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TITLE OF PROPOSED PROJECT **Long-Term Drivers, State Change and Disturbance on the Virginia Coast Reserve: LTER V**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
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PROJECT SUMMARY

Intellectual Merit: The Virginia Coast Reserve (VCR) LTER aims to develop a predictive understanding of how long-term environmental change and short-term disturbances control the dynamic nature of coastal barrier landscapes. The VCR is a heterogeneous landscape comprised of mainland watersheds, tidal marshes, lagoons, and barrier islands. **The central hypothesis of VCR V is that ecosystem dynamics and pattern on the landscape are controlled by the interaction between the vertical positions of the land, sea, and groundwater free surfaces, and the fluxes of organisms and materials across the landscape.** Proposed and continuing research at the VCR is organized around 3 synthetic questions: (A) How do long-term drivers of change (climate, rising sea level, and land-use change) and short-term disturbance events interact to alter ecosystem dynamics and state change, and how is their effect modified by internal processes and feedbacks at the local scale? (B) How do fluxes of organisms and materials across the landscape influence ecosystem dynamics and state change? (C) In the future, what will be the structure of the landscape and what processes will drive ecological state change? The first question is a continuation of VCR LTER research over the past 2 decades, and the latter two questions are new to VCR V. Modeling and process-level studies also address the biogeochemical and trophic consequences of state change on the landscape.

The project uses a combination of long-term monitoring and experiments, shorter-term process-level studies, and modeling. Patterns, processes and interactions are examined at three spatial scales: within landscape units (watershed, tidal marsh, lagoon, barrier island), within mainland-lagoon-island box transects, and across the entire system of islands and lagoons. Temporally, processes are considered at scales from a fraction of a day (e.g., element cycling) to decades (e.g., succession) to more than a century (e.g., sea-level rise). The interdisciplinary research group includes ecologists, hydrologists, biogeochemists, atmospheric scientists, oceanographers, modelers, and specialists in remote sensing and information management.

Broader Impacts: Humans are altering ecosystems at unprecedented rates, especially in the coastal zone. Understanding and predicting how multiple factors influence ecosystems and their services is a critical challenge for environmental scientists and resource managers. The VCR is a relatively pristine coastal system of shallow lagoons and barrier islands that can be compared with other LTER sites to understand how coastal systems in general respond to drivers of global change. The VCR LTER program has been very active in outreach, training and network activities. The VCR Schoolyard Program contributes important training and infrastructure to the primary and secondary schools in the local county, which is one of the poorest in the state, and over half the students trained are women and minorities. Training of future environmental scientists through the graduate programs at VCR participating institutions is one of the priorities of the program. Each funding cycle the VCR LTER trains over 40 graduate students and about 20 undergraduates, about half of which are women and minorities. Scientific findings and technical information are broadly disseminated through the VCR LTER website, scientific publications and presentations, and the media. The VCR LTER has developed links with conservation organizations, and local, state, and federal agencies through outreach efforts. The VCR LTER also has a strong partnership with The Nature Conservancy to address the important management and conservation problems facing this region. This puts the VCR LTER in an excellent position to provide a solid, scientific foundation for making decisions related to planning, management, and ecosystem restoration. This partnership can also serve as a model for science-based management of other dynamic coastal barrier systems.

SECTION 1: RESULTS FROM PRIOR SUPPORT

Long-Term Ecological Research on Disturbance, Succession, and Ecosystem State Change at the Virginia Coast Reserve
Grant # DEB-0080381 Funding (2000-2006) = $4,200,000

The goal of the Virginia Coast Reserve (VCR) LTER program is to understand and predict long-term ecological change in the context of slow, progressive changes in climate, land use, and sea level, and short-term disturbance events such as storms in coastal barrier systems (Fig 1). Biotic feedbacks at the local scale interact with these broad-scale drivers to influence long-term ecological change on the landscape. In VCR IV, our central hypothesis was that ecosystem, landscape and land use patterns within terrestrial-marine watersheds are controlled by the vertical positions of the land, sea and groundwater free surfaces (Fig. 2). The hypsometric framework developed in VCR IV provides the synthetic framework to link the ecosystems (mainland, tidal marsh, lagoon, barrier island) on the landscape (Fig. 1).

We have produced 105 peer-review papers and 21 book chapters thus far during this funding cycle. In addition, 32 theses or dissertations have been completed by January 2006 and 109 datasets have been posted on the web. Two hundred students and teachers have been involved in our Schoolyard LTER program. A full description of our education program is included in the Education and Outreach section, and a complete publication list is included in Supplemental Document 1). As of February 2006, the VCR LTER program will have a new home at the Anheuser Busch Coastal Research Center in Oyster, Virginia.

Below we describe *selected* accomplishments of VCR IV. We have grouped our research results into 3 areas – watersheds and lagoons, tidal marshes, and barrier islands – that reflect the breadth of our program. We have chosen examples that illustrate the importance of understanding processes at multiple scales to show both our progress to date and to set the stage for our future emphasis on cross-site fluxes and landscape dynamics (Fig. 3). Other examples can be found on our webpage (http://www.vcrlter.virginia.edu) and in our publications.

Watersheds and Lagoons:

Our research in this area focuses on the linkage between watershed land use and the impact of nutrient loading on the lagoons, and on the return of the seagrass, *Zostera marina* (eelgrass) as the "foundation" species (sensu Bruno and Bertness 2001). We study the groundwater free surface, which delivers nutrients to the lagoons, and the parallel land (lagoon bottom) and sea level free surfaces, which determine water depth and the tidally-driven exchange with the coastal ocean. Our studies relate nutrient inputs to processing by primary producers and consumers and to physical transport within the lagoon. Our models of hydrodynamics and sediment resuspension set the stage for the planned large-scale recolonization of eelgrass in Hog Island Bay.

Watershed nutrient inputs: Since there are no large rivers that feed into VCR coastal lagoons, nutrient inputs from the watersheds are largely via groundwater and atmospheric deposition (McGlathery et al, in review). Groundwater enters the VCR lagoons either through small tidal creeks that drain each of the watersheds or directly through or under fringing marshes. In VCR IV, we delineated the landscape into 54 small watersheds (0.2 – 19.7 km^2), and have been monitoring 15 of the tidal creeks to calculate baseflow nutrient loading (Fig. 4). We found that land cover (forest, developed land) in the watershed explained 86% of the baseflow NO_3^- loading rate, and that poultry operations in the northern region of the VCR may impact lagoonal water quality (Stanhope 2003). We were surprised to find that overall baseflow nutrient loading rates to the VCR lagoons were low compared to other lagoons, despite large variations in agricultural land use (Chauhan and Mills 2002; Mills et al. 2002; Stanhope 2003). This is in part due to very high removal of NO_3^- from groundwater discharging to the streams by denitrification in a narrow band of sediments and bank materials (Flewelling et al. in prep).

Lagoon nutrient dynamics: We constructed a nitrogen budget for Hog Island Bay, which indicated that sources of groundwater and atmospheric deposition accounted for a small percentage of the total nitrogen demand of the primary producers in the lagoon (Fig. 5). The most important nitrogen source was remineralization in the sediments (Anderson et al., in prep.), indicating that high rates of production were supported mostly by efficient internal nutrient cycling. In the absence of seagrass, benthic algae (micro and macro) are the dominant primary producers (McGlathery et al. 2001), and control benthic-pelagic nutrient coupling (Anderson et al. 2003). In particular, nitrogen uptake by benthic algae suppresses denitrification to negligible rates and prevents the efflux of mineralized nitrogen from the sediment to the water column (Havens et al., 2001; Tyler et al. 2001, 2003; Anderson et al. 2003).`

Hydrodynamics: With additional funding from USDA, we developed a finite element hydrodynamic model for Hog Island Bay (Fugate et al., in review). The model uses wind and tidal forcing to calculate circulation and transport in the lagoon. It shows that local water residence time can vary at least an order of magnitude in different parts of the system, from 1 day near the inlet to as much as 24 days near the mainland (median 16 days).

Seagrass recolonization: We used the hydrodynamic model together with wave and resuspension models to determine the spatial and temporal patterns of sediment resuspension and light availability in Hog Island Bay (Lawson 2004; Lawson et al., in review). High turbidity events were episodic and wind driven (Fig. 6). Based on the modeled average light availability at the sediment surface, 65-87% of the lagoon bottom is suitable for seagrass recolonization (Fig. 7, Lawson 2004; Lawson et al., in review). These data were used to justify a 509-acre “set-aside” for seagrass restoration in collaboration with colleagues at the Virginia Institute of Marine Sciences. Test plots have been set out in anticipation of large-scale seeding in fall 2006. We will follow this state change as part of a new long-term experiment in LTER V.

Tidal Marshes:

Research in the VCR tidal marshes focuses on the oscillatory free surface of sea level and its intersection with the sloping land and groundwater free surfaces, and on how the interactions of these surfaces results in ecological state change. We also examine the interplay between the biological and physical processes and the geomorphology within states. We continue to focus our efforts on long-term measurements of marsh biomass and community change, sediment accretion in relation to sea-level rise, groundwater levels, and marsh food web dynamics. Of particular interest is the occurrence of marsh die-off in parts of the VCR landscape, a phenomenon that has occurred throughout the eastern seaboard (Silliman et al. 2005).

Marsh accretion and sea-level rise: Surface elevation tables (SET) have been used to measure the land free surface in mainland marshes since 1997 and in lagoon marshes since 1999. Rates of elevation change are as variable among plant zones within a single marsh (2.1 mm yr^{-1} to 7.4 mm yr^{-1}; high and low marsh, respectively; Fig. 8) as they are among marshes within similar plant zones (1.4 mm yr^{-1} to 7.4 mm yr^{-1}; lagoon and mainland, respectively). Our observations suggest that lagoon marshes are less sustainable to loss at the current rate of relative sea-level rise (3.5 - 3.9 mm yr^{-1}, Erwin et al. 2004; in press) than mainland marshes (Blum and Christian 2004). Also, the processes that contribute to the land surface change are variable within a given marsh. For example, accretion (measured as accumulation of materials over a feldspar marker horizon) is not correlated with changes in land surface elevation in either mainland or lagoon marshes. In our primary mainland marsh site, Phillips Creek, the land surface elevation changes in the low marsh is correlated with the depth to the groundwater surface, and in the high and mid marsh is correlated with thickness of the root zone.

With sea-level rise, salt marshes along the mainland edge have the potential to transgress inland, while eroding seaward for lack of adequate sediment supply (Christian et al. 2000). The actual changes and the rates of change depend on the frequency and types of disturbances in the various ecosystem states (Keusenkothen and Christian 2004). As transgression occurs, forest is replaced with high marsh, high marsh with low marsh, and low marsh with open water. The high marsh has organic soils and maintains itself by biogenic accretion in the face of rising sea level, whereas accretion in the low marsh, with more mineral soils, is more dependent on sediment deposition (Appolone 2000: Blum and Christian 2004). The transition from high marsh to low marsh involves major changes in species, soil properties and ecosystem functioning (Roberts 2000; Buck 2001), and nitrogen cycling becomes more open during this process (Thomas and Christian 2001).

Mechanisms of state change: We have focused on the responses of vegetation to disturbance in the context of ecogeomorphology at the Phillips Creek marsh (Keusenkothen and Christian 2004). Specifically, we have tested inundation-disturbance interactions, and have shown that high marsh plants have considerable resilience to experimentally enhanced inundation, but respond differently to disturbance by wrack deposition (Tolley and Christian 1999; Brinson and Christian 1999; Roberts 2000; Buck 2001; Miller et al. 2001). Wrack disturbance creates habitat heterogeneity over the short term by removing plant cover and altering a number of ecosystem processes (Tolley and Christian 1999), and succession usually results in recovery to the same state. We assume that the resilience to change in plant community structure after disturbance is in part because a threshold of state change was not reached. Deer trails are another agent of disturbance that causes different responses among marsh ecosystem states (Keusenkothen and Christian 2004). Finally, the stresses of hypoxia and drought cause major shifts in the food webs of marsh ponds, as assessed by network analysis models (Dame 2005).

Barrier Islands:

Our activities in the terrestrial portions of the VCR landscape focus on the relationship between the groundwater and land free surfaces, and how this relationship influences plant community structure, and patterns of nutrient cycling and primary production. Storm disturbance, sea-level rise and nitrogen enrichment are all drivers that influence these free surfaces and biotic structure. We are finding emergent patterns between plant community structure, the abundance of predatory mammals, and nesting patterns of colonial waterbirds.

Patch to landscape scale patterns in island vegetation: Processes operating at the scale of the barrier island complex (climate, storm frequency), the island scale (erosion and accretion) and local scale (seed rain, soil development, herbivory) can each play a role in determining the pattern and dynamics of vegetation. *Myrica* shrub thickets are the dominant woody community on most of the VCR barrier islands (Young 1992; Young et al. 1995a). *Myrica* is intolerant of salinity so the thickets represent relatively protected or stable positions on the island landscape (Sande and Young 1992; Young et al. 1992; Tolliver et al 1997). To determine how shrub thicket distribution may be responding to the effects of sea-level rise at the scale of the entire barrier island complex, at the island scale and within individual islands, we analyzed aerial photos, maps, and hyperspectral imagery to document spatial changes. At the scale of an individual island, shrub thickets have expanded by more than 500% over the past 50 years on the north end of Hog Island, which continues to accrete at approximately 20 m yr^{-1} (Fig. 9). Decadal comparisons indicate that several islands have shown dramatic shrub expansion, often preceded by a lag phase after initial colonization. In contrast, shrub area has decreased on Parramore Island, which has been eroding for nearly a century, and on Smith Island, shrub cover has remained relatively static. Despite general predictions of coastal erosion resulting from climate-driven sea-level rise, the islands within the Virginia barrier complex display a heterogeneous response, and this is reflected in the dynamics of the shrub thicket distribution patterns (Young et al. in prep).

<u>Vegetation patterns and nutrient dynamics</u>: Interactions between the changes in the positions of free surfaces and nitrogen fertilization influence plant community composition on the barrier islands (Day et al. 2004). Our long-term fertilization experiments on the upland chronosequence indicate that retention of nitrogen within fertilized plots is primarily facilitated by increased biomass, predominantly in roots, and larger pools of plant litter (Heyel and Day, in press). Fertilization alters species dominance patterns and increases density (favoring *Ammophila* sp.), but decreases overall diversity (Fig. 10).

<u>Seed dispersal</u>: Positive interactions between the juniper (*Juniperus virginiana)* and woody seedlings may influence succession trends on the VCR landscape. The effect of *J. virginiana* on the recruitment and distribution of woody seedlings may be passive, through the non-random distribution of fleshy seeds by perching birds, or active, through increased seedling survival due to *J. virginiana* initiated alterations in microclimate and edaphic factors (Joy and Young 2002).

<u>Dynamics of faunal populations</u>: Several field studies on Hog Island have determined that insect herbivores have a minimal effect on aboveground primary production on the uplands of the VCR barrier islands (Barimo and Young 2002; Fuest 2005; Fuest et al. in prep). Long-term studies of vertebrate populations on the VCR were initiated in 1974 and focus on the interaction of island size and morphology, vegetation cover, and predator-prey interactions (Dueser and Brown 1980; Brannon et al. 2001). At the landscape scale, radiotracking and genetic analyses have been used to identify probable dispersal routes for racoons (*Procyon lotor)* between islands (Dueser et al., in prep.). The spread of predators (i.e., raccoons, foxes) on the islands has been linked to a dramatic decline in beach nesting birds (Erwin et al. 2001). Also, predator removal experiments showed significant increases in bird breeding success rates (up to 182%) on islands where predators were removed (Dueser et al., in prep.). Loss of marsh habitat associated with sea-level rise also is an important factor causing reduced populations of nesting birds (Erwin et al. 2004). Experimentally manipulating marsh habitats by elevating nesting substrates increased nesting success, but it was primarily social rather than physical factors that influenced nest-site preferences (Rounds et al. 2004).

Synthesis Activities

At the site level, B. Hayden compiled literature estimates of eustatic sea-level rise and land-surface uplift and subsidence over the last 20,000 years (Fig. 11). The time sequences show that up until roughly 8,000 years ago, crustal uplift and eustatic sea-level rise were at similar rates, resulting in a stable sea level during that period. Since then, there has been a net rise in relative sea level, although for a brief period in the last 2000 years the relative sea level actually declined. Current rates of relative sea-level rise for the VCR range from 3.5 to 3.9 mm y^{-1}, the highest rates found on the east coast of the U. S. Hayden also compiled a long-term record of storms that shows that we are now in a period of relatively high storm frequencies, comparable to the 1960's (Fig. 12). Interestingly, the 1930's had a relatively modest number of storms, even though several major hurricanes hit the Virginia coast during this period, including the one that decimated the seagrasses in the VCR lagoons.

Six of the VCR PIs have NSF-funded Biocomplexity projects that integrate with, and expand on, VCR LTER research: Nonlinear Feedbacks in Coupled Elemental Cycles During Eutrophication of Shallow Coastal Ecosystems (McGlathery, Berg), Networking the "Invisible Colleges": Application of Network Theory to Biocomplexity (Christian), and Comparative Stability and Resiliency of Ecosystems: Five centuries of Human Interactions with the Environment on the Eastern Shore of Virginia (Shugart, Porter and Macko). Involvement in these projects extends our VCR research into new geographic regions and into the social science realm. L. Blum and S. Fagherazzi edited a book on the "Ecogeomorphology of Tidal Marshes" (published by the American Geophysical Union). K. McGlathery and I. Anderson wrote several synthesis chapters on nutrient cycling in coastal lagoons and the regulatory role of benthic primary producers (McGlathery 2001; McGlathery et al. 2005; McGlathery and Sundback 2005; McGlathery et al., in review). D. Young contributed a chapter on measuring primary production in shrublands to the LTER synthesis volume "Principles and standards for measuring net primary production." And based on collaborations begun at the 2003 All-Scientists Meeting (ASM), Porter et al. (2005) (BioScience cover story) detailed how wireless networking technologies are expanding the basis of data collection in ecology, and how use of such technology can increase.

Cross-site, Network and Information Management Activities

VCR scientists have been involved in several cross-site research activities during this funding cycle and have been active in LTER Network governance. K. McGlathery (2004-2005), B. Hayden (2002-2004) and J. Porter (1997-2002) each served on the LTER Network Executive Committee. I. Anderson serves on the GCE Advisory committee. J. Fuentes, and student J. Barr, made the first eddy covariance measurements of carbon exchange in mangroves at FCE. Fuentes, B. Hayden, and students studied climate control on fluxes of volatile organics at SEV. L. Blum coordinates an intersite comparison of organic matter accumulation in marshes with researchers from PIE (Morris), GCE (Pennings, Newell), and several other long-term sites. She is also planning a cross-site study of fungal diversity with long-term sites in New Hampshire and Florida. D. Young is involved in a cross-site comparison of shrub expansion. And R. Christian gave a series of Network-funded workshops on ecological network analysis, which resulted in collaborative efforts at other sites (MCM, LUQ). At the Network level, K. McGlathery has been involved in Planning Grant activities. She led the workshop on coupled biogeochemical-hydrological cycles at the Fall 2003 ASM meeting, and the biogeochemistry workshop at the Meeting of 100 in November 2004. She also gave a presentation on LTER contributions to understanding the coastal eutrophication problem at the NSF mini-symposium in February 2005. Finally, we hosted the Fall 2005 Coordinating Committee meeting at the VCR.

We have been strong participants in LTER network information management (Porter 2000, Porter et al. 2005). J. Porter has helped teach courses on databases, with annual participation in RDIFS/RCN training for field stations since 2002, and at international LTER workshops (Southern Africa, 2002; China, 2005). Additionally, he has been involved in >16 workshops during 2001-2005. We hosted an information-manager-in-training from the Taiwan Ecological Research Network for three months in 2005 and will be hosting more in 2006. The data sets and access history of our web page are summarized in Supplemental Document 2.

SECTION 2: PROJECT DESCRIPTION

INTRODUCTION

Overview:

The overall goal of the Virginia Coast Reserve (VCR) LTER program is to develop a predictive understanding of how slow, progressive changes in climate, land use, and sea level, and short-term disturbance events such as storms control ecosystem dynamics and biotic structure in coastal barrier systems (Fig 1). Biotic feedbacks at the local scale interact with these broad-scale drivers and lead to threshold behavior and non-linear responses to long-term environmental change. The VCR is an exceptionally dynamic, heterogeneous landscape comprised of mainland watersheds, tidal marshes, lagoons, and barrier islands (Fig. 1). Our research during VCR I-IV has focused on how abrupt ecosystem state change and slower successional change are driven by these chronic long-term environmental changes and short-term disturbance events. **In VCR V, we will build on our site-based studies to focus on landscape-level synthesis.** We have previously hypothesized that ecosystem dynamics are manifested through changes in the relative elevations of the three free surfaces (land, sea, groundwater table; Fig. 2). We now recognize that to achieve a predictive understanding of ecosystem dynamics and state change at the landscape level, we need to address more explicitly the linkages among landscape units (watershed, upland, tidal marsh, lagoon) and the variation in external drivers at a given position on the landscape (Fig. 3). The hypsometric framework developed in VCR IV provides the spatially explicit landscape structure in which to relate the ecosystem states (Fig. 1). **Our central hypothesis of VCR V is that ecosystem dynamics and pattern on the landscape are controlled by the interaction between the vertical positions of the land, sea, and groundwater free surfaces, and the fluxes of organisms and materials across the landscape.** At our 2003 NSF site review, we were encouraged to examine these linkages to develop a predictive understanding of the implications of climate, sea-level and land-use change. During VCR V we will develop a landscape-scale model to predict ecological change, which builds on our understanding of processes at multiple spatial and temporal scales. Coastal barrier ecosystems like the VCR are prominent features of shorelines on most continents and are important globally (McComb 1995; Boynton et al. 1996). The lessons learned from the VCR LTER program can be applied to coastal barrier ecosystems and compared with other types of land-margin ecosystems.

