Long-Term Ecological Research on Landscape Development and Ecological Processes in a Tide-Dominated Barrier-Lagoon Complex: LTER II

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PROJECT SUMMARY

The Virginia Coast Reserve (VCR) is an extremely dynamic, frequently disturbed landscape which is comprised of elements (e.g. grasslands, marshes) that differ in degrees normally associated with biome-level differences. Because the frequency of disturbance at the VCR is so great the types of ecosystem changes that would normally occur across large distances (continents, biomes) and over long periods of time (e.g. glacial and

interglacial periods) happen on decadal time-scales. Ecosystem state changes are frequent. The central research theme of the VCR LTER project is the understanding of the dynamics of ecosystem state change, both the transitions among ecosystem states and succession within these states. The basic elements of our theoretical concept of landscape dynamics are that 1) there are "attractors" in the ecosystem state space within which successional dynamics operate and 2) there are events that produce transitions from one of these attractors to another. Our approach will be to continue to study succession within several of the more prominent states (Myrica thickets and salt marshes) and the response of these states to disturbance. This will be accomplished by research in the NSF-defined LTER network core areas as well as additional VCR-established areas examining states and state changes that have occurred at the VCR in geologic, historic, and present-day context. In addition, we plan to add two types of manipulative experiments (alteration of inundation patterns in marshes and alteration of the availability of fresh water to terrestrial vegetation on a barrier island) that will allow us to accomplish our goal of understanding within-state ecological processes and their controls, and forces resulting in alteration of states. We will address the following working hypotheses: 1) The controls on succession within states are the availability of water, the salinity of that water, the frequency of tidal inundation, and sediment deposition; and, 2) Gradients in salinity and tidal inundation frequency and thus organic matter accumulation, primary productivity, and nutrients, are a function of the slope, sea level, and astronomical and storm tides. 3. Many ecological state changes are triggered by infrequent, short-duration, intense disturbances such as coastal storms. The products of the proposed work will be the development of a new theoretical base for maintenance and structuring of landscape, further elucidation of controls on ecosystem processes, and new ecosystem and landscape modeling approaches.

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RESULTS OF PREVIOUS LTER SUPPORT

Program Synthesis: The VCR LTER research program in 1987 was a loose confederation of experienced scientists working at a common site. We have progressed from working as a broadly focused research team to becoming a research group with a focal research paradigm that unites us all -- The understanding of state change in ecosystems (see Section II. E.). This focus is a major result of our studies to date, is detailed in this proposal, and has been published as a research synthesis (Hayden et al., 1991; Odum and Hayden, 1991). The Hayden et al., 1991 paper is included in the appendix.

An external review committee provided valuable advice in the fall of 1990. The committee shared our positive impression of the VCR LTER site's role in understanding time/space and pattern/process interactions in a diverse array of ecosystems. Further, they appreciated the need for an interdisciplinary research team on the VCR LTER site. We were advised to clarify and consolidate the VCR LTER research focus. This was good advice. We have attempted to do so and have used this consolidated research focus along with the LTER guidelines to determine project research priorities and to provide the basis for this renewal proposal.

Scientific Productivity: Research endeavor can be gauged to a degree by measures of scientific productivity, particularly publications that communicate findings to other scientists. Two such indications of productivity, the project publication rate and the cumulative publications produced by the project to date, are provided in Figure 1. Because of page limitations in this section, we have listed these papers as a special section of the bibliography which follows the project description (p. 52). Here, we comment on the current patterns of scientific publication as an indication of prior results and to communicate the evolution of the project as a whole.

The annual publication rate of the project is on the order of about 20+ publications per year with the healthy pattern of an increasing number of papers toward the end of the research funding cycle (Fig. 1). This reflects the start-up lag in the initiation of this new project and also reflects the fact that the VCR LTER project developed at a site that did not have a prior history of ecosystem research to "prime the pump" for scientific productivity in the current granting cycle. We take as a healthy sign that not only does the rate of publication for the project as a whole increase toward the end of the project (Fig. 1), but the percentage of our publications in peer-reviewed journals also increases over the time period. We enjoyed an initial burst of thesis and dissertation publications at the initiation of the project (when relatively senior graduate students were encouraged to do comparative work on the new LTER site). There was a subsequent peak of thesis activity in 1989 and 1990 when students who started their research on the site finished their degrees. We fielded the largest graduate class in the history of the site in this past summer and expect that this strong class of students will seed similar bursts of student production in the coming two years or so. Over the five year history of the project we have produced 111 publications with 61 journal articles, 17 book chapters, and 18 M.S. theses and Ph.D. dissertations. The "other publications" category is relative small (14 contributions) over the history of the project and includes a miscellany of symposium proceedings along with two books.

Evolution of the VCR: 18,000 years ago the VCR was an upland spruce-white pine boreal forest (Bonan and Hayden, 1990 a,b) with some 10 shorenormal fresh water stream courses across what is now the mid-Atlantic continental shelf. The post glacial sea level rise transformed the riparian, boreal forest first to a tidal estuary-forest complex and around 5,000 years ago to a barrier island-lagoon-marsh complex dissected by the same fluvial drainage system. This history has been established with our coring program (Oertel et al. , 1989 a,b; 1992 a,b) and has lead to a new theroy for the evolution of barrier island coasts (Oertel, 1992 c). The landward transgression of the VCR barrier islands continues today at a rapid rate (Dolan et al., 1990 a,b). While the net displacement of the islands is landward, the within island patterns of erosion and accretion result in a decade to century scale rotation of Hog Island: counter clockwise prior to the turn of the century and clockwise since (Hayden et al., 1991; Harris, 1992). In the 1930s, the clear water, eelgrass-scallop community of the VCR bay bottoms disappeared with the extinction of the eelgrass. The bay bottoms are now mud flats and th water column is very turbid (Hayden et al., 1991). We have determined that 90% of the landscape of Hog Island seaward of its fringing marsh dates from 1871 or later (Harris, 1992).

Modeling: Considerable progress has been made on ecosystem modeling at the VCR. Rastetter (1991) constructed a Markov model of Hog Island (aka, ISLAND) which incorporated time dependent island topography, depths of saline and fresh water tables and is driven by sea level rise and island transgression. Parameterization of ISLAND as a three dimensional landscape model is in progress using historical aerial photogrphy and GIS/ARCINFO technology. Fahrig (1990 a,b; 1991) determined Hog Island vegetation transition probabilities for use in ISLAND. Significantly, Fahrig's transition probabilities are found to be spatially dependent and to be highly correlated with shoreline erosion rates. Accordingly the model can be parameterized to have direct responses to storm climate and shoreline erosion rates.

A boreal forest FORET model was constructed and driven by late glacial climates estimated independently of pollen and then was nicely verified with pollen spectra from fossil peats (Bonan and Hayden, 1990 a,b; Hayden, 1990). This was the first independent test with paleoecological data and past climate data of a boreal FORET model. A ZELIG forest model was also constructed for the Luquillo LTER tropical forest (an intersite modeling effort) and stressed with a wide range of hurricane intensities and magnitudes to put the spectrum of changes that might be expected in forest structure and composition as a result of global warming (O'Brien et al., 1992).

Trophic and Community Studies: The first detailed study of the vegetation of the VCR was completed in the mid 1970s. We have used our GIS/ARCINFO capabilities to duplicate the maps produced in the 1970s and have developed and tested the procedures to develop companion maps for other sets of input aerial photographs. With the archives aerial photos dating from 1940, the capabilities developed will permit landscape scale analyses of vegetation change and succession pathways and will be essential in the proposed new work.

Nutrient Resource Gradients: We have established that there is a gradient in inorganic nitrogen and phosphorus concentrations along a transect from Hog Island to the mainland (Mills et al., 1990). The Island is nutrient poor and dependent on rainwater nutrient input and nitrogen fixation by Myrica (Young, 1992 a,b; Sande and Young, 1992) while the toward the mainland, nutrient concentrations exceed those found in the Island marshes and eutrophic Chesapeake Bay waters (Mills et al., 1990; MacMillin et al., 1992). This nutrient gradient is thought to result from inputs from Delmarva Peninsula agricultural practices.

Primary Production We have determined that above-ground marsh primary production does not reflect the mainland-island nutrient gradient. Above-ground marsh production is correlated with sediment texture: coarse sediments (agrading southern portions of the islands) supporting the greatest above-ground production while finer textured sediments (mainland and old barrier island fringe marshes) are associated with lower production (Osgood, 1991; Odum, unpublished data). The reverse appears to be true for below-ground production in the marshes (Blum, 1992). Porewater concentrations of salt and H2S and the effects on nitrogen uptake by the marsh plants may be an important control on productivity (Osgood, 1991). Myrica production is limited by sub-optimal temperatures (< 30oC) and the availability of fresh water (Young and Sande, 1992).

Organic Matter Accumulation: Organic matter content in mainland marsh soils is higher and more uniformly distributed within the soil profile than in the island marsh soils. The pattern of sulfur and organic matter distribution in the soils suggest that the soils of the mainland are either older than those of the islands, are developing more rapidly, or microbially mediated processes (such as sulfur cycling and organic matter degradation) are occurring a different rates. In the uplands, surface soil (0 - 1 m) organic matter content is related to the vegetation type and on Hog Island is related to the length of time that the site has been vegetated. Organic matter content across the landscape range from less than 0. 05% (beach grass) to over 68% (high marsh grasses)

GIS/ARCINFO Capabilities: With the help of NSF technological development grants and contributions from the National Park Service and the University of Virginia, we have established a laboratory for remote sensing and GIS work. This facility has enhanced the development of data sets on community and landscape structure and change from aerial and satellite imagery. In addition, these facilities have proven to be of great value in model parameterizations.

Relation of Completed Work to Proposed New Work: The proposed new work follows directly from past work. The field facilities that have been established and the long-term records that are being collected will be continued. These are essential to future successes. More importantly, the scientific accomplishments that have accrued to date form the basis for the re-focusing of the project, the development of a new theroetical base for the maintainence and structuring of the landscape, the development of manipulative field experiments, the further elucidation of controls on ecosystem processes, and new ecosystem and landscape modeling approaches.

STATEMENT ON EDUCATION AND HUMAN RESOURCES

The investigators at the VCR have been active in both graduate and undergraduate education, and the presence of the LTER project has provided an educational facility for a number of public schools from around the Commonwealth of Virginia. Educational advancement associated with the project falls into 4 categories: Graduate thesis research, undergraduate research experience, field opportunities for courses, field opportunities for primary and secondary school groups. While the latter was not one of the original goals and is not a focus of the project currently, it is a fallout of the public interest in the presence of the LTER project at our site.

Graduate theses: During the 4.5 years of the existence of the VCR LTER, a total of 8 Ph.D. and 10 M.S. theses have been completed that had some important portion of their work carried out at the VCR. Several others carried out some occasional sampling there and are not listed. Currently 3 Ph.D. and 15 M.S. students (about half of the M.S. students are from the collaborating institutions) are conducting thesis research in which the VCR is the central focus of the study. Given the level of activity achieved thus far, and given the increased level of support dedicated to graduate support in the current proposal (7 students vs 2 in the original proposal), the VCR LTER project will only increase in this component of educational value.

Undergraduate research experience: The VCR LTER project has provided many opportunities for undergraduates to carry out directed and independent work. In each year of its existence, the project has provided support for 2 to 4 summer students with supplemental funds from the REU program. Additional students (3 to 5 per year) have been supported from the core grant and from investigator-generated funds. Although most of the undergraduates are U.Va. students, individuals from other institutions have participated in the research program. In addition to the research projects, undergraduates working at the VCR attend a bi-weekly seminar series (Saturday morning) given by the faculty investigators on topics of relevance to the VCR research. They also present short papers at the annual (fall) VCR LTER all-scientist's workshop.

Coursework: During the academic year, classes from the Department of Environmental Sciences have traveled to the VCR site and carried out laboratory exercises there (e.g. Biogeography, Microbial Ecology, Aquatic Ecology, Estuarine Ecology). Both graduate and undergraduate courses have used the facility. It is interesting to note that several of our summer undergraduates and several graduate students have become involved with the LTER project as a result of one of these field trips. (Trips are sponsored from instructional funds and are scheduled not to conflict with ongoing research.)

Public Education: Several public school groups have visited the VCR, and heard talks by graduate student and faculty researchers in addition to spending time in the field. It should be noted that the function of the LTER project is interpretation of the phenomena associated with the coastal lagoon complex. (Logistical arrangements do not involve the LTER project). LTER investigators are frequently invited by public schools and public interest groups to present general overviews or specific information on the project and its findings.

Theses and Dissertations

Barr, L. 1989. Sedimentation and Fallout Cesium-137 Cycling in a Virginia Salt Marsh. MS Thesis. University of Virginia, Charlottesville, VA.

Bonan, G.B. 1988. Environmental Processes and Vegetation Patterns in Boreal Forests. PhD. Thesis. University of Virginia, Charlottesville, VA.

Chambers, R. 1990. Nitrogen and Phosphorus Dynamics in Tidal Freshwater Marshes. Ph.D. Thesis. University of Virginia, Charlottesville, VA.

Fetsko, M.E.. 1990. A Water Balance Estimate at Brownsville, Virginia. MS Thesis. University of Virginia, Charlottesville, VA.

