

# Long-Term Ecolo I Research on Disturbance, Succession, and Ecosystem State Change at the Virginia Coast Reserve: LTER IV

## Proposal Submitted to National Science Foundation Ecosystems Studies Program

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### BY:

The Department of Environmental Sciences

The University of Virginia P.O. Box 9003 Charlottesville, Virginia 22906

Principal Investigators: Bruce P. Hayden, Karen J. McGlathery, John H. Porter

Co-Prinicipal Investigators: John D. Albertson, Iris C. Anderson, Linda K. Blum, Mark M. Brinson, Robert R. Christian, Frank P. Day, R. Michael Erwin, Jose Fuentes, James N. Galloway, Stephen A. Macko, Aaron L. Mills, Nancy D. Moncrief, George F. Oertel, Herman H. Shugart, David E. Smith, Patricia L. Wiberg, Donald R. Young, Joesph C. Zieman

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#### **PROJECT SUMMARY**

The Virginia Coast Reserve LTER focuses on understanding the relationships between physical, biological and anthropogenic forces on the dynamic ecology of a coastal barrier island, lagoon and mainland system. The Virginia coast is an extremely dynamic, frequently disturbed landscape with elements that differ in degrees normally associated with biome-level differences, e.g. grasslands, forests, marshes, mudflats, and lagoons. The system is frequently disturbed by storms. Astronomical tides, wind and storms cause sea level variations that impact 70% of the landscape of the VCR. Over the last century sea level rose 35 cm, the highest rise along the Atlantic Coast. Seventy years ago the keystone species *Zostera marina* (eelgrass) disappeared from the lagoons. Recolonization began anew in the last 5 years. Fifty years ago fossil fuel fertilizers initiated tremendous increases in agricultural productivity in the watersheds of the VCR. With 70 m per year groundwater flow rates in the direction of the lagoons and marshes, the potential impact on these systems is real. In addition, 60 to 90% of the upland land surfaces of the VCR barrier islands is new land since 1870. This land creation has left century-long and longer chronosequences of landscapes and ecosystems that we use as natural experiments. It is from this rich, long-term dynamic that the fundamental research questions that we address arise.

How will VCR ecosystems keep up with the most rapid rise in relative sea level anywhere along the Atlantic Coast, much less accommodate even a modest global warming-induced eustatic sea level rise? How will VCR ecosystems change in response to the recent recolonization of a keystone species after 6 decades of absence? With three generations of fossil fuel fertilizer and contaminant loading of watershed groundwater, how will VCR's lagoons deal with the arrival of these nutrients during the next generation? VCR land surfaces are elevated and its ecosystems maintained, on decadal time scales, by episodic sedimentation events arising from coastal storms. How will VCR ecosystems respond to changes under the more moderate storm climate expected with global warming?

# The central hypothesis of VCR LTER IV is that ecosystem, landscape and landuse patterns within terrestrial-marine watersheds are controlled by the vertical positions of the land, the sea, and the freshwater table surfaces.

Within the context of this central hypothesis, our approach to these questions is to utilize shortterm manipulative experiments, long-term observations of decadal and generational time scale system dynamics, and statistical and dynamical models. We will also capitalize on nature's "experiments" where new landscapes continue to be created and where recolonizing keystone species restore the lagoons to conditions of earlier times. In addition, in this renewal of the VCR LTER, we will begin to take advantage of the four-century long experiment in human impacts that began with Captain John Smith's landing and construction of his saltworks on Smith Island in 1609. We will accomplish this long-term regional, experimental research through the study of the 56 morphologically similar watersheds of the peninsula, which currently vary in their human treatment from 80% forest to 80% agriculture. These and other questions regarding the trajectory of VCR ecosystems motivate our research program and go to the heart of solving fundamental societal problems associated with such environmental change.

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Figure 1: The Virginia Coast Reserve is located on the Atlantic side of the Delmarva Peninsula. Research activities are concentrated in the box transect that crosses Hog Island Bay, from the mainland to the barrier islands.

#### **RESULTS OF PRIOR RESEARCH**

VCR LTER III focused on ecosystem change: disturbance, succession and state change in a coastal barrier island, lagoon and mainland complex. Our central hypothesis was that ecosystem, landscape and succession patterns are controlled by the relative vertical positions of the land, sea, and fresh groundwater table. Large transient and small progressive changes in the position of these free surfaces result in disturbance of ecosystem processes and in physiological stresses that may lead to system state change. Variations in the elevations of these critical surfaces result from local weather or climate change, such as short-term storm-generated fluctuation in sea/land levels or long-term sea level rise. Ecological processes, including species extinction and invasion that alter rates of erosion and deposition also affect the positions of these free surfaces relative to one another. In many instances, the joint effects of contemporaneous disturbances at different temporal and spatial scales result in state changes, such as shifts upland to marsh or grassland to shrubland.

From January 1994 through January 2000, we have produced 100 journal articles (84 published or in press, 16 in review). In addition, VCR PIs have contributed 37 book chapters or published proceedings. Fifty four theses and dissertations were completed. Six findings from VCR LTER III with system-wide significance will play key roles in research during VCR LTER IV.

1. Christiansen (1998) and Christiansen et al. (2000) found that sedimentation rates on mainland marshes were highest during the storm surge flooding from coastal storms (Nor'easters) and hurricanes. The role of disturbance in the upward growth of marshes in response to sea level rise had not been quantified prior to this work. For comparison, on the ebb tide flow off the marsh no sedimentation or export of sediment from the marsh was recorded in two years of observation. Disturbance of another sort involved marsh surface erosion. Observations during hurricane Bertha in 1996 suggests that sediment loss from marshes may occur during heavy rains at low tide due to the erosive power of raindrops. These finding will guide our new research on the role of storm disturbances in the dynamics of marsh surface elevation changes.

2. In 1999, the eelgrass *Zostera marina*, locally extinct since 1933, returned to the VCR. *Z. marina* was the keystone species of the sandy bottoms of the lagoons. Historical and anecdotal information confirm that following the demise of the eelgrass the lagoon sediments were mobilized, waters became turbid, the bay scallop and other important filter feeders disappeared and with that many water fowl species no longer returned. Over the next three decades, we expect a major ecosystem state change in the lagoons of the VCR. Resuspension of lagoon sediments will be reduced, water clarity improved and the former communities of benthic flora and fauna will return to the lagoons of the VCR. Monitoring of the trajectory of colonization as a major system state change and the ecosystem consequences of the return of this major keystone species is built into VCR LTER IV.

3. Through measurements of water table elevations in groundwater wells and short-term injection experiments, we found that the horizontal flow rates of freshwater, nutrients and microbes from mainland agricultural systems toward the marshes was around 70 m/yr (Callaghan 1999). Given the size of VCR mainland, terrestrial watersheds one would expect turnover times of 4 to 8 decades. As this turnover time spans the period of introduction of modern fertilizers on Virginia's Eastern Shore, future estuarine eutrophication from past nutrient loading, already in the pipeline, is likely. We will monitor landuse change by remote sensing (GIS), monitor water



Figure: 2: Bathymetric survey of the Machipongo drainage of Hog Island Bay using Global Positioning System coupled to digital fathometry, Panel a) shows the 18,860 individual points collected in the survey. Red dots indicate stations used to control for tidal changes. Panel b) shows the survey results of the survey (vertical exaggeration 1:100).

b)

chemistry in 56 terrestrial watersheds, and measure the short-term groundwater processes driven by extreme events a representative watershed.

4. Hog Island fringing marshes range from 1 to 150+ years in age. While a "climax" monoculture of *Spartina alterniflora* quickly establishes itself, a multi-decade succession in the marsh sediment chemistry and communities of organisms that use the marsh takes place (Walsh 1998, Silliman 1999, Silliman & Zieman 2000, Walsh & Zieman 2000). The associated creeks were found to aid in the retention of nutrients in young marsh/creek systems, and thereby accelerate the development of the marsh (Tyler 1997, Tyler & Zieman 1999). These chronosequences are long-term natural experiments in which new landscapes continue to be generated through storm-generated sedimentation events that convert shallow lagoon areas into marshes (a state change). We will continue to track the evolution of this chronosequence as new marshes evolve.

5. A synthetic system property resulting from prior research that will guide future research is the concept of joined terrestrial-marine watersheds and the hypsometric model of their land surface elevations. Our 18,860 station, bathymetric survey of Hog Island Bay (Oertel et al. 1996, 2000) coupled with USGS digital elevation model data for the terrestrial part of the system now permits us to incorporate watershed concepts into our work and place all of our research locations into a common watershed framework. More importantly it will permit system-level mass budget modeling research to be initiated.

6. Finally, herbivory studies in VCR LTER III indicated the important role played by topdown controls in grass/shrub communities (Barimo 1998, Barimo & Young 2000) and marsh communities (Silliman 1999, Silliman & Zieman 2000). This work will be expanded in our new work with long-term monitoring of key herbivores.

Megasite. Regional (Fig. 1) research during VCR/LTER III focused on three major areas: environmental history of the site, faunal biogeography, and storm-driven ecosystem disturbances. Constructing the history of the site has proceeded at two major levels. Oertel and his students have studied the changes the site has undergone since the Pleistocene using foraminifera (Culver et al. 1996, Oertel et al. 1996, Woo et al. 1997), pollen (Woo et al. 1998), stratigraphic analyses (Foyle. & Oertel 1994, Foyle & Oertel 1997) and analysis of landforms (Oertel & Woo 1994, Oertel & Foyle 1995). For a more recent period, Shao, Young and others used remote-sensing linked to ground surveys and historical maps to quantify dramatic changes in the distribution of Myrica cerifera shrubs on the barrier islands since 1942 (Hayden et al. 1995; Young et al. 1995a,b; Shao et al. 1998). The distribution of mammalian fauna across the islands and marshes of the VCR were analyzed using a variety of sampling and genetic techniques (Loxterman 1995, Moncrief et al. 1997, Moncrief & Dueser 1998, Loxterman et al.2000). Mike Erwin and his colleagues have analyzed on habitat and breeding dynamics of water birds on the islands and marshes (Erwin 1996, 1997; Erwin et al. 1996a, b, 1998a, b, 1999 a, b; Eyler et al. 1999). Changes in climatic patterns that generate storms have dramatic impacts on the island system (Davis et al. 1995, Davis et al. 1997, Hayden 1999, 2000). A surprising conclusion was that there were periods where the geographic patterns of shoreline accretion and erosion reversed (Fenster and Dolan 1994). The most recent of such reversals were in the early 1870s and the late 1960s.

*Barrier Islands*. The distribution patterns of five woody species common along a 120 year, island terrestrial chronosequence on Hog island (Fig. 3) were distinguished based on differences in salinity and flood tolerance (Tolliver et al. 1997). *M. cerifera* shrub thicket distribution was especially sensitive to changes in shoreline accretion and erosion and associated changes in disturbance frequency and salt input (Shao & Shugart 1997). *Juniperus virginiana* was found to



(b)



Figure 3: Barrier island chronosequence on northern Hog Island, VA. a) Topography, ages and characteristic vegetative cover. The map (b) shows the current pattern of landscape/ecosystem units on the island. The black triangles indicate the locations for the dates given in the cross section (a).

(a)

be both salt tolerant and drought tolerant, which explains its abundance across most of the terrestrial microhabitats. Moreover, it may accelerate the establishment of other woody species by acting as a nurse plant (Joy and Young 2000). Successional dynamics were evident at either end of the chronosequence where vegetation colonized frequently disturbed sites (oceanside) or where *M. cerifera* shrub thickets were collapsing and being invaded by many species (bayside). Gaps, which were most prevalent in the oldest *M. cerifera* thickets, were important for increasing species diversity (Crawford & Young 1998). Soil seed banks, the precursor to later successional communities, were most diverse within gaps in the oldest thickets.

Swales had more fine root biomass than the dunes largely due to higher nitrogen levels and higher water table (Stevenson & Day 1996). Nitrogen additions on Hog Island dunes increased plant biomass, with greater allocation to shoots than roots (Day 1996). In response to nitrogen fertilization, soil nitrogen increases were greatest on the oldest dunes while biomass increases were smallest. Aboveground biomass was inversely proportional to nitrogen availability and decreased from younger dunes to the oldest. Vegetation on the oldest dunes may be limited by depth to the fresh groundwater table than to nitrogen. In a minirhizotron study, fertilized plots had greater fine root densities but no change in mortality (Weber & Day 1996). Total aboveground biomass in dunes decreased along the chronosequence on Hog Island (Dilustro & Day 1997) (Fig. 3). Spartina patens biomass decreased, but Ammophila breviligulata biomass increased from the youngest to the oldest dune. Net primary production did not vary significantly across the chronosequence. A cotton strip decomposition assay identified temperature, water table depth and nitrogen availability as the key regulators of belowground decay on the Virginia barrier islands (Day 1995). Among the Hog Island chronosequence dunes, native root decay increased from young to old dunes (Conn & Day 1997). Among swales, higher water levels and associated soil anoxia inhibited native root decomposition and minimized the effects of litter quality on decay. Root decay on younger dunes increased in response to nitrogen fertilization (Conn & Day 1996). Suppressed lignin degradation on the oldest dune suggested possible negative fertilization effects. Nitrogen appeared to be limiting to root decomposition on younger dunes but not older dunes.

The fish assemblages in the barrier island ponds and shallow surf zones off the islands have also received attention. In particular, the temporal and spatial role of abiotic and biotic factors in controlling these assemblages has been addressed (Layman 1999, Layman & Smith 2000, Layman et al. 2000).

Lagoons. In 1997, we began a program to describe seasonal patterns of nutrient cycling and metabolism at three sites in Hog Island Bay (Fig. 2) that represent a gradient in nutrient and organic matter loading. We also established a long-term monitoring program with monthlybimonthly surveys of primary producer biomass and water/sediment characteristics in the lagoon. Using microcosm experiments, and scaling these to patterns of primary production in the field, we established that the lagoon was net autotrophic during the spring-summer, and net heterotrophic in the fall (McGlathery et al. 2000). Macroalgae were responsible for most of the autotrophic production observed and were the dominant temporary sink for nitrogen in the lagoon (McGlathery et al. 2000). Where nutrient loading was low to moderate and herbivore populations large, grazing had an important influence on the net accumulation of macroalgae (Giannotti 1999; Giannotti & McGlathery 2000). Macroalgal biomass peaked in early summer throughout the lagoon. In some locations (mid-lagoon shoals) macroalgae reached densities as high as  $650 \text{ gdw m}^{-2}$  and the population crash resulted in anoxia throughout the water column. The net release of dissolved organic and inorganic nitrogen during this dystrophic event was 70 mmol  $m^{-2} d^{-1}$ . At this rate, all the macroalgal-bound N would be remineralized within 7-10 days (Tyler et al., 2000). Gross mineralization was measured in the sediments using <sup>15</sup>N isotope dilution techniques. We found



Figure 4. Four types of salt marsh response to rising sea level as a function of land slope and sediment. The presence of thick marsh peats is indicative of marsh transgression into upland vegetation on a gentle sloping land surfaces. Peat development is restricted on steeper land surfaces.

that total nitrogen turned over in 7 days or less; however, consumption of N was similar to gross production. These results were supported by microcosm studies which showed net uptake of both ammonium and nitrate by sediments during most seasons, suggesting that inorganic N was removed in the sediments as rapidly as it was formed, either by coupled nitrification - denitrification or by microbial immobilization (Anderson et al., 2000). Dissolved organic nitrogen concentrations in the region were high during all seasons and comprised 55-95% of total dissolved nitrogen. The macroalgae were a net source for dissolved organic nitrogen compounds other than urea, and the sediments also were a significant source of dissolved organic nitrogen to the water column (Tyler et al., 2000).

Mainland Margins. At the VCR evidence abounds that sea level rise has eroded salt marshes and sometimes submerged them and that salt marshes have in turn encroached on field and forest. During VCR LTER III we focused on the dynamics of vegetation in the transition zone from marsh to forest. We began a long-term observational and experimental studies at a marsh on the upper reaches of Phillips Creek (Taylor 1995, Tirrell 1995, Aiosa 1996, Anderson et al. 1997, Tarnowski 1997, Stasavich, 1998, Brinson & Christian 1999, Ricker 1999, Tolley & Christian 1999). We have shown that marsh transgression into forested uplands occurs at rates dependent on the availability of sediments and on the slope of forested surface on which the marsh encroaches as sea level rises (Hmeiliski1994). The upper Phillips Creek high marsh is rich in peat and exhibits a morphology of hummocks and hollows which are typical of salt marshes on formerly forested land (Christian et al. 1999). We also studied the loss of marsh along its tidal creeks and found that erosion of the marsh along the tidal creek banks was slow and progressive except in periods of significant sediment deposition which occurred during extreme high tide usually associated with coastal storms (Christiansen, 1998). As part of our efforts to understand the transition from forest to marsh with rising sea level we developed models that characterize state change in marshes in response to sea level rise. Brinson et al. (1995) modeled expansions and contractions in marsh area based on sediment supply (Fig. 4). At the margin of the marsh and the lagoon progradation or erosion was found to depend on sediment supply. Whether a marsh encroached into a forest or stalled depended on the slope of the antecedent forest surface. All four modeled patterns of long-term marsh dynamics were found at the VCR. However eroding marshes dominate at the VCR because of low supply of new terrigenous sediments from the peninsula. We also developed a model that addresses ecosystem state changes in the upland/marsh transition. Furthermore, we identified limiting processes in this sequence of change and the factors that promote or accelerate such changes (Brinson et al. 1995, Christian et al. 1999, Nuttle et al. 1999).

