.**
   Author(s): Aaron L. Mills, Core Areas: PTD IN OM Uses: 50

8. VCR00073: **Water Quality of Virginia Coastal Bays - physical data**
   Author(s): Robert R. Christian, Karen J. McGlathery, Linda K. Blum, Debbie A. Daniel, Margot T. Miller, James Spitler , Kathleen M Overman, Core Areas: IN Uses: 49

9. VCR01076: **Terrestrial-Marine Watershed Boundaries on the Delmarva Peninsula of Virginia**
   Author(s): Bruce P. Hayden, John H Porter, Core Areas: IN Uses: 48

10. BPH8801B: **Long-term precipitation for the Virginia Coast Reserve 1837-2007.**
    Author(s): Bruce P. Hayden, Core Areas: DIS Uses: 45

11. VCR05131: **Bathymetry of Hog Island Bay**
    Author(s): George F. Oertel, Charles Carlson, Kathleen M. Overman, Core Areas: IN Uses: 30

12. VCR99057: **Water Quality of Virginia Coastal Bays - Nutrients**
    Author(s): Robert R. Christian, Karen J. McGlathery, Core Areas: IN Uses: 39

13. LKB2E8802A: **Spartina alterniflora decomposition in marsh sediments.**
Author(s): Linda K. Blum, Core Areas: PP OM Uses: 36

14. VCR00075: **Land Cover for VCR/LTER Watersheds 1988**
Author(s): John H. Porter, Bruce P. Hayden, Core Areas: IN Uses: 36

15. VCR99056: **Ground Water Level on a Parramore Pimple**
Author(s): John H. Porter, Bruce P. Hayden, Core Areas: DIS Uses: 36

16. VCR06135: **Keywords and Terms from the LTER Network**
Author(s): John H. Porter, Duane Costa, Uses: 33

17. VCR05130: **Ground Water Level at Brownsville and Hog Island, VA**
Author(s): Mark M. Brinson, Core Areas: DIS Uses: 33

18. WO8802A: **Spartina alterniflora leaf measurements, part A. Virginia Coast Reserve 1988-1989**
Author(s): William T. Odum, Jonathan P. Frye, Core Areas: PP Uses: 33

19. VCR97053: **Tide Data for Hog Island (1991-), Redbank (1992-), Oyster (2007-). 12 minute interval**
Author(s): John H. Porter, David O. Krovetz, James Spitler, William Nuttle, Thomas Williams, Kathleen M. Overman, Core Areas: DIS Uses: 32

20. VCR01077: **Phragmites distribution in 1996 on the Eastern Shore of Virginia**
Author(s): Dieu Ngu, John D. Albertson, Linda K. Blum, Barry Truitt, Core Areas: PP Uses: 32

21. VCR99066: **Groundwater well data on Hog Island, Virginia Coastal Barrier Islands**
Author(s): Frank P. Day, Core Areas: DIS Uses: 30

22. LML7O9001A: **A study of water quality conditions in the tidal creeks of Northampton County, VA**
Author(s): Luis M. Lagera, Core Areas: IN, PP Uses: 29

23. VCR09159: **End of Year Biomass in Marshes of the Virginia Coast Reserve**
Author(s): Robert R. Christian, Core Areas: PP Uses: 26

24. VCR04109: **1992-93 Parramore Permanent Plot Baseline Data : Plot Coordinates**
Author(s): David L Richardson , John H Porter , Hank H. Shugart, Core Areas: PP Uses: 25

25. LML7O9001C: **A study of water quality conditions in the tidal creeks of Northampton County, VA**
Author(s): Luis M. Lagera, Core Areas: IN OM Uses: 25

26. GFO9107A: **Trend surface analysis of the 300 YBP stratigraphic horizon and the Holocene/Ples**
Author(s): George F. Oertel , Core Areas: Uses: 25

27. VCR03105: **Hog Island Bay Nutrient Data 2001-2002**
Author(s): Iris Anderson , Amber K. Kozak, Karen J. McGlathery , Core Areas: IN OM Uses: 25

28. JCZ8801B: **Element and biomass partitioning on the VCR landscape, part B. 1988-1989**
Author(s): David T. Osgood, Joseph C. Zieman, Core Areas: PP IN OM Uses: 24