Fitch, G.M. 1991. The Role of Overwash on Hog Island. MS Thesis. University of Virginia, Charlottesville, VA.

Forys, E. 1990. The Effect of immigration on Island Colonization and Populations Persistence on Oryzomys palustris on the Barrier Islands of Virginia. MS Thesis. University of Virginia, Charlottesville, VA.

Frye, J. 1989. Methane Movement in Peltandra virginica. MS Thesis. University of Virginia, Charlottesville, VA.

Halama, K. 1989. Of Mice and Habitats: Tests for Density-dependent Habitat Selection. MS Thesis. University of Virginia, Charlottesville, VA.

Harris, M. 1992. The Geomorphology of Hog Island, Virginia: A Mid-Atlantic Coast Barrier. MS Thesis. University of Virginia, Charlottesville, VA.

Harvey, J. 1990. Hydrological transport in tidal marsh soils: controls on solute cycling at the scale of marshes, plants, and soil pores. Ph.D. Thesis. University of Virginia, Charlottesville, VA.

Hussey, B. 1989. Evapotranspiration from Vegetated Marsh Surfaces. MS Thesis. University of Virginia, Charlottesville, VA.

Lagera, L. 1988. The Role of Macrophyte Decomposition in the Depletion of Oxygen and Sequestering of Nutrients in the Lower Chesapeake Bay. Ph.D. Thesis. University of Virginia, Charlottesville, VA.

Larson, B. 1990. Habitat Utilization, Population Dynamics and Long Term Visibility in an Insular Population of Delmarva Fox Squirrels (Scirus niger cinereus). MS Thesis. University of Virginia, Charlottesville, VA.

McIvor, C. 1987. Marsh Fish Community Structure: Roles of Geomorphology and Salinity. Ph.D. University of Virginia, Charlottesville, VA.

Osgood, D. 1991. Factors Controlling Production and Tissue Element Composition in Naturally Developing Spartina alternifloraBarrier Island Marshes. MS Thesis. University of Virginia, Charlottesville, VA.

Porter, J. 1988. Mice in Motion: Dispersal in Two Series of Peromyscus. Ph.D.University of Virginia, Charlottesville, VA.

Rauch, S. 1989. Geomorphological Indices for Salt Marsh Creek Systems. Senior Thesis. University of Virginia, Charlottesville, VA.

Ray, M. 1989. Below Ground Decomposition and Production Dynamics in a Virginia Salt Marsh. MS Thesis. University of Virginia, Charlottesville, VA.

Snow, D.M. 1990. Characterization of chemical, physical and microbial properties on a salt marsh creek over the course of a spring and a neap tidal cycle. Senior Thesis. University of Virginia, Charlottesville, VA.

Rozas, L. 1987. Nekton Community Structure and Interactions of Submerged Plant Beds and Tidal Freshwater Marshes. Ph.D. Thesis. University of Virginia, Charlottesville, VA.

Wright, E.J. 1988. A History of the Eastern Shore from Articles Published in the Philosophical Transactions of the Royal Society of London (1665-1850). Senior Thesis. University of Virginia, Charlottesville, VA.

Papers Published by Students
Associated with the VCR LTER
(Full citations given in Bibliography A.)

Bonan, G.B. and B.P. Hayden. 1990. Forest Vegetation Structure on the Eastern Shore of Virginia circa 18,000 years B.P.

Bonan, G.B. and B.P. Hayden. 1990. Using a Forest Stand Simulation Model to Examine the Ecological and Climatic Significance of the Late-Quaternary Pine-Spruce Pollen Zone in Eastern Virginia, U.S.A.

Conn, C.E. and F.P. Day. 1992. Belowground Biomass Patterns on a Coastal Barrier Island in Virginia. Bull. Torrey Bot. Club. In press.

DeKimpe, N.M., R. Dolan and B.P. Hayden. 1991. Predicted Dune Recession on the Outer Banks of North Carolina, U.S.A.

Dueser, R.D., J.H. Porter, and J.L. Dooley. 1989. Direct Tests for Competition in North American Rodent Communities: Synthesis and Prognosis.

Garland, J. and A.L. Mills. Classification and Characterization of Heterotrophic Microbial Communities Based on Patterns of Community-level Sole Carbon-source Utilization.

Harvey, J.W., R.M. Chambers and W.E. Odum. 1988. Groundwater Transport Between Hillslopes and Tidal Marshes.

Harvey, J., P. Germann, and W.E. Odum. 1987. Geomorphological Control of Subsurface Hydrology in the Creek Bank Zone of Tidal Marshes.

Hoelscher, J.R., W.K. Nuttle, and J.W. Harvey. 1992. Comment on "Calibration and Use of Pressure Transducers in Soil Hydrology".

Johnson, S.R.. 1991. The Occurrence of State Rare Species on Hog Island in the Virginia Coast Reserve.

MacMillin, K., L.K. Blum, and A.L. Mills. 1992. Comparison of Bacterial Dynamics in Tidal Creeks of the Lower Delmarva Peninsula.

S. O'Brien, B.P. Hayden and H.H. Shugart. 1992. Global Climate Change, Hurricanes and a Tropical Rain Forest.

Odum, W.E. and J.W. Harvey. 1988. Barrier Island Interdunal Freshwater Wetlands.

Rastetter, E.B. 1991. A Spatially Explicit Model of Vegetation-Habitat Interactions on Barrier Islands.

Rozas, L.P. and W.E. Odum. 1987. Use of Tidal Freshwater Marshes by Fishes and Macrofaunal Crustaceans along a Marsh Stream-Order Gradient.

Rozas, L.P. and W.E. Odum. 1987. Fish and Macrocrustacean Use of Submerged Plant Beds in Tidal Freshwater Marsh Creeks.

Rozas, L.P. and W.E. Odum. 1987. The Role of Submerged Aquatic Vegetation in Influencing the Abundance of Nekton on Contiguous Tidal Freshwater Marshes.

Rozas, L.P., C.C. McIvor and W.E. Odum. 1988. Intertidal Rivulets and Creekbanks: Corridors Between Tidal Creeks and Marshes.

Schneider, R.L. and W.E. Odum. 1992. Barrier Island Interdunal Freshwater Wetlands.

1SCIENTIFIC PROPOSAL

2 INTRODUCTION: CENTRAL FOCUS/STATE CHANGE

The Virginia Coast Reserve (VCR) is an extremely dynamic, regularly disturbed landscape comprised of elements (forests, marshes, grasslands, etc.) that differ in degrees normally associated with biome-level differences. The types of ecosystem changes that occur across continental biomes and over glacial and interglacial episodes happen on decadal time scales at the VCR. Successional chronosequences in accretionary island landscapes are well documented and succession proceeds rapidly (Hayden et al., 1991). Ecosystem dynamics at the local level are critical drivers in producing landscape structure at higher levels of organization. Yet for all of this change and disturbance, the landscape is comprised of repeating units and is seemingly self-ordered. Its barrier islands form a gentle arc with the regularity of beads on a string (Fig. 2). The morphologies of barrier islands and their lagoons repeat in form and dimension. At the site, ecosystem state variables exhibit significant secular trends and are driven by extreme perturbations at meteorological and climatological time scales. The central research theme of the VCR LTER is the understanding of the dynamics of ecosystem state change --- the transitions among ecosystem states and succession within these states.

At the VCR, changes in the states of ecosystems at particular points can be dramatic. Tens of thousands of years ago, our site was a maritime boreal forest of Pinus strobus and Picea (Bonan and Hayden, 1989, 1990; Emory et al., 1967). Seven thousand years ago, what are now open lagoons were forested uplands with stream channel estuaries. Five thousand years ago, these sites changed to tidal channels and marshes (Newman and Munsart 1968) and then, in the last 1500 years changed again to today's lagoons and barrier systems (Oertel et al., 1989a, b; Harrison et al., 1965).

While the entire site has undergone a sequence of state changes over the Holocene, landscape/ecosystem units within the site have undergone equally large state changes within the present century. Mockhorn Island (Fig. 3), once agricultural land and formerly forest, has been abandoned and is now a very young salt marsh. The bay bottoms, which were eel grass meadows at the turn of the century, are now mudflats (Hayden et al., 1991). At the time of settlement of Broadwater in the mid 1800s, the south end of Hog Island was forested but it is now an overwash-flat grassland (Rice et al., 1976). The north end of Hog Island was several hundred meters wide and consisted of a narrow beach fronting a marsh in 1852 and is now a complex chronosequence of ridges and swales nearly 1.5 km wide (Hayden et al., 1991). The VCR is a mosaic of landscapes and ecotones with rate of change exceeded in North America only by the coastal margin of the Mississippi delta (Dolan et al., 1982 b).

One striking example of the dynamic nature of this landscape was the "Halloween Storm of 1991". On October 30, 1991, the VCR LTER was hit by a storm that evolved from an extratropical storm (a "northeaster") moving eastward to merge with a tropical storm, "Tropical Storm, Grace." The resultant "Great Halloween Storm" (Dolan and Davis, 1992) was a major event from Cape Hatteras to Kennebunkport. The storm remained offshore and produced considerable damage even at a distance. At the VCR LTER, waves at sea reached over 11 m and the eastern fronts of the barrier islands were pounded with waves of 3 - 5 m. This was the most powerful storm of the 1347 coastal storms in the LTER data archives. Statistical estimations of its probability indicate a 1000 year plus return interval for a storm of this magnitude. The utility of return intervals for such rare events is probably limited, but with little doubt, this storm was exceptional. The Great Halloween Storm is comparable to historically great disturbance events -- the great storm of 1667, the Accomac hurricane of 1693, the hurricane of 1749 (all of which produced still water levels 3 to 5 m above normal). Initial ground and aircraft reconnaissance of the site indicated that 50 m of beach were removed from Hog Island, marshes behind Parramore Island had as much as 1 m of deposited sand, large sections of Parramore Island's south end eroded, fresh water wells in transects across Hog island were saline. The timing of this storm and its magnitude were an excellent constellation for it provides us with a large scale disturbance following 4 years of work characterizing and monitoring the site. It also occurred in the fall following the largest field campaign we have mounted in

terms of numbers of new graduate students and investigators and thus should provide a rich comparative context for the studies that will follow.
2.1 The VCR as a Site for State Change Research

The VCR is a complex assemblage of 14 barrier islands, associated inlets and beaches, extensive back barrier islands, shallow bays and deep channels, mud flats, expansive salt marshes, and contiguous mainland ecosystems (Fig. 2, Fig. 3). It extends approximately 100 km along the seaward margin of the Delmarva Peninsula (Fig 3). Like the North Inlet LTER site, the low lying landscape (mean elevation < 2 m) provides an unusually sensitive location for studying and monitoring the ecological effects of both atmospheric and oceanic climatic variability on a range of natural ecosystems. However, the VCR and North Inlet differ fundamentally in a wide range of attributes (Table 1) and make these two LTER sites ideal for comparative studies.

The 14,000 ha site is part of the mid-Atlantic coastal plain which extends from the fall-line 100 km inland to the edge of the continental shelf. The plain has a seaward slope of only 0.1%. With a level sea intersecting this sloping plain, small changes in elevation of either the land or the sea result in large horizontal changes that determine landscape and ecosystem structure and dynamics. Although some studies in progress span the entire VCR, most of the LTER research projects are concentrated along a belt transect perpendicular to this shallow but critically important topographic gradient (Fig. 3).

The contemporary barrier island-lagoon-mainland complex took its present 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). Rapid change has taken place during the last few thousand years with the barrier island complex migrating westward across the continental slope at a rate as great as a kilometer per thousand years (Finkelstein et al., 1987). The modern islands typically exhibit dynamic shoreline change characterized by lateral accretion and erosion as high as 13 m y-1 (Dolan et al., 1979). The coastline is one of the most dynamic in the United States (Fig. 4).

The climate of the VCR is dominated by extratropical storms (i.e. northeasters) and by tropical storms and hurricanes. Each year an average of 38 extratropical storms occur with magnitude sufficient to rework beach sands and to elevate tides above astronomical norms (Hayden, 1976, 1981; Dolan et al., 1987, 1988). These storms are largely responsible for changes in the morphology of the islands (Dolan et al., 1979), the associated vegetative cover and ultimately in combination with sea level rise, for landward migration of islands across lagoonal marshes (Hayden et al., 1981). In effect, the site is a perpetual experiment in ecosystem disturbance, plant succession and landscape structuring. We (Harris, 1992) have determined that 90% of the landscape of Hog Island (our principal study site for barrier islands) seaward of its fringing marsh dates from 1871 or later (Fig. 4a).

The vegetation of the islands, marshes, and nearshore sections of the mainland is conspicuously patchy, with distinct zonation and sharp transitions between patches (McCaffrey and Dueser, 1990 a,b,c). High and low salt marshes, unvegetated mud flats, grasslands, shrub savannas and maritime forests occur in close proximity, with sharp ecotones. Vegetation heterogeneity is further accentuated by interannual climatic variation. Precipitation records indicate a range of between 85 and 140 cm yr-1 (Hayden, 1979; Bolyard et al., 1979). This variation arises primarily from variation in summer rainfall, with thunderstorm frequency dependent, in part, on local land/sea temperatures. Further, 45% of late summer and autumn rainfall comes from tropical storms (Hayden, 1979).