The System:

The VCR is characteristic of coastal barrier ecosystems that comprise much of the Atlantic and Gulf Coasts (Hayden et al. 1991; Ray and Gregg 1991). It is an extremely dynamic, regularly disturbed landscape that includes an assemblage of 14 barrier islands, shallow lagoons with extensive mudflats, tidal marshes, and mainland watersheds extending 110 km along the seaward margin of the Delmarva Peninsula (Fig. 1). The barrier island and lagoon system supported one of the most prosperous farming and fishing-based communities in the country at the turn of the last century. Now the islands of the VCR are uninhabited. The 14,000 ha reserve was established in 1970 by our partners at The Nature Conservancy and is part of the mid-Atlantic coastal plain that extends from the fall-line 100 km inland to the edge of the continental shelf. The contemporary landscape of the VCR took form during the late Holocene, although the underlying topographic framework can be traced back to relict drainage basins of the antecedent Pleistocene land surface (Oertel et al. 1989a; Oertel 2000a,b). Shoreline change on the modern islands is dramatic, typically characterized by lateral accretion and erosion at rates as high as 13 m/yr, and is the highest along the mid-Atlantic seaboard (Fig. 13; Dolan et al. 1979). This extreme rate of shoreline movement creates one of the most dynamic coastal landscapes in the United States (Dolan et al. 1983). The barrier islands of the reserve, like those elsewhere along the Atlantic Coast, are migrating landward (Hayden et al. 1991). 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. It is now a grassland built on an overwash fan (Rice et al. 1976; Hayden et al. 1991; Fitch 1991), and the location of Broadwater is now hundreds of meters offshore. The north end of Hog Island was several hundred meters wide and consisted of a narrow beach affronting a marsh in 1871; now it is a complex chronosequence of dune ridges and swales nearly 1.5 km wide (Harris 1992; Hayden et al. 1991; Young et al. 1995a; Fig. 14).

The impact of storm disturbance on this exceptionally dynamic landscape is illustrated by the recent effects of Hurricane Isabel, a category 2 hurricane that hit the VCR on September 18, 2003. The beaches of the barrier islands were pounded with 3-5 m waves, all the low-lying islands showed signs of major flooding (wrack deposition in intertidal and upland areas), and significant erosion occurred on some islands. Wreck Island lost considerable upland area (Fig. 15), and on Myrtle Island repeated trapping of small mammals indicated local extinction of the house mouse (*Mus musculus*) occurred as the result of large-scale habitat contraction. Our long-term monitoring of sediment elevation on the mainland tidal marsh showed a significant increase in marsh elevation, especially on the high marsh (Fig. 16). The adjustment in the rate of elevation change associated with Isabel has persisted.

Recent catastrophic climatic events in the U. S. and abroad have highlighted the protective role of barrier-island and coastal vegetation (Danielsen et al. 2005). The lagoons in these systems function as an important "filter" for watershed nutrient inputs on their trajectory to the coastal ocean (Cloern 2001); however, we know less about processes in shallow lagoons compared to deep, river-fed estuaries (McGlathery et al. in review). Also, the shallow seaward slope of the VCR coastal barrier landscape (<0.1%) makes this a particularly sensitive location for studying intertidal marsh dynamics in response to sea-level rise. Finally, at the VCR we can compare multiple watershed-lagoon-island complexes, which gives us an exceptional opportunity to understand the structure and function of these important coastal barrier systems under different environmental conditions.

CONCEPTUAL FRAMEWORK

The VCR LTER project seeks to understand the dynamic nature of coastal barrier landscapes in the context of long-term environmental change and short-term disturbance events (Fig. 17a). We view ecological changes as occurring non-linearly, with systematic progressive changes (succession) interrupted by abrupt transitions between ecosystem states (state change). Biotic feedbacks at the local scale contribute to the non-linear responses to environmental change. Our research since 1987 has focused on the major landscape units of the VCR -- the barrier islands, lagoons and tidal marshes -- and how the relative positions of the land, sea and groundwater free surfaces influence ecosystem states. We are now proposing to investigate fluxes between these landscape units to address landscape-level dynamics. In these systems, tidal marshes, unvegetated inter- and sub-tidal mudflats, grasslands, shrub savannas and maritime forests occur in close proximity, often with sharp boundaries between adjacent communities (McCaffrey and Dueser 1990a, b; Young et al. 1995a; Christian et al. 2000). The hypsometric framework provides a spatially explicit structure in which to relate the landscape units (Fig. 1).

Within each landscape unit we focus our research on how free surfaces influence ecosystem dynamics in response to large-scale external drivers and internal processes (Fig. 2). In the tidal marshes, we focus on the oscillatory free surface of sea level and its intersection with the sloping land and groundwater free surfaces. In the lagoons, we study the interaction between the groundwater free surface that delivers nutrients from coastal watersheds and the parallel free surfaces of the land (lagoon bottom) and seawater, which together determine water depth, light availability and the tidally-driven exchange with the coastal ocean. On the barrier islands, we focus on the interactions of the land and water table surfaces in structuring island vegetation and associated animal communities.

Understanding how multiple drivers interact to influence long-term ecosystem dynamics is central to LTER research (Hobbie et al. 2003). On the VCR landscape, climate change, sea-level rise, and land use change are the drivers of chronic, long-term change. Coastal storms or Nor'easters (Dolan et al. 1987) and the Bermuda high-pressure system (Davis et al. 1997) dominate the **climate** of the VCR and have shown long-term trends related to climate change over the last century. Storm frequency along the U.S. Atlantic coast has changed (Hayden and Hayden 2003), and we are now in a period of relatively high storm frequencies at the VCR (Fig. 12). Each year more than 20 extratropical storms occur with magnitudes sufficient to move sediments and change the morphology of the islands (Hayden 1976, 1981; Dolan et al. 1979) and the associated flora and fauna (Johnson and Young 1992; Young et al. 1995b; Dueser et al. 1990; Erwin et al. 2001; Brannon et al. 2001). Ultimately, storms and sea-level rise cause the landward migration of the islands across lagoon marshes (Hayden et al. 1980) and the encroachment of marshes into forests on the mainland (Brinson et al. 1995; Shao et al. 1998; Christian et al. 2000). The current relative **rise in sea level** ranges from 3.5 to 3.9 mm year^{-1}, and is the highest recorded rate along the Atlantic Coast. This is the sum of the change in elevation of the sea (eustatic sea-level rise) of about 1 mm year^{-1} and the change in the level of the land of 2.5 to 2.9 mm year^{-1} (Oertel et al. 1989b; Emory and Aubrey 1991). Finally, **land use** has changed substantially in coastal regions of the U.S. over the past century, with increases in human populations and abandonment of agriculture (NRC 2000). In the VCR watersheds, land use is still dominated by crop agriculture, which ranges from 20-80% of the area of individual watersheds. Urbanization currently is low in the region relative to other Atlantic coastal regions. However, given the proximity of the VCR to major urban centers, this is likely to change in the coming decades.

Superimposed on these long-term progressive changes are frequent, shorter-term disturbances, with storms being the primary physical agent of **disturbance** on the VCR landscape. Most of the inorganic sedimentation above mean sea level is transported during Nor'easters and tropical storms when sea levels exceed lunar tides by as much as 3 m (Dolan and Godfrey 1973). On the marshes, large deposits of wrack laid down during storms create patchiness within the marsh vegetation (Brinson et al. 1995; Christian et al. 2000), and sedimentation on the low marsh is highest during storm events (Christiansen et al. 2000). In the lagoons, a single storm in 1933 decimated seagrass populations already weakened by disease. Now wave-induced sediment resuspension during storms is the primary factor influencing light availability and the potential for seagrass recolonization (Lawson et al. in review). Other agents of disturbance on the VCR landscape include species invasions, animals, and infrequently occurring fires. The reed grass (*Phragmites australis*), which was historically limited to dredge spoils and small areas between the upland and high marsh along the mainland margin of the VCR, has now expanded onto barrier islands. We have teamed with The Nature Conservancy to map the distribution of this invasive. The macroalga (*Gracilaria vermiculophylla*), which accounts for 90% of the macrophyte biomass in Hog Island Bay, is an invader from the Pacific (Thomsen and McGlathery 2005). Also the red fox (*Vulpes vulpes*), although a long-time resident on some of the larger islands, appears to be increasingly ubiquitous and abundant on the barrier islands (Erwin et al. 2001).

This heterogeneous and rapidly changing landscape is a particularly valuable setting in which to develop an understanding of the relationship between disturbance and long-term progressive environmental change. In LTER V, we will add 3 new initiatives to our ongoing work to increase our focus on landscape dynamics: (1) Two new box transects with different hypsometries will be added for comparative measurements to capture the regional variation on the landscape (Fig. 18). (2) Studies on the fluxes of organisms and materials between landscape units will be initiated. (3) A landscape model that synthesizes our knowledge will be developed and used as a predictive tool to understand ecosystem state change.

PROPOSED RESEARCH

Our proposed and continuing research at the VCR is organized around 3 synthetic questions: **(A) How do long-term drivers of change (climate, rising sea level, and land-use change) and short-term disturbance events interact to alter ecosystem dynamics and state change, and how is their effect modified by internal processes and feedbacks at the local scale? (B) How do fluxes of organisms and materials across the landscape influence ecosystem dynamics and state change? (C) In the future, what will be the structure of the landscape and what processes will drive ecological state change?** The first question is a continuation of our research over the past two decades, and the latter two questions are new to VCR V (Fig. 17a). We have previously worked at large geographic and long time scales (VCR "Megasite"), but have not yet developed landscape models that allow us to synthesize our observations and experiments to achieve a predictive capability. Understanding the biogeochemical and trophic consequences of state change is part of our synthesis effort.

Our research approach relies on long-term monitoring and experiments, shorter-term process-level studies, and modeling. We structure our research activities over multiple space and time scales (Fig. 17b). Spatially, we will conduct research at three scales: within landscape units (mainland watershed, tidal marsh, lagoon, barrier island), within mainland-lagoon-island box transects, and across the entire system of islands and lagoons. Temporally, we consider scales from a fraction of a day (e.g., element cycling) to decades (e.g., succession) to more than a century (e.g., sea-level rise, landscape change). The 'core' databases provide the long-term context for our research and follow the five LTER 'core' areas. These databases span all spatial scales. The long-term experiments allow us to manipulate drivers of change and to follow ecosystem recovery after disturbance events. These experiments are done at our primary research sites in the Machipongo box transect. The addition of two new box transects allows us to capture variation in both the external drivers and the ecological responses to these drivers on the landscape. We will coordinate our research efforts on the responses to multiple drivers of change in the different landscape units in these box transects and will conduct studies of fluxes of materials and organisms between the landscape units (Questions A1, and B1-B4 described below). Variation in the hypsometry of the box transects is reflected in differences in watershed size, marsh area and slope, lagoon size and hydrodynamics, and island size and distance from the mainland (Fig. 18). We will use several types of models to integrate our research across these spatial and temporal scales. A finite-element finite-volume hydrodynamic model will be developed for the three lagoons in the box transects to determine spatially variable water residence times. It also will be used in conjunction with a seagrass population model to assess the exchange of sediments between subtidal mudflats and intertidal marshes/mudflats and the potential for the return of seagrasses in the lagoons to influence this exchange. A landscape model will integrate our core measurements, and site and transect-level studies to address how landscape heterogeneity and fluxes between landscape units influence ecosystem state change. Finally, network models will be used to predict the biogeochemical and trophic consequences of state change on the landscape.

I. Long-term studies

Our long-term monitoring focuses on quantifying the 3 free surfaces as they relate to the drivers of change, as well as the biogeochemical and biotic characteristics of the ecosystem states. We conduct synoptic surveys on changes of biota and of physical and chemical parameters, and use GIS analysis linked to remote sensing to provide baseline information for spatially extensive features and to track changes on the landscape. We quantify key fluxes (land-atmosphere carbon (C) and nitrogen (N), groundwater) that will influence state change over the long-term. Finally, we use long-term experiments to understand the mechanisms of state change in response to long-term drivers of environmental change. We make use of chronosequences within each landscape unit as a "space for time" approach to study ecosystem change following disturbance events. Below we describe the long-term core measurements and experiments briefly; additional details are given in Table 1. These observational and experimental data are used to address the synthetic research questions elaborated on in the following section.

A. Core measurements:

(1) Free surfaces: We monitor a system of 28 Surface Elevation Tables (SET) on the mainland and island marshes as part of a regional and national sediment deposition observation system. This network allows us to relate the land surface with sea level and disturbance events that may either erode or deposit sediments at a variety of locations on the landscape. We monitor a network of wells in the marshes and barrier islands of the Machipongo transect that we use to quantify the groundwater free surface. These wells are currently being upgraded with wireless technology. We will add new wells on the islands and marshes of the new box transects, and will have sensors that we will move between the wells to make intensive periodic measurements. We monitor tide and meteorological stations in the Machipongo watershed, and will add tide and rain gauges in the 2 new box transects. In addition, we will quantify the bathymetry and topography of the lagoons and watersheds of these new core sites.

(2) Biogeochemical and biotic characteristics of ecosystem states:

Nutrients, organic matter and physico-chemical parameters: In the coastal lagoons, we monitor water quality and sediment parameters to track the effects of changes in watershed land use on nutrient and organic matter cycling. We measure water column nutrients, total suspended solids, and light availability, and sediment organic content and nutrients along permanent sampling stations in the Machipongo box transect. In LTER V, we will add periodic measurements of these same parameters along the Metompkin and Smith box transects. We make long-term measurements of soil organic matter and nutrient content on the mainland marsh sites, and on the tidal marsh and barrier island chronosequences (see below). We will initially characterize sediment nutrient and organic matter content at permanent monitoring sites in the marshes and islands of the new box transects. Finally, the root SET measurements give an esimate of organic matter accumulation.

Plant community composition and productivity: We relate patterns of primary production and community composition to long-term changes in the free surfaces and disturbances, as well as to interannual variations in precipitation and temperature. For the tidal marshes, we determine annual production for different species at 8-16 sites across the landscape. We will add a few new sites in VCR V to have coverage in the 2 new box transects. These sites represent variation in hydrogeomorphology and susceptibility to disturbance at the landscape level for the different wetland states (high and low marsh). In Hog Island Bay, macrophyte community composition and biomass, and benthic and water column chlorophyll are determined throughout the year. In VCR V, we will add summertime peak-production estimates of these parameters in the two new focal lagoons to compare patterns across the landscape in relation to differences in nutrient loading and watershed residence time. On Hog Island, aboveground production on the dunes is determined as peak seasonal biomass every three years, and new shoot biomass for *Myrica* shrub thickets is measured every year. In VCR V, we will add new sites on Smith and Metompkin Islands, which are within the new box transects, to characterize production patterns.

Fauna: On the islands we use long-term surveys along with site-based intensive studies to understand the complex relationships between island morphology and disturbance and the distribution and abundance of vertebrate populations. *Mammals* – Our surveys include both small mammals (e.g. rice rats, *Oryzymys palustris*) and predators (e.g., raccoons, *P. lotor* and foxes *V. vulpes*). We link multi-annual surveys of multiple islands (varying in elevation), semi-annual censuses on 3 transects in Hog Island (varying in probability of overwash), intensive observations of inter-island movements (e.g., Forys and Dueser 1993) and genetic (mitochondrial DNA, allozyme and microsatellite DNA) analyses (Montcrief et al. 1997; Loxterman et al. 1998) to understand colonization, extinction and species distributions in the highly fragmented island landscape. *Waterbirds* – Monitoring colony site dynamics of selected species helps to identify the relative importance of physical processes (i.e., elevation change and erosion related to disturbance) and biological processes (i.e., predation, competition, food supply) within metapopulations (Erwin et al. 1998, in press). The Nature Conservancy has shared with us data for island waterbird colony locations from 1974-1998, and we are using these data to study the interaction of mammals and nesting birds on the VCR landscape (Erwin et al. 2001). For LTER V, we propose to add a new monitoring study to link waterbird populations with food supply in the marshes of the box transects. *Invertebrates and fish* – In LTER IV we initiated a database of benthic invertebrate populations that is coupled with the water quality surveys of nutrients, light availability, and primary producer populations. We will augment this database in LTER V, by adding survey sites in Metompkin and Smith Bays. We will also monitor tidal creek invertebrate and fish populations twice annually (spring and fall) at marsh locations on the mainland, lagoon and barrier islands of the box transects. These data will be linked with the waterbird surveys to assess long-term changes in habitat use by wading birds.

(3) Landscape patterns: We maintain remote sensing GIS databases to identify and characterize ecosystem states on the VCR landscape on annual to decadal time scales. In VCR IV, we developed a high-resolution (30 m horizontal, 5 cm vertical) GIS data layer for the terrestrial, marsh and lagoon surfaces of the Machipongo marine watershed to develop the hypsometric model (Fig. 1). We will extend this database in VCR V to include the Metompkin and Smith box transects. New PI C. Bachmann has already developed and validated a species-level map of Smith Island based on multi-season hyperspectral imagery (Bachmann et al. 2002, 2003; Fig. 19). We are also pursuing the acquisition of LIDAR data, which can give us fine-grained resolution on the vertical scale of the land surface to complement traditional satellite and aerial

imagery, and will be valuable in our landscape modeling efforts (Question C). In our synthesis efforts to date, we have identified and characterized elements of the VCR landscape that roughly correspond to land use/land cover (LULC) categories going back 28 years (Fig. 20). Despite a high probability of change at any point on the landscape, the total amounts of upland/marsh/salt water have remained relatively constant, which supports the shifting mosaic steady state theory of landscape dynamics (Bormann and Likens 1994).

(4) Fluxes:

Land-atmosphere fluxes: *Nitrogen deposition* - We will continue our long-term tracking of changes in the input of atmospheric nitrogen to the VCR. These data will be used in constructing N budgets for the ecosystems on the landscape. Available evidence suggests that the nearshore (W to E) gradients in atmospheric nitrogen deposition from the watersheds to the barrier islands are probably small (Russell et al. 2003). *Nitrogen efflux* – We will characterize N_2O emissions from the intertidal marsh at the base of Cobb Mill Creek where we are doing our detailed studies on groundwater nitrogen processing using the eddy covariance approach with a tunable diode laser trace gas analyzer. These measurements will add a new long-term dataset with VCR V and allow us to characterize "hot spots" and "hot moments" of N_2O emissions (Scanlon and Kiely 2003). Continuous, ecosystem-scale monitoring will be coupled with measurements of factors (i.e., water level, temperature, groundwater NO_3- concentrations) that could influence N_2O emissions. This will enable us to determine the processes-level dynamics that control the rate and timing of N_2O emissions so that a predictive capability can be attained and applied to other settings. *Carbon and water fluxes* – Also using the eddy covariance approach, we will continue the work recently begun in VCR IV to determine carbon and water fluxes from the intertidal marsh surface at Fowling Point. Our goal in VCR V is to augment this work with towers on the mainland upland/marsh interface and on the upland of Hog Island to have measurements in the major ecosystem types. We will use the tower for the N_2O efflux work described above at the upland/marsh interface. If supplemental funds become available, we will deploy a tower on the upland chronosequence of Hog Island. With these long-term data, we will address questions relating to carbon and water balances in the different ecosystem types, and the importance of short-term fluctuations in forcing variables (i.e. radiation, temperature, water table depth) on carbon cycling.

Watershed nutrient fluxes: To characterize the spatial and temporal variability of watershed nutrient loading into the coastal lagoons, we will (1) continue our monitoring of groundwater fluxes and baseflow nutrient concentrations in 15 tidal creeks that drain watersheds of varying size and land use (Fig. 4), and (2) continue, with greater spatial resolution, event sampling to capture storm-driven pulses of nutrient flow to the coastal lagoons. Both data sets will be linked with water quality sampling in the lagoons of the 3 box transects to capture the long-term changes in watershed-lagoon linkages.

B. Long-term experiments:

(1) Chronosequences: The highly dynamic nature of the VCR landscape has created natural experiments in which documented chronosequences represent dynamic examples of succession and ecosystem development. Two chronosequences exist on Hog Island, a series of beach ridges (dunes) and swales that have built seaward over the last 120 years, and a marsh chronosequence that has formed from a series of storm overwash events, with the oldest identified stage at least 150 years old (Fig. 21). The age structure of the landscape has been determined by historical survey maps, aerial photos and geomorphic surveys (Harris 1992). In LTER V, we will add a

third chronosequence of seagrass meadows in the lagoons that range in age from newly established (<1 year) to >10 years old (Fig. 22).

Terrestrial chronosequence – Our conceptual model for state changes on the terrestrial portions of the barrier islands shows that changes arise from both erosional and accretionary processes and are driven by disturbances and long-term changes in sea level. We monitor vegetation patterns and productivity in permanent plots and relate these parameters to a network of groundwater wells to test our hypothesis that proximity to the water table free surface and the probability of disturbance at a given position on the landscape determine biotic structure and ecosystem processes on the islands (Table 1; Young et al. 1994; Young et al. 1995a; Shao et al. 1995; Martin and Young 1997; Shao et al. 1998; Day et al. 2001; Day et al. 2004).