29. VCR97026: **Distribution of barrier island overwash disturbance**
Author(s): Lenore B. Fahrig, Bruce P. Hayden, Robert Dolan, Core Areas: DIS Uses: 24

30. RAB9001A: **Hog and Cobb Island nesting seabird study, part A. 1990**
Author(s): Ruth A. Beck, Core Areas: PTD Uses: 24

31. VCR97006: **Brownsville and Hog Island Surficial Well Data**
Author(s): Mark M. Brinson, Laura Stasavich, Core Areas: DIS Uses: 24

32. VCR97048: **Hog Island Soil Nutrient Data 1991-1992**
Author(s): Frank P. Day, Core Areas: IN DIS Uses: 23

33. VCR97025: **Bacterial dynamics in tidal marsh creeks of the Eastern Shore of Virginia**
Author(s): Kathy . MacMillin, Katherine M. MacMillin, Core Areas: PP PTD IN OM DIS Uses: 23

34. VCR00074: **Water Quality of Virginia Coastal Bays - Total suspended solids and chlorophyll data 1992-2004**
Author(s): Linda K. Blum, Debbie A. Daniel M.S., Robert R. Christian, Core Areas: IN OM, PP Uses: 23

35. VCR97049: **Hog Island Chronosequence Soil Eh, pH and Temperature 1991-1992**
Author(s): Frank P. Day, Core Areas: IN, PP Uses: 23

36. VCR97045: **Cotton Strip Decomposition - Tensile Strength**
Author(s): Frank P. Day, Core Areas: OM DIS Uses: 22

37. VCR99064: **Dune Biomass on Hog Island, Virginia Coastal Barrier Islands**
Author(s): Frank P. Day, Core Areas: PP Uses: 22

38. VCR97044: **Rates of Mass Loss During Root Decay**
Author(s): Frank P. Day , Core Areas: OM DIS Uses: 21

39. VCR99060: **GPS Elevations of VCR/LTER Marshes**
Author(s): Cassondra R. Thomas , Charles Randolph Carlson , Core Areas: DIS Uses: 21

40. VCR05123: **1996 Parramore Permanent Plot Resurvey: LAI-Biomass data**
Author(s): David L Richardson , Core Areas: PP DIS Uses: 20

41. VCR97031: **Monte-Carlo Simulation Models of Animal Movement**
Author(s): John H Porter , James L. Dooley, Core Areas: PTD Uses: 20

42. VCR97015: **Inundation Experiment Permanent Plot Data : Biomass**
Author(s): Robert R. Christian, Linda K. Blum, Core Areas: PP DIS Uses: **20**

43. VCR03083: **Precipitation data, four sites, on eastern side of Delmarva Peninsula, 2001-**
Author(s): Jennifer Wu Stanhope, Iris Anderson, Core Areas: IN Uses: 20

44. VCR97047: **Hog Island Soil Water Nutrient Chemistry 1990-1992**
Author(s): Frank P. Day, Core Areas: IN DIS Uses: 19

45. VCR03086: **Annual Number of Storms on the Virginia Coast**
Author(s): Bruce P. Hayden, Core Areas: DIS Uses: 19

46. VCR07139: **Locations of shoreline marker signs on Northern Hog Island, Northampton Co., VA**
Author(s): John H. Porter, Core Areas: DIS Uses: 19

47. VCR09158: **Annual heron counts on Chincoteague Island, Virginia**
Author(s): R. Michael Erwin, Core Areas: PTD Uses: 19

48. VCR09162: **Biomass at Surface Elevation Table plots on the Virginia Coast Reserve**
Author(s): Robert R. Christian, Core Areas: PP OM Uses: 19

49. JCZ8801A: **Element and biomass partitioning on the VCR landscape, part A. 1988-1989**
Author(s): Joseph C. Zieman, Core Areas: IN, PP Uses: 18

50. VCR05133: **Change data layer for the Virginia Coast Reserve, 1973-2001**
Author(s): John H. Porter, Core Areas: DIS Uses: 18