Neither the level of the land nor the level of the sea is stable along the VCR. At the south end of the site, the land is subsiding around 3 mm yr-1 and the eustatic level of the sea is rising at about 0.8 mm yr-1 giving a relative sea level rise of 3.8 mm yr-1. The relative sea level rise rate decreases toward the mainland as well as southward and northward for hundreds of km (Emory and Aubrey, 1991). In general, this rate of relative sea level rise exceeds the capacity of marshes to build upward unless marine sands or terrestrial sediments are readily available for sedimentation (Ray and Hayden, 1991). Land levels and eustatic sea levels which are locally measured as the single parameter relative sea level, are critical state variables for VCR ecosystems. The trends in land and the sea level elevations may exceed threshold magnitudes and give rise to system state changes (Ray et al., 1992). Ecosystem states of the VCR and the critical geophysical and ecological state variables that control transitions to alternate ecosystem states are summarized in Table 2. The characteristic temporal variability of these critical state variables is summarized in Table 3.

Locally, the level of the land is also governed by sedimentation of marine and terrestrial mineral sediments and organic matter accumulation (Hackney and Cleary, 1987). Processes that alter ecosystem elevation by sedimentation may thus directly change this critical state variable. For VCR ecosystems, increases in elevation due to sedimentation within the elevation ranges of the astronomical tides may offset the regional subsidence of the land and eustatic rise of the sea. In addition, because most of the inorganic sedimentation above mean sea level is associated with hydraulically transported sediments, water levels during winter and tropical storms are the critical agents of change because they raise land elevations above the levels of the astronomical tides (Dolan and Godfrey, 1973). Landscapes significantly elevated above mean sea level are thus associated with these meteorological disturbances. Below ground organic matter accretion (Blum, 1992) erosion of terrestrial soils, and overwash of marine sands (Kochel and Wampfler, 1989) are also critical processes at the VCR that alter land elevations and may give rise to system state changes (Table 2).

At the VCR small changes in land or sea levels can result in ecosystem and landscape changes equivalent to continental biome transitions (Table 2). In addition to hydraulically elevated sand, aeolian transport of sand inland from the beach may form dunes. It is 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 fresh water resource for terrestrial vegetation (Bolyard et al., 1979). The volume of this resource depends on the elevation of the land above sea and on local precipitation. Where the fresh water resource is large, forests with high leaf area index (LAI) may develop; where the resource is modest, lower LAI grasslands are common; and, where the land level approaches the high tide line and fresh water reserves are not present, infrequent tidal flooding combined with high evaporation rates may result in hypersaline salt flats or Salicornia virginica-dominated zones.

In addition to geophysical state variables giving rise to state changes, species extinctions and invasions have been equally important agents of state change during the present century at the VCR. In the 1930s, the lagoon-bottom eel grass became extinct and has not yet returned (Table 2). Cattle grazing, common on the VCR islands since the early 1700s, was ended by The Nature Conservancy in 1987. Local extinctions of maritime pines have also been recorded (Hayden et al., 1991). At a smaller scale and from a biogeographic perspective, extinctions, immigrations, and emigrations of small mammals have been documented (Dueser et al., 1976; Dueser and Brown, 1980; Forys 1990). The isolation of the landscape and its insular and patchy structure make these islands an outstanding laboratory for the analysis of the response of these phenomena to environmental trends and profound disturbances.

These considerations have led us to propose several new long-term experiments. The first involves direct manipulation of the pattern of inundation frequency and magnitude for large sections of two types of marsh (fringe and perched lagoon) using approaches appropriate for the marsh type to provide insight into the response of marshes to sea level rise. The second experiment employs a long-term manipulation of the unconfined freshwater lens on a coastal barrier island to study state changes arising from climatic change and to study ecosystem-level water relations. These experiments are designed to build on and to focus our earlier major research findings, and to emphasize the controlling factors of elevation and porewater salinity on alterations in ecosystem states at the VCR.

2.1.1 Ecological State Change

H.C. Cowles (1899) once characterized ecological succession as "a variable approaching a variable" indicating that internal ecosystem processes (the first "variable") interacted to produce structural dynamics that seem directed toward a configuration that changes with the environment (a moving target and the second "variable"). At the VCR, the transitions in ecosystem state can occur with exceptional abruptness. We envision the ecosystem dynamics at the VCR as having a tendency to be more-or-less self-ordering or successional within certain limits. Under certain classes of disturbance, systems are sufficiently displaced and their dynamics track a different target (Hayden et al., 1991) (Fig. 5). For example, islands with maritime forests, like the south end of Hog Island in the 1920s and Parramore Island today, experience forest die back following shoreline erosion and the loss of island elevation and sufficient freshwater reserves. Unless new island building takes place, a replacement forest will not result.

There are two elements to our theoretical conception of landscape dynamics on the VCR LTER. First, there are "attractors" in the ecosystem state space within which successional dynamics operate (Fig. 5). Second, there are events that produce transitions from one of these attractors to another. On the VCR LTER, one can see both successional dynamics within these ecosystem attractors and transitional dynamics between given ecosystem attractors. We need to note at this point that while observational records for the VCR fit a classic chaos-attractor paradigm for ecosystems, we are a long way from specifying a nonlinear numerical model of ecosystem attractor dynamics. In spite of this early stage in theoretical development, we are convinced the observational and multivariate definition of ecosystems attractors is possible in the sense of Allen et al. (1977), Birks and Berglund (1979), Lamb (1985), and Jacobson and Grimm (1986) (Fig. 6). Our theoretical concept of landscape dynamics (see Hayden et al., 1991 appendix) is based on general observations of the dynamics in reconstructions of landscape change over 1000s of years based on pollen records (Emory et al., 1967), from landscape reconstruction from 40 years of aerial photos (Dolan et al., 1979), and from historical accounts and survey maps (Rice et al., 1976). We infer such dynamics from field evidence on the VCR, for example, dead tree trunks in marshes, marsh peats on beach front. We feel that this class of dynamics, while frequent and dramatic, is not unique to our site and it seems relatively widespread in a range of ecosystems (Fig. 6). Although at the landscape level, these dynamics occur over time intervals that are not usually subject to direct observation or experimentation, at the VCR, these dynamics are rapid and accessible through long-term research studies of more reasonable duration.

In the 4.5 years since the inception of LTER-affiliated research at the VCR, we have learned much about the site that has enabled us to establish a system of measurement and monitoring procedures that will continue to yield baseline information on a long-term basis (see Section II.C, II.H., II.J.). Additionally, we have enhanced considerably our ability to handle remotely-sensed observations (see Section II.J.). For example, the extensive aerial photo archive for the VCR has been used to develop unique maps of vegetation dynamics, accurate to about 2 m, over areas exceeding a km2 and at decadal intervals for 50 years (Fig. 7). The presence of that system allows us to quantify responses to significant disturbances such as the Great Halloween Storm of 1991 (Dolan and Davis, 1992).

2.1.2 Statement of Research Focus: VCR LTER

The goal of the research program at the VCR is to understand the relationship between long-term, slowly changing physical forcing functions and rapid, short-term disturbances in triggering ecosystem state changes and alternate successional sequences. As described above, the dynamic nature of, and complexity of major landscape types within the VCR provides us with the unique opportunity to achieve such understanding. Our approach during the past 4.5 years has been to study the controls on succession within several of the dominant states (e.g. Myrica thickets and salt marshes) and the response of these states to disturbance. This is accomplished by research in the five LTER-Network core areas as well as additional VCR core areas examining states and state changes that have occurred at the VCR in geologic, historic, and present-day context. We will continue with this approach and will add manipulative experiments that will further our understanding of within-state ecological processes and controls, and the forces resulting in alteration of state. The following sections of the proposal describe the motivation and more specific approaches that will allow us to accomplish our goal by addressing the following working hypotheses:

1. The controls on succession within states are the availability of water, the salinity of that water, the frequency of tidal inundation, and sediment deposition.

2. Gradients in salinity and tidal inundation frequency and thus organic matter accumulation, primary productivity, and nutrients, are a function of the slope, sea level, and astronomical and storm tides.

3. Many ecological state changes are triggered by infrequent, short-duration, intense disturbances such as coastal storms.

2.2LTER CORE RESEARCH AREAS AT THE VCR

During the past 4.5 years, we have invested most of our efforts into the five core areas and in establishing a paleogeographic record of the barrier island lagoon complex, which has become an integral part of our core research. Our activities will continue to focus on identification of factors controlling the ecological processes within states and the interaction between the ecological and highly dynamic physical processes of the VCR. Conclusions motivating the proposed work and influencing the direction of core research are discussed in this section. Additional details of the past core research are found in the Prior Results Section and Section II.A, as well as a comparison of past and future work in the 5 areas. Modeling is also described in the Prior Results Section, Section I.F. and II.E.

Because the VCR is a large and complex landscape (Fig. 2 and Fig. 3), we have chosen to focus most of our core area research upon several sites where transitions between states are most likely to occur. To accomplish this most effectively and maximize interaction between researchers, we have divided our effort into three scientific working groups: the terrestrial group, the lagoon/marsh group, and the GIS/modeling group. The groups, their organization, and objectives are discussed in detail in Section II.A and II.I. Connection between the groups is maintained by a number of individuals who are members of more than one group and a few individuals who are members of all groups. This organization facilitates coordination and cooperation in our scientific effort across broad areas of research interests.

We have made excellent progress especially in the areas of primary productivity, organic matter accumulation, and disturbance. In the case of nutrients, we have identified key questions that will allow us to address the area of nutrient inputs and movements. Several new projects have recently been initiated that will increase our understanding of the trophic structure of the coastal lagoon system.

2.2.1 Core Research

Primary Production: From our work in Myrica thickets, salt marshes, and the water column, it is clear that, in spite of its abundance at the VCR, water and its movement exerts a major control on primary production throughout the coastal lagoon complex (Young et al., 1992 a,b). In the case of island vegetation, the combined effect of atmospheric humidity and soil moisture appears to be a central factor controlling production (Johnson and Young, 1992 a,b). In the marshes, evapotranspiration and infrequent tidal flooding combine to yield high salinity, and possibly high H2S concentrations, that appear to have a significant impact on net primary production and the allocation of photosynthate above- and below ground (Blum, 1992). In the case of phytoplankton and macroalgae, nutrient limitations do not seem to effect primary production. Possible mechanisms of control on water column productivity may include light limitation resulting from sediment resuspension from extensive shallow mud-flat areas or the effects of herbicides from the extensive agricultural areas on the mainland (MacMillin et al., 1992).

Trophic Structure: The VCR is characterized by great horizontal mobility and net transport of energy and organisms that make the trophic structure of the area more complex than is apparent at first glance. The islands are nutrient poor and are dominated by nitrogen-fixing associations of Myrica and Frankia (Young et al., 1992 a,b). The mainland is nutrient rich relative to the islands and is dominated by intensive agriculture, characterized by high rates of fertilizer and pesticide applications. Both the islands and the mainlands are fringed by marshes which filter and transform carbon and nutrients as they move from the uplands to the lagoon. In an effort to trace nutrient movements and food webs on a wide scale, we are using carbon, nitrogen and sulfur isotope-ratio analyses of organisms by trophic level and across an island to mainland transect. Detailed analysis of individual components of food webs include research on long-term small mammal population dynamics, island emigration/immigration studies using DNA techniques, bird nesting and seed dispersal analyses, and larval and juvenile fish utilization of salt marshes as nursery habitat.

Organic Matter Accumulation: A major focus of the research at the VCR is directed below ground. The balance between production and decomposition and the factors controlling these two processes are critical determinants in organic matter accumulation (Blum, 1992). Work in S. alterniflora-vegetated creekside and interior portions of the marshes suggest that organic matter accumulation in these areas is controlled to a large degree by the rate of organic matter production (Blum, 1992). In the Spartina marsh, decomposition does not appear to be affected by depth in the sediment nor by the hydrologic regime while in the Myrica tickets on Hog Island decomposition patterns appear to be related to the moisture content of the soil. The relative importance of the type of starting material (eg. S. alterniflora vs. J. roemerianus) and extremes of environmental conditions (i.e. xeric mainland soils compared to hydric marsh sediments) to organic matter accumulation is currently being investigated in addition to the importance of flooding frequency.

Nutrient Movements and Transformations: Qualitatively, nutrient transformations are probably not substantially different in the VCR than in other coastal lagoon landscapes; however, movement appears to be quite complex. Nutrient movement among landscape elements at the VCR occurs via groundwater transport and general circulation of lagoon water. Tidal head is hypothesized to partially govern the position, salinity, and movement of the groundwater of the barrier islands. We have initiated studies on atmospheric exchanges (precipitation and evapotranspiration) and tidal forcing (water table fluctuations) to understand the daily to seasonal controls of microenvironmental patterns that influence the availability of fresh and brackish water (as well as inorganic nutrients) to dune plants and barrier island fringe marsh vegetation. Standing stocks of nutrients have been assessed along the mainland to Hog Island transect, including surveys of marshes, marsh creeks, and lagoons. Inorganic nutrient standing stocks are generally much higher in mainland marsh creeks than in their island counterparts (10-fold and 3-fold larger for nitrogen and phosphorus, respectively). Data collection on atmospheric inputs of cations and anions on

Hog Island began in 1991 and a complete atmospheric input data set will begin in 1992. In addition, nitrogen mineralization measurements for soils in the Myrica thickets are currently being done on a monthly basis and the response of Myrica nodule nitrogen-fixation rates to salt stress are being measured in laboratory experiments. Nutrient transport and spatial and temporal variability of nutrients on Hog Island is a prime research priority and will be required prior to the drawdown experiments (see Section I.E.2.).