Marsh chronosequence – During storm events, beach sands wash across the islands and into the lagoon, establishing sediment platforms on which salt marshes develop. The newly deposited sand surfaces are unconsolidated and typically low in nutrients and organic matter. Our previous work has shown that succession on this landscape is characterized more by changes in the biogeochemistry and animal communities than in the plant community, as the marsh grass *Spartina alterniflora* dominates all sites in the chronosequence (Walsh 1998; Tyler and Zieman 1999). We sample the sites for porewater and sediment characteristics, plant biomass and production, and faunal abundance and diversity (Table 1).

Seagrass restoration and chronosequence – The 2003 NSF site review team recommended that the return and expansion of the "foundation species" eelgrass be a fundamental component of the VCR V program focus. We are collaborating with Robert Orth from the Virginia Institute of Marine Science to begin to restore seagrass in our primary lagoon study site, Hog Island Bay, and will begin seeding in fall 2006 in a 509 acre "set aside" we have obtained from the Virginia Marine Resources Commission (Fig. 23). This restoration will build on our 10-year database of patterns and process in Hog Island Bay in the absence of seagrass, and will give us the opportunity to determine experimentally the ecosystem-level effects of a rapid state change back to the original seagrass-vegetated state. We will establish a chronosequence by comparing the Hog Island Bay meadows with those recently seeded (1-7 yr old) using the same technique in South and Spider Crab Bays, just south of Hog Island Bay, and a natural meadow in South Bay, which is at least 10 years old. Water quality conditions are similar in these bays, making the sites comparable. We will make measurements of productivity, nutrient cycling, algal density/diversity and faunal densities/diversity as outlined in Table 1 and Question A2.

(2) Fertilizer experiment: Increased nitrogen loading from the watershed and airshed will likely have a significant impact on the VCR ecosystems in the coming decades. In our past work, we have conducted short-term and long-term nitrogen enrichment studies on different parts of the landscape (Day 1996; Conn and Day 1996; Weber and Day 1996; Day et al. 2004; Heyel and Day 2006). For VCR V, we propose to undertake nitrogen enrichment studies on the marsh, lagoon seagrass meadows, and barrier island a new core long-term experiment. We will expand the long-term nitrogen enrichment experiment on the Hog Island dune chronosequence to include interdunal swales (marshes and shrub thickets). A belt transect across the island marsh and upland chronosequence will be fertilized annually by aerial application, and plant productivity/species composition and soil nutrient/organic matter will be monitored in permanent plots (Table 1). Sediment nitrogen fertilization will be done in plots as part of the long-term experiment on seagrass recolonization in Hog Island Bay (see Question A2).

(3) Inundation experiment: In the 1990's we initiated two long-term experiments in our primary marsh research site at Phillips Creek that address the high marsh response to the interaction of sea-level rise and disturbance. These experiments serve as the foundation for one aspect of the shorter-term disturbance and nitrogen amendment experiments discussed in Question A1.

II. Research Questions

Ecological responses to long-term environmental change are generally characterized by non-linear dynamics at multiple scales (Scheffer et al. 2001; Peters et al. 2004). Many studies have shown threshold behavior where ecosystem change is rapid in response to progressive changes in environmental variables. Biotic feedbacks at the local scale may be responsible for some of this non-linear behavior (Peters et al. 2004). Understanding and predicting change in heterogeneous landscapes requires that we examine processes at the local level as well as fluxes of materials and organisms between adjacent ecosystems (Turner 2005). Disturbance is both a driver of change that creates heterogeneity and a mechanism by which materials and organisms move across the landscape. We address these issues for VCR ecosystems in our three synthetic questions.

A. How do long-term drivers of change (climate, rising sea level, and land use change) and short-term disturbance events interact to alter ecosystem dynamics and state change, and how are their effects modified by local processes and biotic feedbacks? Although the long-term drivers of environmental change are common across the VCR landscape, their relative importance for the different landscape units varies. For that reason, we address this question separately for the tidal marshes, lagoons and barrier islands. For example, the effects of agricultural land-use decrease for ecosystems moving seaward from the mainland toward the islands. Conversely, storm-driven disturbance effects are most important on the islands and decrease moving toward the mainland. Sea-level rise increases the flooding on tidal marshes, the tidal prism, currents and wave energy in the lagoons, and the intensity of storm disturbance on the barrier islands. By comparing multiple watersheds, tidal marshes, lagoons and islands in the VCR system, we can address both how the drivers of change and the responses to these drivers vary on the regional landscape. We address this question in two parts.

A1. ***How can the response to the interaction of external drivers be used to identify thresholds of change?*** Since the inception of the VCR LTER, we have recognized the non-linear nature of ecological change on the landscape in the context of progressive environmental change and periodic disturbance events. We continue to study progressive change within landscape units (succession) and threshold responses that result in abrupt changes to new ecosystem states.

In the **lagoons**, changing land use and sea-level rise cause variations in nutrient and light availability, that along with disturbance events, result in state changes between seagrass and algal communities. The depth of the water column and the extent to which light is attenuated by chlorophyll, suspended sediments, and dissolved organic matter in the water dictates both the quantity and quality of light reaching the sediment surface to support benthic production (Gallegos and Kenworthy 1996). Even small differences in water depth can result in a change in light availability below the threshold for seagrass growth and expansion (Lawson et al., in review). This threshold may be influenced by interannual and decadal temperature changes that make seagrasses more susceptible to increased turbidity by increasing respiratory demand relative to photosynthesis (Short and Neckles 1999; Duarte 2002). Wind-driven sediment resuspension is a key factor influencing turbidity in coastal lagoons because water chlorophyll concentrations are typically low unless the system is impacted by eutrophication (Boynton et al. 2006; McGlathery et al. in review). Lower light availability from eutrophication will ultimately feed back to reduce seagrass growth and enhance sediment resuspension. Our recent work has shown that it is necessary to understand short-term variability in the light climate, rather than relying on periodic surveys, to accurately determine the time-averaged light availability necessary to sustain seagrass growth and meadow expansion (Lawson et al., in review).

Approach: Our approach for assessing the potential for seagrass recolonization and survival is to couple high-resolution measurements of water column turbidity with a mechanistic, system-wide model that describes the amount and variability of light reaching the seafloor (Lawson et al., in review). We will use this model to forecast the potential for seagrass recovery in lagoons that differ in both geomorphology and nutrient loading. As input to the model, we will quantify the variation in the land and sea-level free surfaces in the lagoons. We will conduct detailed bathymetric surveys using GPS coupled to digital fathometry in the lagoons of the new box transects, Metompkin and Smith Bays, just as we have done for Hog Island Bay (Oertel et al. 2001), and will install tide gauges (see Core measurements). We will deploy an Acoustic Doppler Profiler (ADP) at different times in the lagoons to obtain high-resolution data on currents, wave height, and turbidity. These field data and the bathymetry will be used to calibrate the hydrodynamic model that will estimate sediment resuspension under different wind and tidal conditions, which will then be used to determine downwelling irradiance at the sediment surface. The model will run with future sea level and nutrient enrichment scenarios, and disturbance probabilities, to test the effects of these drivers on potential seagrass habitat in the different lagoons and how this state change could propagate across the subtidal landscape.

For **tidal marshes**, the ultimate control over state change is the relative rise in sea level, whether from rising sea level itself or from decreases in surface elevation through lack of sediment supply or organic matter accretion. Because tidal marshes occupy a relatively narrow range in the vertical relationship of the free surfaces along the hypsometric curve (Fig. 1), even though the surface area is considerable, they are particularly vulnerable to changes in the relative elevations of the land and sea level. Thus far we have conducted most of our observations and experiments on inundation-disturbance interactions in what is presumed to be a "stable state" where disturbance results in return to the same state via succession because a threshold was not reached (Hayden et al. 1991; Tolley and Christian 1999; Brinson and Christian 1999). In VCR V, we will emphasize boundaries between states ("unstable states") where disturbance can result in thresholds being reached and irreversible change (e.g., high marsh to low marsh). The concept of "unstable state" on the marsh recognizes that the aging (developmental or maturation) process can foster sensitivity to disturbance (Ulanowicz 1980; Gunderson and Holling 2002), as for example, high marsh soils become peaty and susceptible to wasting and inundation from sea-level rise. The conditions created by increased flooding, high salinity, and accumulation of sulfide are major stressors in salt marshes (Adams 1963; Mendelssohn and McKee 1988). It is the interaction of these two factors (age and stressors associated with sea-level rise) that promote an unstable state. We will use nitrogen enrichment as a treatment to observe the effects of stress relief on the recovery from disturbance by wrack. The expected outcome may vary for the different ecosystem states and associated species as suggested by Emery et al (2001). Monospecific stands of *S. alterniflora* would likely increase standing stock biomass, thus maintaining the dominance of that species, whereas more nutrient poor and irregularly flooded portions of tidal marshes may undergo changes similar to the formation of hummock and hollow patterns that we have observed (Blum and Christian 2004). In marshes where the integrity of belowground biomass is essential to maintaining a free surface close to that of sea level, a shift to aboveground biomass may actually make a state more vulnerable to change (Valiela et al. 1976; Koch et al. 1990; Bradley and Morris 1990). The reduction in wetland elevation from collapse associated with dieback has the net effect of accelerating the relative rate of rising sea level.

Approach: We have used (1) the "space for time" approach by making observations of similar structure and function across two or more states, and (2) long-term field experiments involving altered hydroperiod to test our state-change model for marshes (Fig. 23). We will continue these, but will do so in a more strategic manner that builds upon the observations over the last 10 years. In VCR V, we will examine the interaction of disturbance by wrack and stress relief by nitrogen amendments across the low to high marsh gradient under three conditions: (1) In the high marsh at Phillips Creek, where we have an ongoing experiment since 1998 of increased frequency of inundation; (2) In the center of states and the transitions between states along the low to high marsh gradient in replicate transects in marshes in our box transects. Special attention will be given to separate the responses of conditions within the high marsh: (a) *Juncus roemerianus* vs. the co-dominants of *S. patens* and *Distichlis spicata*, and (b) peaty vs. non-peaty soils; and (3) In an area where we have been monitoring a significant die-off in the low marsh since 2004. Treatments will be replicate plots of simulated wrack-induced die-off, wrack-induced die-off with nitrogen, and controls with and without nitrogen, all with attention to the effects of clonal integration (Pennings and Callaway 2000). The minimum response variables will be plant cover (nondestructive sampling) and biomass harvest by species in years 1, 2, and 3 following treatments. We will observe herbivory as a possible response to nitrogen enrichment (Pennings et al. 2001). Additional variables that will be measured periodically include: relative elevation, soil salinity, loss on ignition, tissue C:N, below-ground biomass, bulk density, sediment nitrogen, and an index of hydroperiod. Results of these observations and experiments across wetland ecosystem states will be particularly important in modeling effects of wrack-generating storm frequencies and intensities based on historic records.

On the **barrier islands**, disturbance from storms is an important and variable driver across the barrier island terrestrial communities. Storms modify the land surface and water table and influence vegetation patterns which feed back to control faunal distributions. Wind damage, sand deposition represented as overwash fans, flooding, and salt spray also result from storms. There is significant interaction among these drivers. For example, elevational changes due to sand deposition or erosion lead to changes in flooding effects and access to fresh water. The discrete distribution patterns of species and ecological communities indicate threshold responses to drivers are a common occurrence on the barrier islands. There is predictable spatial variation across the island landscape due to microtopographic influences (e.g. dune vs. swale) and to the inverse relationship between disturbance magnitude and frequency and distance from the ocean shoreline. Species distribution patterns and, therefore, communities at different positions on the landscape are closely related to their proximity to the ocean and the probability of disturbance (Fahrig et al. 1993). Thus the endpoints of succession may vary considerably across the island landscape. In addition, storm-related effects vary among the islands due to island size and topography, but also due to the storm position along the 110 km chain of islands. Overwash areas and geomorphic changes of beaches are non-randomly distributed along the entire VCR, with certain areas being somewhat predictable over time (e.g., the accretion/erosion of Hog Island). More unpredictable are disturbances such as fires (Parramore Island in 2004) and sporadic predator activities. Interactions between vegetation and topographic features have been recognized for barrier islands (Godfrey et al. 1979). These interactions may lead to state change (e.g., sand accumulation among beach grasses leading to dune formation) and to emergent, predictable patterns across the island landscape (Stallins and Parker 2003).

Approach: We will continue to monitor plant community composition/productivity and soil nitrogen/organic matter in permanent plots along the chronosequence on Hog Island (Table 1). These data have been and will continue to be supplemented by intensive measurements across the VCR landscape (e.g., permanent plots on Parramore Island). To provide a more appropriate landscape-level perspective, we will add new plots on Metompkin and Smith Islands in our new box transects. Photographic records over a 50-year period are available to examine the frequency, location, and size of overwash areas and sand spit changes. In addition, existing hyperspectral imagery will be related to LIDAR-determined spatial variations in elevation across the entire barrier island landscape. Thus, spatial variations in selected species and community distribution patterns will be related to landscape position to identify areas of active change and to predict areas most vulnerable to change (see Core Measurements).

A2. ***How do biotic feedbacks modify the response to external drivers by maintaining a stable state or facilitating a change to another state?*** Important feedbacks in coastal barrier ecosystems include (1) vegetation-sediment interactions that affect turbidity and erosion rates in marshes and lagoons, and (2) trophic interactions that influence the establishment and expansion of vegetation in marshes, uplands and lagoons. Positive feedbacks may be responsible for allowing alternate states to occupy similar free surface positions.

In the **lagoons**, the biotic feedbacks that influence the success of seagrass establishment and growth include the vegetation effects on reducing sediment resuspension and the potential facilitation of seedling establishment by benthic fauna. Seagrasses influence hydrodynamics by reducing water current velocities through extraction of momentum and increasing the thickness of the benthic boundary layer (Paterson and Black 1999; Jumars et al. 2001; Folkard 2005); this both increases particle deposition and reduces resuspension. Increased sediment nutrients may stimulate growth and enhance the positive feedback between seagrass biomass and reduced sediment resuspension. In addition, the onuphid tube-building polycheate *Diopatra cuprea*, which is abundant in Hog Island Bay and throughout North American east coast lagoons (Mangum et al. 1968; Thomsen and McGlathery 2005), may facilitate seagrass establishment by entraining flowering shoots or seeds (Harwell and Orth 2001). A state change from algae to seagrass will have system-wide impacts because these benthic primary producers play key roles in determining rates and patterns of primary production and nutrient cycling (Viaroli et al. 1996; McGlathery et al. 2001) and in trophic interactions (Lepoint et al. 2000; Norkko et al. 2000; Thomsen and McGlathery 2005). Variation in the rates and dominance of these processes as primary producer communities change, will ultimately determine the fate and retention of watershed nutrients as they pass through the lagoon "filter" to the open ocean. As the community shifts to seagrass dominance, we expect the retention time of watershed nitrogen in the lagoon to increase.

Approach: In the large-scale recolonization experiment in Hog Island Bay (Fig. 22), we will have treatments within each replicate 1 acre plot to test for effects on recruitment and growth of: 1) nutrient enrichment and 2) presence/absence of *Diopatra cuprea*. In addition, we will initiate a second experiment to test the effects of patch size (4 m^2, 40 m^2 and 400 m^2) on seedling establishment and growth. *Field measurements* – To determine the effect of seagrass on resuspension events, we will relate seagrass biomass and growth parameters (shoot density and biomass, canopy height, leaf-specific growth) with measurements of light attenuation, suspended sediment concentration, and flow velocity (using the ADP). Both sets of measurements will be done in the middle of the patches of restored seagrass and at a nearby location with a bare seabed. We will also make periodic measurements of these parameters at our sites along the seagrass chronosequence. To evaluate the biogeochemical consequences of the state change from algae to seagrass, we will measure production/respiration ratios (P/R) and will make measurements of key nitrogen cycling processes (denitrification, mineralization, nitrogen fixation, benthic fluxes) as we have done previously in this area under its current algal-dominated state (Table 1). Thus, we will follow the full trajectory of the state change from benthic algae to seagrass, and will compare these data with periodic measurements made in the chronosequence sites. In addition, we will quantify the algae (macroalgae, epiphytes, benthic microalgae) within each sampling plot and will continue our monitoring of benthic invertebrates through the seagrass recolonization period to assess changes in faunal abundance and diversity in vegetated and unvegetated sites (Table 1). We will make annual isotopic surveys of key functional groups in these meadows and in the chronosequence meadows in the adjacent southern lagoons. *Modeling* – The light requirements of seagrass (Duarte 1991; Zimmerman et al. 1995; Dennison et al. 1993) will be used to model seagrass response to both chronic and episodic light limitation and to changes in temperature (as it affects P/R). We will develop a seagrass population dynamics model that will account for seagrass growth through a logistic term (Olesen et al. 1994). The lateral spreading (i.e. encroachment) of seagrasses will be modeled as a diffusion process (Okubo 1989) to account for the diffusive nature of the dispersal process. The ecosystem carrying capacity and the diffusion coefficient will be expressed as a function of the water quality (turbidity). We will also consider patch dynamics as the spatial extent of the restored seagrass meadows increases (Bell et al. 1999).

In the **tidal marshes**, positive feedbacks between vegetation structure and vertical sediment accretion (Christiansen et al. 2000; Leonard et al. 2002; Morris et al. 2002) may provide the mechanism by which tidal flats become vegetated as low marsh and vice versa. Flats and marshes adjacent to the tidal flat – low marsh transition are likely to be among the most vulnerable to change (Erwin et al. 2004), leading to the question "What controls the dynamics of the balance between intertidal flats and intertidal tall *S. alterniflora*? " If low marsh expansion into intertidal flats is limited by the vigor of plants, nitrogen amendments should facilitate this process and result in increased growth rates of *S. alterniflora*, leading to greater biomass and density relative to control areas. Morris et al. (2002) found increased rates of sediment accumulation in N-treated plots relative to controls in South Carolina. This positive feedback is limited by the availability of sediment, which depends on the characteristics of the substrate (Sanford and Maa 2001) and the presence of lagoon vegetation (Cappucci et al. 2004) (Fig. 24).

Approach: Experiments will be conducted along a tidal flat - low marsh transition to determine what controls the dynamics of this margin. A transition proximal to our seagrass test beds with a gradual rather than a step change in elevation from tidal flat to marsh will be chosen for the experiment. Nitrogen will be added to marsh-edge plants to stimulate vegetative growth. By working along the marsh-flat fringe, availability of propagules can be ruled out as a limiting factor to marsh colonization. Simultaneous measurements of flow and turbidity within and outside of the seagrass beds at the Hog Island Bay restoration site will be made to assess the role of lagoon-bottom vegetation in limiting sediment availability. These observations will be used to develop empirical relationships that will be incorporated into our process-based hydrodynamic model to simulate sediment transport at the tidal flat-low marsh transition. The model will be used to investigate the sensitivity of the system to changes in sea-level, climate (temperature, storminess), and land use (increased nutrients) and to determine whether non-linear patterns and thresholds exist in the response of this transition on the scale of decades and longer.

On the **barrier islands**, our past experiments and observations have identified potential biotic feedbacks among plant community structure, the abundance of predatory mammals and nesting patterns for colonial waterbirds (Erwin et al. 2001). In general, physical disturbances such as storms open up new bare-ground nesting habitats for many species of waterbirds of state and federal concern, but reduce vegetation cover that mammals require. For VCR V, we will build on our long-term monitoring of waterbirds and mammals to define the relationships between vegetation, especially relative to landscape variations across several islands of the VCR. Our results to date suggest a reciprocal relationship between certain breeding waterbirds and predators (Erwin et al. 2001), however, much work remains to try to explain how island size, structural complexity, and disturbance events affect both the mammalian and waterbird communities. We will quantify (1) spatial variations in predator abundance and the impact on nesting patterns of colonial waterbirds across the VCR landscape (2) temporal patterns of predator movements, e.g., recolonization rates to islands after trapping and removal of animals, and (3) how predator presence is influenced by vegetation patterns.

Approach: We will extend testing of the inverse relationship between predator abundance and the number and composition of breeding waterbirds found on an island. Colleagues at the College of William and Mary currently are analyzing historical aerial imagery and shoreline maps to test the hypothesis that changes in avian habitat suitability for selected species may account for the changes in species abundances over the past 30 years. We will extend our mammalian predator surveys to provide a complementary test of the role of predation in causing these changes in avian abundance. We will use a variety of trapping, tracking and scent-station techniques to monitor the occurrence and activity of mammalian predators relative to avian colony or nesting sites. Further we will relate predator activity to vegetation patterns, including patch size and distance to extensive woody vegetation. We also will continue trapping and removing selected predatory mammals from some islands and monitor their recolonization rates. Probability of recolonization will be related to proximity to the mainland or to the nearest known source of predators.

B. How do fluxes of organisms and materials across the landscape influence ecosystem dynamics and state change? In LTER V, we are adding studies of the horizontal fluxes of materials (sediment, nutrients) and biota (organisms, propagules) between ecosystem states to our research on the vertical free-surface component within states (Fig. 3). These linkages are critical to develop an understanding of patterns and dynamics at the landscape level. We focus on the key fluxes of groundwater nutrients from mainland watersheds to coastal lagoons, sediment transfer between lagoons and intertidal marshes, water exchange between lagoons and the coastal ocean, and seed transfer via birds among the barrier islands.