51. VCR97011: **1992-93 Parramore Permanent Plot Baseline Data: Tree Data**
Author(s): David L. Richardson, John H. Porter, Johann Knutsen, Frank P. Day, Ed Faust, Core Areas: PP, DIS Uses: 18

52. VCR05114: **1996 Parramore Permanent Plot Resurvey: Tree notes**
Author(s): David L. Richardson, Core Areas: PP DIS Uses: 17

53. VCR99065: **Long-term N-fertilized vegetation plots on Hog Island, Virginia Coastal Barrier Islands**
Author(s): Frank P. Day, Core Areas: PP IN Uses: 17

54. VCR09164: **Bathymetry of Magothy Bay, Virginia**
Author(s): George F. Oertel, Core Areas: IN Uses: 17

55. VCR03099: **End of Year Biomass in Marshes of the Virginia Coast Reserve 1999 on**
Author(s): Cassondra R. Thomas, Linda K. Blum, Robert R. Christian, Core Areas: PP OM Uses: 17

56. VCR02082: **Chemical composition of precipitation at the Virginia coast**
Author(s): James N. Galloway, William C Keene, Core Areas: IN DIS Uses: 17

57. VCR03096: **Annual Myrica cerifera shoot growth on Hog Island**
Author(s): Donald R. Young, Core Areas: PP, DIS Uses: 17

58. VCR01078: **Hog Island, VA boundaries 1852-1993**
Author(s): Guofan Shao, Core Areas: DIS Uses: 16

59. VCR97037: **Shoreline and Upland/Marsh data for Hog Island 1852-2001**
Author(s): Guofan Shao, John H. Porter, Core Areas: DIS Uses: 16

60. VCR97019: **Extratropical Storms (1885-1996) by Month (USA)**
Author(s): Bruce P. Hayden, Core Areas: DIS Uses: 16

61. HHS8802A: **Plant distribution on Hog Island, VA 1989**
Author(s): Terry Cook, Core Areas: PP Uses: 16

62. VCR04107: **Small Mammal Trapping Data for Assateague Island, 1978**
Author(s): John H. Porter, Chris Rucker, Raymond D. Dueser, Core Areas: PTD Uses: 16

63. VCR97043: **Nitrogen and Phosphorus Content of Decaying Roots**
Author(s): Frank P. Day, Core Areas: IN OM Uses: 16

64. VCR05115: **1996 Parramore Permanent Plot Resurvey: Shrub data**
Author(s): David L. Richardson, Core Areas: PP DIS Uses: 16

65. VCR05120: **1996 Parramore Permanent Plot Resurvey: Calibration Saltmarsh Plot data**
Author(s): David L. Richardson, Core Areas: PP DIS Uses: 15

66. VCR09149: **Discharge of three small creeks along the Delmarva Peninsula**
Author(s): Karen J. McGlathery, Jennifer Wu Stanhope , Iris Anderson , Kathleen M. Overman , Core Areas: IN Uses: 15

67. WO8802B: **Spartina alterniflora leaf measurements, part B. Virginia Coast Reserve 1988-1989**
Author(s): William T. Odum, Jonathan P. Frye, Core Areas: PP Uses: 15

68. VCR05111: **1996 Parramore Permanent Plot Resurvey: Plot data**
Author(s): David L Richardson, Core Areas: PP DIS Uses: 15

69. VCR05118: **1996 Parramore Permanent Plot Resurvey: Subplot data**
Author(s): David L. Richardson, Core Areas: PP DIS Uses: 15

70. VCR05121: **1996 Parramore Permanent Plot Resurvey: Calibration Saltmarsh Harvest data**
Author(s): David L. Richardson, Core Areas: PP DIS Uses: 14

71. VCR05129: **Thicket Shoot Growth on Hog Island, VA**
Author(s): Donald R. Young, Core Areas: PP Uses: 14

72. VCR09161: **Biomass for the 2nd UPC Inundation Experiment**
Author(s): Robert R. Christian, Core Areas: PP Uses: 14

73. VCR09169: **Groundwater Levels on Hog Island, VA. 2007-**
Author(s): John H. Porter, Thomas Williams, Mark M. Brinson, Frank P. Day , Core Areas: DIS Uses: 14