Disturbance: Understanding the role of disturbance in system dynamics is a critical part of our research program. It is our view that disturbance 1) is essential to the maintenance of system states, 2) regulates succession and 3) changes system states. Disturbance at the VCR occurs mainly in the form of coastal-storm related phenomena. Fluctuations are commonplace throughout the system, and include semi-diurnal tidal flooding, lower frequency flooding due to astronomical highs in the monthly tide cycles, and longer-term, more monotonic changes in sea level (Table 3). Overlain on these patterns are the aperiodic disturbances such as storm surge flooding, sediment deposition, erosion and fires that occur at the VCR. Although tropical storms are infrequent -- several landfalls per 100 yr (from our records which date back to 1650) -- the magnitude of disturbance is great. Overwash events occur on a more frequent basis (3-5 times per yr) than tropical storms and are related to the occurrence of "northeasters". Overwash events move tremendous volumes of sand and saltwater resulting in saline intrusions into freshwater stores on the islands. We have emplaced a major system of measurement stations that, coupled with appropriate aerial and satellite images, permits careful long-term monitoring of high frequency fluctuations and low frequency and aperiodic disturbance (see Section II.B. and Fig. 8). In addition to continued monitoring through and after disturbance events, supplemental information is often needed to determine the extent of disturbance (erosion, shore-line change, salinity changes etc.) and to establish new baselines for non-automatically-collected parameters. We have established an emergency plan to cope with the increased sampling and maintenance effort that might occur before, during and after a major disturbance (Fig. 9).

2.2.2VCR-Initiated "Core" Research Areas

2.2.2.1 Historical States Reconstruction

The Holocene evolution of the VCR lagoon floor is strongly governed by underlying Pleistocene landforms (Oertel et al., 1989 a,b) and is of ice age vintage rather than of Holocene origin as seen for example on the North Carolina Coast. The topography is an ancient one with only surficial or veneer of Holocene sediments. Consequently, the lagoons associated with each island in the VCR chain have unique "watersheds". The erosional drainage channels in each watershed extend offshore onto the continental shelf. The pre-lagoonal/estuarine watershed of Hog Island Bay is, at present, only partially mapped and will require data-based modeling to properly define the early lagoon structure and age. These models will be completed in the renewal period.

The historical record of VCR ecosystems is rich. The site was first occupied in the 1608 and by the 1680s the islands of the VCR were patented by the King of England for pasture and paddocks (Badger and Kellam, 1989). Grazing continued until the early 1980s. Formal settlements on the islands date from the late 1700s. None of those original settlements remain. Diary records of great storms and of land use in the early history are available. The period of more systematic record keeping dates from 1852 when the first metric map of the site was produced. A system-wide state change in landscape dynamics took place just prior to the turn of the century (Hayden et al., 1991). On Hog Island this change was manifested as a directional reversal of erosion and accretion patterns (Fig. 10). Substantial successional changes followed and continue to this day (Fig. 11). A second system-wide state change occurred in the 1930s with the extinction of the eel grass. With this extinction the bays of the VCR were transformed from a clear water, eel grass/scallop meadows to turbid water, mudflat communities. The lagoonal marshes of the VCR differ from many Atlantic Coast marshes in that the former are almost entirely "high" marsh with an abrupt escarpment where low marsh would typically be found. The perched lagoonal marshes have little relief and are dominated by short-form S. alterniflora and S. virginica with small or no zones of S. patens or Distichlis spicata. One hypothesis to explain the height of these marshes is that a significant redistribution of bottom sediments followed the eelgrass dieoff in the early 1930s. Several hurricanes in the mid-1930s played a part in the restructuring of the lagoonal marshes. This hypothesis will be tested as an alternative to the transgression-inundation model (Oertel, 1992 c). Numerous state changes of smaller geographic extent have also been identified. It is important that we determine the geographic extent and transition dates of ecosystem state changes within the historical period in order to specify their recurrence frequency in time as well as their spatial extent.

We propose to document the landscape state changes on the VCR. For the period prior to 1940 we will rely on local governmental records, the local historical society and a substantial photographic archive at the Library of Congress. For the post 1940 period, we will utilize GIS capability and our library of metric aerial photography to map all landscape changes. The dates on these state transitions across the VCR are critical to the development of succession models. New aerial photography will be used to map state changes associated with the Halloween storm of 1991.

Changes in the extent of the Myrica thickets on Hog Island during the period from 1974 to 1989 based on aerial photography show expansion of Myrica on the oceanside of the island while significant die-off is evident on the "back side" of the island (Fig. 12). A major focus of the terrestrial field work will be on the mechanisms associated with both the establishment and demise of Myrica thickets on barrier islands in recent decades, especially as related to ecological succession. The importance of symbiotic associations with the actinomycete, Frankia, for nitrogen fixation and with mycorrhizal fungi will be evaluated in the context of plant "performance" and potential for colonization. Concurrently, potential interactions with other woody and herbaceous species will be examined. The expansion and distribution of Myrica will be examined in light of the controlling biotic factors in addition to salinity pulses from storms and the depth to the freshwater lens.

Long-term studies will define the ecological impact of this abundant shrub on terrestrial process within the VCR. Our working hypothesis is that: Gaps created by disturbance or through disease influence the rate of successional transition from a Myrica thicket to a maritime forest. We will 1) create experimental gaps of varying sizes within Myrica thickets, 2) identify and age natural gaps using aerial photographs and field observations, 3) determine the principal causes of gap formation (i.e. meteorological events, disease, thicket age, fire, etc.), 4) characterize gap environments, including edaphic characteristics, relative to the thicket environment, 5) follow species recruitment and gap closure in artificial and natural gaps, 6) relate environmental preferences of gap colonizing species to gap environments, 7) determine the importance of Myrica thicket gaps to the rate and direction of terrestrial succession on the barrier islands.

2.2.2.2 Vertical and Horizontal Referencing: The Global Positioning System (GPS)

The VCR LTER is notably flat. Water depths over the extensive flats in the lagoons are typically less than 2 m at high tide, with deeper waters encountered only in the narrow tidal drains. The maximum elevation of the "uplands" is at about 10 m in the center of the mainland peninsula. However, to the east of the Mappsburg scarp (the unofficial western boundary of the VCR LTER), the elevation is always less than 2.5 m. The islands of the VCR LTER are similarly flat with maximal elevations of about 2.5 m. Hog island, one of the main terrestrial experimental sites has > 98% of its surface below 1.5 m of elevation Slopes of 0.1% or less are common throughout the lowlands. Even current sea level rises (3.8 mm/yr) would result in a landward migration of the inundation zone of 4 m/yr.

One of our central hypotheses is that major state changes occur as a result of changes in inundation frequency and duration. In order to deal with changes at the appropriate time/space intervals, it is essential to have the ability to survey accurately and precisely the relief of experimental sites and to monitor the entire area (x, y , and z coordinates). To accomplish the calibration of our surveys we are undertaking an intensive installation of benchmarks throughout the VCR LTER calibrated with the Trimble global positioning system. Placement of these benchmarks will allow us to measure very small changes in all directions over the next several years, and it will also allow us to index our existing coordinate system with the GPS coordinates. We also will add a laser theodolite to our equipment to improve future surveying efforts. All physical monitoring gear (tide gauges, groundwater wells, etc) will be indexed to the elevations and x-y positions obtained from the GPS. We see this activity as a major advance in our ability to test hypotheses related to state change. In this effort we are joined by other LTERs as a major network of GPS activity (see Section II.J.).

2.3 SYSTEM STATE DYNAMICS STUDIES

2.3.1 Island Morphodynamics

Sand elevation is a critical state variable on the VCR islands. We hypothesize the sand elevation determines fresh water reserves, the range of LAI supported and the type of vegetation possible on the islands. Island elevation may be either increased or decreased by the overwash process and may be subsequently elevated in localized areas by winds. The elevation to which overwashed beach sands can be piled on the island is dependent on the magnitude of the storms. During storms, beach sands are transported across the islands. Bay side marshes may be buried and transformed into grass and shrub lands. For example, under the south end of Parramore Island and Hog Island and under most of Smith, Wreck, and Ship Shoal Islands, a paleomarsh exists about one meter below the modern grassland. The deposition of sand by overwash and subsequent development of marshes on these surfaces is widespread along the VCR.

Documenting redistribution of the island sediments is part of our long term monitoring campaign. Preliminary analyses of island morphology following the Halloween Storm of 1991 indicate that storm magnitude plays a dominant role in the loci of beach sand deposition on the islands. Preliminary 1991 records also indicate that the rate at which the islands are transgressing landward, may in part, depend on whether the islands are perched on a paleomarsh or on old inlet or beach sediments. Our working hypothesis is that at the century time scale, islands with a paleomarsh below the island, transgress landward at a slower rate. This has the effect of permitting more time for storms to increase island elevation if sufficient sand is available locally (e.g., inlets and shoals) and thus indirectly increase freshwater reserves and the capacity to support a higher LAI vegetation. This model indicates that the probability of an island having a particular topography and vegetation are, in part, conditioned by pre-existing ecosystems (paleomarshes) on the time scale of decades and centuries. Where paleomarshes exist, a specific range of island ecosystem states in the decades and centuries ahead is possible. Along island reaches without subsurface paleomarshes, a different suite of island ecosystems results. We view the role of paleomarshes beneath the islands as a secondary, limiting condition on short-term dynamics but more important over the longer term. Accordingly, it becomes necessary to monitor and investigate the role of modern marsh fringe erosion and marsh peat-base loss as this is an important state variable governing ensembles of subsequent state changes. This new monitoring effort will begin with aerial photographic analyses using GIS technology. Eroding areas will be identified, erosion rates will be determined (1940-1970) and over the longer term (1852-1991) we will use historical ground surveys. Analysis of these century long records indicate that 16% of the VCR marshes have been eroded in the past 140 years (Knowlton, 1969). We do not know the specific geography of these losses at this point but it is important to chart this specific geography.

We also will utilize historical ground survey data as well as limited surface coring to better understand the dynamics of island rotation and the changes in the directions of island rotation. At our main site, Hog Island, island rotation direction changed just prior to the turn of the century (Fig. 13) and this has fundamentally changed potential ecosystem states and successional sequences. Recent work (Harris, 1992) indicates that Hog Island experienced similar reversals in the mid 1700s and early 1600s. To understand this phenomenon we need to document the physical changes in the other islands at the time of the Hog Island rotation reversal. Alternate hypotheses to explain island rotation include 1) regional readjustments in the sedimentary budget with the most likely candidate being the extension of Fisherman's Spit off Assateague Island prior to the turn of the century (Gawne, 1966; Dolan et al., 1979); 2) changes in local wave climate produced change in ebb and flood tide deltas; and 3) changes in the frequency of storms and the orientation of storm tracks along the mid-Atlantic coast sediment drift direction (Dolan et al., 1979).

Our proposed research program on island morphodynamics will thus be of four parts: monitoring and analysis of overwash deposits, retrospective monitoring of fringe marsh erosion and paleomarsh detection through surface coring, regional study of island rotation patterns using historical land surveys, and modeling of island dynamics.

2.3.2 Water, Nutrients and Shrub Savanna Dynamics.

The evergreen, actinorhizal shrub, M. cerifera is the dominant woody species on the islands. Dense thickets of the shrub can account for as much as 33% of the ground cover above the elevation of the tidal marshes. The leaves, bark, fruits and branches down to the fifth order are photosynthetic. Myrica is photosynthetically active the entire year. This photosynthetic potential and the N2-fixing actinorhizal association with Frankia, facilitate survival and rapid expansion on the nutrient-poor barrier islands.

Stomates of Myrica are sensitive to atmospheric humidity deficits (>1.5 kPa) and to mild water stress (<-0.8 MPa) and cannot tolerate extended droughts or elevated groundwater salinity. Small-scale distribution patterns are likely to be closely related to the depth to the freshwater lens within the soil. M. cerifera seldom occurs near the ocean, indicating a sensitivity to marine salt spray. Additional field work at three sites on Hog Island has focused on spatial variations in the "vigor" of Myrica thickets which differ in exposure to salinity (Fig. 14).

The sandy, nutrient poor soils of the barrier islands (Ehrenfeld, 1990) may impact species establishment. The establishment of Myrica thickets may be possible only because Myrica is capable of symbiotic nitrogen-fixation. Thereafter, other species may invade because of nitrogen enrichment in the soil (Vitousek et al., 1987). Our working hypotheses are that: There are threshold conditions (hydrology, nutrients, salinity, and redox potential) associated with the transitions to or from grass and shrub states; and, the vegetation itself may be more responsible for state transitions than abiotic factors or events. We have already discussed evidence that under drier conditions or higher salinity, the shrub state does not develop or is lost. Increases in nutrient levels shift the abundance and dominance of grass species and alter organic accumulation rates. We feel that the higher nitrogen concentrations on the older dunes are a result of N-rich litter input from the adjacent Myrica swales. Organic turnover rates vary in different ecosystem states and this may feedback to determine the nutrient status of the system. and thus the direction of future transitions. The changing nutrient status of the system will be reflected in different below ground "strategies" (root growth and distribution patterns) that also affect the direction of future transitions.