*Modeling*. Models of system dynamics were used to test the collective assemblage of our findings and to formulate new research questions and hypotheses. We developed a hypometric model of Hog Island Bay (Oertel et al. 1996a, 2000) and have extended it to include the adjacent mainland watersheds. This model is detailed elsewhere in this proposal. Using 150 years of maps, charts and aerial photographs we have build an animated morphometric model of Hog Island and have used this model to project island changes for the next 40 years. Christiansen (1998) constructed a mathematical model of the dynamics of sedimentation in a salt marsh and tested it against observations. Santos (1997) created a hydrologically-based predictive model for island salt flats. Wiberg and Albertson's model for evapotranspiration from salt marshes, and Hayden's model of barrier island vegetation dynamics in response to coastal storms disturbance were completed in late 1999 and will reach publication early in VCR LTER IV.

*Synthesis.* Hayden et al. (1995) introduced the concept of the geometry of land, sea and water-table surfaces as controlling agents in ecosystem patterns within landscapes and related



Figure 5: Land surface area in the VCR/LTER lagoon can vary widely as a result of tidal changes. During an extremely low tide (a) tidal flats and the shallow lagoon bottom can be exposed. During mid-tide (b) lagoon bottoms are inundated, but marshes remain exposed. During extreme high tides (c) marsh areas may be completely submerged for several hours. Extreme tides (both high and low) are associated with unusual astronomical alignments and strong winds.

these controls to the long-term dynamics of the barrier islands, lagoons and marshes of the VCR. Brinson in a series of synthesis papers, focused on wetland function (Brinson et al. 1995), environmental mitigation (Brinson & Rheinhardt 1996), hydrologic controls (Brinson et al. 1998), societal values (Brinson & Rheinhardt 1998) and biodiversity in wetlands (Brinson & Verhoeven, 1999). Thomas (1998) applied network analysis to the nitrogen cycling of different marsh states to predict alterations in response to sea level rise. Oertel (1995; 2000 a, b) has continued his synthetic work on the evolution of the VCR landscape at the regional scale in space and at the scale of glacial and interglacial transitions in time showing the connection between relict drainage patterns on the continental shelf and existing lagoonal landscapes. The central idea was that the antecedent Pleistocene land surface was a controlling legacy for the modern landscape. This notion is in stark contrast to the idea that barrier island lagoons, like lakes, were merely basins that fill with sediments that evolve into terrestrial landscapes. In modeling waterbird colony site damages through time, Erwin et al. (1998) have developed a method for quantifying how a number of extrinsic factors influence patch use dynamics. Population genetic modeling has revealed the degree to which small mammals may also be viewed as a large barrier island metapopulation (Moncrief et al. 1997).

At the LTER Network level and as part of a long-standing network-wide synthetic activity to better understand the mechanisms for ecosystem controls on climate, Hayden (1998) published Ecosystem Controls on Climate at the Landscape Scale in the Transactions of the Royal Society of London. This work was part of the VCR contribution to climate research in the LTER network. Hayden (1998a, b) also joined scientists at the Konza Prairie LTER in the completion of the first in the LTER Network / Oxford Press synthesis series on long-term ecological research. These two papers focus on climate controls on the Prairie and the impact of climate change.

We have been strong participants in LTER Network information management actdivities (Porter et al. 1996; Henshaw et al. 1998; Michener et al. 1998; Porter 1998 a, b; Olson et al. 1999; Porter 2000). During the course of LTER III, we provided over 31 gigabytes of data, text and images to the scientific community and the general public (See the Information Management section for comprehensive statistics).





Figure 6: Terrestrial-Marine Watersheds of the Virginia Coast Reserve. Elevation data is from USGS Digital Elevation Model data. Marsh research sites were sampled for chemical and physical characteristics in 1998-1999.

#### **PROJECT DESCRIPTION**

This is the fourth proposal in support of long-term ecological research at the Virginia Coast Reserve (VCR). We began in 1987 with the hypothesis that ecosystem dynamics in the barrier islands, lagoons and marshes of the Virginia Coast are driven by large-scale events and processes (e.g. species extinction, coastal storms and sea level rise). In our first renewal (VCR LTER II) the concept of abrupt ecosystem change (state change) and slow progressive change (succession) were introduced as emergent properties driven by large-scale events and processes. In VCR LTER III, we built into our research framework the hypothesis that these large-scale events and processes control ecosystem dynamics through changing the relative elevations of three free surfaces: the land and sea surfaces and the elevation of the fresh groundwater table. In this renewal, we add the synthetic, geomorphologic construct of watershed hypsometry to our controlling, central research hypothesis. At our last NSF site review (Summer 1997), we presented terrestrial-marine watershed hypsometry as a unifying concept for our research and were strongly advised to fully integrate this approach into our research planning. Also, in response to this mid-term review we will add on-site technicians to better meet the obligations of all PIs. In addition, in 2000/2001 a new field laboratory will be constructed to help meet expanded VCR/LTER research needs.

In this proposal we use bold type at the ends of paragraphs to indicate if the work is new (*NEW*), associated with our modeling efforts (*MOD*), part of long-term experiments (*LTE*) and/or one of the five core areas (*PP*, *NC*, *OM*, *TS* and *DS*).

#### **INTRODUCTION**

The central hypothesis of VCR LTER IV is that ecosystem, landscape and landuse patterns within terrestrial-marine watersheds are controlled by the vertical positions of the land, sea, and of the fresh groundwater table surfaces. Coastal storms, climate change, long-term eustatic sea-level rise, and land subsidence cause variations in the elevations of these surfaces that drive ecosystem dynamics. Ecological processes, including organic matter production, species extinction and colonization, alter the rates of erosion and sediment deposition and thereby alter land and water table surface elevations. Short-term episodic events and long-term systematic trends in sea level and land and groundwater surfaces give rise to variations in nutrient availability, primary productivity, organic matter accumulation and trophic interactions.

#### THE SITE

**VCR Watersheds** are unions of marine and terrestrial drainages (Fig. 6). There are 13 major, terrestrial-marine watersheds on the VCR site. Each is named for the barrier island inlet through which they drain into the ocean. During the first decade, research at VCR LTER focused on the barrier islands, lagoons and marshes of the Quinby and Machipongo watersheds (Fig. 7). With the advent of GPS-fathometry and the availability of high-resolution, USGS digital elevation products, it has become possible to model land-surface elevations (hypsometry) and apply the watershed concept to both our terrestrial and marine research.



Figure 7: The Machipongo watershed and its terrestrial sub-watersheds.

Nine of the 13 VCR watersheds are "complex watersheds" (Ray & Hayden 1992). Each of these nine has mainland (freshwater) and tideland (saline) sub-watersheds. These fresh and saline sub-watersheds drain into a common channel and exit to the sea through a single inlet between adjacent barrier islands (Figs. 6 & 7). The remaining four watersheds (New Inlet, Ship Shoal, Little Inlet and Fishermans) are "compound watersheds" (Ray & Hayden 1992) made up solely of tideland sub-watersheds which only drain salt marshes and mudflats. Consequently, the four compound watershed systems experience no direct impact from watersheds draining urban or agricultural lands. The tideland sub-watersheds also drain into a common channel that exits to the sea through a single inlet between adjacent barrier islands (Figs. 6 & 7).

The nine complex watersheds with terrestrial sub-watersheds contain, in total, 56 mainland, freshwater, sub-watershed units. They range in size from 1,949 to 19,447 ha. Each has a dominant stream course that flows into the lagoon drainage system. These terrestrial sub-watersheds range from 20 to 80 %, by area, in agricultural use. Portions of these watersheds not in agricultural use are mostly forested. This regional landscape provides us with a hierarchical "experimental" design. We consider the land use of these 56 terrestrial sub-watersheds as experimental treatments and the four compound watershed systems that have no agricultural land as controls. Further, all have a common climate and similar topography effectively holding constant these normally variable watershed attributes. From an experimental perspective, it is also significant to note that the terrestrial sub-watershed streams are filled from groundwater seepage, except during intense storms when overland flow dominates.

At research sites within the watersheds sea level, land level and water table elevations are recorded on a long-term basis as core VCR measurements.

VCR Ecosystems in the 13 major watersheds are divided into three parts: the barrier islands, the lagoons and the mainland. Our research program since 1987 has recognized this three compartment model. On the seaward side there are barrier islands with beaches, dunes, swales, ponds, freshwater marshes, forests, sand flats and fringing salt marshes. In the middle, lagoon component of the system, there are shallow bays, deep channels, extensive mudflats and insular salt marshes. The mainland portion is made up of fringing salt marshes and mudflats, deciduous and evergreen forests, and agricultural fields and settlements. As mentioned above, the diversity of ecosystems within the VCR with the same climate permits comparative studies of relationships that serve VCR LTER cross-ecosystem studies.

The vegetation of the barrier islands, the mid-lagoon salt marsh islands and the mainlandlagoon interface is conspicuously zonal (Ehrenfeld 1990, McCaffrey & Dueser 1990a, b; Young et al 1995a) with sub-scale patchiness and sharp transitions between patches. The zonal aspect of vegetation patterns is exemplified in the hyposmetric curve for the Machipongo watershed (Fig. 9). High and low salt marshes, unvegetated mudflats, grasslands, shrub savannas and maritime forests occur in close proximity, with sharp ecotones between adjacent ecosystems. Vegetation heterogeneity is further accentuated by interannual climate variation: precipitation records indicate a range of between 85 and 140 cm yr<sup>1</sup> (Bolyard et al. 1979, Hayden 1979). This variation arises primarily from the occurrence of summer thunderstorms and from late summer and autumn rainfall from tropical storms (Hayden 1979).

**VCR's Climate** is dominated by coastal storms or Nor'easters (Dolan et al. 1987) and the Bermuda high-pressure system (Davis et al. 1997) (Fig. 8). Each year more than 20 extratropical storms occur with magnitudes sufficient to rework beach sands and to elevate tides



Figure 8. Climate and Sea Level History at the VCR. A) Atlantic coastal storms off the VCR Coast, B) Expansion and contraction of the Bermuda high pressure cell, C) Atlantic hurricane frequencies, D) Land level and relative and eustatic sea level changes during the Holocene, and E) Twentieth century relative sea level rise for the VCR area.

above astronomical norms (Hayden 1975, 1981, 1999a,b; Dolan et al. 1987, 1988) (Fig. 8A). These storms generate waves from the northeast and drive sands southward along the coast. The Bermuda high-pressure system generates southeast swell and when expanded (Fig. 8B) drives sediment northward along the coast. Nor'easters, the Bermuda High, and hurricanes have exhibited long term trends, climate change, over the last century (Fig. 8). These storms are largely responsible for the production of waves and storm surges which in turn change the morphology of the islands (Dolan et al. 1979). In addition, they alter island vegetative cover (Fahrig et al.1993), and ultimately in combination with sea level rise drive the landward migration of islands across lagoon marshes (Hayden et al. 1980, 1991) and the accelerate the encroachment of marshes into the mainland forests (Kastler 1993, Brinson et al. 1995, Shao et al. 1998, Christian et al. 1999, Nuttle et al. 1999). In effect, the landscape and its dynamics is a perpetual experiment in ecosystem disturbance, ecosystem state change and plant succession associated with physical processes. Harris (1992) determined that 90% of the landscape seaward of the fringing marshes on Hog Island (our principal study site for barrier islands) dates from 1871 or later. The extent of VCR marshes declined 16% from 1852 to 1960 (Knowlton 1971). The reason for the loss of marshes over the last has been due to land subsidence and the eustatic sea level rise.

#### THE THREE FREE SURFACES

The three free surfaces that structure landscapes and ecosystems at the scale of VCR watersheds are sea level, land level and the freshwater table. This free surface concept was developed in VCR LTER III. The VCR site is structured to a large extent by the vertical variations in these surfaces and their interacting geometry (Fig. 11). At the VCR small variations in elevations or slopes of the freshwater table, land or sea level surfaces can result in ecosystem changes equivalent to continental biome transition (state changes). The central hypothesis in VCR LTER IV focuses on the dynamics of these free surfaces within the construct of watershed hypometry (Fig. 9).

The Elevation of the Land Surface at the VCR ranges from +13 m to -13 m relative to mean sea level. The barrier islands are generally less than 4 m above mean sea level but undergo great elevation changes (~ 1m) during individual coastal storms. This can result in elevation chages of up to 9 meters when integrated over decadal time scales. The highest elevations in the mainland portion of the watersheds are around 13 m. The mainland elevation as well as that of the Pleistocene surface under the lagoon are sinking at an average rate of 2.5 mm/year (Emery & Aubrey 1991). Surface elevations in the salt marshes and mudflats are generally less than 0.5 meter above mean sea level. Water depths in the lagoons average 1 to 2 m. The coastal plain on which the VCR is located has a seaward slope of less than 0.1%. Where sea level intersects this sloping plain, small changes in elevation of either the land or the sea result in large horizontal changes in landscape pattern and ecosystem structure (Fig. 5). Locally, the elevation of the land free surface is controlled by sedimentation and erosion of marine and terrestrial sediments and by organic matter accumulation and decomposition (Hackney & Cleary 1987, Brinson et al. 1995). For VCR ecosystems, increases in elevation due to sedimentation may offset the regional subsidence of the land and eustatic rise of the sea. Most of the inorganic sedimentation above mean sea level is transported hydraulically during Nor'easters and tropical storms when sea levels exceed the astronomical tides by as much as 3 m (Dolan & Godfrey 1973). Belowground



Figure 9. The hypsometric curve for the Machipongo terrestrial/estuarine watershed. The hypsometric curve shown is a normalized morphometric characterization (model) of a watershed's land surface and lagoon bottoms by accumulative elevation and accumulative area increments. The scale is from 0 to 1. In the case of the elevation, the deepest channel depth is - 13 m and the highest land elevation is +13 m. Mean sea level is at the scaled value of 0.6. Also shown on the illustration are the elevation increments that are associated with various ecosystems of the VCR. The horizontal axis may be read as the fraction of area that resides in various elevation increments.

organic matter accumulation (Blum 1993, Blum & Christian 2000) and overwash of marine sands (Kochel & Wampfler 1989) are also critical processes at the VCR that alter land elevations and may give rise to system state changes.

Hypsometry is a normalized morphometric characterization (model) of a watershed's land surface by accumulative elevation and area increments. The hypsometry (Fig. 9) of the Machipongo watershed (Fig. 2) is based on GPS controlled bathymetric surveys (18,860 points) and USGS digital topographic information (65,000, 30 m x 30 m polygons). Shown with the hypsometric curve is the sequence of ecosystems that characterize height increments. It must be emphasize that this is not an ocean to land topographic profile. For example, land area in the height increment +1 m to +5 meters includes both mainland, riparian bottomlands and barrier islands uplands. The hypsometric approach permits 1) direct calculation of lagoon flushing per tidal cycle; 2) quantification and prediction of system responses to sea level variation; 3) assessment of landuse changes on nutrient cycling; and, 4) a quantitative approach to the biogeochemical dynamics of coastal watershed ecosystem. Significantly, for the VCR research plan, it also permits a detailed, system-wide perspective of the dynamics of three free surfaces that is the focus of our central research hypothesis

**The Level of the Sea** varies on a wide spectrum of time and spatial scales. That part of the variation is driven by the gravitational attractions of the sun and moon (the astronomical tides) and is well known, monitored and forecast at Wachapreague, Virginia within the VCR. This model is calibrated to local research locations using temporary tide gauges. Adjustments for mean elevation, tidal amplitude and phase are empirically based. Storm surges and wind tides resulting in changes in sea elevation are monitored at four tide gauge locations. The attributes of each storm are estimated and recorded. These records reveal large changes in the frequency of coastal storms. The elevated sea levels that result are critical to the transport of sediments on the islands, the mudflats and the marshes.