B1. What controls the variability and long-term pattern of nutrient loadings from VCR watersheds to the coastal lagoons?

The flux of groundwater from coastal watersheds, and atmospheric deposition from the larger airshed, influence the delivery of nutrients and organic matter to coastal lagoons (Giblin and Gaines 1990; Paerl 1995, 1997; Valiela et al. 2000). Land use and land cover within a watershed are important determinants of water and nutrient transport because they influence surface runoff, groundwater recharge, evapotranspiration, groundwater nutrient concentrations, and atmospheric aerosal production. Once nutrient-enriched groundwater reaches the riparian zone, local processes can reduce or remove nitrogen before it reaches the coastal lagoons (Denver et al. 2003). Our knowledge of the impacts of nutrient enrichment on coastal lagoons is limited compared to deep estuaries (Boyton et al. 1996; Nixon et al. 2001; McGlathery et al., submitted). The multiple watershed-lagoon connections of the VCR allow us to characterize how spatial variation in land use influences nutrient loading to coastal lagoons. This, coupled with our studies of the influence of water residence time on nutrient processing and retention (Question B2), give us an excellent opportunity to achieve a synthetic understanding of eutrophication effects on these important land-margin ecosystems in the coming decades.

Approach: Nutrient loading from watersheds of different sizes and representing a variety of land uses will continue to be estimated from the tidal creek monitoring (Fig. 1; Chauhan and Mills 2002; Mills, et al. 2002). We will build on this monitoring to include direct groundwater injection into the lagoons. In addition, we will obtain annual nutrient discharges for the streams in the watersheds of the box transects from a stage-discharge relationship developed for each stream. Measurements of precipitation and evapotranspiration will be made in the watersheds of the three box transects to estimate groundwater transport by the water balance approach. We will use groundwater piezometer nests in the upland areas immediately above the marshes and at several locations within the marshes to estimate nutrient fluxes. Head gradients (horizontal and vertical) determined from these piezometer nests will be used to evaluate groundwater flow paths in the marsh. In addition, we will deploy seepage meters to determine direct discharge of groundwater to the lagoon. Cobb Mill Creek, adjacent to our new research facility, is our primary site for evaluating the transformations of NO_3^- and dissolved organic nitrogen (DON) in discharging groundwater. Here we have observed very high removal of NO_3^- from groundwater discharging to the streams by a narrow band of sediments and bank materials (Chauhan and Mills 2002; Flewelling et al. in prep; Mills et al. 2002). We will continue and expand these studies to include measurements of denitrification (Table 1). We will determine if mineralization of DON occurs in the creeks, or if that process is one that is largely limited to the lagoons. We will also continue monitoring "hot spots" of nitrogen loss as pulsed N_2O emissions that occur in hydrologically dynamic mixing zones at the marsh-upland interface (see Core Measurements).

B2. How does water residence time influence the patterns of production, and the processing and retention of nutrients in coastal lagoons?

The flux of water and its constituents within the lagoon influences nutrient retention time and ultimately the transport of watershed nutrients to the coastal ocean. It also influences the dominance of benthic vs. pelagic production in response to nutrient enrichment, with benthic producers typically favored in systems with short residence time and phytoplankton dominating in systems with long residence time (e.g., Valiela et al. 1997). Typically within coastal barrier lagoons, there is high spatial variability in water residence times as a result of the lack of riverine input, limited exchange with ocean water through barrier inlets, and extensive shallow subtidal flats (Oertel et al. 2005). While we have a general understanding of how eutrophication in lagoons causes a change in plant functional groups (Sand-Jensen and Borum 1991; Duarte 1995), and associated fauna (Henriksen et al. 1980; Gray 1989), we do not have an adequate understanding of how these responses are influenced by residence time (Nixon et al. 2001).

Approach: *Hydrodynamics* –We will continue to refine our hydrodynamic model for Hog Island Bay, as well as apply it to Metompkin and Smith Bays in the new box transects. The different hypsometries of these three lagoons will be reflected in differences in water residence times and will provide valuable comparisons. We will use data from periodic deployments from the ADP to calibrate the models. We will also determine the repletion pattern for the coastal lagoons using bathymetry data and flow data available from ADP deployments. This is a general metric that distinguishes between water that is regularly exchanged with the coastal ocean ("repletion" water) and water that sloshes back and forth ("residual" water) with each tide. *Process measurements* – Annually, during mid-summer peak production, we will measure the following key variables as indicators of response to nutrient loading in the lagoons of the box transects: the ratio of benthic P/R, net ecosystem metabolism (NEM), denitrification, and sediment – water column nutrient fluxes. We will use the same methods for NEM, denitrification and benthic fluxes as we have used in our previous work in Hog Island Bay (Table 1; McGlathery et al. 2001; Tyler et al. 2001, 2003; Anderson et al. 2003). We will use a new eddy correlation technique to measure oxygen exchange across the sediment – water interface to calculate benthic P/R, which is done under in situ conditions and integrates fluxes over a large (20 – 100 m^2) spatial scale (Berg et al. 2003; Berg et al. in review). We will relate these measurements to the plant and animal community composition (see Core Measurements).

B3. How do land-atmosphere and wetland-lagoon fluxes of organic and inorganic material influence the vertical accretion of tidal marshes in relation to sea-level rise?

Tidal marshes must vertically accrete to keep pace with rising sea level. Marsh accretion depends on delivery and storage of inorganic (sediment) and organic (carbon) material. Horizontal fluxes of sediment in tidal creeks and marsh surface flows are responsible for delivery of most inorganic material to the marsh surface, particularly the low marsh (e.g., Christiansen et al. 2000). Storage of organic material depends strongly on vertical fluxes of carbon and on partitioning of carbon to above and below ground pools. Vertical carbon fluxes can be estimated by net ecosystem exchange (NEE) measurements and are influenced by tidally induced variations in atmosphere-water and atmosphere-sediment exchanges (Fig. 25) as well as rates of decomposition (Blum and Christian 2004). Rainfall runoff has the potential to transport organic and inorganic material from the marsh into tidal creeks (Torres et al. 2003), where it may be exported or redistributed back onto the marsh. Developing a budget for organic and inorganic material on tidal marshes from which to assess net rates of accretion requires quantification of NEE and its partitioning above- and belowground and fluxes of material in and out of tidal channels. Marshes with more well developed channel networks may have higher export rates than those with few channels (Ganju et al. 2005). And sediment supply, from headward erosion of tidal creeks or from the lagoon bottom, will influence import rates. A return to a seagrass-dominated lagoon bottom may reduce sediment supply to tidal creeks and thereby decrease rates of inorganic material accumulation on tidal marshes.

Approach: We will measure NEE using eddy covariance to establish the vertical fluxes of carbon. Aboveground organic carbon will be determined from end-of-growing-season clip plots and will be used to estimate partitioning to belowground pools by difference (NEE – aboveground carbon). SET, root SET, and marker horizons, like those used on lagoon and other mainland marshes, will be used to determine land surface elevation changes and accretion (Cahoon et al. 2002a,b). Time series measurements of flow and turbidity will be made in a tidal creek to assess horizontal fluxes of material during fair-weather and storm conditions, including measurements of the concentration of dissolved and particulate carbon. These results, together with previous work on marsh depositional processes (Christiansen et al. 2000) and organic matter decomposition (Blum 1993, Blum and Christian 2004, Thomas and Blum, in review), and ongoing measurements of marsh elevation change (Erwin et al. 2004), will be used to begin to develop sediment and carbon budgets for the marshes. A numerical model will be used to simulate tidal flow and related organic carbon fluxes through the marsh channel network. The in situ measurements and modeling results will be combined to evaluate the linkage between NEE, export of organic material from the system, and the morphological attributes of the marsh.

B4. What is the role of seed fluxes via bird dispersal in influencing vegetation community structure and patch dynamics on the barrier islands?

Our work, and that of others, on the vegetation patterns of barrier islands has focused primarily on the influence of hydrologic and physical stresses, e.g. salt spray (Ehrenfeld 1990; Young et al. 1992, 1994; Martin and Young 1997). We have identified key relationships among the terrestrial flora and fauna that provide models for investigating landscape level hypotheses, especially interactions among patches of varying size and distance. However, there has been little attention paid to seed fluxes between patches with birds as important vectors in temperate systems, particularly barrier islands, compared to the tropics (Wenny and Levey 1998; Tewksbury et al. 2002). Frugivorous birds such as gray catbirds, yellow-rumped warblers, robins, cedar waxwings and others are common Atlantic coastal breeding birds as well as migrants. It is widely recognized that the distribution patterns and ranges of many fleshy fruit-bearing shrubs and trees are, to varying degrees, dependent on the dispersal dynamics of birds (Estrada and Fleming 1986). The geographic location and topographic configuration of the VCR provides excellent opportunities for testing ideas related to patch sizes and connectivity, bird species migration patterns, and feeding specificity by different bird species. Barrier island plant communities differ considerably from corresponding mainland communities, presumably due to filtering, and bird dispersed species are more abundant on the islands (Ehrenfeld 1990). Joy and Young (2002) analyzed the seed content of bird guano and determined that migrating songbirds may be essential to the establishment and maintenance of fleshy-fruited species on barrier islands. Among the VCR islands, Smith Island has the highest species richness for woody species, despite being ranked fifth in total area. We believe that this may be related to island position at the southern tip of the Eastern Shore. Migrating passerines may use the island as a staging area for crossing the Chesapeake Bay. Variations in size and position of the VCR islands relative to the mainland, when coupled with the variability in topographic features among the islands may result in patch interactions across multiple scales of the regional landscape.

Approach: We will relate spatial variations in seed fluxes among the islands and mainland to patch size, plant species richness, connectedness, and species distribution patterns. We will quantify plant species richness in patches of different sizes relative to the frequency of birds of different seed specialization. We will determine if an “inverse peninsular effect” exists along the barrier islands, where the concentration of migrant birds funneling to the tip of the peninsula (e.g. at Smith and Fisherman Islands) result in both higher bird species diversity and/or densities and tree species diversity and densities. Monitoring and experimental measurements will address patch interactions among migrating birds, fruit dispersal, and plant distribution patterns. Standard phytosociological methods will be used on fixed transects along the mainland – island gradient. Permanent forest/shrub plots will be used to establish species richness and diversity. Within-habitat variability and interhabitat differences will be assessed using shorter perpendicular transects. Additionally, to examine patch size/diversity relationships, barrier island forest patches of different sizes (ranging from a few hectares to > 100 ha) will be sampled for both species and structural diversity. The effects of migrating birds on seed transport will be analyzed using artificial perches with automated cameras, and fecal seed collectors will be operated during migration (August – October), and winter (December – February). Fixed-radius (25 m) point count methods will be used in patches of different sizes during the fall migration to assess bird abundance and diversity in conjunction with associated plant diversity.

C. In the future, what will be the composition and structure of the landscape and what processes will drive ecological state change? We are using two types of models to synthesize our long-term monitoring and experiments and shorter-term process studies to address the causes and consequences of state change on the landscape. The goal of this modeling effort is to be able to predict the non-linear and threshold responses of the ecosystems to long-term environmental change and short-term disturbance events.

Landscape modeling: Previous VCR efforts have focused on developing various conceptual and mathematical models of limited parts of the landscape. A conceptual model for intertidal marshes related the land and sea-level free surfaces to state change (Brinson 1993; Brinson and Christian 1999). Biophysical modeling identified the sensitivity of relations in *Myrica* shrub thicket water to environmental change (Shao et al. 1995). An integrated study of remote sensing and GIS related thicket distribution to shoreline changes among the VCR islands (Shao et al. 1998). More recently, a hydrodynamic model was developed to assess the effects of environmental variables on seagrass recolonization (Oertel et al. 2005; Fugate et al., in review; Lawson et al. in review). These models demonstrated a need to integrate the diverse spatial and temporal information into a regional model for the VCR. Using the information generated by VCR I-IV, we plan to develop a mechanistic, process-based ecological basin model to assess the relationship between land, sea, and groundwater free surfaces and their effects on the landscape (e.g., wetland, lagoon, island habitats). The general goal is to build and use a landscape model to understand the coupling between hydrologic and geomorphic free surface changes and the ecological responses of state change on scales that vary from local to the entire reserve. Effects of heterogeneity on ecological functions are expected at larger scales (Strayer 2005). Our specific objectives are: (1) to predict landscape changes based on remote sensed imagery and historical water inputs; (2) to build an improved multiple-scale process ecological model for the lagoons, marshes, and uplands to understand regional habitat change over the long term, and; (3) to predict the long-term response to cumulative changes, such as sea-level rise, channel development and vegetation colonization, and disturbance events.

The model will integrate physical and ecological processes over a grid of landscape cells. Each cell contains a unit ecosystem model that represents a certain habitat type and incorporates location-specific algorithms to quantify fluxes of materials between cells (Hopkinson et al. 1988; Fitz et al. 1996). This type of landscape model combines physical and biological information at different scales into three modules: hydrodynamic, soil, and plant productivity. The three modules are dynamically coupled via a unit ecosystem model as described by Reyes et al. (2000, 2004). The model also contains a habitat-switching module that tracks habitat characteristics for each land parcel within the model boundary, such that long-term processes and ecological responses can be examined. The model will assess the spatial correlation between groundwater and land surfaces, associated sediment load and the interaction with the present plant communities. The spatial modeling effort includes the collection, organization and synthesis of environmental data, combined with the development, update and implementation of the landscape simulation model that incorporates a shallow-water hydrodynamic module, a soil-building component to account for elevation changes (Rybczyk 1996; Rybczyk et al. 1998), and a vegetation module that computes above- and belowground biomass (Sklar and Costanza 1991). An additional module contains the algorithms that determine habitat change (named "Habitat Switcher") according to the computed environmental conditions. For example, the main habitats present will be determined by a combination of elevation, sea level, flooding regime and vegetation biomass (Costanza et al. 1990; Brinson et al. 1995).

Network modeling: Ecological network analysis is an effective tool for evaluating both the biogeochemical and trophic consequences of state change (Finn 1976; Wulff et al. 1989; Christian et al. 1996; Christian 2005). Network analysis helps to examine import vs. recycled nutrients, the interactions and relative roles of different compartments in the passage of material, the distribution and importance of feedback loops, and higher order indices of global attributes. We have used ecological network analysis at the VCR to evaluate nitrogen cycling within mainland marshes (Thomas and Christian 2001) and the lagoon (Voss et al. 2005) and also the food web structure of salt marsh ponds (Dame 2005). We will expand this effort to include states across the entire VCR landscape to provide assessments of nitrogen cycling relative to the contributions of biomass storage, recycling, physical and biotic exchanges. We will build annual nitrogen networks accounting for ecosystem states within the mainland, lagoon and islands using common rules for model structure and variable values similar to those used by Thomas (1998) and Thomas and Christian (2001). These networks will then be connected to assess interactions among neighboring states. Information on each state will come from members of the LTER team and related literature. Analysis of networks will be performed using WAND (Allesina and Bondavalli 2004), a Windows version of NETWRK4, Ulanowicz 1987).

III. Cross-site activities

Since the VCR is such a diverse landscape, we have the opportunity for cross-site comparisons with many sites in the LTER network. D. Young is participating in the LTER funded effort: "Shrub Dynamics: A Cross-Site Examination for Patterns and Consequences." *Myrica* shrub thicket expansion on the VCR barrier islands provides an excellent contrast to the shrub studies at many of the relatively arid LTER sites in western North America. The workshop goals are to write a synthesis manuscript and an NSF proposal for further research on shrub expansion, to create an updated bibliography on woody plant encroachment, and to develop a shrub dynamics database that will be available to all LTER sites. We are also participating in a new study with GCE and FCE that focuses on isolated uplands that are common in coastal areas. We anticipate these will represent areas of increased biodiversity in the coastal landscape, akin to the role of isolated wetlands in the terrestrial landscape. We will determine whether the biodiversity "boost" in animal and plant diversity is similar (and similarly related to upland island size) across these different coastal landscapes. J. Fuentes and his students are continuing eddy covariance flux measurements to determine net ecosystem exchange in the mangrove forests of FCE; these measurements are similar to those being conducted in the VCR tidal marshes and provide an excellent comparison of patterns of primary productivity in these two important wetland types. R. Christian continues to work with D. Moorhead and K. McKenna at MCM to study Antarctic microbe-dominated food webs of the Dry Valley Lakes. Finally, L. Blum is involved in a cross-site comparison of tidal marsh organic matter accumulation and a comparison of microbial community structure and ecosystem function in tidal marshes.

SYNTHESIS AND SIGNIFICANCE

The research we propose for the VCR addresses the dynamic nature of coastal barrier landscapes in the context of long-term environmental change and short-term disturbances. Table 2 synthesizes how our long-term observations and experiments, shorter-term studies and modeling address long-term change in this coastal barrier system. We have a history of strong interdisciplinary research addressing questions that integrate physical (climatology, meteorology, hydrology, oceanography), ecological, and modeling approaches (Supplemental Document 3). This is particularly important as we consider fluxes both between and within landscape units. We are also committed to using new technologies to improve and expand our measurements of key variables (e.g., tunable diode laser trace gas and laser-based carbon isotope analyzers for land-atmosphere gas fluxes, subtidal sediment-water gas exchange by eddy correlation, compound-specific isotopes for foodweb analysis). We have been successful in leveraging LTER funds to support our research (Supplemental Document 4).

In addition to a general understanding coastal barrier systems, our research addresses globally important ecological questions. Human populations are altering ecosystems at unprecedented rates, and this demands that ecological science provide the fundamental knowledge to understand and manage ecosystems (Palmer et al. 2004). The National Academy of Sciences identified a number of ecological "grand challenges" (NRC 2000, 2003) to address these changes, which are also echoed in the conceptual domains of current LTER planning activities. Research at the VCR addresses many of these 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. We address the interaction of slow progressive change and episodic events in structuring ecosystems (Turner et al. 2003), ecosystem function in a heterogeneous landscape (Lovett et al. 2005; Strayer 2005), and threshold dynamics and feedbacks influencing ecological change (Scheffer et al. 2001; Peters et al. 2004). We work at a wide range of spatial and temporal scales to address these issues.

The VCR is a relatively pristine coastal system of shallow lagoons and barrier islands that can be compared with other LTER sites to understand how coastal systems in general respond to drivers of global change. Human land use is largely agricultural, but pressures from neighboring metropolitan areas are increasing development. Climate change will impact freshwater and nutrient delivery (Scavia et al. 2002), but likely in a different way than for deep, river-fed estuaries. With time the pressures of human activities in the watersheds will increase, and we will be able to compare their effects on the responses of the reserve ecosystems. Thus, our basic understanding of how these ecosystems respond to change will be used to predict change in future global change scenarios and inform management decisions at a variety of scales. What also makes the VCR system unique is the extremely dynamic nature of the landscape. This gives us the opportunity to address how frequent disturbance events propagate across the landscape and interact with slower environmental changes to influence long-term ecosystem dynamics.

We have a strong partnership with The Nature Conservancy, which puts us in an excellent position to provide a solid scientific foundation for making decisions related to planning, management, and restoration (see letter in Supplemental Document 5). Together we address the challenging issues of how to manage ecosystems that have the potential to change rapidly and episodically, and how to balance species conservation and ecosystem functioning. And together we work on a large-scale ecosystem restoration program to return the lagoon systems to their former seagrass-dominated state, and on a long-term monitoring program of waterbirds and nesting success. Through this partnership we can serve as a model for other dynamic coastal barrier systems. On a global scale, recent efforts with the Global Terrestrial Observing System, the Integrated Global Observing Strategy, and the Global Environmental Outlook - UNEP Coastal Community of Practice have identified the need to link terrestrial, wetland and aquatic observations. The VCR is a being considered as a potential sentinel site for these coastal observations, as a member of both the LTER and Man and the Biosphere networks (Mazzilli and Christian 2006).

SECTION 3: SITE MANAGEMENT

Organization and Oversight: The VCR LTER has a hierarchical organization with a Lead-PI (K. McGlathery), an Executive Committee and a PI Committee-of-the-whole. McGlathery is the lead PI and is responsible for project management and administration. She has been involved in the LTER program for 10 years, and took over as lead PI in 2004, after many years of on-the-job "leadership training" within the VCR. The VCR Executive Committee consists of the Lead PI, other signatory PIs (P. Wiberg and J. Porter) and rotating PIs who serve as research group leaders for specific research topics. P. Wiberg is an oceanographer specializing in sediment transport processes and has been involved in the LTER program for over 12 years. She brings a strong physical sciences component to the VCR Executive Committee. J. Porter is full time on the LTER program and formerly served as lead PI (1998-2000). He has been involved in the program since its inception and is completely versed in project management and administration. Both K. McGlathery and J. Porter have served on the LTER Network Executive Committee. The lead PI and Executive Committee have the primary decision-making responsibilities for the project, with the Lead PI having the final say on budgetary issues. They are also responsible for project communication, including timely annual reports to the NSF, facilitating annual scientific meetings, intersite and international activities, weekly PI meetings and long-term research planning sessions. K. McGlathery is the corresponding PI for interactions with the LTER Network Office and LTER Coordinating Committee.

During VCR IV, we hired a Ph.D.-level site manager (A. Schwarzchild) at the new Anheuser Busch Coastal Research Center (ABCRC). He reports to K. McGlathery, and has day-to-day responsibility for supervising three full-time research technicians and a part-time fiscal technician. The technical staff and the Executive Committee have monthly meetings to track progress and set research goals.