We will continue to investigate root elongation rates, root density, and vertical patterns of root distribution with permanently installed minirhizotrons (Brown and Upchurch, 1987). The questions related to below ground strategies can be directly approached without disturbing the soil environment. Organic matter decay will be monitored via long-term collection of root litter bags and wooden dowels. Cotton strips will periodically be buried and retrieved to facilitate cross site and temporal comparisons. Also, leaf litter bags will be used to address the question of nutrient origin in the different age dunes. Other monitoring will include production measurements of litter fall to address the question of nutrient origin. Abiotic monitoring will consist of quantifying soil nutrient levels, soil redox potential, salinity, and hydroperiod.

2.3.3 State Change in Flooding Basins

For regions subjected to tidal flooding, state change may arise in response to alteration of the inundation frequency. As sea level rises, some portions of the landscape will undergo tidal inundation for the first time while others will become permanently submerged. The low-lying areas of the VCR provide an excellent system in which to examine the relationship of inundation frequency to changes in ecosystem state occurring there. Over most of the VCR, inundation occurs within very shallow basins which often represent depressions or swales between ancient ridges of Pleistocene, Holocene, or even recent origin and vary in length (1-10 km) and width (0.5-2.0 km).

We hypothesize that the high marsh transition zones assume their landscape position through community responses to the pattern of inundation and porewater salinity that are ultimately controlled by slope. These transition zones are examples of what we have termed the "dynamic edge." (See Fig. 15 for an explanation of the dynamic edge concept and its application to the flooding basins of the VCR). The maintenance of elevation and hence horizontal position of a high marsh relative to the frequency of tidal inundation is based largely on organic matter accumulation. Biogenic accretion is, in turn, the net result of below ground primary production and decomposition. We also hypothesize that the position of maximal organic matter accumulation in the marsh-upland gradient occurs in the dynamic edge (Fig. 16). Historically, the dynamic edge exemplified by the high marsh has been defined by the vegetative community found there. At the VCR, the high marsh is comprised of communities containing short Spartina alterniflora, Spartina patens, Distichlis spicata, and/or Juncus roemerianus. As we develop more information, we may be able to refine the definition based on other properties (e.g., potential for biogenic accretion).

In the past, explanations of salt marsh and mangrove zonation have been based solely on soil salinity gradients (Chapman 1960). More recently, mid-littoral plant zonation is considered to be a response to the combined effect of several environmental factors. For example, Odum (1988) and Odum and Hoover (1987) pointed out the combined action of salts, sulfide, soil pore water movement, evaporation, tidal inundation, and interspecific competition. In many cases, salinity is both a limiting factor and a correlate of other important environmental parameters.

Sites flooded frequently will present soil salinity concentrations similar to those of the flooding waters because of intensive leaching, while upper mid-littoral sites flooded only by spring tides, may have either high or low soil water salinities (Oliver, 1982, Mitsch and Gosslink, 1986). In regions with a dry season, the water of the flooding tide will be exposed to increasing evaporation, which over a long term will lead to a soil salinity build-up through rainfall leaching (MacNae, 1967, Spenceley, 1976, Walter, 1977, Hutchings and Saenger, 1987). However, this does not occur at the VCR. Work in progress at the VCR has resulted in an alternate hypothesis that the slope of the upper mid-littoral zone, should be added to the existing conceptual framework of flooding, frequency, climate, and upland seepage to explain the geography of hypersaline ecosystems. Sites with a steep slope, even in areas under dry climates, would not develop hypersalinity because of enhanced draining of the seawater brought in by the tides, preventing the exposure of stagnant water to evaporation, whereas the shallow slope would enhance salt water retention and salinity build-up even in areas of higher rainfall. Further development of this conceptual model to a dynamic model will be continued in the future, as will be associated field and experimental studies.

Although state changes are generally of predictable direction in response to sea level change, such trajectories can be rapidly altered by disturbance. Plant zone transitions of concern include those at the ecosystem level between the high marsh and upland or low marsh, and those at the community level between different plant species groupings. In response to long-term changes in sea level, transitions occur slowly through the invasion of one state into another. Transitions, however, may occur rapidly in response to changes in the flooding pattern and salinity brought about by man or from disturbances associated with major storms. Such disturbances may involve changes in elevation associated with overwash or erosion. These impact on the flooding pattern. Also, high tides may transport salt into the uplands which may stress vegetation and allow subsequent invasion of a marsh. Subsequent high tides may transport and deposit wrack which can smother plants and alter or reinitiate a successional sequence.

We will monitor plant transitions within the high marsh and along the gradient through the upland, high marsh, and low marsh for changes in species composition and abundance, primary production (above and below ground), decomposition and other properties of potential significance (Fig. 16) to test the dynamic edge hypothesis. In addition, we will evaluate the responses of these factors in the context of long-term, large-scale experiments designed to modify the pattern of inundation or salinity regime (see Section I.E.1.). In the event of a major storm or other perturbation that could affect the high marsh or one of its transitions, we will respond with appropriate sampling.

We have begun preliminary studies using nondestructive procedures to examine ground cover changes within decimeter scale at transitions between community type. We will expand these to a broader range of sites. Ecosystem transitions between low and high marsh and between high marsh and upland will involve a combination of remote sensing and transects designed to observe change at the decimeter scale. Net primary production will be evaluated as change in above ground standing crop (Turner, 1976) and below ground processes (root production and decomposition) using methods reported by Blum (1992). Nutrient analyses will periodically be made to obtain information on N and P (Chambers and Odum, 1990). Below ground decomposition measurements will be augmented by measurements of macroorganic matter loss in clipped and pruned plots where appropriate (Christian et al., 1978). Preliminary studies on the efficacy of this approach are underway. The quality of decaying substrate will be assessed through the measurements of C and N percentages, their ratios, and lignocellulose and lignin percentages. These methods are in use and preliminary studies are underway.

Frequency, duration and depth of flooding will be monitored at selected locations by an array of water level recorders. Salinity will be monitored in permanent wells also strategically placed though the marshes and surrounding ecosystems. Water samples from these wells will periodically be analyzed for sulfate to chloride to index sulfate reduction and pore water turnover time. Redox potential measurements will take place as necessary.

2.4 SYSTEM SUCCESSION DYNAMICS

During the first five years of the VCR project, we installed a continuous vegetation/environment monitoring system on Hog Island (Fig. 17). This system is designed to provide a regularly resurveyed base for determination of change on Hog Island, for characterizing the dynamics of the fresh water lens on the island, for calibration of remote sensing of the vegetation, and for model parameterization. We can also use parts of the transect grids as experimental units (Fig. 17). Having characterized the vegetation pattern on Hog Island, we intend to also inspect processes that are involved in the successional dynamics of the island.

Over time, terrestrial succession on a stable barrier island will progress from a grass dominated community, to a Myrica thicket and eventually to a maritime forest. After establishment, Myrica species form dense thickets in island swales, often encroaching on the adjacent dunes. Given sufficient time and a well-developed fresh-water reserve, thickets will be replaced by a maritime forest. This change is a function of the recruitment of species to the island and to a favorable microsite.

Myrica dominance on Atlantic barrier islands is related to rapid growth characteristics (Young, 1992) but may also be due to a lack of biotic interaction, ie. competition. The successional replacement of Myrica, or the breakup of extensive Myrica thickets, is related to the abundance of both competitor and replacement species. The rate of change is, therefore, related to the rate of recruitment. Our working hypothesis is: Successional changes in terrestrial island communities are at least partially controlled by the parallel development of edaphic factors, especially soil nutrient reserves. We will investigate this hypothesis using control and treatment plots on dunes and swales of varying ages across the island, using slow-release fertilizer in N, N and P, and P, treatments and monitoring primary production (above and below ground), relative abundance and species composition through time, plant nutrient levels, soil nutrient availability and changes in edaphic factors (ie. organic matter content, bulk density, water holding capacity, etc.).

Myrica thicket density and an associated high leaf area index, as well as heavy leaf litter, produce a homogeneous environment at the soil surface that is unfavorable for recruitment. Thicket gaps enhance environmental variability and create a diversity of microsites for the establishment of other woody species. After establishment, these species may out compete Myrica and succession will rapidly proceed to a maritime forest.

We hypothesize that: The rate of successional transition from a Myrica thicket to a maritime forest is a function of the rate of island species recruitment and biotic interactions with Myrica. To investigate this hypothesis, we will identify an age series of Myrica thickets and establish permanent plots in each; follow changes in thicket characteristics (i.e. production, age structure, mortality, gap size, and frequency, etc.) and recruitment of other woody species; monitor the growth and survival of planted seedlings of potential competitors (eg. vines) and replacement species (i.e. maritime hardwoods) within thickets, at the edge of thickets and in thicket gaps (artificial and natural); and relate natural spatial and temporal variations in thicket characteristics to thicket dynamics.

2.5 LONG-TERM EXPERIMENTS IN ALTERING SYSTEM STATES

2.5.1 Inundation Frequency-Caused State Changes

Although examination of a large number of marshes for plant zone transitions with elevation within the VCR can provide evidence in support of the inundation frequency hypothesis for ecosystem state change (see section I.C.3) such surveys do not constitute experiments. Because the hypothesis of inundation frequency control (see hypothesis p. 20) on state transitions is central to our understanding of the effect of sea level rise on marshes, we propose long-term manipulations of sea-level in two types of marshes. One approach will be to alter the frequency and magnitude of flooding utilizing manipulated and control flumes in a portion of one of the transition zones centered in a marsh with a well-defined gradient from mudflat to upland (i.e. a fringe marsh). The other approach will be to lower the elevation of a section of a "perched" lagoon marsh thus increasing the frequency and magnitude of flooding.

Fringe Marsh: The goal of this experiment is to simulate elevational changes of sea level in a fringe marsh (see definition p. 14) without altering the history of biogenesis within the marsh (i.e. not depositing large amounts of new sediment on the surface of the marsh). To accomplish this, a flume will be constructed on the marsh surface orientated in the direction of the tidal head gradient with plant zonation following associations of species (highest to lowest elevation) 1). S. patens, Distichlis, Iva; 2) S. patens, Distichlis; 3) Juncus; and 4) Distichlis, S. alterniflora. We will initiate the flume experiment early in the funding period with preliminary site work in the summer and fall of 1992 and installation in the spring of 1993. We will allow the site to recover from the installation and to equilibrate during the 1993 growing season. Manipulation of the flooding regime will begin in the early Spring of 1994. The experiment will focus on the high marsh where we increase the frequency of flooding two-fold. Preliminary survey work has been done in Phillips Creek marsh (Barr, 1989; Ray, 1989) which was a slope of 0.2% and plant zone transitions have been mapped. Based on these observations we believe it that a flume 100 m long should be adequate to encompass several plant zone transitions. More detailed studies will be necessary to set flume size limits based on the characteristics of the specific marsh selected for studied. We believe that altering the inundation frequency of a section of the high marsh may will result in increased primary productivity, altered allocation of photosynthate to the above- and below-gorund portions of the plants, and changes in the composition of the plant community. Routine measurements (frequency to be determined) in the flumes will include community composition, above and below ground primary production, organic matter accumulation/disappearance, sediment physical/chemical properties. Comparisons with unaltered high marsh areas and control flumes will also be made.

Perched Marsh: We propose to manipulate land levels along the margins of perched salt marshes (see definition p. 14) to artificially bring about local increases in relative sea level. Because the land levels of the VCR lagoon marshes are significantly higher than other marshes along the US east coast and because these a marshes have low productivity, we hypothesize that modest accelerated sea level rises will result in increased Spartina biomass and productivity. At rates of sea level rise at the high end of projections, productivity will initially rise and then fall as submergence exceeds a critical threshold.

Land level manipulations will be accomplished using a modified commercial chain saw as a horizontal "ditch-witch" to remove a layer in the sedimentary column just below root base of a marsh cross-section. The marsh section will then be collapsed. The result is a lowering of the marsh surface in the water column affecting a change in relative sea level rise. Two adjustment scenarios are planned: shock and transient. In the shock sedimentary column adjustment, one to four blade widths will be removed in 1992 and the sites will be monitored yearly for the following 5 years. In the transient adjustment scheme one blade width will be removed from the sedimentary column at a fixed calendar schedule: twice a year, once a year and once every other year. Preliminary experiments in which small slumped edges (change in elevation of 10 - 30 cm) were created resulted in a change of S. alterniflora from short to intermediate growth form. Above ground marsh productivity (Morris 1990) and peak standing crop will be monitored yearly and total biomass (above and below ground) will be measured every second year. Secondary production will be monitored as well. We hypothesize that secondary production will also increase with increasing relative sea level rise. Specifically we expect increases in juvenile fish and crustacean utilization of the treated sites, resulting in increased secondary productivity. Sedimentation will also be monitored.

All marsh level manipulations will be performed along the edges of mid-lagoon marshes. Each manipulation will result in the lowering of the four square meters of marsh surface and will be paired with an adjacent control surface of the same size. Each treatment will have 5 replicates.

2.5.2 State Variable Trend -- Draw Down Experiment.

The terrestrial surface of the VCR is a mosaic of discrete patches, with abrupt edges between communities that are dominated by different growth forms.