Long-term sea level changes are relative as both the level of the sea and the land change simultaneously. The relative sea-level rise at the VCR is the sum of the change in the elevation of the sea (eustatic sea level change) of about 1 mm/yr and the change in the level of the land of about 2.5 mm/yr (Oertel 1989b, Emory & Aubrey 1991) (Fig. 8E). Harrison (1959) detailed the changes in relative sea level, eustatic sea level and land levels at the southern end of the VCR for the last 20,000 years (Fig. 8D). The contemporary rate of relative sea level rise exceeds the measured rate of marsh upward accretion of 2 mm/yr at the VCR (Kastler 1993). Unless marine sands or terrestrial sediments are readily available for deposition (Ray & Hayden 1992) or biogenic accretion is adequate to keep pace with the rising sea (Blum 1993, Brinson et al. 1995, Blum & Christian 2000) loss of marshlands results. Knowlton (1971) reports a loss of marsh area of about 16% for the preceding 100 years. Seawater tends, with time, to flood terrestrial environments. Farm fences on hypersaline marshes are evidence of the encroachment of saline water into fields and freshwater marshes along the lagoon-mainland margin.

**Water Table Levels** at the VCR are generally related to surface elevations, precipitation and evapotranspiration. On the mainland where land surface elevations are as high as 15 m, water tables are 0 to 4 m below the surface. Horizontal flow rates are on the order of 70 m/yr but range from 40 to 100 m/yr (Callaghan 1999). On the barrier islands, water table surfaces are generally within 2 m of the land surface and in interdunal areas outcrop as coastal ponds.



Figure 10. Comparison of system attributes from hypsometric and topographic perspectives. Vertical elevations are exaggerated in the topographic perspective. Elevation and area are normalized and scaled from 0 to 1. The magnitudes of system attributes are scaled from 0 to 1. VCR research in hypsometric terms centers on the intersection of mean sea level (msl) and the land surface and the adjacent lagoons and uplands. In topographic terms we study this intersection at three locations (the barrier islands, the lagoons and the mainland margin). From the topographic perspective it is clear that there are marine controls on the system as well as mainland, human influenced, controls. Our research sites are end-members of those gradients but from the hypsometric perspective the intersection of msl and the land is where the action is. The green areas indicate the consequences of a return of the eelgrass to the VCR lagoons.

In these environments, for each meter of fresh groundwater elevation above mean sea level there will be approximately 40 m of freshwater below the island. In effect, each island is like a large natural lysimeter in a matrix of saline water. Horizontal flow rates are estimated from injection experiments and are modeled based on high-resolution, digital terrain data from the USGS. Water table elevations are monitored using wells

Storm-caused transport of sand inland from the beach and nearshore changes the hypsometry by increasing base island elevations (Dolan & Godfrey 1973). Aeolian processes subsequently give rise to local topographic maxima and minima (dunes and swales) producing a fine-scale topography in the water table surface. It is the base elevation of the land above the extremes of the astronomical tides that permits significant trapping of rainwater and the development of a perched freshwater lens which is the confined freshwater resource for terrestrial vegetation on the islands (Bolyard et al. 1979). Island topography directly determines water table depths. The storage capacity for this resource depends upon 1) the difference between the elevation of the water table and the elevation of the land free surface (Ghyben-Herzberg principle), 2) precipitation and 3) evapotranspiration. Where the freshwater storage capacity is large, maritime forests with high leaf area index (LAI) may develop. Where storage capacity is modest, lower LAI grasslands are common. Where the land level approaches the level of high tides and freshwater reserves are not present, infrequent tidal flooding combined with high evaporation rates may result in hypersaline salt flats or Salicornia virginica-dominated zones. Land elevation changes give rise to frequent state changes on the islands. It is significant to note that it is hurricanes and extreme winter storms that give rise to state changes from estuarine ecosystems to terrestrial ecosystems. Sea level rise and land subsidence produce state changes from terrestrial ecosystems to estuarine ecosystems. The hypsometric and topographic perspectives of system organization are illustrated for a number of important aspects of VCR ecosystems in Figure 10.

#### LONG-TERM CHANGES

The site history of the VCR includes both systematic and abrupt changes that fundamentally alter the structure and function of its ecosystems. Changes in the states of VCR ecosystems can be dramatic. At the end of the Pleistocene, 18,000 years ago, the site was a maritime boreal forest of *Pinus strobus* and *Picea* sp. (Emory et al. 1967; Bonan & Hayden 1990a, b). Seven thousand years ago, with a lower sea level, what are now open-water lagoons were forested uplands with stream channel estuaries. Five thousand years ago when sea level was approaching the current level, these sites changed to bays, mudflats, salt marshes and tidal channels (Newman & Munsart 1968). In the last 1500 years the site changed to today's lagoons, marshes and barrier islands perched on the much older, Pleistocene surface (Harrison et al. 1965; Oertel et al. 1989a, c).

Consequently, contemporary barrier island-lagoon-mainland complex took form during the late Holocene rise in sea level, although the underlying topographic framework can be traced back to earlier high stands of sea level during the Pleistocene (Oertel et al. 1989a). On top of this Pleistocene surface is a veneer of Holocene sediments that has adjusted the hypsometric form of the system including the extent of mudflats and marshes. Rapid change has taken place during the last few thousand years via land subsidence and sea level rise. The barrier islands have been migrating westward across the continental slope at a rate as high as 1 m/yr (Finkelstein et al. 1987). The modern islands typically exhibit shoreline change characterized by lateral accretion



Figure 11. Geometric relationships between free surfaces characteristic of landscape and ecosystem elements of the VCR. Landscape elements A - G may occur as a spatial sequence

and erosion at rates as high as high as 13 m/yr (Dolan et al. 1979) creating one of the most dynamic coastal landscapes in the United States.

Landscape/ecosystem elements within the site have undergone equally large state changes within the present century in response to the background rate of relative sea level rise of 3.5 mm/yr. The flattest section of the hypsometric curve is at tidal elevations (Fig. 9). Consequently, the 35 cm increment rise in sea level in the past 100 years means that large areas once sub-aerial are now below current mean sea level. Mockhorn Island, once agricultural land and formerly forest, has been abandoned and is now young, hypersaline salt marsh. At the turn of the century, many of the salt marshes that now fringe the mainland were fenced as upland pastures. The bay bottoms, which were eelgrass meadows at the turn of the century, are now primarily unvegetated as a result of the extinction of this keystone-species (Hayden et al. 1991). 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 an overwash-flat grassland (Rice et al. 1976, Fitch 1991 Hayden et al. 1991,). The north end of Hog Island was several hundred meters wide and consisted of a narrow beach fronting a marsh in 1852; it is now a complex chronosequence of ridges and swales with associated vegetation nearly 1.5 km wide (Hayden et al. 1991). In summary, the VCR is a mosaic of landscapes and ecotones with rates of change exceeded in North America only by the coastal margin of the Mississippi Delta (Dolan et al. 1982).

The "Great Halloween Storm of 1991" and its effect on the VCR landscape illustrates the exceptionally dynamic nature of this landscape. On October 30, 1991, the VCR was hit by a storm that evolved from an extratropical storm (a "Nor'easter") moving eastward to merge with a passing tropical storm, Grace. The resultant Great Halloween Storm (Dolan & Davis 1992) was a major coastal-storm event from Cape Hatteras, N. C. to Kennebunkport, ME. At the VCR, waves at sea reached heights over 11 m and the beaches of the barrier islands were pounded with waves of 3 - 5 m. This was the most powerful storm of the 1,447 coastal storms in our LTER data archives (1942-1994). The intensity of this storm was so great that statistical estimations of its probability indicate a 1000-year plus return interval; this storm was exceptional. Tens of meters of beach were removed from Hog Island. The inlet between Parramore and Crescent Islands was filled with sand. Marshes behind Parramore Island were buried by as much as 1 m of sand. Large sections of Parramore Island's south end eroded away. Freshwater wells in transects across Hog Island became saline. The Halloween Storm and other large storms leave extensive deposits of wrack that appear to be partly responsible for patchiness of marsh vegetation (Brinson et al. 1995). Several new marsh surfaces developed on which we have installed an extensive array of permanent plots and transects to chart the colonization and development of a salt marshes on newly deposited substrates. Significantly, research following this storm led to the identification of a 150 year sequence of marshes of different ages that we now study as a marsh chronosequence.

Finally, during the waning years of the 1990s, colonization of lagoon bottoms by *Zostrea marina* has been discovered at several locations. Since its extinction in the early 1930s, the lagoon bottoms of the VCR have been largely devoid of submerged aquatic vegetation and the rich ecosystems that associated with these seagrasses, most notably the filter-feeding bay scallop. Since the 1930s, lagoon waters have been highly turbid as the fine-grained sediments of unvegetated bay bottoms are entrained into the water column by wave action. If the enhanced colonization of *Z. marina* is successful, a major ecosystem state change potentially extending over 50% of the VCR will ensue. This natural experiment will be monitored over the decades to come.

#### **TABLE 1: Relationships Between Free Surface Dynamics and VCR Ecosystems**

1. Long-term (> 1 yr) changes in the mean elevation of a horizontal free surface intersecting a sloping free surface causes associated ecotones to shift position horizontally.

2. Long-term (> 1 yr) changes in the mean elevation of a free surface parallel to a static free surface causes an ecosystem state change.

3. Short-term ( $\leq 1$  yr) periodicities in the elevation of a free surface relative to parallel, static free surface gives rise to a characteristic ecosystem type which depends on the frequency of surface elevation variation, the amplitude of the free surface elevation change, and the relative position of the static free surface.

4. A horizontal gradient in the mean elevation of one free surface relative to a horizontal second free surface results in horizontal zonation of ecosystems. A change in magnitude of the gradient in elevation compresses or expands the zonal arrangements of ecosystems. A change in the elevation of the horizontal surface displaces the zonal system of ecosystems horizontally.

5. Long-term maintenance of ecosystem structure, in an environment with free surface elevation changes, requires parallel changes in at least one of the other free surfaces. If these conditions are not met, an ecosystem state arises, a results that could not be achieved by autogenic succession.

6. Patchiness in community structure arises from a spatially commensurate variation in the elevation of one or more free surfaces. The land free surface elevation heterogeneity is a primary source of patchiness at a number of spatial scales at the VCR.

7. Disturbances that change the geometry of free surfaces may cause ecosystem state change. A disturbance that does not change the geometry of the free surfaces does not cause an ecosystem state change, but may set the system back to an earlier successional stage.

8. Nutrient cycling, above and below ground production, decomposition, and local trophic structure are directly or indirectly dependent on positional inter-relationships of the free surfaces associated with the specific ecosystem.

9. Keystone species at the VCR are those that have the capacity to alter the elevations of the three free surfaces. Ammophila on islands, Spartina on marshes, oysters on mudflats, and sea grass on bay bottoms all influence the deposition or erosion of sediments.

#### CONTINUING AND NEW RESEARCH

The VCR LTER project seeks to understand the relationships between slow, long-term changes in land, sea and groundwater free surfaces and rapid, short-term disturbances in these same surfaces that trigger ecosystem state changes and set in motion or alter successional sequences within terrestrial/marine watersheds.

The central hypothesis of VCR LTER IV is that ecosystem, landscape and landuse patterns within terrestrial-marine watersheds are controlled by the vertical positions of the land, sea, and of the fresh groundwater table surfaces. Coastal storms, climate change, longterm eustatic sea-level rise, and land subsidence cause variations in the elevations of these surfaces that drive ecosystem dynamics. Ecological processes, including organic matter production, species extinction and colonization, alter the rates of erosion and sediment deposition and thereby alter land and water table surface elevations. Short-term episodic events and long-term systematic trends in sea level and land and groundwater surfaces give rise to variations in nutrient availability, primary productivity, organic matter accumulation and trophic interactions.

Characteristic relationships between the geometry and geography of the land, sea and groundwater table free surfaces are shown in Figure 11. Our synthetic understanding of these relationships, that is the metaphysical construct detailing how we think the terrestrial/marine watersheds of the VCR work, goes directly to the theoretical basis for the sub-hypotheses that guide our field studies. Nine axiomatic relationships are detailed in Table 1. At any one location within the VCR a subset of these relationships apply. We do not refer to these relationships as hypotheses as, in their general formulation, they are not the object of our field studies. Nonetheless, the sub-hypotheses of our central hypothesis are founded on this system of relationships.

Our research program is designed to investigate relationships between the three free surfaces and the ecosystems that depend on them. Our approach during the past 13 years has been to study the controls on succession and state changes at four research venues within the Virginia Coast Reserve: the VCR Megasite, the Barrier Island Sites, the Lagoon Sites and Mainland-Margin Sites (Fig. 1). At each site we are engaged in LTER core-area research as part of the testing of our research hypotheses. At the VCR Megasite we focus our research on the intersections of the three free surfaces at large geographic and long time scales using remote sensing tools and annual (and longer) interval surveys of both biotic and abiotic system components. At our Barrier Island Sites, primarily Hog Island, we take advantage of two 120 year plus ecosystem chronosequences that continue their active past record of change. At the cross-island, terrestrial chronosequence site we focus on the interactions of the land and water table surfaces (two non-parallel and sometimes intersections surfaces) in structuring island ecosystems. We also take advantage of a second150 year plus chronosequence of marshes with largely parallel sea and land levels. At our Lagoon Site in Machipongo Bay we study how nitrogen and carbon are processed along a gradient from the more heavily impacted mainland to the barrier islands. At the Mainland-Margin Sites we focus on the oscillatory free surface of the sea level and its intersection with the sloping land and water table free surfaces. We rely on imagery, networks of sensors and permanent plots, wide-area surveys, transects, and

#### TABLE 2: Sub-hypotheses for Megasite/Regional Research at the VCR LTER

1. The long-term impact of sea-level rise on ecosystem state will depend on hypsometric position of current and antecedent land free surfaces and the rate of change of both the sea-level and land free surfaces. In turn, changes in the relationship of the two dominant free surfaces, land and sea-level, will alter the nature of the fresh-water free surface. (Oertel, Hayden, Wiberg, Zieman)

2. Changes in terrestrial land use and/or land cover influence the condition of adjacent wetlands and lagoons. Anthropogenic influences (agriculture, forestry, and urbanization) dominate on the mainland while natural successional and state-change processes dominate on the islands. (Porter, Blum, Hayden, Mills, McGlathery, Anderson)

3. The stratigraphy of antecedent sediment layers and diversity in the slopes among VCR watersheds determines the extent of groundwater advection directly to lagoons and marshes thus impacting the delivery of terrestrially-derived nutrients to these regions of the watershed. Storm-driven recharge events accounts for the majority of the total discharge to the lagoons and marshes. (Mills, Albertson, Wiberg)

4. Atmospheric inputs of nitrogen via wet deposition will continue to increase due to increased intensity of agricultural practices and changes in land use. These inputs are becoming sufficiently high to have significant consequences for the barrier islands, lagoons, and marshes. (Galloway, Keene, Young, McGlathery, Christian)

5. Species invasions are dependent on disturbance frequency. The interval between disturbances determines the success of any specific invasion. Examples include *Phragmites australis* on barrier island, lagoon, and mainland marshes and red fox (*Vulpes vulpes*) on the barrier islands. (Zieman, Hayden, Porter)

6. Because productivity and growth from of *S. alterniflora* vary as a function of the difference between marsh surface elevation and sea-level, marshes that were buried by the 1933 hurricane and the surface elevated are dominated by short-form *S. alterniflora* and are less productive than the tall from marshes. Experimental lowering of the marsh land surface or increasing sea level will increase productivity and promote dominance of *S. alterniflora*. (Zieman, Hayden)

7. Because grazing of *S. alterniflora* is ubiquitous throughout the system, top-down control by grazers (and their predators) is equally important as nutrient availability and salinity stress (bottom-up control) in regulating the productivity of *S. alterniflora*. In addition grazers can detect and show a preference for higher nitrogen content *S. alterniflora*. (Zieman)

8. Food sources of top-level predators in the VCR will show greater spatial and temporal variability in watersheds with greater human impact than in those that are less human-influenced. (Erwin, Macko, Smith, Porter)

9. Processing of below ground organic matter occurs at two scales: (a) a slowly growing, quasi-steady state turnover over the short term (annually to a few decades) with a given state, and (b) a qualitative replacement (greater than a few decades) between successive states. The hypsometric position integrates both of these scales, and therefore, organic matter processing can be predicted from position on the hypsometric curve. (Brinson, Blum, Christian, Day)

10. Net carbon flux in the most organic marshes will be similar to that of equal latitude forests. Net carbon sequestration will increase from the island marshes to the mainland. (Fuentes, Zieman)

reconnaissance programs as well as sediment coring programs to deal with historical and paleoecological variations in VCR landscapes.

**The Megasite** consists of the islands, marshes and lagoons of the Virginia Coast Reserve and mainland uplands westward to the watershed divide of the Delmarva Peninsula (Fig. 1). Megasite research focuses on phenomena occurring over the entire site, such as changes in largescale landscape structure and the distribution of biota. The 13 major watersheds in the VCR Megasite contain 56 small terrestrial sub-watersheds on the mainland and hundreds of marsh sub-watersheds that are drained by individual tidal creeks (Fig. 6). The major boundaries of this strikingly zonal and patchy landscape arise from the separation between free surfaces or intersections of two or three free surfaces, giving rise to rapidly changing ecosystems. The central hypothesis as applied to the Megasite is as follows:

Long-term progressive and short-term disturbance-driven changes in the intersections of the land, the sea and the groundwater table of the VCR cause changes in the spatial (10s m to 10s km) organization of VCR. The landscape-scale context of individual systems affects the nature and degree of successional and ecosystem state changes. Sub-hypotheses are listed in Table 2.