Communication: During the academic year, PIs in Charlottesville and the site manager meet weekly (monthly during the summer) to deal with research planning, general administrative issues, advice and consent regarding policies and procedures, and to respond to NSF initiatives and Network and Intersite activities. PIs from other institutions may participate in the meetings via videoteleconferencing. The minutes of these meetings are sent by email to all PIs and are published on the VCR website in a secured PI-only section. We hold an annual "All Scientists" meeting for VCR researchers, which we will now hold in the new field station. We invite our collaborators from The Nature Conservancy and other affiliated institutions to the meeting. At this meeting, VCR PIs, collaborators and students give formal presentations (talks or posters) of research findings, and we have smaller group meetings to address specific research issues. Routinely during the year, smaller groups of PIs meet in informal workshops to work on collaborative research projects. For example, several PIs have met to synthesize patterns of primary production in response to climatic variables in all the VCR ecosystems.

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 systems (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. During LTER IV, we expanded our use of Internet conferencing to allow investigators and staff at multiple sites to participate in meetings.

New Investigators: During VCR V we will be losing several long-time investigators through retirement. However, we will be adding several new PIs based on perceived needs and the recommendations of the NSF 2003 site review. Specific additions include E. Reyes (ECU), who is a landscape modeler with extensive experience in modeling the Gulf Coast. He was recruited to aid us in achieving a synthetic and predictive understanding of our landscape through process-based landscape modeling. S. Fagharazzi (FSU) was recruited to do the hydrodynamic modeling for the coastal bays and to work with current VCR researchers on sediment transport between the lagoons and marshes. He has been working at the site for the last 2 years. C. Bachmann is a hyperspectral remote-sensing expert who works at the Remote Sensing Division of the Naval Research Laboratory. Todd Scanlon (UVA) is catchment hydrologist who specializes in land-atmosphere interactions. He will be aiding in our increasing focus on land-atmosphere nitrogen fluxes applying the new tunable diode laser trace gas technology to the site. P. D'Odorico (UVA) is a hydrologist with special interests in stochastic modeling of hydrologic processes and ecosystem state change. He will work with P. Wiberg, K. McGlathery, and S. Fagharazzi on modeling the consequences of seagrass recolonization on sediment resuspension in the coastal lagoons. P. Berg (UVA) specializes in modeling biogeochemical processes in marine systems. He brings to the VCR his new eddy correlation technique for measuring oxygen fluxes at the sediment-water interface. We also encourage non-LTER researchers to use our site as a research platform, and often this results in new, productive collaborations. This will be even more desirable to our colleagues with the opening of our new field station. A list of VCR LTER investigators and their research specialties is given in Supplemetal Document 3.

Diversity: The VCR LTER and the University of Virginia are committed to involving a diversity of scientists in our program. Currently, 28% of our PIs are representative of women and minority groups. The Department of Environmental Sciences is currently recruiting a coastal hydrologist to contribute to the LTER (McGlathery is committee chair), and we are working with the University to actively solicit applications from women and minority candidates.

New Field Station: The VCR LTER program will have a new home as of February 2006 at the University of Virginia's Anheuser Busch Coastal Research Center in Oyster, Virginia. D. Smith has been the responsible PI for assuring the timely completion of this project. The new facility will provide high quality laboratory and living space. The Center is located on 42 acres on Oyster Harbor, with boat access to the coastal ecosystems of the VCR. The laboratory building includes 9369 sq. ft. of dry and wet lab space, and the residence building (5767 sq. ft.) can house 22 people in double-occupancy rooms with full kitchen facilities.

Synthesis Volume: With the change in VCR leadership and B. Hayden's retirement from the program, and our commitment to establishing the new field station, we are behind schedule in producing our synthesis volume. The 2003 NSF site review team recommended that we have a plan in place at the time of our renewal application. D. Smith and K. McGlathery both have been awarded sabbatical leaves in the Fall 2006 to begin working on the volume. We anticipate that the volume will be completed and published by the time of our next NSF site review.

Institutional Relations: Training graduate students is a top priority of the VCR LTER program. Since the time of our last renewal, the costs of graduate student support has increased dramatically. Significantly, the Vice President of Research and Graduate Studies, the Dean of the College, and the Department of Environmental Sciences have collectively committed $90,000 a year in support of graduate student training through the LTER program.

SECTION 4: INFORMATION MANAGEMENT

The VCR Information Management System (VCRIMS) has as its goal serving as a comprehensive "file cabinet" for the project, containing all the information resources needed by researchers, both at the site and in the larger ecological community. We share the strong belief that development of information resources by ecologists is critical to allowing us to attack the major scientific questions of the 21st century (NRC 1995, 1997, Arzberger et al. 2005, Porter 2000, Porter et al. 2005). The VCR provides a large variety of information resources (Figure IM-1), including full-text theses and dissertations, images and 106 formally documented datasets.

Since 1992 we have provided access to VCR information resources via an online system. Major benchmarks in the development of that system occurred in 1995 with the introduction of a web-editable personnel directory, 1997 when we introduced a web-form-based database system for metadata and 2005 with the development of tools to generate Ecological Metadata Language (EML)-compliant metadata and tools to use EML to create automated statistical programs. As recommended by the 2003 NSF review team, the interface for the VCR web site has been upgraded through the use of a content management system that provides a more modern look and feel than did the old interface, which had been in place since 1995. We will pursue additional recommendations regarding the improvement of spatial indexing of datasets and management of GIS data and models during VCR V.

We have been very active in outreach, training and network activities because we believe that our scientific objectives can best be achieved through fostering a vigorous ecoinformatics community. We fully participate in ClimDB, SiteDB, DTOC and Metacat databases. The VCR Information Manager (J. Porter) has helped teach courses on databases, with annual participation in RDIFS/RCN training for field stations since 2002, and at international LTER workshops (Southern Africa, 2002; China, 2005). Additionally Porter has participated in, or organized, over 16 workshops during 2001-2005. We also hosted an information-manager-in-training from the Taiwan Ecological Research Network for three months in 2005 and will be hosting several more in 2006.

System Utilization

The best evidence that the VCRIMS is achieving its goal is use of the system, which has been expanding ever since the creation of our first online system in 1993. For the current funding cycle (Nov. 2000-Dec. 2005) we have served 16.2 million requests, 7 million of them for web pages (excluding known search engine robots), totaling 532 GB in volume. Requests came from 514,292 different computers from more than 184 different countries. During the first full year of the current grant (2001) we averaged 2,685 page requests per day with an average of volume of 81 MB/day. By 2005 usage has risen to an average of 6,513 page requests per day, with an average daily volume of 644 MB/day – increases of 243% and 795%, respectively. A more complete analysis of web logs is at http://www.vcrlter.virginia.edu/analog/2000thru2005/.

Formal data requests, where users fill in a web form stating their name, contact information and reason for requesting data, are a direct measure of dataset use. During the period of 2000-2005 we have received 771 formal requests for data. Most of the requests (76%) originated from non-VCR researchers, and were for research (70%) purposes with the rest of the requests for educational uses (e.g., demonstration data, class projects). Formal requests came from 15 different nations, with USA, India, Netherlands, United Kingdom, Canada and China logging ten or more requests.

System Description

The VCRIMS focuses on end-to-end information management, from the planning of a project, through its inception, to the collection of data, the creation of metadata and the dissemination of data. The VCR web page (http://www.VCRLTER.virginia.edu) was redesigned in 2005 using a content management system that uses a database backend to create dynamic web pages. Specialized pages for investigators, graduate students, Schoolyard-LTER and the general public are linked to the main page (Figure IM-1). A large number of the pages incorporate interactive features that allow users to edit or add to databases.

The technologies and products that support the system include the Apache Web Server, MySQL and MiniSQL databases, the PostNuke content management system, the Mapserver online GIS tool, the Gallery image management tool, the SPSS, SAS and R statistical packages, and language support including PERL, PHP, C and JAVA. The data model underlying our metadata system is shown in Fig. IM-2. A more detailed description of VCR/LTER technologies and data models is available at:
http://www.vcrlter.virginia.edu/elecvol/ecoinformatics/VCR_IM_Description_06.pdf.

Policies and Procedures

As specified in the 2005 “Review Criteria for LTER Information Management Systems” the VCR/LTER data access policy specifies that data should be freely available online within 2 years, with rare and justified exceptions (http://www.vcrlter.virginia.edu/data/docs/IMPolicy_VCRLTER06.pdf). At this time only one researcher has requested an exception, and this is for data that was collected without the use of LTER funds. Also, as recommended, a management plan spells out the roles and responsibilities of researchers, the information manager and the VCR Executive Committee (http://www.vcrlter.virginia.edu/elecvol/ecoinformatics/VCRInfoMgmtPlan.pdf). Additional documentation in a password-protected portion of the web page (accessible to all PIs) contains details on operation of the IM system should the VCR Information Manager be incapacitated. This document is not publicly accessible because it includes information that could negatively impact system security should it be widely disseminated.

Ecological Metadata Language

A major innovation facilitating cross-site exchanges of metadata is Ecological Metadata Language (EML). In conformance with the LTER EML “best practices” document (http://cvs.lternet.edu/cgi-bin/viewcvs.cgi/emlbestpractices/emlbestpractices-1.0/), in late 2004 we created a PERL/DBI program that queries data from our metadata database and dynamically creates EML documents for all VCR datasets. We published details on using XML text tools for transforming HTML-formatted text to the limited “docbook” documents in the Fall 2005 issue of “Databits” (http://intranet.lternet.edu/archives/documents/Newsletters/DataBits/05fall/#2fa). Our EML metadata is harvested weekly by the LTERNET Metacat Server. A September 2005 Databits review of progress on implementing EML indicated that we are one of seven LTER sites to have 100% of our datasets documented with EML Level-5 metadata (http://intranet.lternet.edu/archives/documents/Newsletters/DataBits/05fall/#8fa). We have also been active in creating technologies for using EML documents. During 2005 we created XSL stylesheets that create SPSS, SAS and R statistical programs for reading the underlying data files (http://www.vcrlter.virginia.edu/data/eml2/).

Future Directions

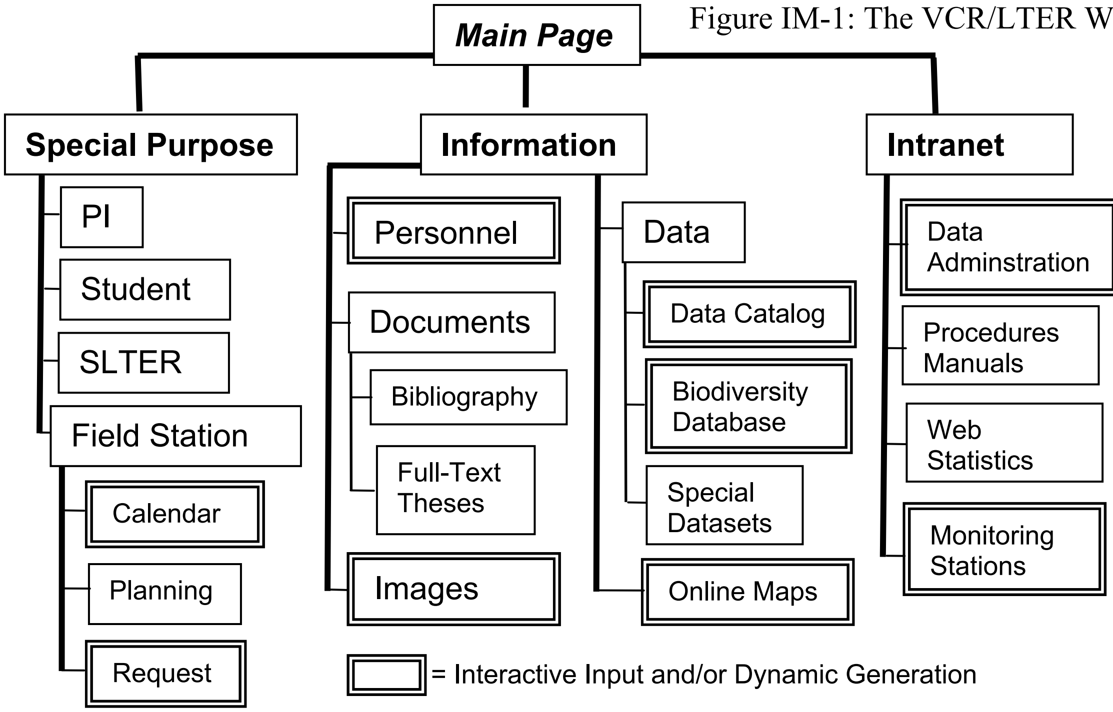
In addition to continuing the day-to-day operations and improvements of the VCRIMS during the term of the proposed research, we plan to focus on improving system by:

1. ***Providing Improved Geospatial Perspectives*** – As recommended by the 2003 NSF site review team we will be revamping how we deal with geospatial information. For research locations, the current approach using a location data table containing coordinates or bounding boxes for named locations is sound, but needs to be extended to support arbitrary polygons. We also need to enhance the VCRIMS metadata system to better deal with geospatial data such as GIS coverages and model products, by increasing its compatibility with Ecological Metadata Language data structures. Currently FGDC metadata is included as text inside our metadata descriptions. However, a more structured approach will extend the utility of our metadata for data discovery. These improvements will also demand improved online tools for capturing geospatial information. We plan to expand our use of Mapserver and OpenGIS technologies to help meet that need.

2. ***Streamlining Data Ingestion*** - During 2002-2003 we installed a wireless network that extends from our laboratory to Hog Island, 20 km off the coast of Virginia. Since then, we have used the network for harvesting tide and meteorological data and over 400,000 images from webcams that observe landscapes and species-specific research sites at hourly or higher frequencies. Currently the information systems and databases for processing these data sources are hand-coded. To streamline this process we will develop metadata-driven tools that automatically create programs for ingestion, QA/QC and processing of data streams once the basic metadata describing the data stream has been entered. In addition to "home grown" solutions, we are evaluating solutions developed elsewhere, such as the ROADNET project at the San Diego Supercomputing Center which is using a software system called "Antelope" (Porter et al. 2005). We also will continue work on the development of more generic systems for entering field data collected by individual researchers, staff and students.

3. ***Improving Data Storage to Aid Integration*** – Thus far, the majority of VCR/LTER datasets are stored in text files. Unlike many more complex forms of data which are subject to frequent revisions (e.g., Excel v1.0 vs Excel97 files), text files have excellent archival characteristics. Similarly, most researchers are familiar with the use of text files and can easily use them with analytical software. However, use of text files can also introduce challenges. For example, researchers often code missing values with a letter or word such as "NA" for Not Available. However, when imported for analysis some software (particularly databases) respond badly to finding non-numerical data in a numerical field and may fail. Similarly, for a few very large datasets (e.g., meteorological data), data users may not wish to have all stations and dates, but only a subset. For these reasons we plan to develop database structures that will allow our data to be accessible both as the existing ASCII text and directly from either a database, or a structured form that has existing tools associated with it (e.g., OpenDAP, NetCDF). This will improve our capability to provide data tailored for use with particular analytical or visualization software. It will also facilitate sharing data using web services and similar network technologies with remote application software.

Figure IM-1: The VCR/LTER Web



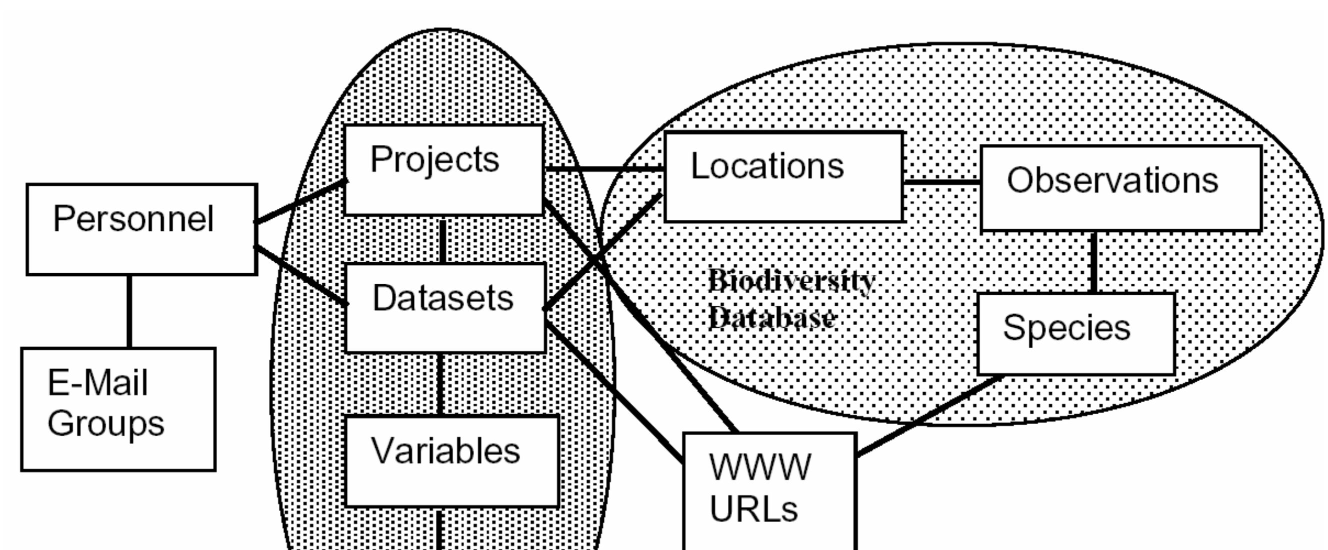


Figure IM-2. Entity relationship diagram describing links between major data tables. This system allows us to reduce redundancy while improving quality.

SECTION 5: EDUCATION AND OUTREACH

Introduction: The past six years have seen significant growth in our outreach/education initiatives. These activities at the VCR LTER have focused on both traditional and non-traditional venues, and have targeted multiple audiences. Our general outreach/education goal is to continue to train the scientists of tomorrow and to create an environmentally literate citizenry.

Primary/Secondary Outreach and Education: The Virginia County (Northampton) that houses the VCR program is one of poorest counties in the Commonwealth. It has been our experience that the majority of primary and secondary school students on Virginia's Eastern Shore have never spent significant time on the water, and few have ever ventured into the marshes or mudflats. Consequently our involvement with this audience is very important. We involve about 200 students each year in our Schoolyard LTER program, more than half of whom are representative of women and minority groups. The VCR Program has helped outfit the science faculty at the county high school with badly needed computers, specialized software (e.g., GIS software), portable GPS units, supplies, reference material, etc. The VCR professional staff and faculty have also assisted the high school in developing education modules focused on such topics as GPS, GIS, Plant Taxonomy, and Environmental Water Quality. These activities have been supported through the SLTER initiative which provides the core of our primary/secondary education efforts. However, VCR faculty have successfully attracted other funding as well. For example, funding from the Virginia Environmental Endowment was obtained to assist in the creation of a "wireless Internet cloud" over Hog Island that allows real-time streaming video from several video camera on the island. This technology was then used to create materials, content, and web sites for use by high school students' studying the natural science of the Eastern Shore. Plans are underway to expand this effort (see Future Plans).

Teacher Outreach/Education: Recognizing the multiplier effect of "training teachers to train students", VCR researchers (Hayden, Porter, Smith, Blum) have interacted directly with the high school teachers on the Eastern Shore of Virginia through the development and teaching of a summer graduate class for science teachers entitled "Field Methods in Ecology and Environmental Sciences". This class provided re-certification credit for the participating teachers. Another class, offered by a VCR researcher (Moncrief) at UVA's Roanoke Higher Ed. Center, makes extensive use of the VCR organism distributional data from the barrier islands. We also have sponsored several RET teachers who have focused on research ranging from oyster growth dynamics to a phenological study of trees and shrubs indigenous to the Eastern Shore.

Undergraduate Outreach and Education: The VCR typically involves 2-3 REUs through supplemental NSF funding each year. These supplemental monies are usually matched with funds from our core program to increase the number of REUs that participate each year. The mentoring model we use involves the REU, a graduate student working at the VCR, and a faculty member who all work together to enhance the REU experience. In addition the VCR laboratory has routinely served as a base for academic class field trips from both universities directly affiliated with the VCR and those with no direct affiliation (e.g., Randolph Macon University). Special summer classes, such as "Environments of Virginia" use the VCR facilities. This field class travels the Commonwealth visiting the VCR, UVA's Blandy Experimental Farm, and UVA's Mountain Lake Field Station where the students are exposed to the different natural environs of each location and plan and conduct focused research projects at each site.

Graduate Outreach and Education: The heart of our VCR Program is the training of future environmental scientists through the graduate programs at VCR participating institutions. Graduate students are involved with every aspect of the VCR research program. During the LTER grant period ending in 2006, the number of graduate students supported at some level from the VCR is approximately 45, and their work is presented at national and international meetings. The VCR was also represented at the recent LTER Graduate Student Committee meeting at the Andrews LTER (2005). Graduate student involvement and support is viewed as so critical to the VCR that the University of Virginia is committing $90,000 for Research Assistantships from internal funds to the VCR effort during the next proposed six year cycle.

International Outreach and Education: VCR researchers have been very involved with international initiatives, particularly via the International LTER effort. R. Christian has helped in the development of the Italian LTER program (Christian and Gosz 2001), has served as chair of the Coastal GTOS panel of experts (FAO 2005) and most recently helped develop the GEO Coastal Community of Practice. S. Macko, J. Porter and J. Zieman are active in the ILTER efforts in southern Africa (they and a VCR LTER student participated in the ELTOSA workshop in Mozambique in 2002); and J. Porter is working closely with Taiwanese researchers particularly with regard to scientific data management.