74. VCR05113: **1996 Parramore Permanent Plot Resurvey: Tree data**
Author(s): David L. Richardson, Core Areas: PP DIS Uses: 14

75. VCR05116: **1996 Parramore Permanent Plot Resurvey: Shrub notes**
Author(s): David L. Richardson, Core Areas: PP DIS Uses: 14

76. VCR05119: **1996 Parramore Permanent Plot Resurvey: Clip plot data**
Author(s): David L. Richardson, Core Areas: PP DIS Uses: 14

77. VCR05122: **1996 Parramore Permanent Plot Resurvey: Calibration Salt marsh Stem data**
Author(s): David L. Richardson, Core Areas: PP DIS Uses: 13

78. VCR09150: **Nutrient concentrations in three small streams on the coast of the Delmarva Peninsula**
Author(s): Iris Anderson, Jennifer Wu Stanhope, Kathleen M. Overman, Core Areas: IN Uses: 13

79. VCR09163: **Biomass in marsh transition plots on the Virginia Coast Reserve**
Author(s): Robert R. Christian, Core Areas: PP Uses: 13

80. VCR09147: **Stream Water Level and Temperature for Mainland Creeks on the Atlantic Coast of Virginia**
Author(s): Iris Anderson, Karen McGlathery, Jennifer Wu Stanhope , Kathleen M. Overman , Core Areas: IN, DIS Uses: 13

81. VCR08144: **Water Quality of Virginia Coastal Bays - Total Suspended Solids, Particulate Inorganic and Organic Matter**
Author(s): Karen J. McGlathery, Robert R. Christian, Linda K. Blum, Core Areas: IN OM PP Uses: 13

82. VCR09167: **Water Quality of Virginia Coastal Bays - Chlorophyll and Phaeopigments 2005-**
Author(s): Karen J. McGlathery, Core Areas: PP IN Uses: 13

83. VCR05117: **1996 Parramore Permanent Plot Resurvey: Land cover Class Aggregation data**
Author(s): David L. Richardson, Core Areas: PP DIS Uses: 13

84. VCR05124: **2002 Parramore Permanent Plot Coordinates: UTM (NAD83/GRS80) zone 18**
Author(s): David L. Richardson, Core Areas: Uses: 12

85. VCR09166: **Biomass of benthic macroalgae in Virginia Coastal Bays**
Author(s): Karen J. McGlathery, Amber K. Hardison, Core Areas: PP Uses: 12

86. VCR03087: **Nutrient concentrations in fertilized and unfertilized dune plots on Hog Island 1990-91**
Author(s): Frank P. Day, Core Areas: PP IN Uses: 12

87. VCR08145: **VCR LTER Global Positioning System Projects 1992 to 2004**
Author(s): Charles Randolph Carlson, Core Areas: DIS Uses: 12

88. VCR03085: **Stream Discharge for Cobb Mill Creek**
Author(s): Aaron L. Mills, Core Areas: IN DIS Uses: 12

89. VCR05112: **1996 Parramore Permanent Plot Resurvey: Session data**
Author(s): David L. Richardson, Core Areas: PP DIS Uses: 12

90. VCR09160: **Biomass for the 1st UPC Inundation Experiment**
Author(s): Robert R. Christian, Core Areas: PP Uses**: 11**

91. VCR09165: **Bathymetry of Gargathy and Kegotank Bays, Virginia**
Author(s): George F. Oertel, Core Areas: IN Uses: 11

92. VCR09148: **Barometric Pressure near Nickawampus Creek, Virginia**
Author(s): Iris Anderson, Karen J. McGlathery, Jennifer Wu Stanhope, Kathleen M. Overman, Core Areas: DIS Uses: 11

93. VCR08143: **Water Quality of Virginia Coastal Bays - Total Dissolved Nitrogen**
Author(s): Karen J. McGlathery, Core Areas: IN OM PPUses: 11

94. VCR97014: **Creekbank physico-chemical data from Hog Island salt marsh chronosequence**
Author(s): A. Christy Tyler, Core Areas: PP IN Uses: 10

95. VCR99059: **A Spatially Explicit Model of Vegetation-Habitat Interactions on Barrier Beaches**
Author(s): Edward Rastetter, Core Areas: DIS Uses: 10