Testing of Megasite hypotheses relies on three major approaches. Repeated synopic surveys provide information on the changes of biota and physical systems. Geographical Information System analyses, linked to remote sensing, provide baseline information for spatially extensive features and can also be used to track rapidly changing features. Finally, models (both statistical and deterministic) help to synthesize the synoptic survey and GIS data.

*Long-Term Sea-Level Rise.* We recently developed a high-resolution (30 m horizontal, 5 cm vertical) GIS data layer for the terrestrial, marsh and lagoon surfaces of the Machipango watershed. This layer was constructed from existing USGS data sources (upland), marsh cover (remote sensing coupled to Global Positioning System, GPS, elevations) and intensive bathymetric surveys (18,860 points obtained using the GPS coupled to digital fathometry). We now need to extend this database to other watersheds and use models, coupled to information from a doppler current meter, to better understand the hydraulic turnover in the lagoons. Turnover estimates are important for spatially explicit models using GIS that involve mass balance approaches when using past, present and future sea level scenarios. (*MOD, DS*)

Long-Term Change in Terrestrial Systems. With the completion of the detailed hypsometric data layer, we are now in a position to address questions of the impact of terrestrial land-use on estuarine systems. We will use differential land use change in these watersheds as the treatment in a "natural experiment". Specifically, we will address the effects of changing land use on groundwater quality and the impact of these waters on the adjacent marshes and lagoons. Following a period of intensive sampling of three watersheds with different characteristics to establish the degree of spatial and temporal variability inherent in the system, we will adopt a long-term sampling scheme designed to capture important differences between watersheds and changes in land use. Sampling is facilitated by the presence of State Route 600, which runs parallel to the shore along most of the peninsula and thus crosses all of the streams to be sampled. Classified remote sensing imagery will be used to tabulate all land use changes in



Figure 12. Groundwater, groundwater recharge and flow into the marshes. Fluctuations in the (unconfined Columbia aquifer) water table at the VCR from June (1997) to April (1998). Recharge begins in mid-Dec. Panel A show the fluctuations in ground water elevation at three locations along a topographic gradient (B). C and D show groundwater flow to the marshes without (C) and with (D) confining layers. When confining layers with low vertical hydraulic conductivity are present fresh water may pass below the marshes and into the tidal creeks.

each watershed. We have created high resolution (<5 m) georeferenced coverages based on aerial photos for all the barrier islands in 1974, 1991, and 1993 and have full coverage for the mainland in 1989 and 1990. The advent of new satellite-based high-resolution platforms and innovative aircraft-based sensors (e.g. LIDAR) will allow us to extend and improve this data record at a higher frequencies. (*NEW, LTE, DS, NC*)

Groundwater Advection. Relatively rapid horizontal movement of groundwater is observed in the uplands near Oyster, VA (Callaghan 1999); thus, groundwater discharge could represent a major source of nutrients (and other compounds) to the marshes and adjacent lagoons. We will show the potential contribution of groundwater (and dissolved agricultural chemicals) to the marshes by examination of hydraulic conductivity of the stratigraphic layers underlying Phillips Creek (Fig. 7) and Oyster using a subcoring technique (Mills & Hornberger 2000) to generate vertical profiles of horizontal hydraulic conductivities. Vertical cores are collected from the sediment, and small (~1 cm) cores are taken perpendicular to the original. The hydraulic conductivity of these subcores is determined to generate the profile. By examining the stratigraphy and the conductivity of the sediment layers underlying the marsh, we can determine if the sediments are adequately transmissive to permit freshwater from the uplands to rise into the root zone of the marsh, and, at times, even to exfiltrate from the marsh surface (Fig. 12). In the presence of confining strata below the marsh, the groundwater would travel below these impervious confining layers and discharge through adjacent channel walls. We will monitor the position of the groundwater table at locations that represent the 4 marsh transition modes shown Figure 12, The response of the groundwater table to tides and storm events will be recorded using nested piezometers at a range of depths chosen to include the salt water-freshwater interface. Samples will be drawn regularly from the piezometers for determinations of the concentrations of agricultural chemicals in the fresh groundwater (Lorah et al. 1997). (NC)

*Nitrogen Deposition*. Long-term tracking of changes in the input of atmospheric nitrogen will rest on the continuing operation of our wet and dry deposition collectors and subsequent chemical analyses. This information will continue to be applied in nitrogen budget studies in the lagoons and on the islands. We will also focus on local anthropogenic sources of nitrogen to the atmosphere and its subsequent deposition at the site. (*NC*)

*Invasive Species.* Historically *Phragmites australis* has colonized dredge spoil and small areas between the upland and high marsh along the mainland margin of the VCR, but has not been recorded on the Virginia barrier islands or lagoon marsh islands until the late 1990s. Recently, *P. australis* has been found in significant stands near the Hog Island marsh chronosequence and on southern Parramore Island. Additonally, a 1996 aerial survey of the mainland margin revealed that rapid expansion of the *P. australis* is occurring. Part of a five-year vegetation resurvey will be to track changes in the distribution of this invasive plant using aerial photography and ground reconnaissance. Also the red fox (*Vulpes vulpes*), although long resident on some of the larger islands, appears to increasingly ubiquitous and abundant. Dueser (pers. comm.) completed the first comprehensive multi-island survey in 1999. We will undertake periodic resurveys to track changes in this predator. (*TS, DS*)

*Sea-Leve/Land Elevation Interactions.* The barrier island and marsh systems of the VCR are highly responsive to changes in climatic driving forces. When natural erosion undercuts the



b) Probability of Overwash



Figure 13: Landscape age and overwash disturbance probabilities for Hog Island, VA. a) Landscape element ages as determined from historical maps, aerial photos and geomorphological surveys.

b) Probability of vegetation burial by beach sands. Probabilities are calculated from measurements of aerial photographs (1949-1990).

creek bank marshes, blocks of marsh up to several square meters in area are lowered 10-30 cm relative to the original perched marsh. Rather than reduce production, this stimulates increased biomass and productivity of *Spartina alterniflora*. In 1992 we conducted a series of experiments to simulate changes in sea level rise and the effects of differential sedimentation on the marsh communities. Follow-on experiments will be conducted that raise and lower the marsh surface relative to mean sea level through sediment removal and additions. To better understand the processes driving community development on these marshes, and the relative roles of the physical, chemical, and biotic driving variables, a simulation model of the dominant marsh plants is being developed. This will be based on the MARSH model originally developed to predict recolonization of dredge spoil areas (Zieman et al. 1977). Model development and refinement will be in conjunction with the field experiments simulating sea level rise and differential sedimentation. (*MOD, DS, OM*)

Prior to 1933, the lagoons and marshes of the VCR were dramatically different in appearance and function than today, with extensive beds of eelgrass, *Z. marina*, and marshes that were lower in the water column and thereby more productive. By 1933 the wasting disease had greatly reduced the beds and thus weakened the sediment stabilizing ability. On 24 August 1933, the greatest hurricane ever to hit the mid-Atlantic region crossed the VCR and completely decimated the weakened eelgrass beds. Preliminary cores have shown that the sediments of the eelgrass meadows were redistributed on the marshes and raised the surface to near present levels. In LTER IV we will document the spatial extent of this change, and its effect on the system. The simulation model will be used explore the effects of rapid elevation change on the system. (*NEW*, *MOD*, *PP*, *DS*)

*Top-Down vs Bottom-Up Community Control.* The marsh literature has historically focused on biogeochemistry and the biogeochemical control of biomass and productivity (Redfield 1972, Valiela & Teal 1974, Morris 1982). In this program we have investigated the roles played by nutrients (Osgood & Zieman 1993a, b; Osgood 1996), salinity (Santos 1996), stream age and water source (Tyler 1997, Tyler & Zieman 1999), and marsh age (Walsh 1998, Walsh & Zieman 2000) in controlling marsh productivity and development. Top-down control has been demonstrated, with littorinid snails exhibiting greater control of *S. alterniflora* productivity than nitrogen fertilization (Silliman 1999, Silliman & Zieman 2000). Replicate cage experiments, using the same design as previous experiments (Silliman & Zieman 2000), will continue to be used to determine the interaction of grazing and fertilization. The next set of experiments will give grazers the choice of different fertilization levels within the same cage to explore the mechanisms of preference selection. (*PP*, *NC*)

*Changes in Trophic Structure*. One of the major questions that LTER sites address concerns the relationship between animal populations and trophic dynamics through time and space. Preliminary work by Knoff (1999) demonstrated the value of using stable isotope analysis to assess both spatial and temporal changes in diet by a dominant predator in the system, the Laughing Gull, *Larus atricilla*. Additional research is needed to determine whether human-altered systems result in a more unstable suite of food sources for top level predators than in systems that are more pristine using similar stable isotope techniques. *(TS, DS)* 

*Land Use and Organic Matter.* During LTER I-III we measured the processing of organic matter (belowground production and decomposition) and organic matter concentrations in a

	TABLE 3: Sub-hypotheses for Barrier Island Research at the VCR LTER
Marsh	and Terrestrial Chronosequences
1. Accr and fro the ma cal var	reting regions of the islands have landscapes ordered in age from the lagoon landward om the sea landward, marsh and terrestrial chronosequences respectively. Within b rsh and terrestrial chronosequences, autogenic succession accounts for biogeochem iations. (Young, Day, Porter, Zieman)
Terres	trial Chronosequence
2. Spec table a	ies composition and successional processes are determined by depth to the freshwand by magnitude of disturbance from storms. (Young, Hayden)
3. Abo the am ture ar	ve and below ground production are limited by proximity to the freshwater table as ount of available nitrogen. In addition, decomposition rate is a function of soil mois ad thus, proximity to the water table. (Young, Day)
Marsh	Chronosequence
4. Suce sumer	cessional change in the marsh chronosequence will show biogeochemical and con- changes without plant species change. (Zieman)
5. In ea show h their p	ich 5-year resurvey of the marsh chronosequence, all stages (except the 150+ age) woogeochemical and consumer characteristics of the next successional stage rather threvious characteristics. (Zieman)
Barrie	r Islands
6. Utili plexity and str alterati	zation of the island landscape by mammals and arthropods varies with age and con- of the landscape and vegetation type. Mammalian consumers affect the composition ructure of vegetation, which in turn alters the rates of change of free surfaces throug ion of aeolian deposition and evapotranspiration. (Young, Porter)
7. Mor impact ing fro	phology, elevation and rate of change of barrier islands and marshes will have a ma on the distribution of mammals and nesting shorebirds. Second-order effects resul m colonization of the islands by predators will also be large. Extinctions of mamma nds are mediated by habitat destruction associated with state changes. In contrast,

variety of ecosystem states including sites on the mainland, barrier islands, and lagoons (Blum 1993, Day 1995, Conn & Day 1996, 1997, Blum & Christian 2000). The development of hypsometric models of the VCR watersheds will allow us to integrate these measures across the VCR landscape to predict organic matter processing based on any given location's position on the hypsometric curve. These predictions will be tested by direct measures of organic matter processing at selected locations in a variety of VCR watersheds. In the long-term, this approach will allow us to determine how land use impacts organic matter processing across the VCR landscape and ultimately affects sensitivity of system states to sea level rise. *(OM)* 

*Carbon Sequestration.* We will expand our preliminary investigations of the environmental controls on the magnitude of carbon fluxes and sequestration by the ecosystem utilizing the eddy covariance approach (Fuentes & Wang, 1999, Lee et al. 1999). To derive carbon dioxide fluxes from and to the marshes, we will deploy our eddy covariance system above the marsh surface mounted on a tower. Equipment for this work is being provided by non-LTER sources. Measurements of wind speeds and gas concentrations will be made at 10 Hz and used to derive carbon dioxide and water vapor flux. In addition to the calculation carbon dioxide fluxes, the fluxes of sensible heat and momentum will also be determined from town data.

**The Barrier Island** research at the VCR is primarily conducted on Hog Island. Major study efforts are focused on a terrestrial chronosequence, a marsh chronosequence, and the island as a whole. A highly dynamic environment, 90% of the terrestrial environment is new land since 1871 (Harris 1992). During this time the northern half of Hog Island the land has accreted seaward more than one kilometer. While on the south of Hog Island more than a kilometer of land has been lost to erosion. During storm events, beach sands now wash across the islands and into the lagoon, establishing sediment platforms on which salt marshes develop.

The age structure of this landscape was determined by historical maps, charts and aerial photos, and by geomorphic surveys. Rather than just static transect surveys, these chronosequences represent dynamic, active successional examples of ecosystem development and evolution. In the terrestrial system, the identified chronosequence is at least 120 years old, while in the marsh chronosequence the oldest identified stage is at least 150 years. The central hypothesis applied to the Barrier Island Sites is:

Vegetation on coastal barrier islands and their fringing marshes is limited primarily by the relationship of the non-parallel land and groundwater table free surfaces. The relative elevation of the water table and the reserve of freshwater available structures the vegetation of the barrier islands. While the type of community and level of productivity of marshes is initially set by the relative elevations of the marsh sediment surface and the interacting sea level surface, they are continually modified by physically and biogenically driven processes. These processes can be altered nearly instantaneously by physical disturbance events. Working sub-hypotheses for the barrier islands are summarized in Table 3.

*Island 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 (Fig 13). The landscape of the northern tip of Hog Island consists of a series of beach ridges (dunes) and swales that have built seaward over the last 120 years or so. We have dated the landforms of



Figure 14. Comparison of attributes of terrestrial and marsh 120 year + chronosequences on Hog Island.
this landscape using survey maps and aerial photographs in conjunction with field excavations. To document these changes we have established a chronosequence transect with permanent plots and a network of groundwater wells that record spatial and temporal variations in the elevation of the water table. In addition, we have established productivity, decomposition and nutrient cycling study plots along this chronosequence transect (Day 1995, Conn & Day 1996, Stevenson & Day 1996, Conn & Day 1997, Dilustro & Day 1997) (Fig. 14). Chronic N-addition experiments have been performed along the transect for the last eight years. Using groundwater wells we are evaluating the relationships among land surface elevations, water table free surfaces, and island vegetation patterns. The role of disturbance in modification of the water table controlled pattern of vegetation on barrier islands continues to be an important research area. Along this chronosequence, we are also examining the hypothesis that proximity to the water table free surface is a principal controller of above and belowground production, decomposition, and nutrient availability. As a companion study, the utilization of landscapes of varying age and productivity by small mammal populations will be determined through longterm censuses coupled with structural habitat measurements (Dueser & Shugart 1978, Dueser & Porter 1986 Scott & Dueser 1992). Mammal and insect exclosures will be used to establish the effects of herbivores on vegetation composition and structure. (LTE, PP, NC, TS, DS, OM)

*Island Marsh Chronosequence*. The salt marshes of the VCR barrier islands offer unique opportunities for the study of ecosystem development processes. Following storm events, the newly deposited sand surfaces are unconsolidated and typically low in nutrients and organic matter. Thus development is more like primary succession rather than secondary succession over these disturbed but this intact substrate. (Walsh 1998, Walsh & Zieman 2000)

In LTER II work on the barrier island and bay marshes focused on determining the differences in the plant communities and biogeochemistry of old and young marshes. This work (Osgood & Zieman 1993) showed that as marshes aged, they showed biogeochemical changes similar to maturing terrestrial ecosystems. In 1995 we discovered a unique chronosequence of marshes on south Hog Island ranging in age from one year to greater than 150 years and were able to date the age of this sequence of marshes (Fig. 13).