Community Outreach and Education: VCR faculty are active in outreach activities to broader audiences. Examples of community and government efforts have included: (1) Governor's Advisory Board of Soil Scientists and Wetland Professionals (Young), (2) Organization of ERFs Annual Meeting (Blum, Christian, Smith, McGlathery, Schwarzschild), (3) Scientific and Technical Advisory Committee of the Albemarle/Pamlico National Estuaries Program (Christian), (4) chair and member of advisory committees to the NC Marine Fisheries Commission (Brinson), (5) member of GCE LTER advisory committee (Anderson) and Atlantic Coast Environmental Indicators Consortium (Anderson) and (6) Florida Coastal Everglades Advisory Committee (Hayden). M. Erwin serves on the National Science Panel for the San Francisco Bay Salt Pond Restoration (2003-2008), and on two technical committees (as the only USGS scientist) of the Poplar Island Environmental Restoration Project in the Chesapeake Bay.

Diversity: The VCR LTER and the University of Virginia are committed to train students from traditionally underrepresented groups at the graduate and undergraduate level. Several of our PIs work with the University's mentoring program through the Office of African-American Affairs, and in reciprocal programs the University has developed with historical black colleges and universities in the area.

Future Plans: In the next grant period we plan to continue and enhance our outreach and education efforts. For example, researchers at UVA have successfully attracted a significant private endowment for educational activities (Smith, Hayden). In addition, a multiyear proposal has also been submitted to the NOAA B-Wet Program Office (Smith, Schwarzschild) that would focus primarily on teacher development at all grade levels on the Eastern Shore of Virginia and lay the groundwork for every primary and secondary school student to have a "meaningful watershed experience" at some point during their school career. We will use funds from both sources to support a full-time education coordinator who will expand our educational program to beyond the high school in Northampton County. This success is a direct result of SLTER funding over recent years. And with the completion of Phase One of our new ABCRC field station, we anticipate further growth in the outreach and education arena.

Table 1. VCR LTER core data sets. Measurements are taken in watershed, tidal marsh, lagoon and island locations. More details on measurement protocols and data sets are available at http://www.VCRLTER.virginia.edu. LTER core areas: 1) primary production, 2) organic matter, 3) nutrients, 4) disturbance, 5) trophic dynamics. Program area refers to the research questions outlined in the proposal.

PARAMETER MEASURED	CORE AREA	PROG AREA	FREQUENCY	LOCATION	METHOD
Free Surfaces					
Marsh surface elevation and accretion	2, 4	A, B	Semi-annually	Phillips Creek, Fowling Point, lagoon marshes	SET, marker Horizons
Groundwater levels	3, 4 3, 4	A, B A, B	1.5 hr-Monthly Continuous	Phillips Creek Hog Island Chronosequence	Wells, YSI Wells
Tides	4	A, B	12 min	Hog Island Bay, New stations in Metompkin and Smith Bays	Tide Guages
Meterological (Air temperature, wind speed/direction, relative humidity, precipitation)	4	A, B, C	Hourly	3 stations. New stations in Smith and Metompkin for precipitation	Campbell Scientific weather station
Biogeochemistry					
Lagoon Water Quality (Temp, salinity, NH_4^+, NO_3^-, PO_4^{3-}, DON, PN, PC, PP, TSS, light)	2, 3	A	Bi-monthly/ Seasonal	9 stations in Hog Island Bay. New stations Smith and Metompkin Bays (seasonal)	Lachat auto-analyzer, persulfate digestion, CHN
Lagoon sediments (PN, (PC, organic content)	2, 3	A	Yearly	9 stations in Hog Island Bay. Metompkin/Smith Chronosequence	Carlo Erba CHN, high temperature combustion
Lagoon benthic fluxes/ Denitrification, N fixation, mineralization	3	A	Yearly	Hog, Smith, Metompkin Bay	Core incubations
Denitrification	3	A	Semi-annually	Box transect bays and streams	Core incubations
Marsh sediments (PN, (PC, organic content)	2, 3	A	2 years 5 years	Phillips Creek New stations in Metompkin and Smith Marshes, Chronosequence	Carlo Erba CHN, high temperature combustion
OM accumulation	2, 3	A	Semi-annually	Phillips Creek	Root SET
Barrier island soils (PN, organic content)	2, 3	A	Yearly	Hog Island Chronosequence Fertilization exper.	Keldahl, high temp combust

Table 1 cont.

PARAMETER MEASURED	CORE AREA	PROG AREA	FREQUENCY	LOCATION	METHOD
Vegetation Lagoon primary production	1	A, C	Bimonthly/ Seasonally	Hog Island Bay New sites in Metompkin and Smith Bays Chronosequence	Algal biomass seagrass growth, pigment analysis P/R by eddy correlation
Marsh primary production	1	A, C	Yearly 5 years	Phillips Creek, 8-15 sites Marsh chronosequence	Phenometric – End of year biomass
Juncus abundance	1, 4	A	Yearly	Phillips Creek	Percent cover
Upland primary production	1	A	Yearly	Hog Island Chronosequence, and Fertilization experiment	Peak biomass, new shoot biomass Percent cover
Upland plant cover/density	1	A	3 years		
Fauna Mammals	5	A, B, C	Semi-annually 5 years	3 transects on Hog Island All VCR islands	Trapping
Waterbirds	5	A, C	Bi-weekly in summer	All VCR islands	TNC data base Survey
Lagoon invertebrates and fish	5	A, C	Seasonally	Hog, Smith, Metom-pkin, Chronosequence	Core samples, seines
Marsh creek invertebrates	5	A, C	Spring, Fall	Hog, Smith, Metompkin marshes	Core samples, Seines
Land-atmosphere fluxes Wet deposition (Conductivity, H^+, SO_4^{2-}, $CH_3SO_3^-$, Cl^-, NO_3^-, NH_4^+ Na^+, K^+, Mg^{2+}, Ca^{2+})	3	A, C	Weekly	LTER met station	Electrodes, Ion chroma-tography, flame spectroscopy colorimetry
N_2O emmisions	3	A, C	Continuous	Cobb Mill Creek Marsh-Upland	Tunable diode laser trace gas analyzer
Carbon/water fluxes	1, 2, 3	A, C	Continuous	Fowling Point, Cobb Mill Creek	Eddy correlation
Watershed fluxes Discharge	3, 4	A, B, C	15 minutes	15 tidal creeks	Marsh-McBirney current meter, ADP
Nutrients (Cl^-, NO_3^-, SO_4^{3-}, NH_4^+, DON)	3, 4	A, B, C	Monthly	15 tidal creeks	Ion chroma-tography, colorimetry

Table 2. Synthesis of long-term data collection, long-term experiments and short-term studies and modeling in relation to programmatic research questions.

RESEARCH QUESTION	LONG-TERM DATA	LONG-TERM EXPERIMENTS	SHORT-TERM STUDIES & MODELING
(A) How do long-term drivers of change (climate, rising sea level, and land use change) and short-term disturbance events interact to alter ecosystem dynamics and state change, and how is their effect modified by internal processes and feedbacks at the local scale?	- Land, sea and groundwater free surfaces - Land-atmosphere gas exchange - Lagoon water quality - Marsh SET - Marsh organic matter - Faunal surveys - Island vegetation surveys	- Barrier island, marsh and seagrass chronosequences - Marsh inundation-disturbance experiment - Fertilization experiment in barrier island, marsh and seagrass ecosystems	- Watershed N loading model - Lagoon turbidity model - Seagrass population model - Seagrass-sediment resuspension model - Marsh disturbance-N enrichment experiments - LIDAR imagery - Island vegetation mapping
(B) How do the fluxes of organisms and materials across the landscape influence ecosystem dynamics and state change?	- Watershed N fluxes - Faunal surveys - Vegetation surveys - Land-atmosphere gas exchange	- Seagrass recolonization	- Watershed N loading model - Hydrodynamic and sediment/C flux model - Seagrass-sediment resuspension model - Lagoon N cycling - N enrichment of low marsh-mudflat transition - Island vegetation patch dynamics - Landscape model
(C) In the future, what will be the structure of the VCR landscape and what processes will drive ecological states changes?	- Land, sea and groundwater free surfaces - Vegetation surveys - Faunal surveys - GIS data bases - Land use/land cover change	- Barrier island, marsh and seagrass chronosequences - Marsh inundation-disturbance experiment - Fertilization experiment in barrier island, marsh and seagrass ecosystems	- Hydrodynamic model - Landscape model - Network model

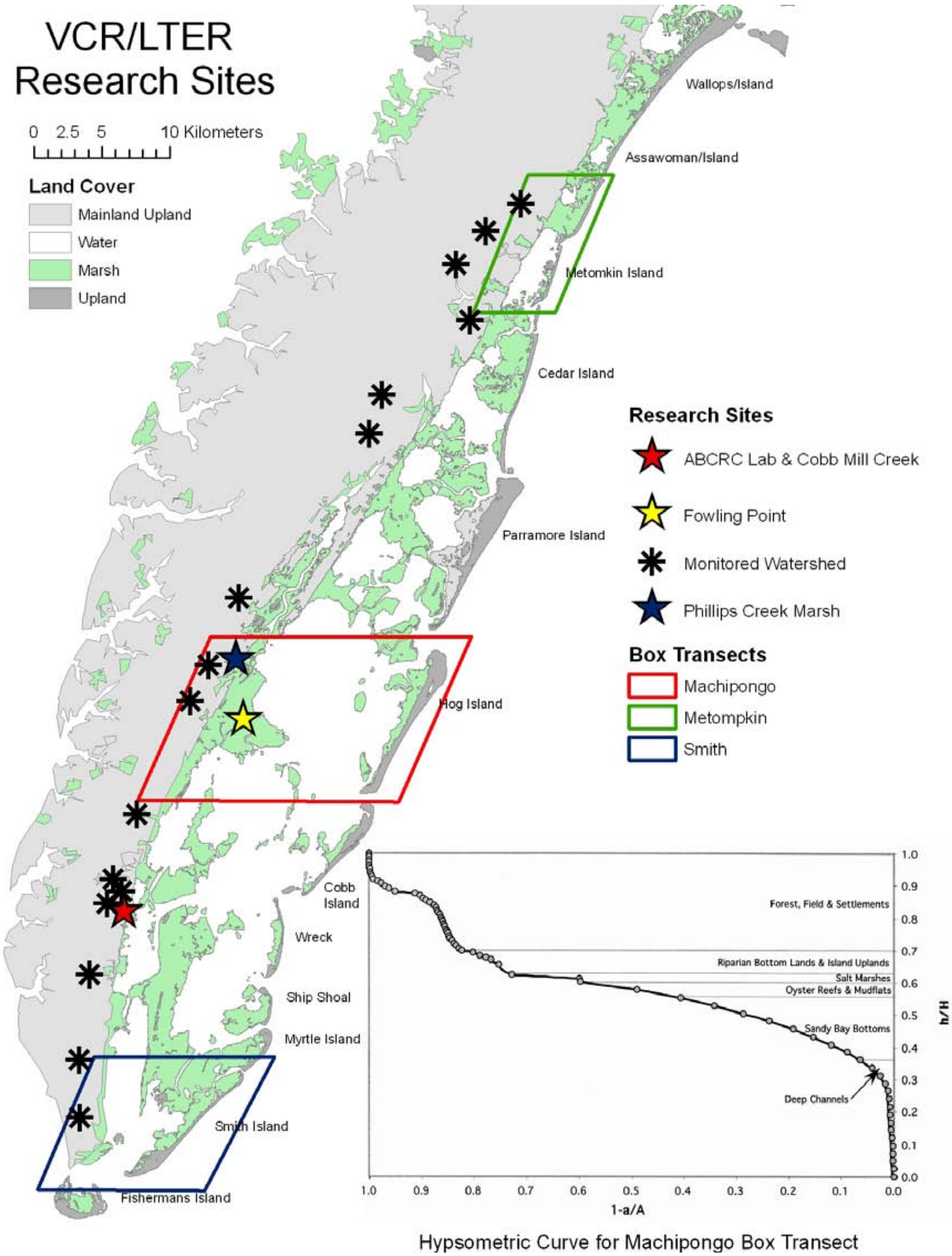


Fig. 1. The Virginia Coast Reserve LTER site, located on the Atlantic side of the Delmarva Peninsula. Research activities are concentrated in the box transects that mainland watershed, marsh, lagoon and barrier island ecosystems. The hypsometric framework provides the synthetic framework to link the ecosystems on the landscape. The hypsometric curve for the Machipongo box transect shown is a normalized morphometric characterization (model) of the land surface and lagoon bottom by accumulative elevation and accumulative area increments. The elevation of the land surface ranges from +13 m (highest point on the mainland watershed) to –26 m (lagoon channel) relative to mean sea level. The barrier islands are generally <4 m above mean sea level. Mean sea level is at the scaled value of 0.6.

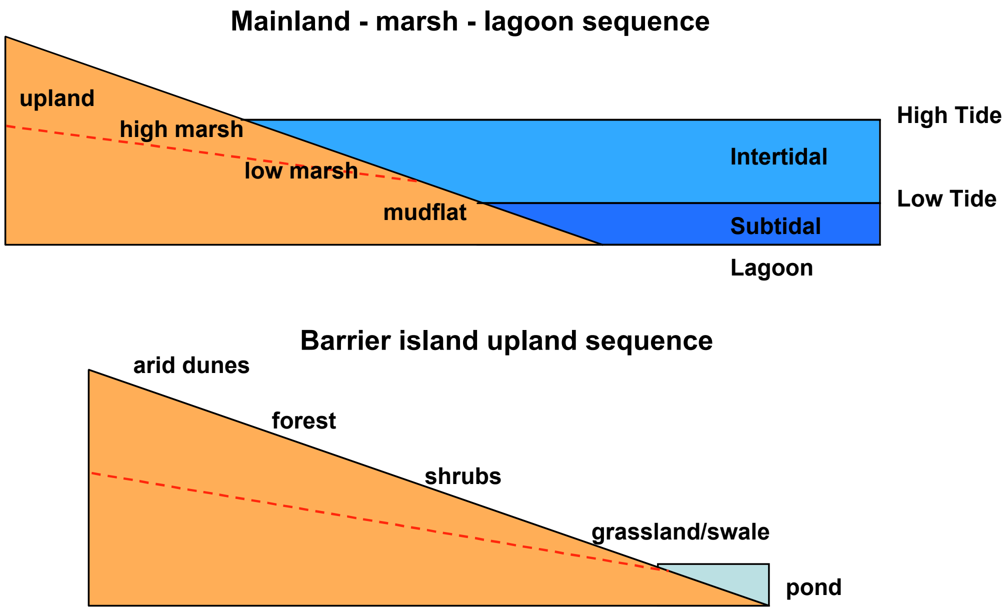


Fig. 2. Relationships of the land, sea and groundwater free surfaces in the mainland-marsh-lagoon and upland sequences of ecosystem states. Changes in the relative vertical positions of the free surfaces as they are influenced by climate/land-use change and disturbance give rise to ecosystem state change.

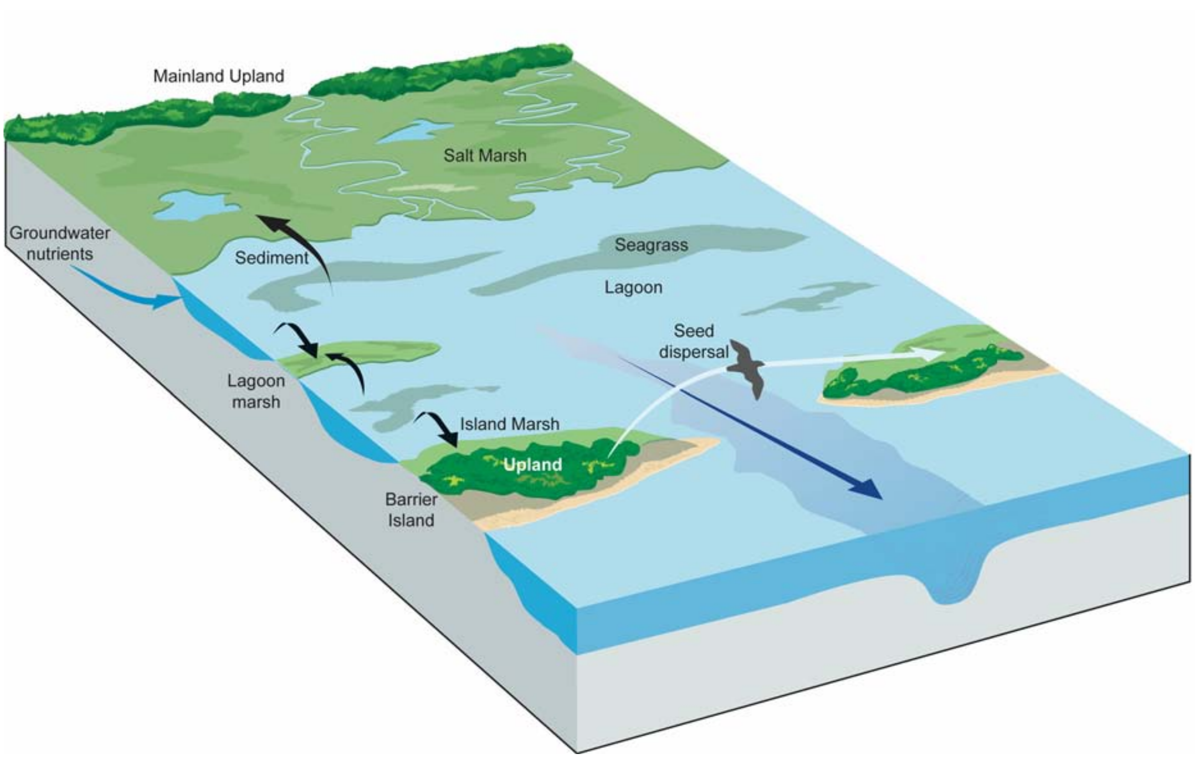


Fig. 3. The key fluxes of materials and organisms between landscape units (mainland watershed, marsh, lagoon, barrier island) that influence ecosystem state change. These include groundwater nutrient input from mainland watersheds to coastal lagoons, sediment transfer between lagoons and intertidal marshes, water exchange between lagoons and the coastal ocean, and propagule transfer via birds among the barrier islands.

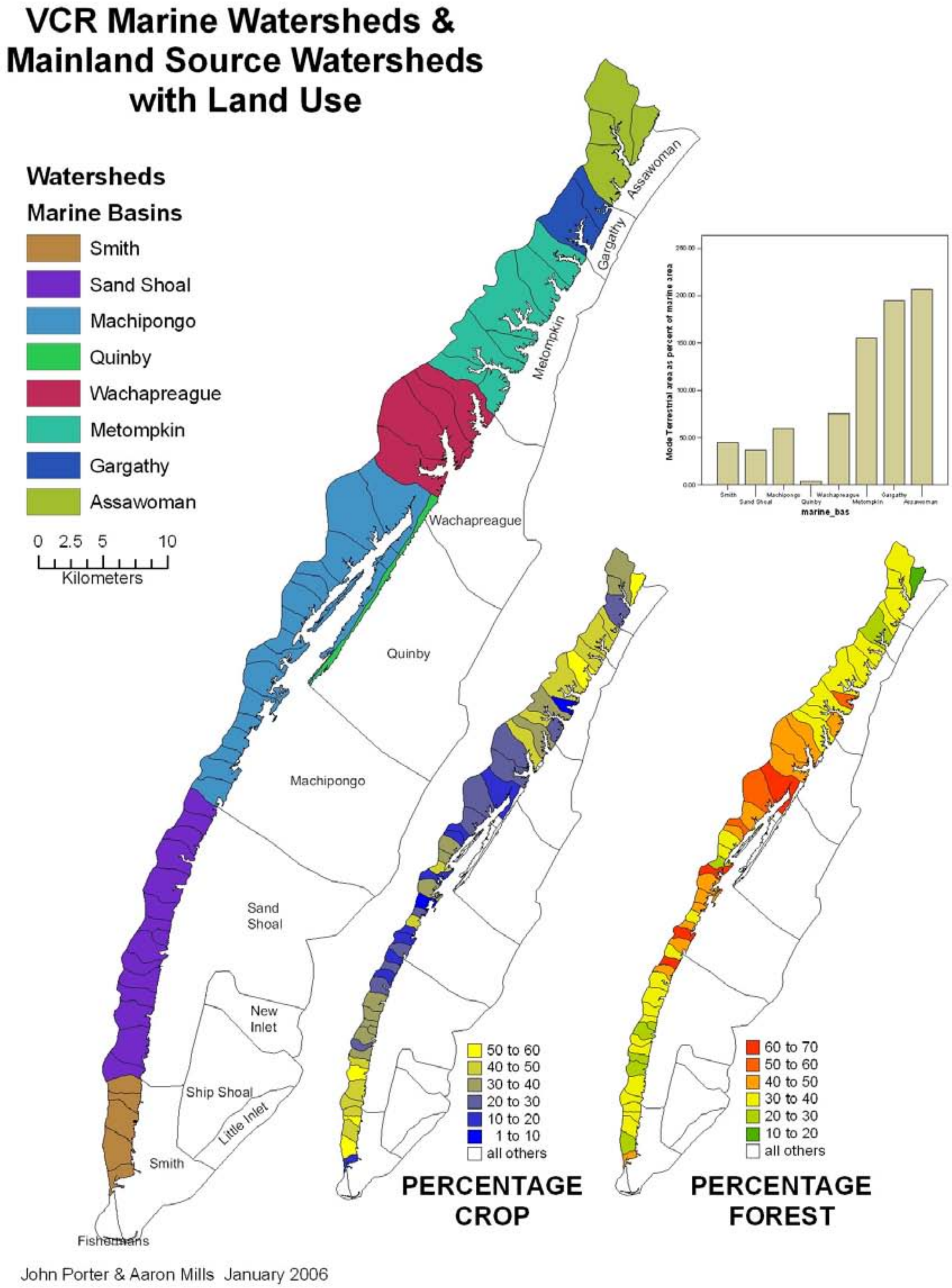
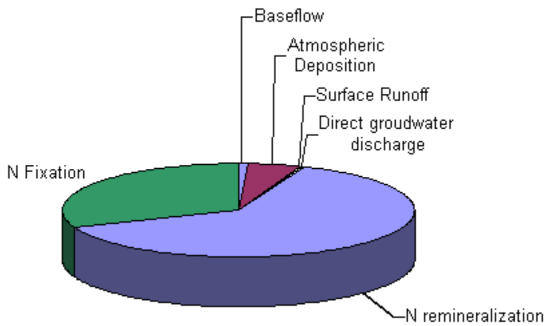


Fig. 4. Thirteen marine and mainland source watersheds of the VCR, and the percentage of the dominant land covers, crop and forest, in each of the 54 subwatersheds that make up the mainland watersheds. The watershed area relative to lagoon area increases from south to north along the peninsula.