96. VCR97036: **Morphometry of Atlantic Barrier Islands, Lagoons and Marshes**
Author(s): Bruce P. Hayden, Core Areas: DIS Uses: 10

97. VCR06134: **Acoustic Doppler Profiler (ADP) Time Series Measurements**
Author(s): Sarah Lawson, Patricia Wiberg, Core Areas: DIS Uses: 10

98. VCR03092: **Aboveground biomass of dune vegetation on the Hog Island chronosequence**
Author(s): Frank P. Day, Core Areas: PP Uses: 9

99. VCR09170: **Integrated Water Quality Data Spreadsheets for Coastal Virginia Lagoons**
Author(s): Patricia Wiberg, Robert R. Christian, Karen J. McGlathery, Linda K. Blum, Core Areas: IN Uses: 9

100. VCR97017: **Inundation Experiment Permanent Plot Data : Macroorganic Material**
Author(s): Robert R. Christian Ph.D., Core Areas: OM DIS Uses: 9

101. VCR06137: **2003 GPS shorelines for Hog, Wreck and Metompkin Islands, Northampton Co., VA**
Core Areas: DIS Uses: 9

102. VCR98054: **Birdwood Mammal Trapping Data, Charlottesville, VA, 1974-1978**
Author(s): Raymond D. Dueser, Robert K. Rose, John H Porter, Core Areas: PTD Uses: 8

103. VCR06136: **Surface Elevation Data for the Virginia Coast Reserve**
Author(s): Linda K. Blum , Robert R. Christian, Mark M. Brinson, Patricia L. Willis , Core Areas: DIS Uses: 8

104. VCR97012: **1992-93 Parramore Permanent Plot Baseline Data: Shrub Data**
Author(s): David L. Richardson, John H. Porter, Johann Knutsen, Frank Day, Ed Faust, Core Areas: PP DIS Uses: 8

105. VCR97008: **1992-93 Parramore Permanent Plot Baseline Data : Site Data**
Author(s): David L. Richardson, John H. Porter, Johann Knutsen, Frank Day, Ed Faust, Core Areas: PP DIS Uses: 8

106. VCR05132: **Historical shorelines on Wreck Island - 1888-2003**
Author(s): John H. Porter, Core Areas: DIS Uses: 8

107. RAB9001B: **Hog and Cobb Island nesting seabird study, part B. 1991**
Author(s): Ruth A. Beck, Core Areas: PTD Uses: 8

108. VCR11172: **Ground surface elevation measurements for Surface Elevation Tables on the Virginia Coast**
Core Areas: DIS Uses: 8

109. WO8802C: **Spartina alterniflora leaf measurements, part C. Virginia Coast Reserve 1988-1989**
Author(s): William T. Odum, Jonathan P. Frye, Core Areas: PP Uses: 8

110. VCR97028: **Crab Burrows, Soil Nutrients, and Spartina alterniflora: nutrients**
Author(s): Winli Lin, Core Areas: IN PP PTD Uses: 7

111. WKN7S8802A: **Marsh sediment dynamics and organic matter survey VCR/LTER 1987-1988**
Author(s): William K. Nuttle, Core Areas: IN OM Uses: 7

112. VCR97046: **Bryson Archeoclimate Model for Painter VA**
Author(s): Robert E. Davis, Core Areas: DIS Uses: 7

113. VCR97035: **Plant Cover for Upper Phillips Creek Marsh, Nassawadox, VA**
Author(s): Mark M. Brinson, Robert R. Christian, Core Areas: DIS PP Uses: 7

114. VCR97030: **Crab Burrows, Soil Nutrients, and Spartina alterniflora: organic content**
Author(s): Winli . Lin, Core Areas: PP PTD DIS OM Uses: 7

115. VCR10171: **Network analysis of nitrogen cycling in Hog Island Bay, VA and Sacca di Goro, IT**
Author(s): Robert R. Christian, Christine M. Voss, C. Bondavalli, P. Viaroli, M. Naldi, A. Christy Tyler, Iris Anderson, Karen J. McGlathery, R.E. Ulanowicz, V. Camacho-Ibar, Core Areas: IN Uses: 7