A well-developed dune-swale unit exhibits segregated growth forms (i.e. grass-dominated ridge vs shrub-dominate swale) related to water availability. Recent ecophysiological work (Young, 1992) has demonstrated that the dominate shrub on the islands, Myrica, occurs in close proximity to ground water reserves (i.e. swales) because of drought sensitivity. Reducing the size of the confined fresh water lens by pumping should lead to drought stress, reduced production, and increased mortality. By comparison, the addition of water to the more xeric grass-dominated dunes should enhance water availability and lead to successful establishment by Myrica and other woody species. Through time, the edge or ecotone between the two communities will change in response to the manipulation of the fresh water lens.

Our experimental hypotheses include: 1) characteristics of the confined fresh water lens control the well-defined boundary between grass-dominated dune communities and shrub thickets, and 2) differential responses to changes in water availability will lead to shifts in species composition and growth from through time. Experiment objectives are to determine the variability and extent of root absorption for principal species, reduce fresh water availability (via pumping) to below the zone of root absorption at a shrub-dominated site, increase fresh water availability by addition of water (from shrub site) at a grass-dominated site, determine seasonal water relations and production responses of principal species relative to control sites and follow changes in species composition and abundance through time.

Preliminary work will need to address the location for the experiment, the spatial scale of the treatment effects, and appropriate control plots. It is likely that we will utilize a randomized block design with the nutrient enrichment experiments with Myrica nested within. Technical considerations that will need to be addressed include the pumping system, pumping times (continuous or at "critical times" such as the growing season), and a water redistribution system. Much of the necessary information regarding the feasibility of this experiment will come from a similar experiment that is currently being conducted by the National Park Service (NPS) on the North Carolina coast. The purpose of the NPS experiment is to examine the affects of utilizing the fresh water lens on a large barrier island for a residential water supply.

2.6 MODELING ECOSYSTEM STATES, STATE CHANGES, AND DISTURBANCES

The current modeling efforts for the VCR arise from our interest in bringing a diverse array of modeling approaches (state variable change models, disturbance frequency models, material flux models and sediment dynamics models) to bear on the central problem of understanding state change and dynamics on the VCR LTER.

2.6.1 Ecosystem State Models.

Individual-based models of ecosystem state (Huston et al., 1988) have been developed to simulate succession to a quasi-equilibrium or steady ecosystem state for the VCR LTER and the Luquillo LTER (respectively, Bonan and Hayden, 1990; O'Brien et al., 1992) and are under development for a network of LTER sites (Shugart et al., 1991 a, 1992 a; Smith et al., 1992 a,b). A new model of this type will be developed for the island pine forests of the VCR. This model will emphasize water balance and will be controlled, in part, by the "natural lysimeter" aspect of the VCR islands. Unlike most terrestrial systems, the VCR islands are isolated, almost hydroponic systems. The fresh water reserves are perched on a saline, sand matrix limited horizontally by the ocean and the lagoon. Fresh water input is only from rainwater and runoff is a very small fraction of input rainwater. The size of the reservoir is determined by island topography (Strack, 1971; Noest, 1991; Bolyard et al., 1979). Loss of fresh water is predominantly by evapotranspiration and by evaporation from small ponds. Maximum LAI and life form vary with rainfall input and island topography (Eagleson, 1982, Woodward, 1987).

We will develop a FORET type model (Shugart, 1984) of island vegetation "perched" on a barrier island "lysimeter". The model will be used to analyze ecosystem changes due to coastal storms and overwash of sand (changes in island elevation) and to changes in island width (shoreline erosion due to storms and shoreline erosion due to sea level rise). The proposed model will permit the direct inclusion of critical climate change variables (storm frequency and sea level rise) into the FORET model genre' of models. Because models of this type have been developed or are under development for all of the forested LTER sites (often in corporation with the modeling group at the VCR LTER), the development of this model for our site will also promote a wide array of LTER intersite comparisons.

Historical evidence indicates that changes in the freshwater reservoir of Hog Island in the 1930's were associated with drastic change in maximum leaf area index (LAI). We will test the feasibility of Woodward's (1987) LAI-evapotranspiration hypothesis using the Penman-Monteith (Campbell, 1977) equation to solve for the leaf area that optimally uses the available water for the island (the LEAF model). The island to the north of Hog Island, Parramore Island, is poised to go though large changes in its sand mass and freshwater supply as a result of the current rate of sea level rise. For Parramore Island, simulations from the LEAF model will provide predictions that can be tested directly against data we will obtain over the coming 6 years and, significantly, against the results of our drawdown experiment.

I.F.2. Threshold State Variable Change Models.

A key tenet of the VCR research program is that when certain ecosystem state variables exceed thresholds, the state of the system and the ends of succession are fundamentally changed (Hayden et al., 1991). We further envision that both geophysical and biological state variables, when thresholds are exceeded, give rise to a state change. In the model developed for Hog Island by Rastetter (1991), a species' extinction at a specified time in model years can give rise to a new island state (Fig. 18). Rastetter's model ISLAND is a Markov model of vegetation on cellularized transects across an island with a specified topography controlled by ocean delivery of sand and trapping of sand by plants (see also Noest, 1991).

We will determine temporal transition probabilities for ISLAND using a series of aerial photographs, flown at 5 year intervals, that can be resolved using our GIS facilities at a spatial resolution of 2 m. This data base will permit an estimate of the spatial variability of transition probabilities of ISLAND on a transect specific basis. The geophysical details to run ISLAND are available at 50 m intervals along Hog Island. The output of ISLAND, when parameterized in this way, will be interfaced through ARCINFO to make ISLAND a spatially explicit, three dimensional landscape model. This will allow testing system state changes due to extinction and invasion at local and island-wide spatial scales. In addition, geophysical state changes arising from changes in shoreline erosion, storm frequency, overwash frequency and relative sea level rate rise changes can be studied using a common dynamic structure.

We will also develop an ISLANDII model of the dynamic interactions of grasses, shrubs and trees in an individual-based simulator framework. This model has several implications for a wide variety of mixed life form systems (see Wu et al., 1985; Sharpe et al., 1985, 1986 for related approach). Under other funding, one of us (Shugart) is involved directly with an effort to compare similarly derived models at several LTER sites. We have also been designated as coordinators of an international effort to develop mixed-life form simulators (such as the modified ISLANDII model) for savanna ecosystems. The modeling group (Jean-Claude Menaut, France and the Ivory Coast; Ian Noble, Dean Graetz, and Brian Walker, Australia; Oswaldo Sala, Argentina; Peter Frost, Zimbabwe; Bob Skole, South Africa) will meet at the VCR LTER in May

1992 to initiate the development of a shared mixed-life-form model for global applications. Our most likely role will be to lead in water/plant interaction simulation, project coordination, and development of the central competition program. Our contribution will pivot on the ISLANDII model.

I.F.3. Disturbance Frequency Models

Fahrig (1990 a,b) determined that Markov transition probabilities for occurrence of Hog Island plants were strongly dependent on: (1) their proximity to and variabilty of the shoreline and (2) to the variability in the proximity to the inland limit of penetration of overwashed beach sand. These measures of island variability are available at 50 m intervals along the 8 kilometers of Hog Island. Additionally, we know that the variations in the position of the shoreline and the overwash penetration limit are related to the frequency of coastal storms for which we have a 100 year record (Hayden, 1981). Accordingly, statistical-dynamical models coupling disturbance frequency to vegetation change have been developed (Fahrig, 1990a; Fahrig et al., 1992). Recently, we have developed a statistical simulation model for both the shoreline variability and overwash penetration limit variability. With these models defining the quasi-equilibrium of island geomorphology for the period 1941-1977 and using Fahrig's transition probabilities for the same period, we propose use the model to produce the null statistics against which possible state changes in the post 1977 period can be measured, i.e. do they depart from the null statistics model that is beyond a definable chance probability. We have also used Fahrig's model to compare the disturbance response of vegetation at the VCR LTER with that at the CPR LTER (Fahrig et al., 1992). We hope to repeat this investigation at other LTER sites with well characterized disturbance regimes.

We are convinced that through detailed modeling of disturbance dynamics we can distinguish successional changes from state changes if sufficient long term ecosystem records are available. For example, we have used Fahrig's model without the vegetation response, i.e. the straight geophysical model, to determine that the state changes in the direction of rotation of Hog Island that took place around the turn of the century are unlikely to have occurred by chance, alone (alpha = .02). We concluded that the loss of forests on the south end of Hog Island with no regeneration over the past 60 years was a system state change brought about by a reversal in the erosion/accretion direction of the Island (Hayden et al., 1991).

I.F.4. Material Flux Models

Below-ground organic matter is particularly important in marshes because it is largest component of net primary production (based on root/shoot measurements, Gallagher, 1974; Stroud, 1976; Good and Frasco, 1979; Valiela et al., 1976; Stout, 1978) and because it has a volume equivalent to that of the mineral matter in most marsh soils (DeLaune and Patrick, 1980). Organic matter is also important to soil diagenesis (Howarth and Teal, 1980; Teal, 1962), response to sea level change (DeLaune and Patrick, 1980), and succession in marshes (Gray and Bunce, 1972). Because the organic matter dynamics are so important in marsh systems, we developed a marsh organic matter model as a tool for synthesis and a guide for determining research priorities in our marsh research. The model focused on the dynamics of net primary production, turnover, and decomposition of belowground structural material (i.e. the materials with the greatest potential for long term storage as sedimentary organic matter). We specifically focused on developing a model to estimate the sources of bias in estimation of net below-ground production and in interactions between timing of root growth, translocation of photosynthate, and decomposition of dead material.

The model simulates production/turnover and decomposition dynamics of structural carbon in marshes (Fig. 19), and ignores other critical but difficult to estimate aspects of the carbon budget such as respiration and root exudates. We hypothesized that these fluxes impact less directly on dynamics of the structural pool of carbon. This provided reasonable simplification of model structure necessary to proceed.

The model has served as a data source (based on South Carolina and Georgia data for parametrization) for investigating sensitivities of harvest method to sample frequency and to the shapes of production and death functions and translocation dynamics. The model is a differential equation model that evolved from experimentalists who work on marshes interacting directly with project modelers to produce a working research product. Such model exercises are a continuing endeavor in the group. We will continue to generate such working models as a guide to the priorities for research as the project continues into the second renewal.

I.F.5. Sediment Deposition Model for Marsh Surfaces.

We will develop a model of sediment deposition on marsh surfaces that will provide quantitative relationships between flow events (storms) of various magnitudes and frequencies and the resultant sediment deposits/accumulations including thickness and spatial distribution of grain sizes. We have added a co-PI (Wiberg) with the ability to develop this rather demanding type of model. The model will consist of three linked models for flow and sediment dynamics in an intertidal marsh environment. The first model will describe sediment deposition from a flow over a vegetated marsh surface. This depositional model will be linked to a second model that will provide initial flow and sediment conditions for the marsh deposition model. This second model will be an out-growth of a model already under development from funding from the Office of Naval Research. The third component model would simulate the combined channel and flood plain flow (e.g. Knight and Demetriou, 1983). The conjunction of the three model will provide an integrated view of flow and sediment dynamics for the VCR LTER marsh systems.

The component models, particularly the deposition model and the resuspension model, will be tested against field and laboratory data. There are some data available on flow over vegetated surfaces (Pasche and Rouve, 1985; Kadlec, 1980; Smith et al., 1990). The research work of one of the graduate students working on the project, Ms. Kastler, involves measurement of sediment accumulation over various time scales will provide valuable local measurements for comparison. Further verification can be obtained using the flume in the Department of Environmental Sciences for marsh surfaces.

By combining the proposed modeling with the historical frequency and magnitude of storm events, it will be possible to estimate the likelihood of depositional events of particular magnitudes.

3

4 TECHNICAL/ADMINISTRATIVE PROPOSAL

4.1 THE FIVE CORE AREAS

Three working groups have been established to maximize our research effort: the terrestrial team, the lagoon/marsh team, and the GIS/modeling team (see section II.I, Fig. 24 scientific organization of groups and Appendix copy of blue book pages). Each of the working groups meets individually at least once a year for a day-long workshop and all of the working groups meet together annually for a several day workshop. This organization allows us to understand better the details of major state changes caused by the interaction of climate change, sea level rise, storms, ecological succession, and human activities, and it serves to facilitate coordination and cooperation across the broad areas represented by the groups.

The working groups have and will continue to contribute to the core research program in each of the system states studied (Table 4). The goal of each of the working groups is to identify and understand the mechanisms controlling primary production, trophic structure, organic matter and sediment accumulation, and nutrient inputs, transformations, and movements in a highly dynamic environment. Distrubance, the fifth LTER core area, is a major component of the VCR LTER's central focus in understanding state change and the conditions that produce state change. Thus, each of the first four core areas is examined from the prespective of disturbance. Because physical disturbances occur fairly regularly in the form of northeasters and tropical storms, we have added additional core areas of research to our program at the VCR including: shoreline change, storm tracks, storm magnitude and intensity, overwash sediment erosion/depostion patterns, and extensive GIS/ARCINFO analyses of landscape change over much of the VCR.

Much of the data collected in the core research areas contribute to our long-term data base, but also allow us to address fundamental scientific questions in our individual areas of expertise.