Despite having a monoculture of *S. alterniflora* throughout the chronosequence, there were significant changes in both the physical makeup and chemistry of the soils, and in the associated animal communities (Walsh 1998, Walsh & Zieman 2000) (Fig.14). This area has been extensively mapped, and GPS locations are known for all previous sampling and hydrological well sites. Originally sampled in 1995-96, the ages of the marshes were 1, 6, 13, 21, and 150<sup>+</sup> years. Beginning in the summer of 2000, we will resample these sites, and will continue to do so at five-year intervals into the future. Pore water chemistry will be taken from a succession of wells established on the site. Plant production will be measured by the method of Morris & Haskin (1990). Belowground biomass and sediment parameters will be determined from individual core samples. (*LTE, PP, NC*)

*Faunal Assemblage Dynamics*. Examination of the impact of mammalian, and arthropod herbivores is being investigated using exclosures. Four large 5x5 m mammal exclosures were established on southern Hog Island in 1998. Smaller exclosures, centered on *Myrica* seedlings, linked to periodic surveys of arthropods (primarily grasshoppers) are being used to assess the role of insect herbivory. (*TS*)

#### **TABLE 4: Sub-hypotheses for Lagoon Research at the VCR LTER**

1. Exchange of water between the ocean and lagoons is accomplished by a standing tidal wave and tidal currents moving through well-developed antecedent valleys. The exchange is determined by the water-mass trajectory path, not by diffusion of stratified flows. (Oertel)

2. Water mass boundaries in lagoons are determined by differences in current "drag" created by bottom friction and fluctuating water levels. (Oertel, Porter, Hayden)

3. The trophic status of the lagoons is controlled by the magnitude and ratio of organic to inorganic nutrients and the light available to support autotrophic production. On an annual basis, the lagoons are net autotrophic systems in which benthic macroalgae are the major biological sink for dissolved inorganic nitrogen. (McGlathery, Anderson)

4. The lagoon functions as a "filter" to retard and/or remove reactive N during its transport from the mainland watersheds to the coastal ocaen because biological process rates mediated primarily by macroalgal uptake and bacterial immobilization and denitrification exceed physical transport rates. (Anderson, McGlathery)

5. Spatially varying residence times in different parts of the lagoons influences the degree to which organic matter and nutrients are retained or exported. (Wiberg, McGlathery, Anderson, Oertel)

6. Variability in macroalgal populations influences the distribution and abundance of macrofauna (invertebrate, fish) and the degree to which fish are net exporters of organic material (carbon, nitrogen) from the lagoons. (Smith, McGlathery, Macko)

7. Storm-induced resuspension of lagoon sediments is the major process influencing light availability for primary producers in the lagoons. The lagoons are in the early stages of undergoing a state change from a muddy bottom to a seagrass-vegetated bottom. The timing and frequency of the turbidity events is a key factor in the return of seagrasses to the VCR. (Wiberg, McGlathery, Anderson, Zieman, Porter)

8. Faunal diversity and abundance is expected to change as seagrasses acheive dominance over macroalgae and benthic microalgae in the lagoon. Species diversity will remain relatively constant, but a few species will increase in abundance and become community dominants. (Smith, Erwin, Macko, McGlathery)

Understanding the complex relationships between barrier island morphology and disturbance and the distribution and abundance of vertebrate populations demands both long-term surveys to establish patterns and detect changes and intensive work to examin processes. For mammals we link multiannual surveys of multiple islands (varying in elevation), semi-annual censuses of small mammal populations on three transects on Hog Island (varying in availability of fresh water and probability of overwash), intensive observations of inter-island movements (e.g., Forys and Dueser 1993) and genetic (mitochondrial DNA, allozyme and microsatellite DNA) analyses (Loxerman 1995, Moncrief et al. 1997, Loxterman et al. 2000). We are progressing in developing genetic markers useful in the exploration of ecological processes such as colonization and extinction in the highly fragmented landscape of the VCR. Ultimately, this work will allow us to assign relative rates to the processes which determine species distributions among the islands. Extensive multi-island mammal surveys were completed in 1988-1989, 1993 and 1998. Intensive (monthly) trapping has been conducted on two low-lying barrier islands (Myrtle, Ship Shoal) since 1997.

For waterbird communities, monitoring colony site dynamics of selected species helps to identify the relative importance of physical processes (i.e. elevation change and erosion) and biological processes (i.e. predation, competition) and disturbances within metapopulations (Erwin et al. 1998a). The Nature Conservancy has shared with us data for island waterbird colony locations from 1974-1998. The interaction of mammals and nesting waterbirds across the entire VCR barrier island megasite is also receiving attention (Erwin & Truitt 2000). (*TS, DS*)

The Lagoons within the VCR are the functional links between watersheds and the coastal ocean; activities of primary producers and heterotrophs influence the degree to which the lagoons retain or remove nutrients and organic matter during transport from the mainland to the coastal ocean. Three free surfaces intersect in the lagoons: the fresh groundwater delivers nutrients to the lagoon, the land (lagoon bottom) and the seawater free surfaces are horizontal and parallel, and together determine the tidally-driven water exchange between the lagoon and coastal ocean. In addition, the lagoon surface and its intersection with the sloping land surface of the adjacent intertidal mudflats and marshes at the edge of the lagoon influences the exchange of nutrients and organic matter between these systems. The central hypothesis as applied to the Lagoon Site is:

The interaction of groundwater delivery of nutrients from the land and factors regulating lagoon water residence time and sediment resuspension influences patterns of primary and secondary production and determines the degree of nutrient and organic matter processing in the lagoon during transport to the coastal ocean. Sub-hypotheses are listed in Table 4.

Our conceptual model relating nitrogen inputs from groundwater to biological processing within the lagoon and physical transport to the coastal ocean is shown in Figure 15. A hydrological model relating groundwater nutrient concentrations (primarily nitrogen) to physical transport within and from the watersheds will provide estimates of nutrient loading to the lagoon. In addition, we will obtain estimates of atmospheric deposition which is considered to be the secondary source of nitrogen to the lagoon. Within the lagoon, we will relate nutrient concentrations and biological transformation rates to residence times calculated using the hydrodynamic model. (*NEW*, *MOD*)



Figure 15. A conceptual model describing processes that influence the degree to which the lagoon retains or removes watershed nitrogen inputs. Processes that temporarily retain nitrogen include uptake of DIN and DON by autotrophic and heterotrophic organisms, and consumption by grazers. Those that remove N include denitrification, transformation to recalcitrant forms followed by burial, grazing, and export to the coastal ocean. The ability of the lagoon to retain or retard delivered nutrients will vary with the character and quality of the material and water residence.

The detailed bathymetry that has been completed (coupled with information from VCR tide stations) will allow us to calculate water turnover times within the lagoon. As a first step, the bathymetry provides the boundary conditions for flows within the lagoon from which we can calculate the volume of the lagoon in relation to tidal stage and determine the average turnover ("flushing") time for water in the entire lagoon. We can also use the bathymetry to create a 2-D (depth-averaged) circulation model for the lagoon that will permit the calculation of residence times in different parts of the lagoon (Ip et al. 1998). Variations in water residence time within the lagoon will be a key factor influencing the degree to which organic matter and nutrients are retained or exported from specific locations. Direct measurements of current made at representative locations in the lagoon with an Acoustic-Doppler Current Profiler will be used to validate the circulation model and also to provide a high temporal resolution of current speed and direction. In particular, we will measure currents over a range of conditions including storm events, which will allow us to separate the tidal signal from atmospheric forcing (wind) as well as the response of the lagoon bottom to these forces (i.e. resuspension). (*NEW, MOD*)

Primary Production and Ecosystem Metabolism. We have established 12 permanent sites within Hog Island Bay to monitor the distribution and abundance of primary producers (macroalgae, benthic microalgae, phytoplankton), sediment characteristics (% organic matter, carbon and nitrogen content), and light attenuation in the water column. These surveys are done monthly in the summer and bimonthly during the remainder of the year and are used to monitor long-term trends in patterns of primary production. We determine macroalgal biomass and species composition, sediment chlorophyll as proxy for benthic microalgal biomass and water column chlorophyll. In addition, we plan to use plant C and N content and isotopic composition  $(\delta^{13}C, \delta^{15}N, \delta^{34}S)$  as a biotic indicator of long-term trends in the magnitude and source of nutrient inputs to the lagoon (Gerloff & Krombhotz 1966, Atkinson & Smith 1983). Over the last 1.5 yr, we have documented that shallow areas within the lagoon (<1 m MLW) formerly colonized by seagrasses (Zostera marina) now support dense macroalgal populations. Macroalgal biomass peaks in early summer with a marked decline in mid-summer and a subsequent increase throughout the fall, winter and spring (Fig. 16). In localized areas (midlagoon shoals), macroalgae reached densities as high as 650 gdw m<sup>-2</sup>, and the population crash resulted in anoxia throughout the water column. Macroalgae, in particular, are important in temporarily retaining nitrogen in the system. We will estimate the N assimilated and temporarily bound into biomass of the different functional groups of primary producers (macroalgae, benthic microalgae, phytoplankton) by relating biomass, production rates, and tissue C:N content. (NC, OM. PP)

In 1997, we began a seasonal study of metabolism and nitrogen cycling at 3 locations within the lagoon that represent a gradient in nutrient loading: a mainland creek site, a midlagoon shoal site, and a barrier island embayment site (Fig. 16). Our initial studies, performed in microcosms to compare the contributions of the various autotrophs in the system, indicate that the lagoon is net autotrophic during the spring-summer, and net heterotrophic in the fall; macroalgae were responsible for most of the autotrophic production observed (McGlathery et al. 2000). We will expand these studies with *in situ* measurements at each of our 3 sites. At monthly intervals during the summer and bimonthly during the remainder of the year, we will estimate system metabolism with measurements of vertical dawn-dusk profiles of DO, temperature, salinity (using a profiling Hydrolab datasonde), and pCO<sub>2</sub> in the water column. We hypothesize that on an annual basis, Hog Island Bay is net autotrophic and therefore a net sink



Figure 16. Location of permanent research sites in Hog Island Bay representing (1) mainland creek, (2) mid-lagoon shoal, and (3) back-barrier embayment. Site characteristics reflect the gradient in nutrient and organic matter loading across the lagoon. The system is net autotrophic in the spring/summer, with macroalgae being the primary sink for DIN. Despite high mineralization rates, the sediments also are a strong sink for DIN.

for  $CO_2$  and inorganic nutrients. There is no evidence of a long-term accumulation of macroalgal biomass in the lagoon, which suggests that organic matter either is rapidly decomposed or lost from the system by grazing and movement of secondary consumers, by advective transport, or by burial in the sediments. The horizontal movement of organic matter in the system as macroalgae and *S. alterniflora* wrack is driven by wind and water currents. We will develop an empirical model of advection of plant material within the lagoon using the macroalgal biomass data and information from the VCR meterological and tide stations and the current profiler (*MOD*, *PP*, *DS*)

Light availability is a key factor influencing primary production in Hog Island Bay. In the absence of dense seagrass meadows that stabilize the sediments, resuspension and periods of high water column turbidity are common. We have been measuring light attenuation within the water column at our 3 sites at monthly-bimonthly intervals. In 1998, we began deploying Licor  $4\pi$  light sensors over 48 hr periods in the fall, winter and spring at the 3 stations together with hydrolab datasondes and ISCO autosamplers to assess diurnal variation in water quality pparameters. Our results indicate that on an annual basis, for a mean depth of 1 m (~50% of lagoon area), approximately 11-18% of incident irradiance reaches the lagoon bottom. This amount of light is sufficient to support production of seagrasses, which require 11% of surface irradiance, compared to <0.1% needed by benthic macroalgae (Duarte 1991, Markager & Sand-Jensen 1992). However, average values of light availability from relatively infrequent measures may mask the high variability in light attenuation from frequent, short-term turbidity events. We will obtain qualitative information from the Acoustic Doppler Current Profiler on the timing of high turbidity events that can be related to known seasonal variation in seagrass light requirements. Additionally, we will deploy Licor  $4\pi$  sensors and data loggers to monitor light attenuation in the water column continuously for 1 yr at 2 locations: 1) our mid-lagoon station in Hog Island Bay to determine its suitability for seagrass recolonization, and 2) within the VCR south of Hog Island Bay where Z. marina has recently been discovered. Given the hypsometry of the bay bottom, the high temporal resolution data on light attenuation in the water column, and the known light requirements for seagrasses, we can estimate what portion of Hog Island Bay is potentially suitable for seagrass recolonization. (NEW, PP)

*Nutrient Cycling*. Studies on the fluxes of nitrogen from the benthos to the overlying water showed that macroalgae were a temporary sink for dissolved inorganic nitrogen (DIN) and urea, but were a net source for other dissolved organic nitrogen compounds (Tyler et al. 2000). The sediments also were a significant source of DON to the water column (Tyler et al. 2000). We will begin studies of net and gross mineralization in the water column to determine how bioavailability of DON and DOC varies seasonally at the different stations along our transect using <sup>15</sup>N isotope dilution techniques (Anderson et al. 1997). At the same time, we will determine bacterial respiration and phytoplankton production/respiration rates as changes in DO concentrations in light-dark incubations of "whole" and filtered (1.2 µm) water. Our initial work also indicated that although gross mineralization rates in the sediments were high, there was little inorganic nitrogen efflux to the water column, suggesting that microbial immobilization was important in retaining nitrogen in this system (Anderson et al. 2000) (Fig. 16). We will continue this work with seasonal measurements of net and gross mineralization of DON and DOC in the sediments of our 3 sites. In addition, we will measure rates of denitrification using the N<sub>2</sub>:Ar (Kana et al. 1998) and isotope pairing techniques (Nielsen 1992). The rates at which these biological transformations and losses occur relative to the water

## TABLE 5: Sub-hypotheses for Mainland Margin Research at the VCR LTER

### Transition from forest to high marsh

1. Storm-generated influxes of saline water facilitate this transition by stressing and killing trees. Tree mortality initiates light penetration to forest floor and allows dominance by herbaceous halophytes typical of high marsh. Timber removal and fire have similar consequences. (Brinson, Christian)

2. The width of the upland-high marsh transition zone responds to the interaction between the fresh water surface and tidal forcing as controlled by slope, sediment/soil type (i.e., hydraulic conductivity), and distance from the tidal creek. (Albertson, Wiberg, Mills, Brinson, Christian, Blum)\*

### Transition from high marsh to low marsh

3. Disturbance in the high marsh, mainly through wrack deposition, facilitates replacement of high marsh species by low marsh dominants. Hummock (vegetated) and hollow (no emergent plants) microtopography develops in response to disturbances on high marshes with significant peat accumulation. Other disturbances (herbivory by muskrats, historic and current trampling) also facilitate development of microtopographic complexity. (Christian, Brinson)

4. Headward incision and lateral erosion by tidal creeks facilitates the transition by strengthening hydrologic connections with the lagoon. (Christian, Brinson, Blum, Wiberg)

5. The organic high marsh surface subsides in part because plant stress reduces the rate of accumulation from below ground organic matter and in part because better drainage increases the rate of decomposition. (Blum, Christian)

6. Biogenic accretion is an intrinsic function of the high marsh state. The amount of accretion above the antecedent surface is proportional the lifetime of the state. (Christian, Brinson)

### Transition from low marsh to subtidal lagoon

7. This transition is inhibited by a depositional environment due to baffling by marsh plants aggregation of sediment particles, and infiltration of water through the marsh surface on falling tides. (Wiberg, Albertson)

8. Sediment deposition on marsh surfaces occurs during storm events; erosional processes dominate on typical tidal cycles. (Wiberg, Brinson, Blum, Christian)

### Transitions spanning upland to subtidal lagoon

9. While state changes ratchet landward due to rising sea-level over the long term, short-term reversals occur. Premature disturbances, during the early stages of the state and predisposed by relatively high hypsometric position of the state, are likely to be reversed. (Brinson, Christian, Blum)

residence time at different locations in the lagoon are central to determining the fate of nutrients entering the coastal lagoon and the magnitude of export to the coastal ocean. (*NC*, *PP*)

*Trophic Structure*. Given the absence of seagrasses in this system, benthic macroalgae provide an important habitat and potential energy source for numerous fish and invertebrate species. We will determine the macrofaunal community structure at representative sites within the lagoon using seine and trawl sampling for fish and core sampling for benthic invertebrates. In addition, we will determine the relative importance of sources of organic matter (phytoplankton, macroalgae, marsh grass) to key functional groups in the lagoonal food web using stable isotopes of C, N and S. (*NEW, TS*)

Periodic aerial and satellite surveys will be used to track changes in the abundance and distribution of benthic macrophytes (seagrass, macroalgae) in the lagoons. This will be used in conjunction with ground-reference data from GPS-equipped boat surveys and macrophyte biomass determinations. We anticipate that a detailed survey every 5 years will be sufficient to capture major changes in macrophyte distribution, but we will evaluate the need for extensive surveys on an annual basis. We believe that the system may be beginning a shift from being primarily physically controlled by high turbidity events that inhibit seagrass growth to being biologically controlled, where bottom sediments are stabilized by vegetation and turbidity is thus reduced (facilitating growth by additional aquatic macrophytes). Our periodic surveys will allow us to link these large scale changes to our detailed process studies in the lagoon. We believe there will be a shift in trophic dynamics in the lagoon as seagrasses replace macroalgae and benthic microalgae. We will evaluate this with repeated surveys of faunal abundance and diversity using the trawling, seining, and core sampling techniques described above. (*TS*)

**On the Mainland Margin** our broad objective in incorporating hypsometry within our research program is to predict how the VCR mainland margin will be altered by sea-level change over the next century. We have developed conceptual models of ecosystem state change that guide our understanding of how the free surfaces (and antecedent fixed surface) interact to establish or maintain a particular state (e.g., organic high marsh) (Brinson et al. 1995, Christian & Luczkovich. 1999, Nuttle et al. 1999). Furthermore, we have assessed aspects of ecosystem function within each state and how those functions change with state change with respect to both natural disturbance and human impacts. However, we have been unable to predict at the watershed level how the surface area associated with each state, and hence the areal extent of its functioning, may change with time. Hypsometry provides this opportunity.