116. VCR97009: **1992-93 Parramore Permanent Plot Baseline Data: Subplot Data**
Author(s): David L Richardson, John H. Porter, Johann Knutsen, Frank Day, Ed Faust, Core Areas: PP DIS Uses: **7**

117. LML7O9001B: **A study of water quality conditions in the tidal creeks of Northampton County, VA**
Author(s): Luis M. Lagera, Core Areas: IN PP Uses: 7

118. VCR09168: **Trace Gas Analyzer Data for a Virginia Salt Marsh**
Author(s): Todd M Scanlon, Core Areas: IN OM Uses: 7

119. VCR03089: **Nutrients in roots on Hog Island, VA 1989**
Author(s): Frank P. Day, Core Areas: IN OM Uses: 7

120. VCR03091: **Fine root production on Hog Island chronosequence**
Author(s): Frank P. Day, Core Areas: PP OM Uses: 7

121. VCR03090: **Root biomass on Northern Hog Island**
Author(s): Frank P. Day, Core Areas: PP OM Uses: 6

122. VCR07142: **High and Low Tides for the Virginia Coast Reserve**
Author(s): John H. Porter, David O. Krovetz, James Spitler, Thomas Williams, Kathleen M. Overman, William K. Nuttle, Core Areas: DIS Uses: 5

123. WKN7S8801B: **Groundwater budgets on Hog Island and at Brownsville.**
Author(s): William K. Nuttle, Core Areas: PP OM Uses: 5

124. VCR97033: **NOAA Hourly Tidal Heights for Wachapreague, VA 1985-1989**
Author(s): NOAA, Core Areas: DIS Uses: 5

125. VCR97032: **Marsh Grass Production data from Brownsville Marsh, Nassawadox, VA 1992**
Author(s): Jerry Bellis, Core Areas: PP Uses: 5

126. VCR97022: **HHS8802B: Plant distribution on Hog Island: T1 : Myrica allometry - dia.+wgt.**
Author(s): Terry Cook, Core Areas: PP Uses: 5

127. VCR97016: **Inundation Experiment Permanent Plot Data: Bulk Density**
Author(s): Robert R. Christian Ph.D., Core Areas: DIS Uses: 5

128. VCR09153: **VCR triangular mesh**
Core Areas: DIS Uses: 4

129. WKN7S8903A: **Morphological study of tidal creeks on the Virginia Coast Reserve 1988**
Author(s): William K. Nuttle, Core Areas: DIS Uses: **4**

130. VCR97034: **NOAA High and Low Tidal Heights for Wachapreague, VA 1985-1989**
Author(s): NOAA, Core Areas: DIS Uses: 4

131. VCR97029: **Crab Burrows, Soil Nutrients, and Spartina alterniflora: weekly nutrients**
Author(s): Winli Lin, Core Areas: IN PP PTD Uses: 4

132. VCR97013: **1992-93 Parramore Permanent Plot Baseline Data: Subplot Water Cover**
Author(s): David L. Richardson, John H. Porter, Johann Knutsen, Frank Day, Ed Faust, Core Areas: PP DIS Uses: 4

133. VCR07140: **Landscape Age Map for Hog Island, Northampton, Co., Virginia. 1852-1985**
Author(s): Michael S. Harris, Guofan Shao, John H. Porter, Core Areas: DIS Uses: 4

134. HHS8801A: **Elevation Surveys near the inlets of Hog and Parramore Islands, VA**
Author(s): Terry Cook, Core Areas: DIS Uses: 4

135. VCR07138: **EcoTrends-Socioeconomic Catalog data for the VCR/LTER Airshed**
Author(s): Ted L. Gragson, Nichole Rosamilia, Core Areas: IN Uses: 3

136. VCR12194: **LiDAR-based Digital Elevation Model for Northampton and Accomack Co., VA, 2010**
Author(s): VITA, Core Areas: DIS Uses: 3

137. VCR97024: **HHS8802B: Plant distribution on Hog Island : Myrica allometry - cuttings**
Author(s): Terry Cook, Core Areas: PP Uses: 3

138. VCR97023: **HHS8802B: Plant distribution on Hog Island: T2 : Myrica allometry - dia.+wgt.**
Author(s): Terry Cook, Core Areas: PP Uses: 3