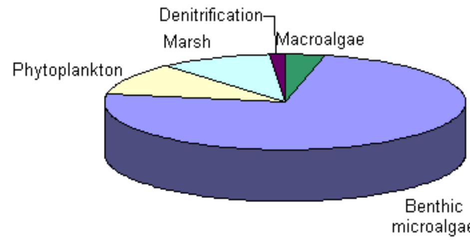
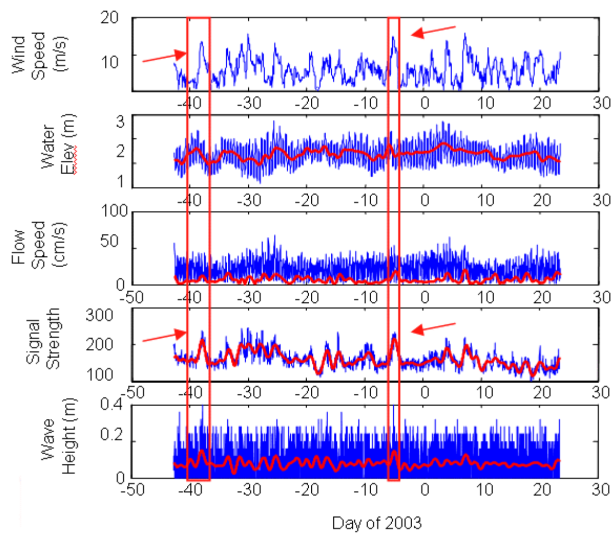


Fig. 5. Basin-scale nitrogen budget of Hog Island Bay comparing sources and sinks of nitrogen. The budget is based on detailed nitrogen-cycling process measurements in the bay, and monitoring of groundwater and atmospheric nitrogen inputs.

Fig. 6. Results from deployment of Acoustic Doppler Profiler in Hog Island Bay. Signal strength is a proxy for turbidity and is correlated with wind speed, indicating that wind rather than tides is the driving force for high turbidity events in the lagoon and that these events are episodic.



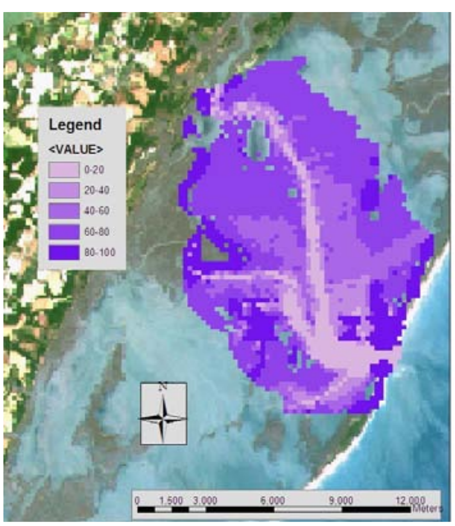


Fig. 7. Results of process-based model that predicts sediment resuspension and light reaching the seafloor in Hog Island Bay which is used to forecast the potential for seagrass recovery. The data shown are precentages of light reaching the lagoon bottom. The modeling coupled the hydrodynamic model, a wave model, a sediment-resuspension model, and an empirical equation relating water column characteristics to light attenuation. This August run of the model showed that 87% of the lagoon was suitable habitat for seagrass restoration.

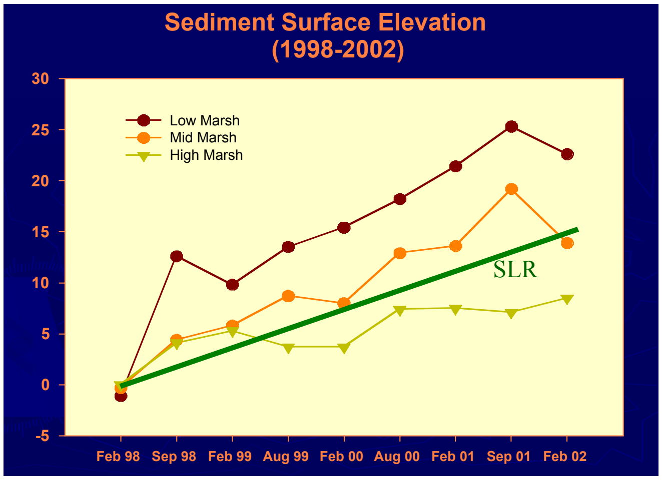


Fig. 8. Variation in sediment surface elevation in the high, mid, and low marsh regions of Phillips creek. The frequently flooded low marsh has gained elevation at a rater higher than sea-level rise, whereas the infrequently flooded high marsh has shown only modest increases in elevation, at a rate below that of sea level rise.

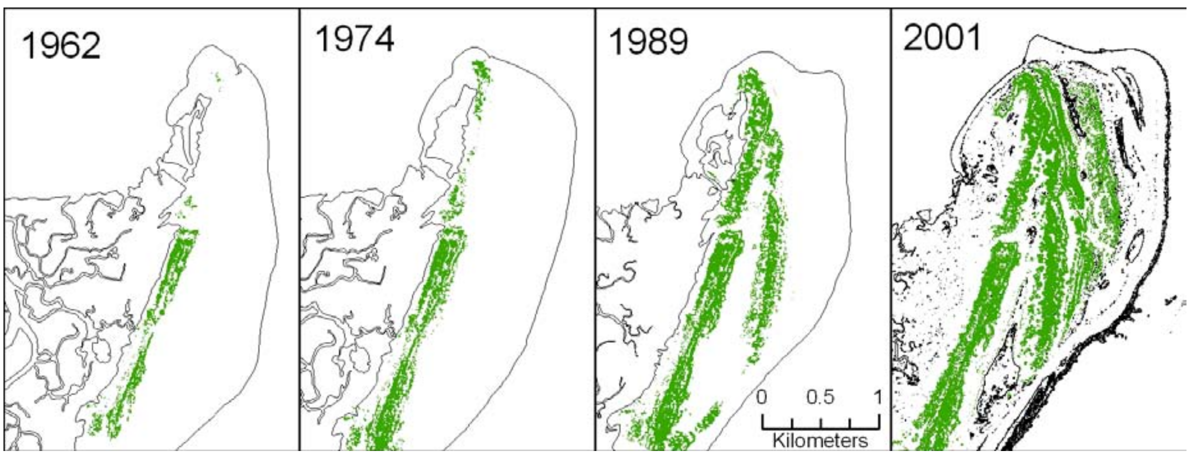


Fig. 9. Shrub expansion on the north end of Hog Island. The coverage of shrub thickets has increased >500% over the past 50 years.

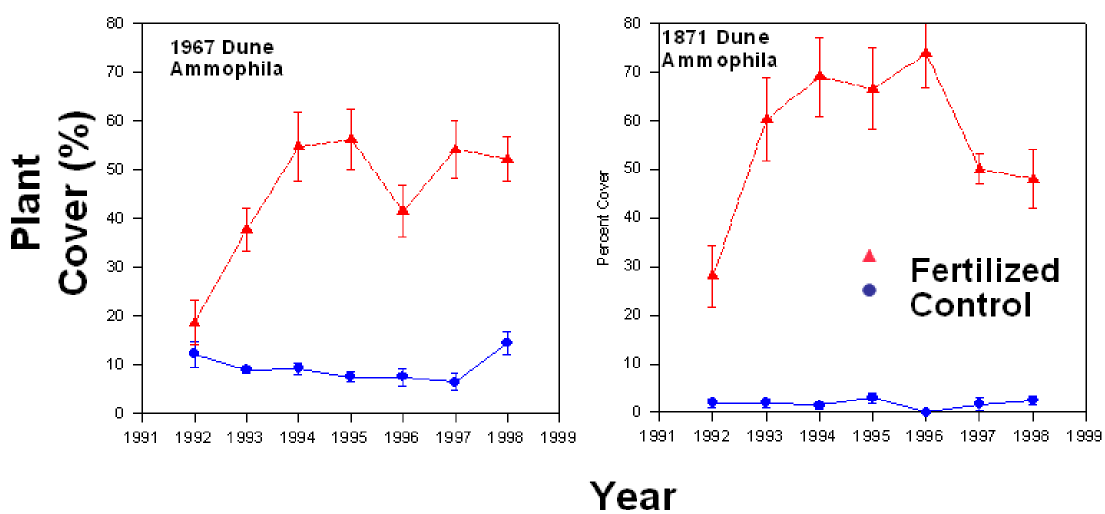


Fig. 10. Results of long-term nitrogen fertilization on the Hog Island chronosequence. Greater cover of *Ammophila* in fertilized plots indicates that with N fertilization, this species is a better competitor for light with enhanced aboveground dominance.

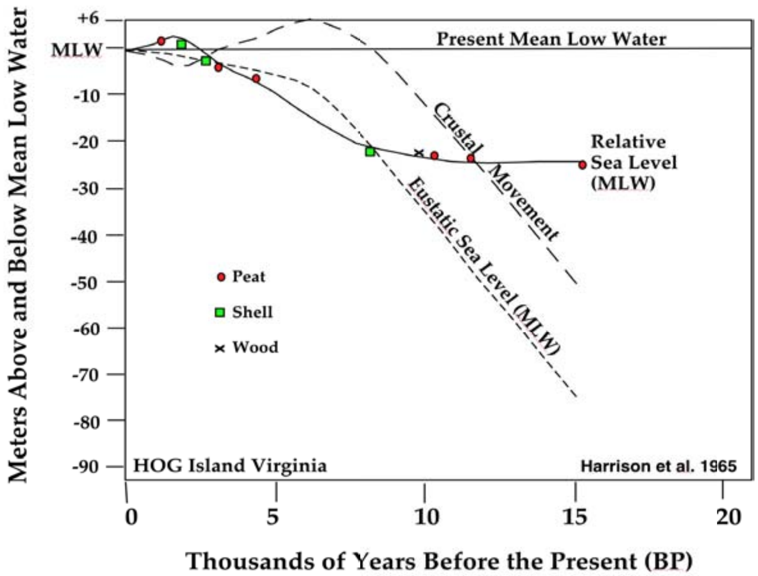
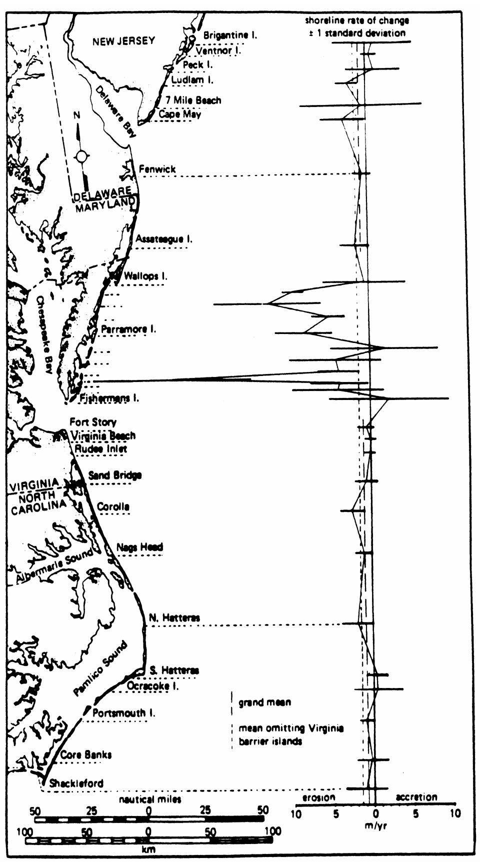


Fig. 11. Patterns of eustatic sea-level rise and land surface uplift and subsidence of the last 20,000 years. Current rates of sea-level rise are 3.5 – 3.9 mm yr^{-1}, the highest rates found on the east coast of the U. S.



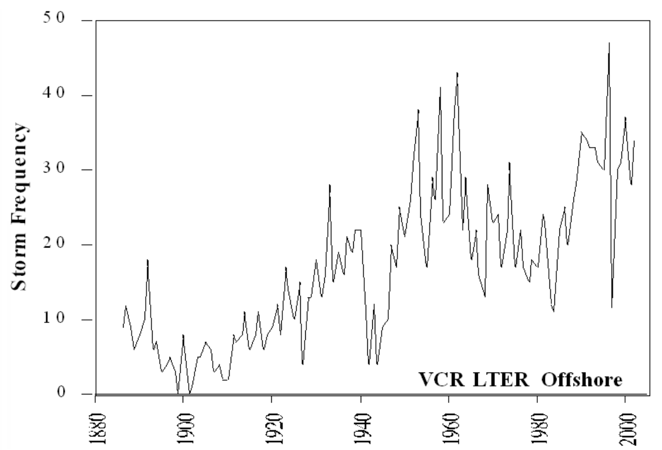
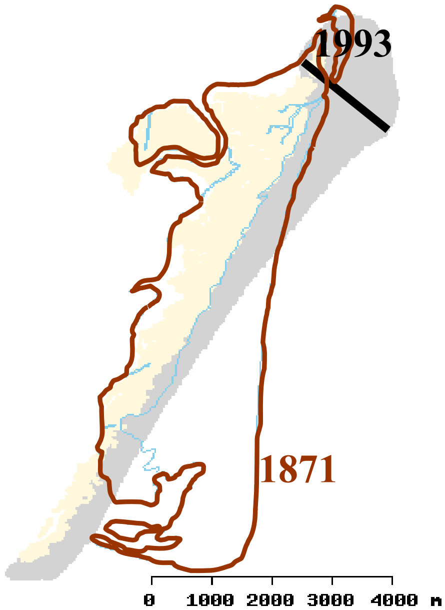


Fig. 12. (above) Record of storm frequency since 1880. On average, 20 extra-tropical storms hit the VCR each year.

Fig. 13. (left) Erosion and accretion rates on the mid-Atlantic Coast barrier islands. Shoreline changes on VCR islands as high as 13 m yr^{-1} are the highest along the mid-Atlantic seaboard.



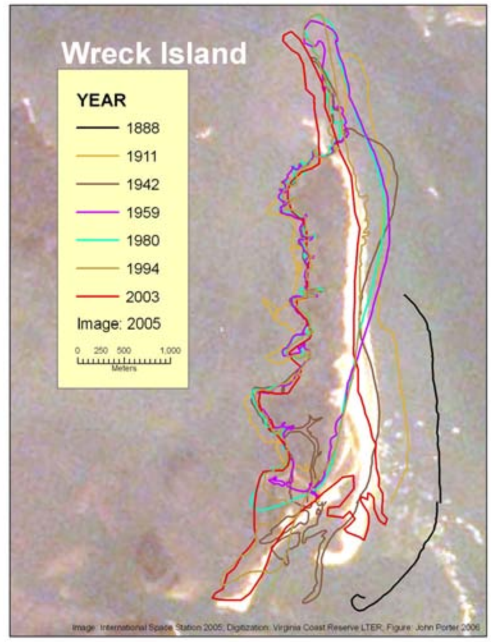


Fig. 14. Changes in the position and geomorphology of Hog Island between 1871 and 1993. The original town of Broadwater at the time of island settlement is now hundreds of meters off shore.

Fig. 15. Shoreline changes of Wreck Island between 1888 and 2003. The northern spit of the island was lost during Hurricane Isabel.

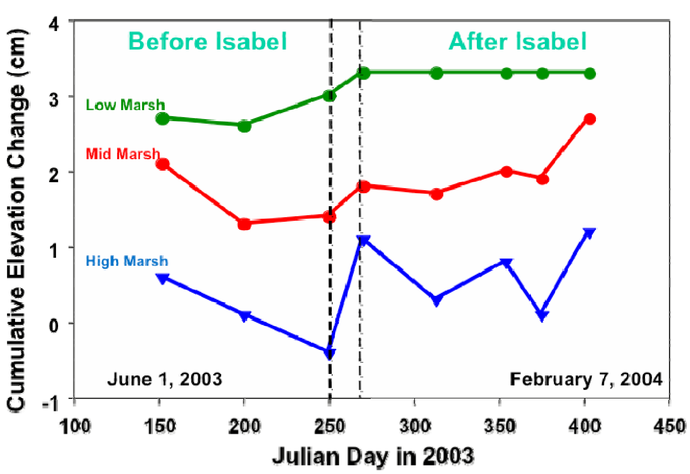
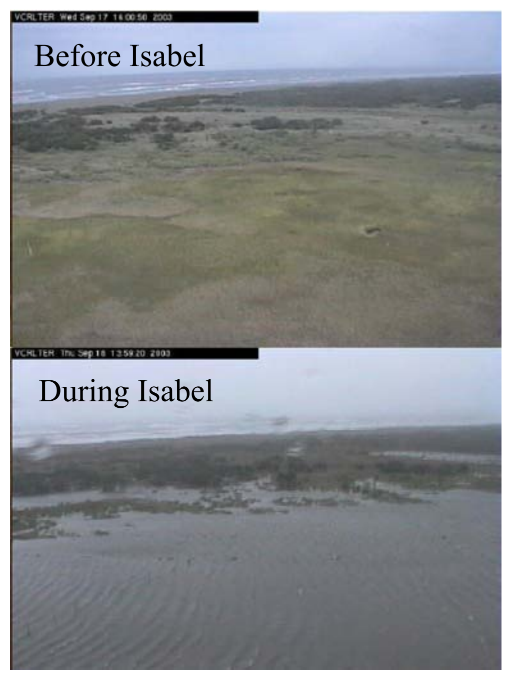


Fig. 16. Impact of Hurricane Isabel in sediment elevation in the Phillips Creek Marsh. The surface elevation increased at all locations on the marsh, however, the marker horizons did not reveal consistent accretion or loss of material across locations.



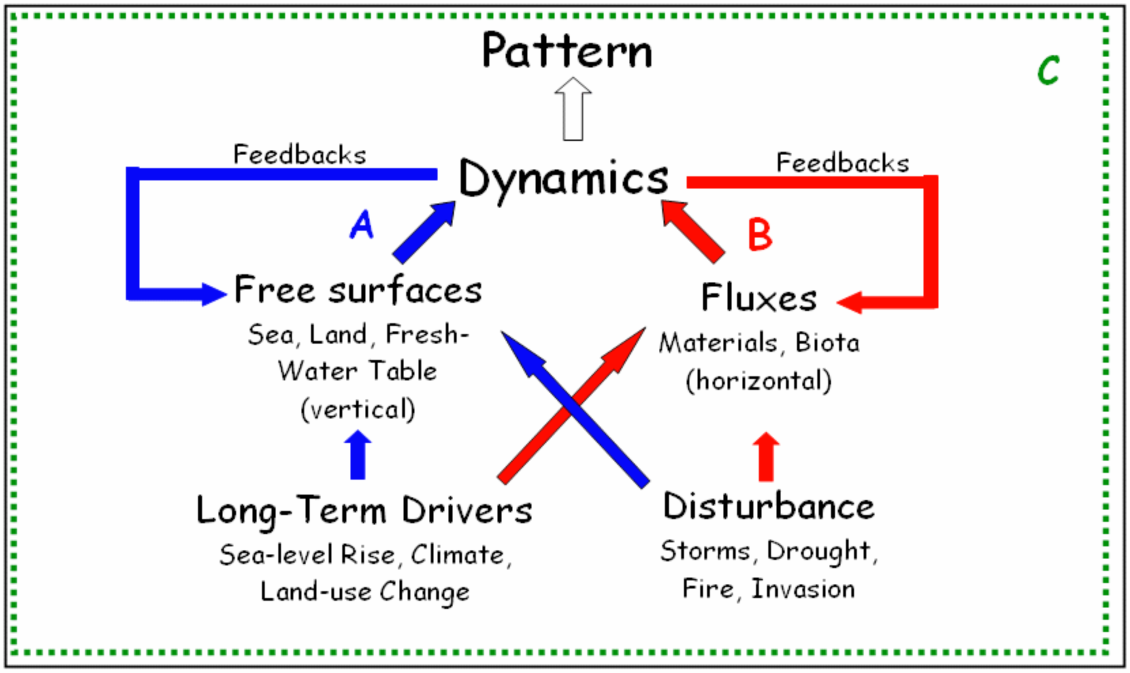


Fig. 17a. Overview of conceptual approach of VCR V to understanding ecosystem state change and landscape pattern in the context of long-term drivers of change and short-term disturbance events, and the relationship to the 3 programmatic research questions (A-C) detailed in this proposal. Changes in the relative positions of the land, sea and groundwater free surfaces are the mechanisms of state change, and these are influenced by fluxes of materials and organisms between landscape units.