The mainland margin of the VCR LTER can be divided into a series of watersheds, each extending from an upper boundary (high on the hypsometric curve) of naturally forested upland or modified land use. The lowest boundary (low on the hypsometric curve) is the shallow lagoon environment. Salt marshes straddle the two and can be subclassified into two major ecosystem states: organic high marsh and mineral low marsh. Sea-level change, natural disturbance and human impacts affect the relative proportion and position of each. The central hypothesis as applied to the Mainland Margin Site is:

A series of ecosystem states within the mainland margin are positioned by factors associated with the interaction of the non-intersecting, sloping free surfaces of the saline lagoon water, fresh groundwater table, and land surface. These states are ordered along a gradient maintained by disturbances against a background of chronic



Figure 17. Classification of upland forest sites (N = 149): Susceptibility for three regions the VCR to an ecosystem state change to high marsh as sea level rises by 15 cm .

sea level rise. Each state has characteristic ecosystem functions, and changes in state along the gradient are caused by mechanisms which are characteristic of each. Human activities can alter the ability for states to maintain themselves or change (Brinson et al. 1995). Sub-hypotheses are listed in Table 5.

In LTER IV, we add to our work at Phillips Creek (Fig. 7) with two initiatives: We will add a margin that contrasts well with that of Phillips Creek. The marsh at Oyster is young, prograding, stalled, and impacted by human activities in the upland (Fig. 4). *We will establish an array of studies here to complement those at Phillips Creek with infrastructure similar to that currently in place at Phillips Creek.* In-depth studies of ecosystem state function, transitions between system states, and community composition at both sites will allow evaluation of these contrasting conditions.

We will broaden our understanding of state changes within the mainland margin to encompass areas with a range of landscape and free surface characteristics. This comparative ecosystem approach is necessary to incorporate hypsometry more fully. Ricker (1999) classified numerous sites along the entire VCR for susceptibility to sea-level rise (Fig. 17). Last summer we extended this initiative by characterizing 18 margins across the VCR LTER megasite (Fig. 6), two of which are on the barrier islands. At each margin, permanent plots were established in the low marsh, high marsh and upland forest. Vegetative community composition, soils, and elevation above mean sea level were determined in each permanent plot and are archived in our electronic data collections. These sites were found to represent (1) all four classes of horizontal marsh movement, (2) variations in edaphic factors and hydrogeomorphology among each of the ecosystem states, (3) differences in human activity in or around the sites, and (4) susceptibility to disturbance (Fig. 4). These sites are taken as a reference domain for the ecosystems of the mainland margin. The sites fall into discrete subclasses, and therefore provide replication of the various conditions lacking in previous work.

We will begin long-term observations of these sites to assess the variation and thereby the extent to which our in-depth studies at Phillips Creek and Oyster are applicable to the margin in general. As disturbance is a major factor in promoting state change, these sites will also be used in an experimental context; these will be primarily experiments of opportunity (e.g., wrack deposition after a major storm or herbivory by muskrat, geese or feral hogs). These characterized sites also represent a resource bank for controlled experimentation in the future. Some hypotheses will be addressed by comparison of detailed process-level studies at Phillips Creek and Oyster with long-term monitoring across the various system states of the 18 designated marshes (Fig. 6). For example, organic matter production and decomposition measures from Phillips Creek and Oyster might be compared with long-term monitoring of organic matter concentration changes across the these 18 marshes to provide a suitable basis from which to predict organic matter content from position on the hypsometric curve. Comparison of detailed studies and monitoring of the reference sites will allow us to address questions about the impact of land use changes within watersheds on the condition of land margin system states and resistance to state change on long and short-term time scales. (*NEW, DS, PP, OM, NC*)

The studies described in the prior results section for Phillips Creek associated with testing the hypotheses listed in Table 5 will continue. Here we highlight the direct relationship between ongoing studies and identify how the two major new initiatives and some new projects will aid in testing our hypotheses. We consider the transitions to be between ecosystem states and not merely communities; ecosystem function is being studied as well as community structure. The Dynamics of Saline and Fresh Groundwater at the High Marsh Upland Contact



At the Beginning of the Flood Tide



With an Incoming High Tide



With Drainage on the Ebb Tide



With Major Precipitation Event



Figure 18. Relative position of the fresh and saltwater free surfaces in the transition zone between the high marsh and the upland. This conceptual model is based on elevation and salinity measurements made in the top 20 cm of the high marsh/upland transition at Phillips Creek. The proximity of salt water at or near the land surface is a primary factor in determining the width of the transition zone between the high marsh in the upland. On rising tides a wedge of salt water intrudes into the transition zone and partially recedes on falling tides. During high intensity storms the salt water can be completely flushed from the transition zone. Note that the scale of this figure is much smaller than in Figure 12. The distance from the marsh surface to the bottom of the panel represents approximately one meter, whereas the overall depth below MSL depicted in figure 12 is on the order of 10 to 15 meters.

Transition From Forest to High Marsh. We have hypothesized that the transition from forest to high marsh is a result of salt-water intrusion. Ricker's work (1999) and our recent characterization of 18 designated marsh sites (Fig. 6) has provided evidence of the influence of saline water at this transition. Tree mortality in the permanent plots of the forested uplands will be tracked. Tree mortality data combined with elevation data and tide records are used to assess the role of saline water intrusion as a cause of state change. We also hypothesize that the varying width of the transition zone is a function of the interaction between the freshwater surface and tidal forcing (Fig. 18). We will explore this relationship through a merger of existing spatial data sets, new field data, and hydrological modeling tools. A centerline transect through this forest/marsh transition zone will be used in these studies. From existing data sets (USGS digital elevation maps and digitized topographic maps), the land surface elevation, slope, and distance to the nearest tidal creek will be referenced to this centerline. During a series of proposed intensive field measurement campaigns, the near-surface (0-20 cm) soil moisture will be measured (with hand-held Time-Domain Reflectometers) at predefined and marked intervals and mapped along the transition centerline, with sampling timed to capture multiple periods of wet, dry, and moderate wetness conditions. Soil texture will also be mapped. A spatially distributed hydrological model, with constraints imposed by existing groundwater well levels and soil moisture measurements, will characterize the freshwater discharges along the transect. A functional relationship will be derived to describe the interaction of these independent variables to control observed spatial variations in the width of the transition zone. This relationship represents an important tool to relate potential changes in any of the controlling variables to changes in the width of the transition zone in order to predict the response of the marshes to sealevel rise. (NEW, MOD, DS)

Transition From High Marsh to Low Marsh. Several mechanisms including disturbance and extension of tidal creeks into the high marsh have the potential to facilitate the transition from the high marsh system state to the low marsh state (Fig. 19). These will be investigated at both Phillips Creek and Oyster. At Phillips Creek (an overland-migrating, erosional marsh) (Fig. 4), disturbance in the high marsh facilitates replacement of high marsh species by low marsh vegetation (Christian et al. 1999). Do similar mechanisms operate at Oyster, a prograding, stalled condition? In the organic high marsh at Phillips Creek, we continue to use permanent plots to track the movement of the interface between patches of Juncus roemerianus and its neighboring plant species (short-form S. alterniflora and Spartina patens/Distichlis spicata association) at different locations reflecting different states and flooding regimes (Brinson & Christian 1999, Tolley and Christian 1999). In our experiments we deposited wrack as a disturbance and flooded plots in the high marsh to simulate the increased inundation associated with sea-level rise from 1994-1996 (Taylor 1995, Tolley 1997, Miller 1999, Tolley & Christian 1999, Miller et al. 2000). We are now conducting additional experiments. The factors examined for response include (1) plant community structure, (2) primary production, (3) N-cycling, (4) soil and pore water conditions (5) gas fluxes, (6) microtopography, (7) plant physiological response (e.g., adenylate nucleotides) and (8) belowground production and decomposition. Studies of permanent plots at Phillips Creek will be extended to Oyster. Watershed marshes will be monitored for occurrence of wrack disturbance and subsequent changes in plant community structure, soil conditions and microtopography and elevation. (*LTE*, *DS*, *PP*, *OM*, *NC*)



Figure 19: Ecosystem state change in response to sea-level rise on the barrier islands and along the mainland margin. The legend indicates the system changes at Phillips Creek over the last 50 years. Changes on Hog Island took place over 15 years. In each of these cases the transition from terrestrial to marine environments is the predominant direction. of change.

To examine the influence of headward expansion of tidal creeks on the replacement of high marsh by low marsh, we have instrumented a tidal creek exhibiting rapid headward erosion with Sediment Elevation Tables (SET) and marker horizons to quantify changes in sediment elevation due to erosion/deposition (Baumann et. al. 1984, Cahoon et.al. 1995). We also monitor a suite of permanent plots adjacent to an incising creek in relation to others farther away from the creek. Response variables include plant community structure and physiological state, groundwater salinity and elevation, primary production, organic matter accumulation, and microtopography. Similar studies will be extended to Oyster and the megasite marshes. (*PP, OM, DS*)

The rate of organic matter accumulation in marsh sediments has a dramatic effect on maintenance of the salt marsh sediment-surface as sea-level rises (Reed & Cahoon 1992, Delaune et al. 1994). We have hypothesized that disturbance in the high marsh and the effects of headward erosion on sediment properties is expressed as subsidence of the high marsh surface as a direct result of reduced rates of organic matter accumulation. In addition, we propose to use measures of <sup>14</sup>C- and <sup>210</sup>Pb-dating of peat and underlying soil to determine if the depth of the peat layer is proportional to the age of the high marsh state at Phillips Creek and Oyster (Bricker-Urso et al. 1989, Spaur and Snyder 1999). While we do not expect the <sup>14</sup>C or <sup>210</sup>Pb dating of basal peat to provide absolute dates, we expect that relative ages (time since initial accumulation) of high marsh sites can be evaluated this way. By extending peat and soil dating to the watershed marshes, we can compare rates of OM turnover and accumulation with sediment surface elevation among these marshes to understand how these processes occur in the different states. (*NEW, DS, OM*)

*Transition from Low Marsh to Subtidal Lagoon.* Recent research at Phillips Creek Marsh (Christiansen 1999) has revealed that marsh sedimentation during the daily tidal cycle occurs entirely at the lagoon margin of the marsh. This observation has broad implications for long-term marsh surface dynamics. It suggests the upward growth of marshes required to keep pace with rising sea level (3.5 mm/yr) must be episodic (storm driven) rather than periodic (tidally driven) (Fig. 19). The marshes themselves must then undergo periods of submergence and erosion punctuated by episodes of sedimentation and renewed marsh vigor. The most likely agents of disturbance resulting in sedimentation events are winter Nor'easters and summer and fall Hurricanes. The system of 15 SETs established on the mainland margin as part of a regional and national sediment deposition observation system will be used to make short-term measures of erosion and deposition after significant tidal and or weather events. Additionally, 13 SETs are in place at a variety of island and lagoon marsh locations that can be used to examine similar questions on a regional basis. The 28 permanent SET installations permits us to structure a long-term experiment testing controls on sedimentation associated with sea level rise, disturbance and marsh elevation. (*LTE, DS*)

Studies of permanent plots and inundation/wrack experiments have indicated that to have state change there must be the combined conditions of disturbance and a suitable flooding regime. We have also seen indications of this anecdotally at Mill Creek, a drainage between Phillips Creek and Oyster, where a fire in the upland resulted in conversion of forest to marsh vegetation. The marsh vegetation in the burned area currently appears to be going back to forested upland. Examination of this hypothesis will be continued at Phillips Creek and Oyster with permanent plots, inundation experiments at Phillips Creek, and across watershed marshes

# Table 6: Summary of VCR Core Area Activities.

	MEGASITE	BARRIER ISLANDS	LAGOONS	MAINLAND MARGIN
Primary Production (PP)	Biomass: Remote Sensing with vegetation plots for ground truth	Myrica productivity Spartina productivity: above and below ground	Phyoplankton standing stocks Macroalgae: biomass and productivity Sediment chlorophyll	Marshgrass* production: Above and below ground DBH trees
Nutrient Cycling (NC)	Atmospheric Wet Deposition Monitoring of Watersheds	Soil and Sediment: N & P stocks Nitrogen amendments Nitrogen-fixation Groundwater salinity	Sediment N&P Water Column: Inorganic N & P, DON, DOC, POC, TSS, salinity, DO, pH, light extinction	Sediment: N, P, H <sub>2</sub> S, salinity, pH
Organic Matter (OM)	% OM	Soil/Sediment OM % Below ground biomass Root turnover Root decomposition LIDET	Sediment & Water Column OM%	Soil/Sediment OM% Below ground biomass OM accumulation Root production Root decomposition LIDET
Trophic Structure (TS)	Small Mammal: Population Surveys Genetic Analyses Vegetation Composition: Plots & Transects GIS mapping Shrub Colonization Water Birds: Population Surveys Nesting Surveys Trophic Interactions	Small Mammal: Population Monitoring & Surveys Genetic Analyses Vegetation Composition: Plots & Transects GIS mapping Shrub Colonization Mammal & Insect Exclosures Water Birds: Population Surveys Nesting Surveys Trophic Interactions Invertebrate grazing on Spartina	Macroalgal Community Structure Nekton Community Structure Bacterial Community Structure Invertebrate & Fish Community Structure Trophic Interactions using stable isotopes Water Birds: Population Surveys Seagrass colonization	Plant Community Structure Permanent plots Nekton Community Structure Bacterial Community Structure
Disturbance (DS)	Storm frequencies Storm intensity Storm waves: height, period, energy Storm surges	Salt water intrusions Sand overwash Shoreline change Myrica gap dynamics Vegetation burial Herbivory	Sediment suspension and deposition Advection of macroalgae and marshgrass wrack	Wrack deposition Salt water flooding Sediment deposition & erosion Fire Herbivory - Animal "eat outs"

\* includes S. alterniflora, S. patens, J. roemerianus, and D. spicata

through observations of "experiments of opportunity" for example after fire, major wrack deposition, muskrat/snowgeese "eat outs" etc. occur. (*LTE*, *DS*)

There are 3 components of modeling the mainland margin: (1) relating marsh position and ecosystem state to hydrogeomorphology and associated factors for transition, (2) relating ecosystem states to hypsometric curve to predict areal extent of states, and (3) relating ecosystem state to ecosystem function. We will continue to evaluate hydrogeomorphological influences on margin states and dynamics by extending the approaches of Schneider (1984) and Ricker (1999), previously used at the VCR. The elevation ranges associated with each state and transition will be predicted by the aforementioned models and field results. These ranges will be placed along hypsometric curves within each watershed and across the VCR deterministically, but with extensive sensitivity analysis to assess uncertainty. Static networks, (structured models) of nitrogen and carbon cycling for the various states will be constructed and analyzed through "network analysis" (Wulff et al. 1989). Network analysis provides an understanding of the strength of indirect relationships and systems-level indices. We have considerable experience with this approach (Christian et al. 1996, 1998; Christian & Luczkovish 1999) and have already applied it to nitrogen cycling within Phillips Creek salt marshes (Thomas 1998). We will conduct network analysis of ecosystem function in the context of both individual watersheds and the VCR megasite within the context of system hypsometry. (MOD, DS, PP, OM, NC, TS)

**Fundamental Questions and Significance** – **A Summary**. How will VCR ecosystems keep up with the most rapid rise in relative sea level anywhere along the Atlantic Coast, much less accommodate even a modest global warming-induced eustatic sea level rise? How will VCR ecosystems change in response to the recently begun recolonization of a keystone species after 6 decades of absence? With three generations of fossil fuel fertilizer and contaminant loading of watershed groundwater, how will VCR's estuarine wetlands deal with the arrival of these nutrients during the next generation? VCR land surfaces are elevated and its ecosystems maintained, on decadal time scales, by episodic sedimentation events arising from coastal storms. How will VCR ecosystems respond to changes under the more moderate storm climate expected with global warming? These and other questions regarding the trajectory of VCR ecosystems motivate our research program and go to the heart of solving fundamental societal problems associated with such environmental change.