139. VCR03106: **Salt Marsh Biogeochemistry and Sediment Organic Matter Accumulation**
Author(s): Cassondra R. Thomas, Core Areas: IN OM DIS Uses: 2

140. VCR05128: **Muskrat Lodge Locations near T1 on northern Hog Island**
Author(s): John H. Porter, Core Areas: PTD DIS Uses**: 2**

141. VCR11174: **Sediment Carbon and Nitrogen of Seagrass in Hog Island Bay, VA**
Author(s): Karen J. McGlathery, Core Areas: IN PP OM Uses: **1**

142. VCR12195: **LiDAR point cloud for Northampton and Accomack Co., VA 2010**
Author(s): VITA, Core Areas: DIS Uses: 0

143. VCR08146: **Flux Tower Data for Fowling Point Marsh**
Author(s): Jose D. Fuentes, James C. Kathilankal, Core Areas: PP OM DIS Uses: 0

144. VCR12193: **A time series of images of egret and cormorant colonies on Chimney Pole Marsh, VA**
Author(s): Charles E. Clarkson, R. Michael Erwin, Core Areas: PTD Uses: 0

145. VCR11181: **Soil Characterization of the End of the Year Biomass Marshes**
Author(s): Linda K. Blum, Cassondra R. Thomas, Robert R. Christian, Core Areas: PP OM Uses: 0

146. VCR12186: **Topographic GPS profiles of Hog and Metompkin Island Cross-shore Transects**
Author(s): Catherine Wolner, Laura J. Moore, Core Areas: PP DIS Uses: 0

147. VCR12189: **Sediment Characteristics of Hog and Metompkin Islands**
Author(s): Catherine Wolner, Laura J. Moore, Core Areas: DIS Uses: 0

148. VCR12188: **Hog and Metompkin Island Beach Characteristics**
Author(s): Catherine Wolner, Laura J. Moore, Core Areas: Uses: 0

149. VCR12187: **Vegetation and Morphology of Hog and Metompkin Islands**
Author(s): Catherine Wolner, Laura J. Moore, Steven T. Brantley, Spencer N. Bissett, Donald R. Young Core Areas: PP DIS Uses: 0

150. VCR11176: **Above- and Below-Ground Biomass and Canopy Height of Seagrass in Hog Island Bay, VA**
Author(s): Karen J. McGlathery, Core Areas: PP Uses: 0

151. VCR12185: **Elevation Surveys of Hog Island, VA Transects in 1989**
Author(s): Terry Cook, Core Areas: DIS Uses: 0

152. VCR11184: **Species-level map of Smith Island, VA from remote sensing**
Author(s): Charles M Bachmann, Core Areas: PP Uses: 0

153. VCR11180: **GPS Locations of Seagrass Sites in Hog Island Bay, VA**
Author(s): Karen J. McGlathery, Core Areas: PP Uses: 0

154. VCR11177: **Organic Matter of Seagrass in Hog Island Bay, VA**
Author(s): Karen J. McGlathery, Core Areas: OM IN PP Uses: 0

155. VCR11179: **Productivity of Seagrass in Hog Island Bay, VA**
Author(s): Karen J. McGlathery, Core Areas: PP OM Uses: 0

156. VCR11178: **Ammonium Exchange in Seagrass in Hog Island Bay, VA**
Author(s): Karen J. McGlathery, Core Areas: IN Uses: 0

157. VCR11175: **Benthic Chlorphyll in Seagrass Meadows in Hog Island Bay, VA**
Author(s): Karen J. McGlathery, Core Areas: PP Uses: 0