4.2 LONG-TERM EXPERIMENTS

As part of our scientific proposal (I.E.1 and I.E.2) we propose two major experimental manipulations, one that will examine inundation frequency-caused state changes in two types of marshes and another that will demonstrate the effect of altering the groundwater reserves on Myrica thickets. These experiments will be implimented over the course of the next six years. Both experiments will require substantial preliminary work to determine, for the marsh experiments, suitable locations and site characterizations and, for the groundwater experiment, feasibility studies. We plan to maintain these experiments for a minimum of five years from the time that they are put in place. The data that we will gather during the course of these experiments will make a substantial contribution to our understanding of the effect of climate change (rising sea level and changes in precipitation) on ecosystem states.

4.3 LONG-TERM DATA SETS

During its first 4.5 years the VCR LTER has collected a large number of "baseline" data sets and established or extended many long-term data sets. Both baseline data and long-term data sets are stored in the VCR LTER database. Baseline data sets come from intensive measurements of ecological parameters with slow rates of change at specific locations. Although such data are not part of a long-term sampling program, they are indexed by location and time and archived so that they can form the basis of very long-term data sets with resampling intervals on the order of decades. Because they are not strictly long-term data sets, baseline data sets are not listed here.

Long-term data sets include a periodic sampling component. As with the baseline data, they are geographically and temporally indexed. Long-term data sets archived in the VCR LTER database are listed below:

Meteorology - 17 weather variables have measured on an hourly basis at two weather stations conforming to LTER type III meteorological station standards. A third station was recently added. Data period: 6/88 - present. This extends data on precipitation from a nearby long-term station (Fort Monroe) from 1832 to the present.

Tides - Two tide gauges (one on Hog Island, one on the mainland) measure tidal height every 12 minutes. They were converted from analog (paper chart) to digital recorders to facilitate data access in 1990. Additional stations are planned. Data period: 6/88 - present.

Wells - 72 permanent ground-water wells are monitored on a weekly to quarterly basis (frequency of monitoring is dictated by occurrence of rainfall and inundation events). Measurements include the depth of the water table and its salinity. Data period 7/89 - present.

Cores - a program of vibracoring provides our longest data set, extending back into the Pleistocene. 29 cores have been completed. Period of data collection: 1988-present.

Permanent vegetation plots - Cover and biomass are measured in 23 replicated 5x5 m plots along transects 1 and 5 on Hog Island on a biannual basis. Data periods: 8/89 - present.

Productivity - Spartina alternaflora (the dominant species of marsh grass) productivity and biomass are monitored. Data period: 6/88 - present.

Bacteria - Microbial biomass, growth and activity are monitored monthly at 10 permanent stations from the mainland saltmarshes to Quimby Inlet at the north end of Hog Island. Data period: 6/88 - present.

OM survey - Soil and sediment organic matter content were measured in at least the top 10 cm across the ecosystem states in each major vegetation type between 1988 -1990. Locations will be resampled at least every 5 years.

Mammals - Semiannual censuses of small mammals are conducted on 4 transects on Hog Island. Data period: 8/88 - present. Extensive surveys of the small mammal faunas of the islands of the VCR were conducted in 1974-1977 and 1988-1989.

Birds - In conjunction with a consortium of other institutions and agencies, an annual breeding shorebird survey is conducted on all the islands of the VCR. This extends data available from the Virginia Department of Game and Inland Fisheries. Data period: 1975 - present.

Water Quality - Temperature, salinity, pH, light extinction, dissolved nutrient (NH_4, PO_4) and oxygen variables are monitored monthly on six mainland tidal creeks. Quarterly, continuous (every 5-30 minutes) measurements of temperature, salinity, pH and dissolved oxygen are made over a 2-5 day period using Hydrolab units. Data period: 1/91 - present.

Aerial Photographs - In cooperation with the National Park Service, and the National Aeronautics and Space Administration 6 new flights, covering all of the VCR (and some covering all of the Virginia portion of the Delmarva Peninsula) were conducted in 1988, 1989, 1990 and 1991. With cooperation of the UVA Science and Engineering Library we obtained 11 color SPOT satellite images of Virginia for the year 1989, two of which cover the VCR south of Assateague. Through a cooperative agreement with the Nature Conservancy we obtained a Thematic Mapper satellite scene for 1989. Finally, in association with the LTER Network Office we obtained a panchromatic SPOT image and (pending) a Thematic Mapper image for 1991. This supplements our archive of historical photography which extends back to 1933 for some sites (see below for more details).

Storm Models - Storm wave hindcast and storm surge models are applied to significant storms along the mid-Atlantic coast as a routine matter. These analogs for the VCR are meshed with earlier work covering the period 1942 - 1990. Over that period nearly 1500 storms have been studied. This record of stormines in terms of frequency and magnitude is part of a longer record (1885 - 1990) on storm frequency alone) This work requires the standard National Weather Service data which are available in Charlottesville.

Additional long-term datasets are available from sources outside the VCR LTER. They were detailed in the 1986 VCR LTER proposal. These include the following databases available within UVA but not within the VCR LTER data management program: Coastal Erosion (30-year period), Coastal Storm Overwash Penetration (30-year period), Coastal Storms Data (1885-present), Coastal Wave Climate Data (1942-present), Coastal Storm Surge data (1899-1966), Weather and

Climate Records (compiled from 19 stations during the period 1836-present) and Historical Aerial Photography (239+ sets of overlapping, metric photography from over 100 photographic missions from 1933-present). Wave Gauge Data, Tide Gauge Data and Virginia Fisheries Statistics (1962-present) are available from Federal sources. Winter Waterfowl Surveys (1967-present) and Peregrine Falcon Data (1977-present) are available from Virginia state agencies.

4.4 DATA MANAGEMENT

The VCR LTER has established a centralized data management system, which is the responsibility of a full-time data manager and a student assistant. The data manager reports directly to the project PIs and heads a data management committee. Our data management philosophy has been that data management begins with project inception, not project completion, that principle investigators have primary responsibility for quality assurance, that data should be accessible by a wide variety of software packages, and that data management activities should not infringe on the rights of investigators to exploit the data they collect. A site data management policy has been formulated and implemented which is based on this philosophy while providing a general framework for quality assurance and data accessibility (Table 5).

The data management system has four general objectives. The first is to provide archival storage of data. To accomplish this objective, online copies of data files are backed-up on a variety of tape and optical media with at least one copy maintained off-site. Data is stored in a standard form (the American Standard Code for Information Interchange - ASCII) which is almost universally accessible by different software packages.

A second objective is to provide access to data by researchers while protecting the interests of PI's who initially collected the data. So far, much of the data has had security constraints associated with it, so access has been available only to the data management staff. However, as a greater proportion of the data becomes publicly available, we anticipate moving into the use of interactive data access systems and data publication. Use of data from the VCR LTER database (most requests have been for meteorological variables) has been made by The Nature Conservancy and the LTER Climate Committee.

A third objective is to provide a data catalog. This includes a centralized repository for documentation and keyword indices that facilitates automated searches. Development of the catalog entries begins with the initiation of each research project (Fig. 21). An initial project description and yearly progress reports form the basis of each entry. For individual data sets (a data set consists of observations containing a common set of variables), additional documentation describes the storage of the data and specific methodologies used in collecting it. Thus a hierarchical structure of documentation is formed (Fig. 22). The data catalog is maintained in digital form using a relational database program (currently DBASE IV).

The final objective is to facilitate linkages between data sets. To this end, we maintain a number of site-resource databases. These include a research location database (so that different datasets can use a common vocabulary of site names), master species lists (which define a unique 6 letter identifier for each species) and a database of GIS coverages. Standards are also imposed on the formats for temporal and spatial information that facilitate merging of different data sets.

4.5 SYNTHESIS AND MODELING

The VCR has an active program in theoretical studies and has produced synthesis articles in journals and in presentations at professional meetings and workshops. These activities are summarized below. We have been particularly active in developing and applying a diverse array of models to theoretical topics, cross-site synthesis, and global change. Our modeling group has had a traditional interest in the applications of individual-based simulation models for landscape-scale simulations and for understanding global responses of vegetation systems. We have directed considerable effort in diversifying our modeling approaches beyond these individual-based simulators, in part to better understand the role of these models in research, and to avoid being limited by a single paradigm in interpreting and synthesizing information developed at the VCR LTER site. This is evidenced in the publications produced by our group and listed below:

VCR LTER Modeling and Synthesis publications
(Full citations given in Bibliography A.)

Agren, G.I., R.E. McMurtrie, W.J. Parton, J. Pastor, and H.H. Shugart. 1991. State-of-the-art of models of production-decomposition in conifer and grassland ecosystems.

Antonovsky, M.Ja., F.S. Berezovskaya, G.P. Karev, A.Z. Shvidenko, and H.H. Shugart. 1991. Ecophysiological Models of Forest Stand Dynamics.

Bonan, G.B. and B.P. Hayden. 1989. Forest vegetation structure on the Eastern Shore of Virginia.

Bonan, G.B. and B.P. Hayden. 1989. Using a forest stand simulation model to examine the ecological and climatic significance of the late Quaternary pine-spruce pollen zone in eastern Virginia, USA.

Emanuel, W.R., I.C. Prentice, T.M. Smith, H.H. Shugart and A.M. Solomon. 1989. Models for analysis of vegetation responses to global environmental change.

Fahrig, L. 1988. Nature of ecological theories.

Fahrig, L. 1990. Interacting effects of disturbance and dispersal on individual selection and population stability. Fahrig, L. 1991. Simulation methods for developing general landscape-level hypotheses of single species dynamics.

Fahrig, L. 1990. Relative importance of spatial and temporal scales in a patchy environment.

Fahrig L., D. Coffin, W.H. Lauenroth and H.H. Shugart. The advantage of long-distance clonal spreading in highly disturbed habitats.

Franklin, J.F., H.H. Shugart and M.E. Harmon. 1987. Tree Death as an Ecological Process.

Friend, A.D., H.H. Shugart and S.W. Running. A physiology-based model of forest dynamics.

Hayden, B.P., R.D. Dueser, J.T. Callahan and H.H. Shugart. 1991. Long-term Research at the Virginia Coast Reserve.

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Odum, W.E. and B.P. Hayden. 1991. Virginia Coast Reserve.

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Shugart, H.H.. 1987. The Dynamic Ecosystem Consequences of Coupling Birth and Death Processes in Trees.

Shugart, H.H. 1990. Ecological models and the ecotone.

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Shugart, H.H., G.B. Bonan and E.B. Rastetter. 1988. Niche theory and community organization.

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Smith, T.M., H.H. Shugart, F.I. Woodward, P.J. Burton. 1992. Plant Functional Types.

Solomon, A.M. and H.H. Shugart 1992. Vegetation Dynamics and Global Change.

Urban, D.L., G.B. Bonan, T.M. Smith and H.H. Shugart. 1991. Spatial applications of gap models.

4.6 INTERSITE AND NETWORK ACTIVITIES

The scientists associated with the VCR are active in a number of different intersite and network activities including participation in intersite experiments, network workshops, presentations at the LTER All-Scientists Meeting, and network committees. In some cases, these activities have resulted in publications.

Examples of intersite and network experiments include Blum's participation in the LIDET experiment, Young's Myrica response to salt water intrusion at the VCR and NIN, and Blum's root production and decomposition work at the VCR and NIN. Blum and Sklar (NIN) have comparitive work on sediment deposition/erosion in salt marshes scheduled to begin in February, and Blum and Morris (NIN) plan to begin comparitive work on salinity effects on S. alterniflora allocation of photosynthate above- and below-ground. Zieman plans to extend his marsh creek comparison (accretional vs erosional) to North Inlet LTER this spring or summer.

The VCR is participating in the global positioning system (GPS) activities that NIN is coordinating with the east coast LTER's. The VCR GPS campaign began in January, 1992 with the participation of a nubmer of federal and Virginia agencies (see II.J.). We believe that the campaign planned by Carlson of the VCR will come to be seen as a model for other GPS campaigns.

4.6.1 INTERSITE ACTIVITIES

Intersite publications, presentations, and committee work are listed below.

Publications
(Full citations given in Bibliography A.)

O'Brien, S., B.P. Hayden and H.H. Shugart. 1992. Global Climate Change, Hurricanes and a Tropical Rain Forest. Climate Change. In press.

Presentations

Blum, L.K. 1991. Root dynamics in a mid-Atlantic salt marsh. North Inlet LTER.

Hayden, B.P. "ESA presentations with UVa student (Alan Yeakley) doing disseration at Coweta LTER: Bull Ecol. Soc. Amer. 71:376 and 72:297, and 1991 Amer. Meteor. Soc. Special Session on Hydrometeorology."

Other Activities

Dueser, R.D. "Vole Damage Recovery Tean" for Niwot Ridge-Green Lakes Valley LTER Site.

Fahrig, L. "Collaborative Research on Landscaape Disturbance, with M. Walker. Niwot Ridge-Green Lakes Valley LTER Site.

Hayden, B.P. "Provided Analysis of Desert Hydrocarbon Climate Inpacts for Sevilleta Mid-Term LTER Site Review.

4.6.2 NETWORK ACTIVITIES

Publications

(Full citations given in Bibliography A.)

Hayden, B.P. 1990. Climate Change and Ecosystem Dynamics at the Virginia Coast Reserve 18,000 BP During the Last Century, pp. 76-84. In, Climate Variability and Ecosystem Response. Southeastern Forest Experiment Station Gen. Tech. Report SE-65.