## VCR/LTER III Publications & Datasets

*Note: Online listings by LTER Core Area and specific system component can be found online on the VCR/LTER review page* <u>http://www.vcrlter.virginia.edu/vcr2k</u>

## **Refereed Journal Articles**

- Anderson, I. C., K. J. McGlathery, and A. C. Tyler. in review. Microbial processing of reactive nitrogen in a temperate coastal lagoon. Marine Ecology Progress Series.
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## Datasets

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- ALM7D8802A: Temporal and spatial distribution of microbial biomass, growth and activity.
   Author(s): Aaron L. Mills
   Keywords: bacteria, carbon flux
   Data Available Online
- BPH8801A: LTER hurricane record for the Virginia Coast Reserve. Author(s): Bruce P. Hayden Keywords: Hurricane, Landfall, Tropical storm Data Available Online
- BPH8801B: Long-term precipitation for the Virginia Coast Reserve 1837-1987. Author(s): Bruce P. Hayden Data Available Online
- GFO9107A: Trend surface analysis of the 300 YBP stratigraphic horizon and the Holocene/Ples Author(s): George F. Oertel Data Available Online
- HHS8801A: Establishment of island transects. Author(s): Terry Cook Keywords: ground water, intercept, salinity Data Available Online
- HHS8802A: Plant distribution on Hog Island. Author(s): Terry Cook Keywords: Plants Data Available Online
- JCZ8801A: Element and biomass partitioning on the VCR landscape, part A. Author(s): Joseph C. Zieman Keywords: Carbon:Nitrogen ratio Data Available Online
- JCZ8801B: Element and biomass partitioning on the VCR landscape, part B. Author(s): David T Osgood PH.D, Joseph C. Zieman Keywords: Ammonium, Nutrients, Phosphate, Spartina alterniflora Data Available Online

- LKB2E8802A: Spartina alterniflora decomposition in marsh sediments. Author(s): Linda K. Blum Keywords: Spartina alterniflora, decay rate Data Available Online
- LML7O9001A: A study of water quality conditions in the tidal creeks of Northampton County, Vs Author(s): Luis M. Lagera Keywords: Water Quality, Water column, estuary Data Available Online
- LML7O9001B: A study of water quality conditions in the tidal creeks of Northampton County, Vs Author(s): Luis M. Lagera Keywords: Eastern Shore, Northampton County, dissolved nutrients, dissolved oxygen Data Available Online

 LML7O9001C: A study of water quality conditions in the tidal creeks of Northampton County, Vs
 Author(s): Luis M. Lagera
 Keywords: Eastern Shore, Northampton County, ammonia, biochemical oxygen demand, chlorophyll a, dissolved nutrients, nitrate, organic matter, phosphate, total suspended solids
 Data Available Online

RAB9001A: Hog and Cobb Island nesting seabird study, part A. Author(s): Ruth A. Beck Keywords: Bird, Nest Data Available Online

RAB9001B: Hog and Cobb Island nesting seabird study, part B. Author(s): Ruth A. Beck Keywords: Bird, Nest Data Available Online

 RDD6B7501A: Survey of island small mammals - trapping data.
 Author(s): Raymond D. Dueser , Susan A. McCuskey, Gregory S. Hogue, John H Porter
 Keywords: Blarina, Cryptotis, Microtus, Mus, Oryzomys, Peromyscus, Rattus, mammal, mouse, rat
 Data Available Online VCR97006: Brownsville and Hog Island Surficial Well Data Author(s): Mark M. Brinson , Laura Stasavich Keywords: conductivity, ground water, groundwater, salinity, water table Data Available Online

- VCR97008: 1992-93 Parramore Permanent Plot Baseline Data : Site Data Author(s): David L Richardson, John H Porter, Johann Knutsen, Frank .D, Ed Faust Data Available Online
- VCR97009: 1992-93 Parramore Permanent Plot Baseline Data : Subplot Data Author(s): David L Richardson, John H Porter, Johann Knutsen, Frank .D, Ed Faust Data Available Online
- VCR97011: 1992-93 Parramore Permanent Plot Baseline Data : Tree Data Author(s): David L Richardson, John H Porter, Johann Knutsen, Frank .D, Ed Faust Data Available Online
- VCR97012: 1992-93 Parramore Permanent Plot Baseline Data : Shrub Data Author(s): David L Richardson, John H Porter, Johann Knutsen, Frank .D, Ed Faust Data Available Online
- VCR97013: 1992-93 Parramore Permanent Plot Baseline Data : Subplot Water Cover Author(s): David L Richardson, John H Porter, Johann Knutsen, Frank .D, Ed Faust Data Available Online
- VCR97014: Creekbank physico-chemical data from Hog Island salt marsh chronosequence Author(s): A. Christy Tyler data under construction
- VCR97015: Inundation Experiment Permanent Plot Data : Biomass Keywords: decomposition, plants, primary production Author(s): Robert R. Christian Data Available Online
- VCR97016: Inundation Experiment Permanent Plot Data : Bulk Density Author(s): Robert R. Christian Data Available Online

VCR97017: Inundation Experiment Permanent Plot Data : Macroorganic Material Author(s): Robert R. Christian Data Available Online

 VCR97018: Hourly Meteorological Data for the Virginia Coast Reserve LTER Author(s): John H Porter , David O Krovetz , William K. Nuttle, James Spitler
 Keywords: Precipitation, Rain, Relative Humidity, Solar Radiation, Temperature, Weather
 Data Available Online

VCR97019: Extratropical Storms (1885-1996) by Month (USA) Author(s): Bruce P. Hayden Data Available Online

VCR97021: Data from NOAA Marine Environmental Buoy Database on CD-ROM: Atlantic Ocean Author(s): Donald W. Collins data under construction

VCR97022: HHS8802B : Plant distribution on Hog Island : T1 : Myrica allometry dia.+wgt. Author(s): Terry Cook Data Available Online

VCR97023: HHS8802B : Plant distribution on Hog Island : T2 : Myrica allometry dia.+wgt. Author(s): Terry Cook

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VCR97025: Bacterial dynamics in tidal marsh creeks of the Eastern Shore of Virginia Author(s): Katherine M. MacMillin Data Available Online

VCR97026: Distribution of barrier island overwash disturbance Author(s): Lenore B. Fahrig, Bruce P. Hayden, Robert Dolan Keywords: Disturbance Data Available Online VCR97027: Water level fluctuations, Brownsville Marsh -MID MARSH SITE - Stevens water levs Author(s): Mark Brinson data under construction

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- VCR97032: Production data from Brownsville Marsh 1992 Author(s): Jerry Bellis Keywords: Distichlis, Juncus, Spartina data under construction
- VCR97033: NOAA Hourly Tidal Heights for Wachapreague, VA 1985-1989 Author(s): NOAA Data Available Online
- VCR97034: NOAA High and Low Tidal Heights for Wachapreague, VA 1985-1989 Author(s): NOAA Data Available Online
- VCR97035: Plant Cover Upper Phillips Creek Author(s): Mark M. Brinson data under construction
- VCR97036: Barrier Islands Lagoons and Marshes Author(s): Bruce P. Hayden Keywords: complexity, lagoon, landscape Data Available Online

VCR97037: Shoreline and Upland/Marsh data for Hog Island 1852-1993 Author(s): Guofan Shao Ph.D. Data Available Online

VCR97038: Hog Island Small-Mammal Trapping Author(s): John H Porter , Raymond D. Dueser Keywords: Mus musculus (house mouse), Oryzomys palustris (rice rat), Rattus norvegicus (Norway rat) Data Available Online

VCR97043: Nitrogen and Phosphorus Content of Decaying Roots Author(s): Frank P. Day Keywords: decomposition, nitrogen, nitrogen amendment, phosphorus Data Available Online

VCR97044: Rates of Mass Loss During Root Decay Author(s): Frank P. Day Keywords: nitrogen amendment, root decomposition Data Available Online

VCR97045: Cotton Strip Decomposition - Tensile Strength Author(s): Frank P. Day Keywords: cellulose, cotton strip assay, decomposition Data Available Online

VCR97046: Bryson Archeoclimate Model for Painter VA Author(s): Robert E. Davis Keywords: Pleistocene Data Available Online

VCR97047: Hog Island Soil Water Nutrient Chemistry 1990-1992 Author(s): Frank P. Day Keywords: ammonium, dunes, fertilization, nitrate, nitrogen, phosphate, soil water Data Available Online

VCR97048: Hog Island Soil Nutrient Data 1991-1992 Author(s): Frank P. Day Keywords: ammonium, nitrate, nitrogen, nitrogen fertilization Data Available Online

VCR97049: Hog Island Chronosequence Soil Eh, pH and Temperature 1991-1992 Author(s): Frank P. Day Keywords: soil pH, soil redox potential Data Available Online VCR97051: Small mammal live trapping on islands and mainland - 1995-Author(s): Nancy D. Moncrief, Raymond D. Dueser Keywords: data under construction

VCR97052: Fertilization Above & Below Ground Biomass and Species Number on Hog Island Dunes

Author(s): Frank P. Day Keywords: biomass, dune vegetation, nitrogen fertilization, roots data under construction

VCR97053: Tide Data for Hog Island (1991-), Redbank (1992-). 12 minute interval Author(s): John H Porter , David O Krovetz , James Spitler , wnuttle Keywords: barometric pressure, temperature (water) Data Available Online

VCR98054: Birdwood Mammal Trapping Data, Charlottesville, VA, 1974-1978
 Author(s): Raymond D. Dueser, Robert K. Rose, John H Porter
 Keywords: Meadoww vole
 Data Available Online

VCR99056: Ground Water Level on a Parramore Pimple Author(s): John H Porter, Bruce P. Hayden Keywords: Parramore Island, fresh water Data Available Online

VCR99057: Water Quality - Nutrients data under construction

VCR99059: A Spatially Explicit Model of Vegetation-Habitat Interactions on Barrier Beaches

Author(s): Ed Rastetter Keywords: Pascal Program, island Data Available Online

- VCR99060: GPS Elevations of VCR/LTER Marshes Author(s): Cassondra R. Thomas , Charles Randolph Carlson Keywords: Elevation, Global Positioning System Data Available Online
- VCR99062: Long Term Mammal Data from Powdermill Biological Station Author(s): Joseph F. Merritt Keywords: Small Mammal, population data under construction

VCR99063: Minirhizotron fine root length and width data - Hog Island Author(s): Frank P. Day Keywords: minirhizotrons data under construction VCR99064: Dune Biomass - Hog Island Author(s): Frank P. Day Keywords: data under construction VCR99065: Long-term N-fertilized vegetation plots on Hog Island Author(s): Frank P. Day Keywords: data under construction VCR99066: Groundwater well data - Hog Island Author(s): Frank P. Day Keywords: data under construction VCR99067: Fine Root Biomass on North Hog Chronosequence Author(s): Mark Stevenson Keywords: data under construction VCR00070: Lagoon primary producer biomass and elemental composition Author: Karen J. McGlathery Keywords: macroalgae, microalgae, phytoplankton, seagrass, carbon, nitrogen, phosphorus Data under construction VCR00071: Lagoon sediment organic matter and elemental composition Author: Karen J. McGlathery Keywords: sediment, organic matter, carbon, nitrogen, phosphorus Data under construction WKN7S8801B: Groundwater budgets on Hog Island and at Brownsville. Author(s): William K. Nuttle Keywords: Data Available Online WKN7S8802A: Sediment dynamics and organic matter survey in mainland, lagoon, and island marss Author(s): William K. Nuttle Keywords: Bulk density, Cesium, Organic content Data Available Online

WKN7S8903A: Morphological study of tidal creeks. Author(s): William K. Nuttle Keywords: Drainage Density, Marsh creek, Morphology Data Available Online

- WO8802A: Spartina alterniflora leaf measurements, part A.Author(s): William T. Odum, Jonathan P. FryeKeywords: Crabs, Invertibrates, Plants, Primary production, Spartina alternifloraData Available Online
- WO8802B: Spartina alterniflora leaf measurements, part B.Author(s): William T. Odum, Jonathan P. FryeKeywords: Crabs, Invertibrates, Plants, Primary production, Spartina alternifloraData Available Online
- WO8802C: Spartina alterniflora leaf measurements, part C. Author(s): William T. Odum, Jonathan P. Frye Keywords: Crabs, Invertibrates, Plants, Primary production, Spartina alterniflora Data Available Online

Online data resources not included in VCR/LTER Data Catalog

Biodiversity Database (Hayden, Porter) - 6,000+ genera

Photographic Images - 1400+ images of the site (135 MB)

Global Positioning System Projects (Carlson) - GPS Data from 25+ individual GPS surveys (many of which have tens of thousands of individual points)

Northampton Co., VA GIS Coverages (Porter, Richardson) - Hydrography, Transportation, Soil and Landuse, Plant Associations, Bird Nesting Sites

LIDET experiment data for the VCR/LTER (Blum)

Summary Water Quality Data (Brinson, Blum)

Online Student Theses and Dissertations (including summarized and raw data)

1999

Lisa D. Ricker (1.2 MB .pdf file)

Resistance to State Change by Coastal Ecosystems Under Conditions of Rising Sea Level. 1999. East Carolina University, advisor Dr. Mark M. Brinson.

Laura Stasavich (319 KB .pdf file)

Hydrodynamics of a Coastal Wetland Ecosystem. 1999. East Carolina University, advisor Dr. Mark M. Brinson.

## 1998

Trine Christiansen (2.1 MB .pdf file)

Sediment Deposition on a Tidal Salt Marsh 1998. University of Virginia, advisor Dr. Patricia Wiberg.

Cassondra Thomas (1.3 MB .pdf file)

The Use of Network Analysis to Compare The Nitrogen Cycles of Three Salt Marsh Zones Experiencing Relative Sea-Level Rise. 1998. East Carolina University, advisor Dr. Robert Christian.

John Walsh (18 MB .pdf file)

Low marsh succession along an over-wash salt marsh chronosequence. 1998. PhD. Dissertation. University of Virginia. Charlottesville VA, 211 pp. Advisor: Jay Zieman

#### 1997

Christy Tyler (~3M including images)

Geomorphological and Hydrological Controls on Pattern and Process in a Developing Barrier Island Salt Marsh. 1997.

University of Virginia, advisors Jay C. Zieman, Bruce Hayden, Steven Macko, Jeff Raffensperger.

Rebecca Tarnowski (3K abstract)

Effects of dissolved oxygen concentrations on nitrification in coastal waters. 1997. East Carolina University, advisor Dr. Robert R. Christian.

### 1996

Patricia M. Tolley (385K plus images)

Effects of Increased Inundation and Wrack Deposition on a Saltmarsh Plant Community. 1996. East Carolina

University, advisors Robert R. Christian, Dr. Mark M. Brinson, Claudia L. Jolls, Kevin O'Brien

### 1995

Janet L. Loxterman (76K plus images)

Allozymic Variation in the Marsh Rice Rat, Oryzomys palustris, and the White-footed Mouse, Peromyscus leucopus, on the Virginia Barrier Islands and Southern Delmarva Peninsula. 1995. Virginia

Commonwealth University, advisors John F.

Pagels, Nancy Moncrief, and Donald Young.

Heather E. Quinley (55K; 298K w/ images)

A Stable C and N Isotope Study of Marsh Sediments Cattleshed Creek, Virginia Coast Reserve. 1995. University of Virginia, advisors Stephen A. Macko and Linda Blum.

Riddervold, L.B. (4.6 MB .pdf file)

Sources of nitrogen to the high marsh/upland transition zone of a Virginia back-barrier system. 1995. M.S. Thesis. University of Virginia.

#### Mark J. Stevenson (2.3 MB .pdf file)

Fine root biomass distribution and production along a barrier island chronosequence. 1994. M.S. Thesis. Old Dominion University. Advisor: Frank Day

James H. Taylor (1M Adobe Acrobat (.pdf) file)

The Effects Of Altered Inundation And Wrack Deposition on Nitrification, Denitrification, and the Standing Stocks of NO 3 - and NO 2 - . (Under the direction of Robert R. Christian, Ph.D.) Department of Biology, August 1995. 1994

Dilustro, J.J (5.5 MB .pdf file)

Aboveground biomass and net primary productivity along a Virginia barrier island dune chronosequence. 1994. M.S.

Thesis, Old Dominion University, Norfolk, VA. pp. 50. Advisor: F. Day.

Joseph I. Hmieleski (150K)

High marsh-forest transitions in a brackish marsh: the effects of slope. 1994. East Carolina University, advisor Mark Brinson.

Weber, E. (9 MB .pdf file)

The effect of nitrogen fertilization on the phenology of roots in a barrier island sand dune community. 1994. M.S. Thesis, Old Dominion University. Advisor: F. Day.

David J. Yozzo (285K)

Patterns of Habitat Use by Sub-Adult Marsh Nekton: Comparison Between Tidal Freshwater and Salt Marshes. 1994.

University of Virginia, advisor Dave Smith.



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## VCR Organization and Oversight

The signatory PIs of the VCR LTER are Bruce Hayden, John Porter and Karen McGlathery. Hayden is the lead PI and is responsible for project management and administration. Other than academic duties, all of Hayden's funded research is focused on the VCR and his time is fully invested in LTER duties. John Porter is full time on the LTER program and has served as lead PI for the past two years and is versed in project management and administration. He is also the VCR information manager, serves on the LTER Exec. Committee, and is in charge of our GIS laboratory. Karen McGlathery has been asked to play a lead role in project management and administration in anticipation of future service as lead PI. The signatory PIs have primary responsibility to insure that network, intersite and international responsibilities are fully met.