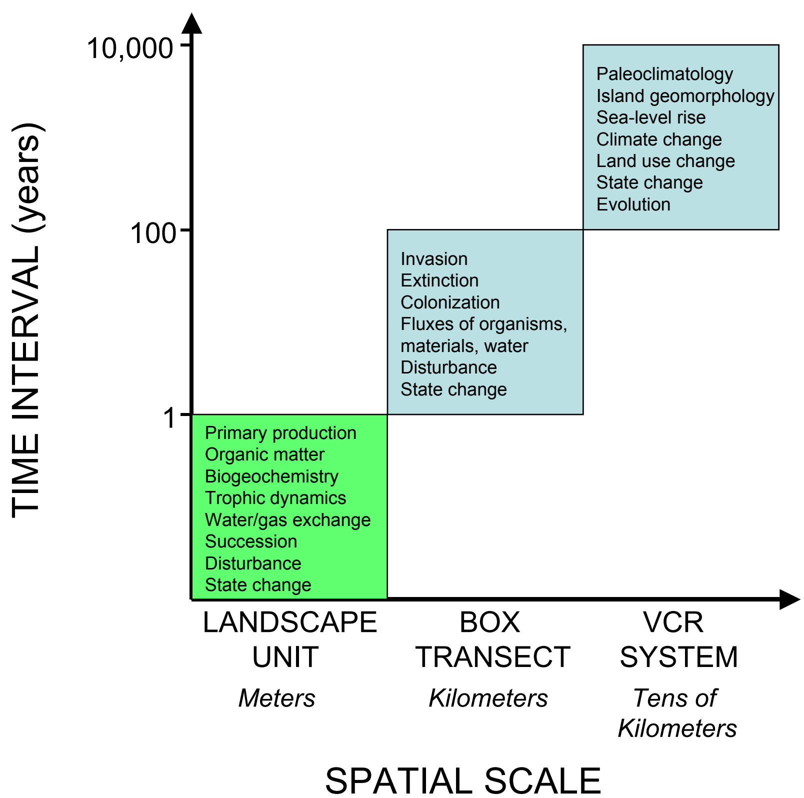


Fig. 17b. Time and space scales of VCR research. The green box indicates LTER core data collection.

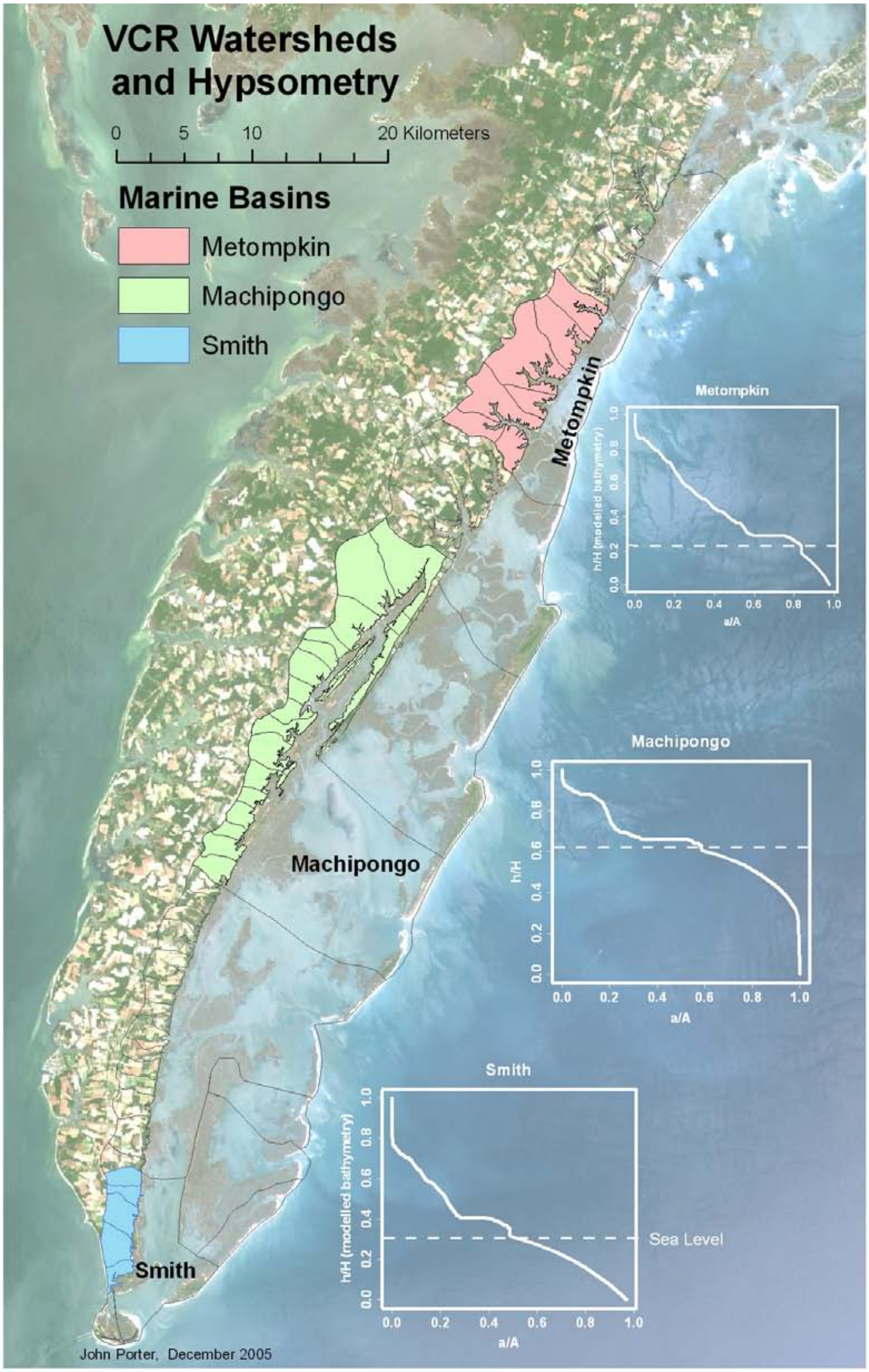


Fig. 18. The three mainland watershed – marsh – lagoon – barrier island box transects that are focal study areas. Our primary research sites are in the Machipongo box transect. The Metompkin and Smith box transects are new with LTER V. The insets are the hypsometric curves for the three box transects.

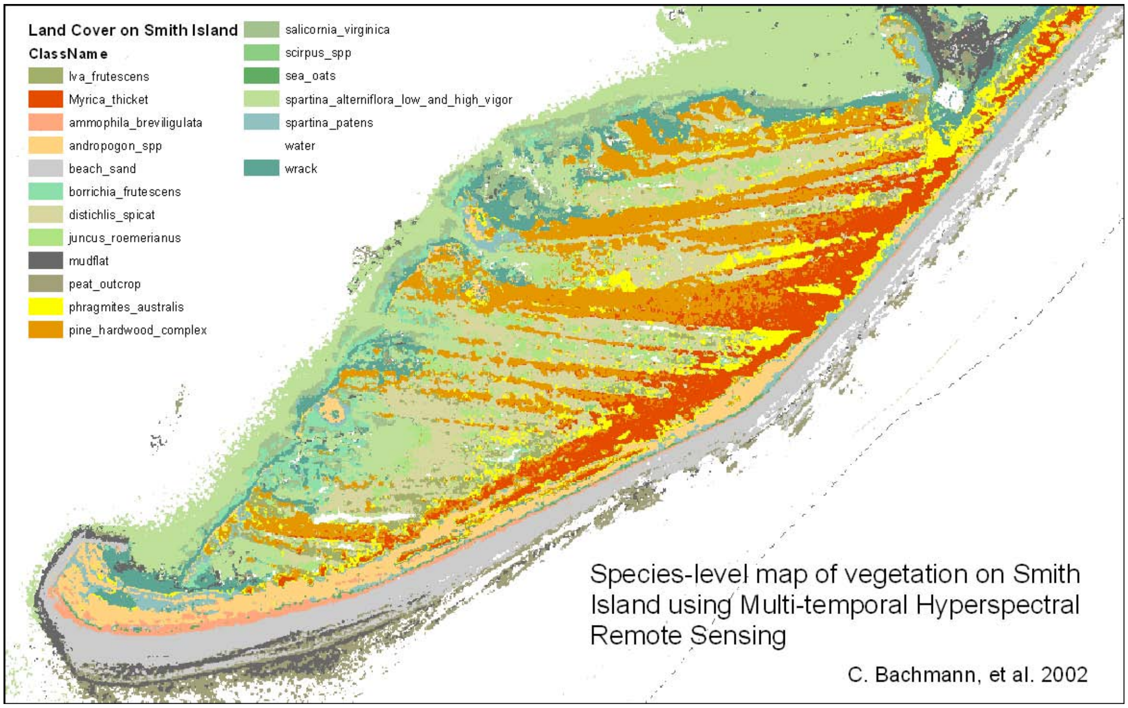


Fig. 19. Species-level vegetation map of Smith Island based on multi-season hyperspectral imagery.

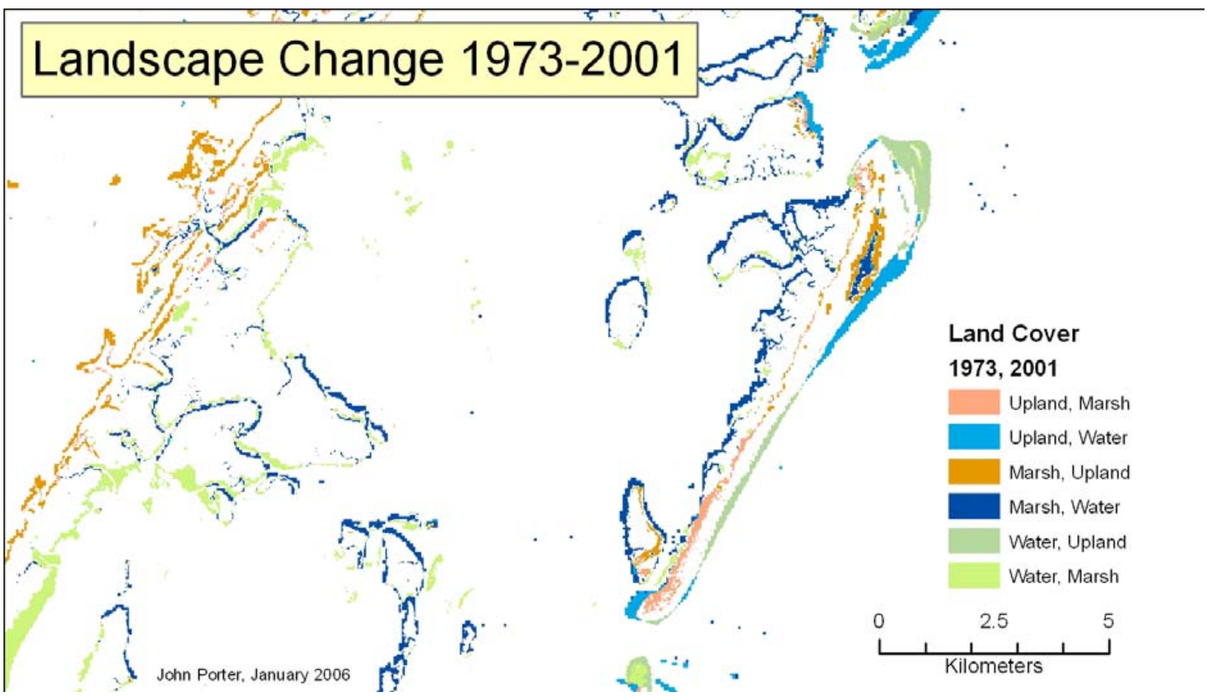


Fig. 20. Results of change analysis for land cover for the Machipongo box transect for the 28-year period from 1973-2001. Despite a high probably of change at any given point on the landscape, there was little overall change in the proportion of the landscape in each land cover category. For more details on this analysis, see http://www.vcrlter.virginia.edu/~jhp7e/change_analysis/.

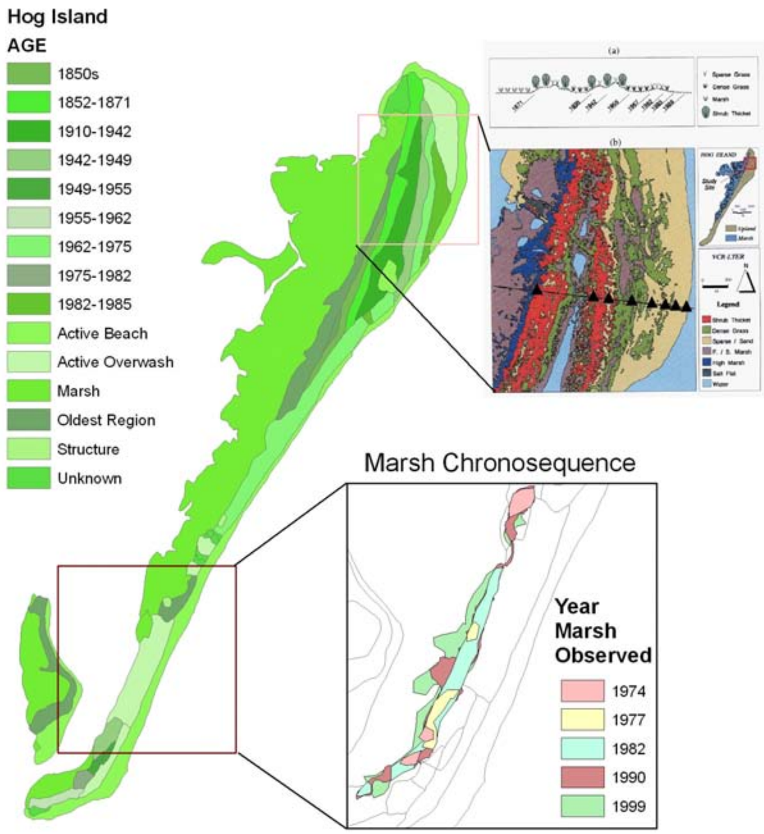


Fig. 21. Terrestrial and marsh 120+ year chronosequences on Hog Island.

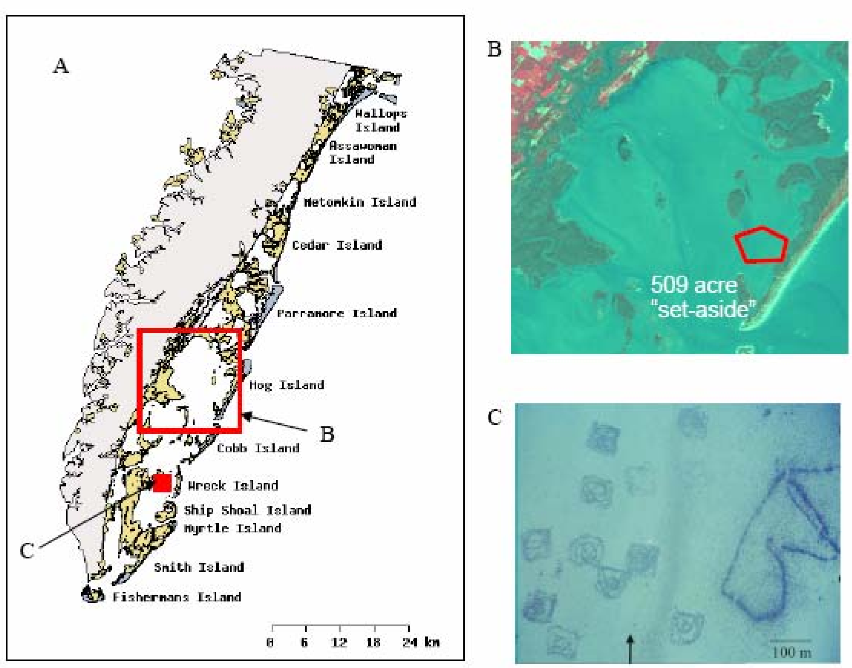


Fig. 22. (A) Location of the primary recolonization sites in Hog Island and Smith Bays. A third site, Spider Crab Bay, makes up the seagrass chronosequence. (B) The location of the 509 acre “set aside” that was recently established in Hog Island Bay for seagrass restoration. (C) An aerial photo of seagrass meadows planted in South Bay, near Wreck Island, showing the success of seeding in establishing seagrasses in the area. The stipled areas around the seeded meadows are where natural expansion by seeding has occurred.

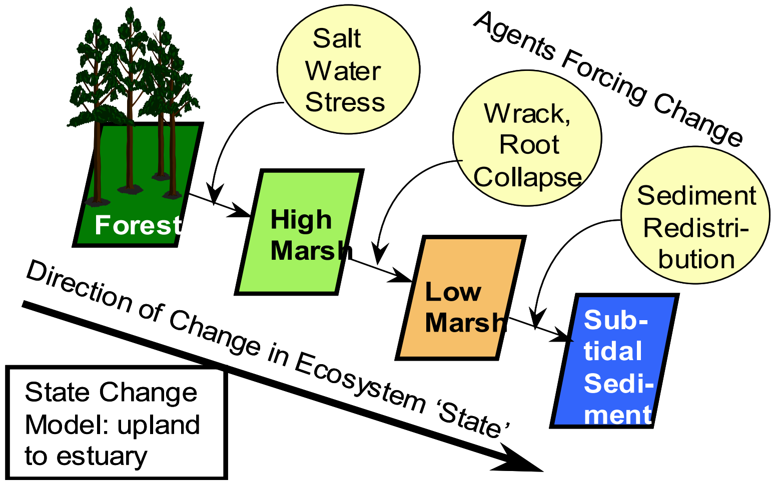
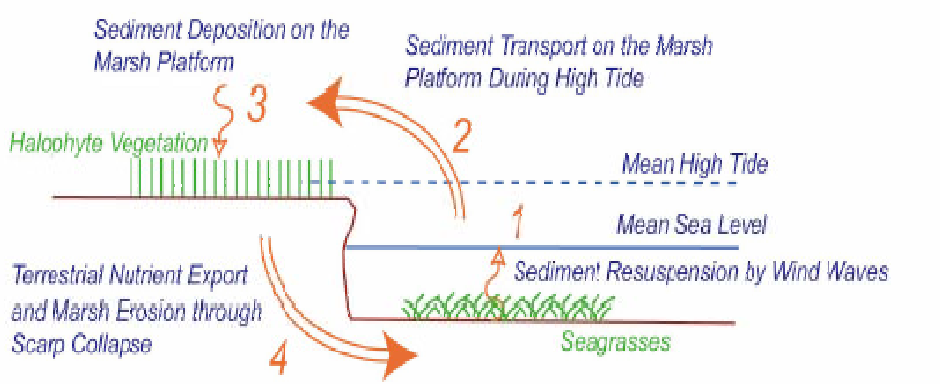


Fig. 23. Conceptual model of ecosystem state change on intertidal marshes in response to change in the relative positions of the land, sea, and groundwater free surfaces.

Fig. 24. Non-linear feedbacks between vegetation, sediment redistribution and landforms in intertidal areas.



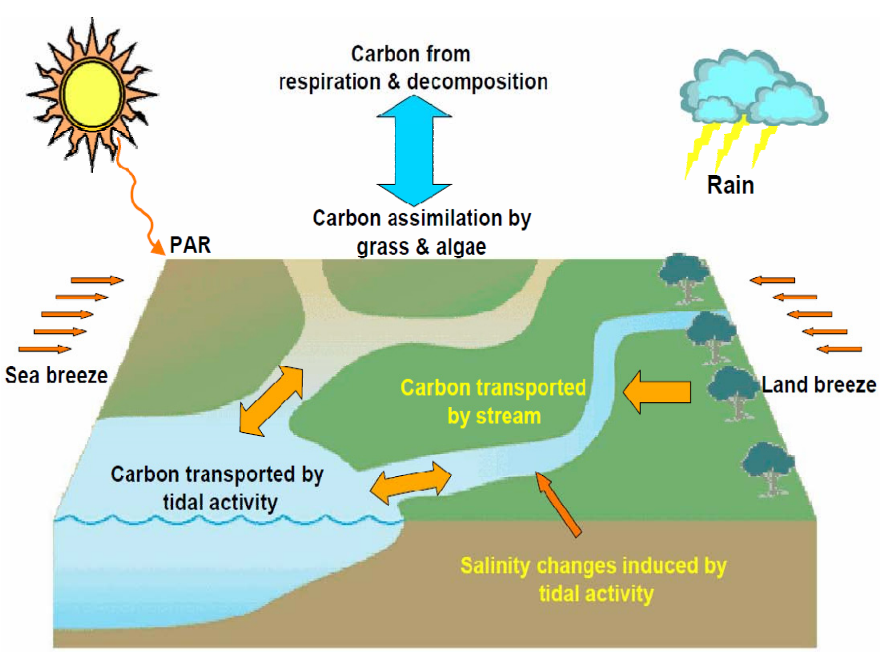


Fig. 25. Conceptual model of land-atmosphere and wetland-lagoon fluxes of carbon that influence the vertical accretion of tidal marshes in relation to sea-level rise.

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