158. VCR11173: **Density of Seagrass in Hog Island Bay, VA**
Author(s): Karen J. McGlathery, Core Areas: PP Uses: 0

159. VCR03088: **Root data from pits on Hog Island transect 2**
Author(s): Frank P. Day, Core Areas: OM Uses: 0

SECTION 10. FACILITIES

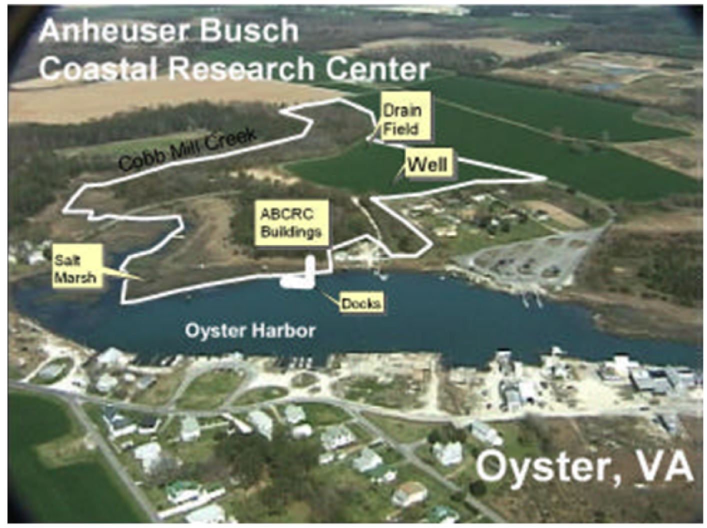

Fig. 1. 42-acre property of the new VCR LTER home at the Anheuser-Busch Coastal Research Center in Oyster, VA.

The VCR LTER program had a new home as of August 2006 at the University of Virginia's Anheuser Busch Coastal Research Center (ABCRC) in Oyster, Virginia, built with support from private donors ($2.25 M) and NSF ($305 K). The Center is located on 42 acres on Oyster Harbor, with boat access to the coastal ecosystems of the VCR. Oyster Harbor is one of the few deep-water harbors on the Eastern Shore of Virginia. There is also a tidal creek on the property (Cobb Mill Creek) where we do much of our riparian work.

The laboratory building includes 9369 sq. ft. of dry and wet lab space and a conference room. The laboratories have equipment for basic wet chemistry analyses, including fume hoods, spectrophotometer, microscopes, and also for wet and dry sample preparation and storage, including archived cold storage, an ultra-cold freezer, freeze-drier, and drying ovens.

The residence building (5767 sq. ft.) can house 30 people in 1-5 bedroom apartments, each with private kitchens. There is office space for the LTER/ABCRC staff (1 site director, 3 field technicians, and a fiscal technician). There are computer facilities to support the technical staff, and common-use computers for PIs and students. The Center is supported by a high-speed wireless internet system in both the laboratory and residence buildings. This system also allows internet access both inland from the ABCRC and out to the barrier islands.

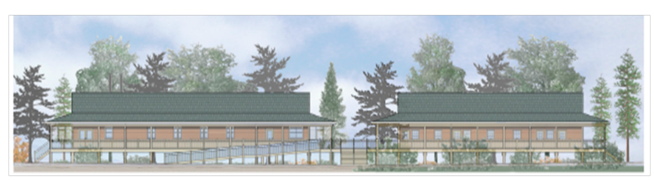

Fig. 2. Photo and architectural drawing of the completed Anheuser-Busch Coastal Research Center laboratory (rear, left) and housing facility (front, right). The buildings are connected by a large deck with screened porches that provide additional fair-weather research space.

PIs McGlathery, Schwarzschild and Smith received a NSF FSML grant for three enhancements of the ABCRC dock facility that facilitate LTER research: 1) fuel and electrical power added to the dock; 2) access improved for research and education by adding a ramp and floating platform to facilitate all-tide access to boats; and 3) design and install a flow-through seawater system with holding tanks for short-term maintenance of specimens and experiments that require running seawater and in situ conditions.

The ABCRC has a fleet of boats to support LTER and affiliated research activities: one 24' Privateer, one 21' Privateer, two 21' Carolina Skiffs, and one newly acquired 25' Carolina Skiff. There is a dock with 10 deep-water slips for our fleet and other larger vessels, as well as space for several smaller boats. There is a Polaris 4-wheel all-terrain vehicle with a tow-behind trailer for transporting gear on the barrier islands. The ABCRC also has two vehicles for staff to use for towing boats to other staging areas (e.g., Red Bank) and for general logistical support.

The University of Virginia also supports the VCR LTER with the availability of graduate student positions, which can be filled on an as-needed basis.