The Internet is used widely within the project to coordinate activities and to exchange information. A calendar of project activities is emailed weekly to all investigators. An email forwarding system (linked to the personnel database) facilitates inter-investigator communication. WWW forms are extensively used to facilitate submission and retrieval of datasets, bibliographic entries, project reports and plans. During LTER IV we will expand our use of Internet conferencing facilities (e.g., webcasts) to allow investigators at remote sites to participate in weekly PI meetings.

During the academic year PIs in Charlottesville meet weekly and in the summer biweekly to deal with general administrative issues, advice and consent regarding policy and procedures, respond to NSF initiatives and to Network and Intersite activities. The minutes of these meetings are published on the VCR website in a secured PIs only section and are electronically archived. We hold meetings of all PIs three times per year (Fall, Winter and Spring). The location of this meeting varies according to needs. In addition to the PIs, officials of The Nature Conservancy are invited and usually to attend these meetings. The winter quarterly meeting is our All VCR Scientists meeting. At this meeting oral research presentations (including REU presentations) are made and short written versions are subsequently collected and published as electronic volumes.

VCR scientists are classified as Signatory PIs, Co-PIs, Subcontracting PIs, and Affiliated PIs. Signatory PIs as indicated on the cover-sheet of this proposal have responsibility for management and administration, as well as oversight and coordination of the research. Significantly, these PIs have the additional responsibility to insure project communication including, timely reports to the National Science Foundation, annual scientific meetings, intersite and international activities, weekly and quarterly administrative meetings, and long-term research planning sessions. Hayden will serve as Corresponding PI and the main contact with NSF for the duration of this proposed research. Hayden is the designated PI with respect to the LTER Network Office. Co-PIs are scientists with a long-term research commitment to the VCR LTER research program and are responsible for the conduct of the research outlined in this proposal. Sub-contracting Co-PIs have part of their research financed by the Core VCR LTER grant through subcontracts with UVa. Affiliated PIs are scientists whose research is independently funded and have research missions consistent with the VCR LTER, support our data and reporting protocols and contribute to the data archives of the project including long term-data sets. Logistics support for their research is provided where possible. Changes in the organization and oversight of the VCR LTER since our last submission include:

- We were encouraged by the 1997 NSF site review team to rely more on technical staff in meeting our Core Area responsibilities. We have include two additional on-site science technicians. We pay for this change with our funding increase and by keeping a flat funding model for PIs and their students. The PIs agreed to this model. In effect, we will all redouble our efforts to win research dollars from other sources.
- Informal discussions during the 1997 site review questioned the number of participating scientists. Our philosophy is that the VCR is a resource that should attract scientists to work at the site and encourage leveraging additional resources. Our current leverage multiple on core funds is 1.9X. Nonetheless we have had changes in our roster of participating scientists. For productivity reasons we have reduced our subcontracts (Bucknell) by one. In addition, two individuals, Shugart and and Dueser, have new administrative and managerial responsibilities that will limit their participation in the coming years. We have lost two PIs, Furman and Shao, to other Universities and they will have only very limited future participation. We continue to be very active in our efforts to become a more diverse research team. We expect to attract new, young faculty to the program after they establish their career paths.
- We have completed the hypsometric model of the watershed in which most of our work is conducted and have in factored this framework into the majority of our activities as reflect in this proposal. We were encouraged by the review team to incorporate the hypsometric watershed model broadly in our program
- To achieve better integration across sites within the VCR and between PIs (as recommended by the site review team), we have reorganized the structure of our annual, VCR all-scientists meeting such that break-out groups are organized across scientific themes rather than by research sites.
- With the addition of three new coastal sites to the LTER Network in 2000, we propose to use PIs from the coastal sites, when the sites are announced, as outside VCR advisory committee members. We will encourage the committee to attend our annual All Scientists meetings. We propose that this advisory committee will meet in years 2, 4 and 6 in order to provide advice in the year before and after the mid-term NSF site review and early in the year in which the next renewal proposal is due. We believe that this oversight committee will also serve to advance intersite research among the 6 sites with coastal landscapes and set the stage for synthetic publication efforts.

# **Information Management**

The data and information management systems of the Virginia Coast Reserve Long-Term Ecological Research (VCR/LTER) site are designed to support the full scientific enterprise, from site management to data archiving and retrieval, and to meet our obligations to the wider research and educational communities.

Principal foci of VCR/LTER information management activities are: to provide data resources needed by researchers (both inside and outside the VCR/LTER), to facilitate communication among researchers, to meet the information needs (beyond data) of researchers, and to provide access to physical samples. The VCR/LTER Data Page (<u>http://www.vcrlter.virginia.edu/data.html</u>) provides access to a wide variety of investigator, student and technician-collected data. Metadata for 75 datasets are provided online, 56 of them with instantly downloadable data (see the list of datasets on pages 20-31 of the Publications and Data listing). In addition to these "routine" data, special purpose databases are established in order to meet the needs of specific projects. Examples of these are the Biodiversity database, which includes both a query system and a data input system that are fully WWW accessible, and the meterological and tide databases, which provide a query system with extensive graphical output.

The VCR/LTER Personnel Directory is the heart of our communication system. The personnel database allows researchers to manage their own personal data and to add new students as they join the project. VCR/LTER Electronic Mailing Lists are based on the Personnel Directory, each researcher can add themselves to groups they are interested in or remove themselves from groups that no longer interest them. Messages sent to the mailing groups are automatically archived in a WWW-accessible form. The VCR/LTER Calendar system helps keep researchers apprised of site activities. This system sends electronic mail each day that highlights activities on the VCR/LTER and provides a long-term summary at the beginning of each week. Researchers add their calendar entries using an on-line form.

In addition to traditional forms of data, researchers also need access to other materials. For this reason we provide on-line access to: all our LTER proposals, full-text of 17 student theses and dissertations, copies of presentations and annual research summaries. These online texts are important resources for preparing new proposals and for keeping in touch with the research progress of other researchers. Annual research summaries and reports are submitted using WWW forms. Publication lists are another important resource. In addition to providing searchable lists of references generated by the VCR/LTER project, we also provide capabilities for searching the annotated bibliographies maintained by individual researchers.

Physical samples, in the form of voucher specimens, tissue samples and water and soil samples are an invaluable resource for future researchers. To better meet this need for the long term, in 1999 we concluded a Memorandum of Partnership with the Virginia Museum of Natural History (VMNH) in Martinsville, VA to manage the off-site sample archives of the VCR/LTER. VCR/LTER samples will be available to all researchers through standard VMNH policies. So far we have archived over 1,500 vials of frozen tissues, along with over 850 voucher specimens from the Delmarva penninsula. As part of a recent stable isotope analysis, we

collected over 320 tissue samples from 42 different species. Tissues from this analysis are preserved both as dried and frozen specimens and will be added to the VCR/LTER permanent collection at the VMNH as soon as the stable isotope analysis is completed.

**VCR/LTER information resources are widely used.** During the period October 1, 1995 through December 29, 1999, our WWW server downloaded 1.9 million files containing 31.8 gigabytes of information. During that period, we averaged on a daily basis 1,237 requests from 281 different "visitors" transferring a total of 20.5 MB per day. However, that number is



misleading since we have seen a strongly increasing trend in usage throughout the existence of the site (Figure IM-1). If only the period 1 Jan. 1999 through Dec. 29, 1999 is considered, the averages rise to 1,809 requests by 443 visitors totaling 61 MB per day. Educational users make up 28% of all visitors, but account for 41% of files requested, reflecting strong academic and educational interest in the material on our WWW site. However, WWW logs only can tell part of the story. Since mid-1997 we have been logging requests for datasets. Under our data license agreement, each download requires giving your name, email and a brief statement of why you want the data (not just a click!). We have received (and automatically granted) 160 of these "serious" data

requests. Understandably, a majority of the requests were from researchers and students associated with the VCR/LTER (68%), but 32% of requests were from researchers outside the VCR/LTER. There were eight international requests from Italy, Spain, Thailand and Peru. Fifteen percent of requests cited educational use (classwork, examples etc.). It should be noted that these requests do not include many of our more popular databases (such as graphical descriptions of weather and tides and GPS locations), and electronic texts which are available without filling out a license agreement.

**Information management policies are critical to the success of the VCR/LTER**. Scientists participating in the VCR/LTER project and affiliated investigators (who use the project infrastructure, but receive no specific support) are required to submit their data to the VCR/LTER database. Pursuant to the VCR/LTER data policy (which conforms to the LTER Network data policy), data may be kept "private" for up to 2 years, but metadata documenting the characteristics of the data are available to the public immediately. Investigators have the option of requesting a longer period of privacy if there are special conditions (e.g., student still completing thesis, data contains locations of endangered species), but this is seldom invoked. A full copy of the data policy is available on our data page on the WWW.

To encourage investigators to fully participate in the system and to provide necessary

legal protections, we require data users to fill out a "Data license" (similar to a software license) which dictates the responsibilities (proper citation and acknowledgment) of the user. Once a data request is submitted: 1) the user is granted immediate access to the data requested, and 2) the investigator who collected the data is emailed a notice that the data was downloaded. We have found this second step to be very important in securing the support of our PIs for providing online data. Many investigators did not mind sharing the data, but they wanted to be notified about with whom they were sharing it.

To serve a widely distributed array of investigators, the VCR/LTER information systems make extensive use of the WWW for both input and output. A relational database is linked to online forms to provide a user-friendly and efficient interface for investigators. Use of a database allow us to minimize the level of duplication among inputs, so that investigators need not provide redundant information (Figure IM-2). For example, changes to addresses in the



personnel database automatically show up when data are accessed. Similarly, named locations defined in our biodiversity database can also be used to locate datasets and projects.

Archival copies of data and metadata are made periodically and stored off site to safeguard the information in the event of a catastrophic event or major computer failure. The VCR/LTER also participates in many LTER-wide information management efforts. In 1997 we developed the prototype data catalog system that is now in place at the LTER Network Office and have served as a prototype testing site in the cross site climate database project. We have also participated widely in national informatics efforts. For example, VCR/LTER Information Manager John Porter is on the Biological Data Working Group of the Federal Geographic Data Committee and co-chairs the User Working Group of the Global Change Master Directory.

# **OUTREACH AND COLLABORATION**

**Outreach to Scientists Outside the VCR/LTER:** One of the things that distinguishes an LTER site from many traditional research enterprises is that an LTER site requires a wide array of disciplines and approaches to ecological questions. The expertise needed is frequently wider than the core LTER grant can support. We try to meet this challenge by capturing the interest of researchers with complimentary expertise from outside the VCR/LTER project. We use a number of inducements. First, we try to make as much information about the site and the research conducted there available on the WWW as possible. The wide variety of information resources available, from data, to species lists to maps, frequently prove attractive to external researchers. We also take every opportunity to talk with other researchers about our activities on the VCR/LTER site at scientific meetings and other science forums. Additionally, we have hosted field trips to the site when nearby meetings permit a field trip. For example, we hosted 80 scientists attending the ESA/GSA Penrose Conference in 1997 on a full-day field trip.

Once a scientist has expressed interest in doing some work on the VCR site we do our best to make available the VCR/LTER research infrastructure in ways that do not negatively impact VCR/LTER core research activities. For example, if we have boats going out to the islands or to lagoon study sites for VCR/LTER research activities, we allow "affiliated" researchers (who receive no direct support off the VCR grant), to use open spaces on in the boats. Similarly, if there are empty beds in the VCR/LTER field laboratory, we have allowed visiting researchers to stay free of charge. In return, we require affiliated investigators to share their data under the VCR/LTER information policy.

**Establishment of new Research Infrastructure:** Long-standing efforts at improving the research infrastructure available for studies of the Virginia Coast are close to fruition. In the past, the VCR/LTER has occupied a large rented farm house. However, the University of Virginia is currently completing acquisition of 43 acres of land in Oyster VA for the development of a true field facility. The work of the VCR/LTER attracted the attention of the alumni of the University of Virginia. More than \$2,200,000 has been donated to the University for the establishment of a new Coastal Research Center. Construction of the first phase of this project is scheduled for Fall 2000. This facility will serve has home to the VCR/LTER, but will serve all researchers.

**International LTER activities:** Investigators at the VCR/LTER have an active interest in the opportunities afforded by the development of an international LTER network. This developing network provides us for opportunities for comparative studies. Several VCR/LTER investigators have played important roles in helping to expand the ILTER network. Activities have included:

- INTECOL 1994 & 1998 Data Mangmnt. Demo. (Porter), 1998 Organizing Committee (Christian and Hayden),
- IGBP participation GCTE (Shugart) and BAHC: (Hayden) CGOOS and GTOS participation: (Christian)
- Latin American ILTER workshop, Puerto Ordaz, Venezuela, information management group. (Porter)
- Organizers: ILTER symposium and workshop. Intecol: Florence, Itlay 1998. (Christian and Hayden)
- Toward new ILTERs in Italy, Slovenia and Croatia (VCR delegates: Christian, Smith, and McGlathery)
- ILTER Delegation Membership -- Czech Republic (Anderson and Macko); Italy, Slovenia and Croatia (Christian, Smith, and McGlathery); Hungary (Hayden and Blum);and, Portugal/Spain. (Christian and Hayden)
- Workship on Functional Ecology at Academia Sinica, Taipei (Christian and Brinson)
- Workshop:Wetland hydrogeomorphic classification and functional assess. Puerto Rico. (Christian and Brinson)

Scholastic and Undergraduate Student Outreach: In the Spring semester (1997) 33 students contributed to the biodiversity information system project and nearly 6,000 species observations

were entered into the system (1996: Hayden & Porter, 1997: Smith & Porter). VCR has been supplemented for 2 to 3 REU students per year and we match that with internal funds. The VCR is often used as a base for field trips by college classes and by the public school. Local staff assist. The Schoolyard LTER program is supported by NSF and augmented by Sea Grant (\$8,000 per year) and funds from UVa Alumni. Charlottesville area schools are also served by VCR PIs.

**LTER Network:** We have been active in the governance and committees of the U.S. LTER Network. Porter serves on the LTER Executive and Information Management Committees. Hayden is a past member of the Executive Committee and past chair of the Publications Committee.

National Outreach: VCR/LTER researchers have participated in many national intitiatives:

- Leadership in ESA Long-term Studies Section (Porter), Statistical Ecology Studies Section (Porter),
- ESA's SBI Programs: Global change. (Hayden)
- LTER representative to the Mid-Atlantic FRAMEWORK workshop initiated by the White House Science Office (Hayden)

**Cross-site:** Cross-site activities continue to be important for our researchers. Past and ongoing activities include:

- LIDET -- The VCR continues to participate in the network decomposition experiment (LIDET). (Blum)
- LTER Workshop on Soil Methods March 1996 at Sevilleta; developed book on standard soil methods published by Oxford University Press..(Day)
- Graduate student, Rett Weber, conducting intersite study at Konza and VCR.
- X-Roots Workshop: Participatedin a workshop aimed at integrating. LTER Climate Data into advanced relational databases (Porter)
- Assisted in the installation of GPS benchmark system at Plum Island. (Carlson)
- Advisory Panel for the Luquillo LTER site (Hayden and Porter)
- Konza Synthesis Volume. Oxford Press. 1998. Two Chapters. (Hayden)

## **NSF Service:**

- LTER site reviews: Toolik Lake, Bonanza Creek, Konza, Luquillo, and Palmer Site Reviews.(Porter) Sevilleta (Dueser) Short Grass Steepe, Harvard Forest. (Hayden).
- Hayden served as DD for DEB BIO NSF 1997-1999.
- Porter served as PO for Database Activities in BIR BIO NSF 1994-1995

**Community Service:** We recognize that interacting with government and community organizations is important to the continuing success of the VCR/LTER. Past activities have included: State and local Government; 1) Shared GIS layers with - Northampton County and with Cape Charles (Porter and Hayden), 2) Participated in Economic Impacts of Research Study for Northampton County (Hayden, Oertel, Blum and Mills), 3) Natural Resource Values and Vulnerabilities. 4) The second Virginia Eastern Shore Natural Resources Symposium. (Hayden, Oertel, Blum and Mills), 5) Participant in the Eastern Shore Birding Festival (Hayden), 6) Virginia Professional Wetlands Delineation Workshop (Hayden and Oertel), and 7) Eastern Shore Water Quality Monitoring Program (Blum)

Media: We conducted a Media Day event at the Eastern Shore of Virginia National Wildlife Refuge, Cape Charles VA in 1999. Blum, R.M. Erwin, B.P. Hayden, J. H. Porter, and J.C. Zieman gave briefings. Resulted in 1) "With Good Reason" 1/2 hour public radio feature, 2) Chronicles of Higher Education article, 3) Washington Times feature article.