Hayden, B.P. 1992. William Eugene Odum: 1942-1991: A Tribute to the Late Virginia Coast Reserve LTER Principal Investigator. LTER Network News: Winter 1991/1992 Issue 10:2.

Hayden, B.P. 1989. Symposium on Climate Change and Long-Term Ecological Research Sites. Denver, CO.

Hayden, B.P. 1989. Global Climate Change and the Virginia Coast Reserve: Site Perspectives. Symposium on Climate Change and Long-Term Ecological Research Sites. Denver, Co., 27 pp.

Odum, W.E. and B.P. Hayden. 1991. Virginia Coast Reserve. In Long-Term Ecological Research in the United States. LTER Publication No. 11. Network Office, Seattle, Wa.

Presentations

Hayden, B.P. Global Warming: What All Scientists Should Know." Lecture at the All Scientists Meeting, Estes Park, CO.

Hayden, B.P. 8/88. Climate change and ecosystem dynamics at 18,000 BP and during the last century. Workshop on Climate Variability and Ecosystem Response. Niwot Ridge-Green Lakes Valley LTER Site, University of Colorado. Published as General Technical Report SE-65. U.S.D.A. Forest Service: Southeastern Forest Experiment Station.

Hayden, B.P. 8/89. MAB, LTER, and the Virginia Coast Reserve. AIBS Annual Meeting. IN Symposium and Workshop: Coastal Barrier Biosphere Reserve on the U.S. East Coast.

Hayden, B.P. 11/89. Global Climate Change and the Virginia Coast Reserve: Site Perspectives. Symposium on Clumate Change and Long-Term Ecological Research Sites.

Hayden, B.P. 11/89. Global Climate Change and the Virginia Coast Reserve: Site Capabilities. Symposium on Climate Change and Long-Term Ecological Research Sites.

Hayden, B.P. 11/89. Global Climate Change and the Virginia Coast Reserve: Network Interaction. Symposium on Climate Change and Long-Term Ecological Research Sites.

Committees

Blum, L.K.. 1990. Chaired Network Workshop in Belowground Dynamics. All Scientist Meeting. Estes Park, CO.

Hayden, B.P. NSF Ecosystems Advisory Panel; LTER Network Climate Committee; LTER Network Paleoecology Committee; LTER GCM Committee.

Hayden, B.P. LTER Climate Committee.

Hayden, B.P. Coordinating Committee (1991-1992) Planning group for LTER initiatives in paleoecology.

Hayden, B.P. LTER Network Working Group on Climate Change and Long-Term Ecological Research Sites.

Hayden, B.P. LTER Committee on GCM Use by Sites.

Hayden, B.P. LTER Network Bulletin Board on Climate/Ecosystem Dynamics.

Odum, W.E. NSF-LTER Review Panel; Advisory Committee. North Inlet LTER Program.

Porter, J.H. LTER Data Management Committee; LTER Wide Area Network Workshop on Weather Data.

Porter, J.H. NSF-LTER Connectivity Team

Porter, J.H. Managing Editor, "LTER DATABITS", a data management newsletter with network-wide distribution.

Porter, J.H. Planning Committee, data management workshop for biological field stations.

Shugart, H.H. United States Representative, Committee on Ecotones, Man and the Biosphere Program. UNESCO.

Shugart, H.H. Advisory Panel, El Verde Research Site, Luquillo Experimental Forest, Puerto Rico (1988 -).

Shugart, H.H. Advisory Panel, Bonanza Creek LTER Research Site, Fairbanks, Alaska, (1988 -).

Shugart, H.H. Steering Committee, National Science Foundation / Society for Conservation Biology Workshop on Priorities in Conservation Biology (January 11, 1988).

Shugart, H.H. Chairman, National Science Foundation's LTER Advisory Committee on Scientific and Technological Planning (1987, 1988).

Shugart, H.H. Member, Committee for the International Geosphere Biosphere Pilot Study on Data Bases, National Research Council, Commission of Physical Sciences, Mathematics, and Resources (1989-1991).

Shugart, H.H. Member, Science Advisory Committee, Climate Systems Modeling Project, University Corporation for Atmospheric Research (UCAR) and Joint Oceanographic Institutions (JOI).

Shugart, H.H. Member, Advisory Committee, Climate Systems Modeling Program, National Center for Atmospheric Research,

Shugart, H.H. International Geosphere/Biosphere Project (IGBP):
- Numerical Data Advisory Board, Member
- Global Change and Terrestrial Ecossytems CP4, Team Member
- NRC Committee on Global Change, Member
- Committee for the International Geosphere Biosphere Pilot Study on Data Bases, National Research Council, Commis sion of Physical Sciences, Mathematics, and Resources (1989-1991), Member.
- Global Change and Terrestrial Ecosystems (GCTE) Scientific Steering Committee, Member

Shugart, H.H. National Science Foundation Advisory Committee on Scientific and Technological Planning for Long-Term Ecological Projects, Member

Shugart, H.H. National Science Foundation, Alliance for Minority Participation, Invited Participant

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4.6.3 GLOBAL CHANGE ACTIVITIES

The VCR has an active program in global change studies and is affiliated with a global change center at the University of Virginia housed within the Department of Environmental Sciences. Synergism between the Center and the VCR LTER has resulted in numerous published articles, presentation at professional

meetings and contributions at climate change workshops. These activities are summarized below

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Publications
(Full citations given in Bibliography A.)

Emanuel, W.R., I.C. Prentice, T.M. Smith, H.H. Shugart, and A.M. Solomon. 1989. Models for Analysis of Vegetation Responses to Global Environmental Change.

Hayden, B.P. 1990. Climate Change and Ecosystem Dynamics at the Virginia Coast Reserve 18,000 BP During the Last Century, pp. 76-84. In Climate Variability and Ecosystem Response. Southeastern Forest Experiment Station Gen. Tech. Report SE-65.

Hayden, B.P. 1989. Symposium on Climate Change and Long-Term Ecological Research Sites. Denver, CO.

Hayden, B.P. 1989. Global Climate Change and the Virginia Coast Reserve: Site Perspectives. Symposium on Climate Change and Long-Term Ecological Research Sites. Denver, Co., 27 pp.

Ray, G.C., B.P. Hayden, J. McCormick-Ray and A. Bulger. 1992. Effects of Global Warming on Biodiversity of Coastal-Marine Zones.

Shugart, H.H. 1990. Using Ecosystem Models to Assess Potential Consequences of Global Climatic Change.

Shugart, H.H. 1990. Modeling Future Changes of Vegetation Succession.

Smith, T.M., H.H. Shugart, and G.B. Bonan. 1992. The Use of Models in Predicting Vegetation Response to Climate Change.

Presentations

Hayden, B.P. 1990. Storms, Waves and Climate Change in a Warming World. Symposium: Toward a Realistic View of Global Change - A Research Agenda. Pheonix, AZ.

Hayden, B.P. 1990. Global Warming: Coastal and Marine Implications. VIMS, Va.

Hayden, B.P. 1988. Climate Change and Ecosystem Dynamics at the Virginia Coast Reserve 18,000 BP During the Last Century, LTER Workshop on Climate Variability and Ecosystem Response. Niowot Ridge, CO.

Hayden, B.P. "Global Warming: What All Scientists Should Know". All Scientists Meeting of the Long-Term Research Consortium of the National Science Foundation, Estes Park, Co.

Hayden, B.P. "Global Warming: Coastal and Marine Implications". Virginia Institute of Marine Sciences, Gloucester Point, Va.

Ray, G.C., B.P Hayden, J. McCormick-Ray and A. Bulger. 1989. Effects of Global Warming on Biodiversity of Coastal-Marine Zones. Conference on Consequences of Greenhouse Effect for Biodiversity. Washington, DC.

Shugart, H.H. "Modeling Future Changes of Vegetation Succession". 1990 American Meteorological Society Symposium on Global Change Systems, Anaheim, CA.

Shugart, H.H. "Terrestrial Vegetation Response to Global Climate Change". 1990 Society of Automotive Engineers Government/Industry Meeting, EPA sponsored.

Shugart, H.H. "Modeling Forest Response to Climatic Change", TERRAVision Project, Battelle Northwest Laboratories.

Shugart, H.H. "Global Warming: How do we know?" Environment 2000: Issues and Questions, Francis Marion College.

Shugart, H.H. "Climate Change and Forest Dynamics". World Climate Conference, Geneva, Switzerland.

4.7 RELATED RESEARCH PROJECTS

The policy of the VCR LTER has been to encourage collaboration with non-UVa scientists. As a result of this policy, several of our initial collaborators (Brinson, Christian, Day, Kochel, and Young) have become important contributors to the LTER program. These people have been instrumental in the development and success of the VCR LTER during the past 4.5 years and have been closely involved in planning for the next 6 years. Their continued participation in this project is critical to the continued success of our program.

There are a number of research projects either completed or on-going at the VCR which have been awarded to active contributors to the VCR LTER and are supported by non-LTER sources. These include:

Blum (UVa)	NSF	$50,000.00
Blum and Mills (UVa)	NOAA	$60,000.00
Day (ODU)	NSF	$400,000.00
Dolan (UVa)	NOAA	$70,000.00

Dolan (UVa)	FEMA	$60,000.00
Dueser (USU)	Va Game Inland Fish	$22,000.00
Dueser (USU)	Wistar Institute	$50,000.00
Hayden (UVa)	NOAA	$105,000.00
Lagera (UVa)	VEE	$24,000.00
Porter (UVa)	TNC	$16,000.00
Young (VCU)	NSF	$50,000.00
Young (VCU)	Nat. Geog.Soc.	$18,000.00
Zieman (UVa)	MAB	$40,00.00

In addition there are number of scientists working at the VCR for which the LTER has provided some form of support from logistical to collecting specimans. These people include:

Dr. Iris Anderson -- microbial ecology, Virginia Institute of Marine Sciences, Glouchester.

Ms. Ruth Beck -- avian ecology, College of William and Mary, Williamsburg.

Dr. R. Michael Erwin -- fish biology, U.S. Fish and Wildlife Service, Patuxent.

Dr. James Galloway -- environmental chemisty, University of Virginia, Charlottesville.

Mr. James Hill -- avian ecology, Maryland Natural Heritage Program, Annapolis.

Dr. Hiro -- genetics, University of Virginia, Charlottesville.

Dr. Richard Mills -- insect ecology, Virginia Commonwealth University, Richmond.

Dr. Nancy Moncrief -- genetics, Virginia Museum of Natural History, Martinsburg.

Dr. George Simmons -- hydrology, Virginia Polytechnic Institute, Blacksburg.

Dr. Soneneshine -- epidemiology, Old Dominion University, Norfolk.

Dr. R. Wayne Tyndall -- coastal plant ecology, Maryland Natural Heritage Program, Annapolis.

Dr. Brian Watt -- avian ecology, College of William and Mary, Williamsburg.

Dr. Richard Wetzel -- estuarine ecology, Virginia Institute of Marine Sciences, Glouchester.

4.8 ARCHIVES AND INVENTORIES

The VCR LTER maintains a number of archives and inventories. Inventories perform two basic functions: to facilitate comparative research and to aid in coordinating extant research. Our research-site database fulfills both these functions. Maintained in a geographical information system, it provides researchers with instant access to information on sites used by present or past projects. Data on sites can be accessed based either on geographical or tabular (type of site, site name) referents. Additionally, it facilitates merging of disparate data sets by providing a vocabulary of common site names. Additional inventories include species lists for avian, mammalian and plant species indexed by island and year and the site bibliography, listing research publications of the VCR LTER.

Archives include an extensive inventory of aerial photography of the VCR site. It includes photos from hundreds of flight lines over the islands of the VCR from 1942 to the present. A detailed listing of in-house and external aerial photography was compiled in 1989. It includes over 70 sets of photography, each consisting of between two and 130 frames. Portions of the photographic archive have been transferred using an Eikonix high-resolution color scanner to digital form for use with remote-sensing systems. Archives of physical samples include an archive of vibracores from VCR islands and lagoons and a site herbarium.

4.9 LEADERSHIP, MANAGEMENT, AND ORGANIZATION

The VCR LTER is administered through the Department of Environmental Sciences of the University of Virginia. The organizational structure for management and administration and for scientific activities are summarized in Figures 23 and 24, respectively.

Herman Shugart, Bruce Hayden and Linda Blum are the principal investigators responsible for management, administration, and leadership of the VCR (Fig. 23). Shugart is the official correspondent with NSF, the landlord for the site (The Nature Conservency), the MAB program, and with federal agencies involved in joint ventures at the site. Blum is VCR LTER program coordinator and budget manager. Hayden coordinates LTER Network activities on behalf of the VCR. The P.I.s assess annual productivity of all investigators and encourages the investigators to maintain active publication and development of supplemental proposals to support research at the site.

The P.I.s also maintain a close alliance with the Center for Global Change at the University of Virginia with which there is considerable overlap in mission and interest. In addition, many of the princples of the VCR LTER are also part of the Center. We envision significant synergism in this area. In addition, Shugart and Hayden serve on the executive committee for the National Park Service global climate change program (Barrier Island Focus) which is an NPS cooperative unit at the University of Virginia Department of Environmental Sciences.

Our tripartite administrative structure evolved from two changes in administrative responsibility caused by the departure of Raymond Dueser from the University of Virginia (project P.I. during 1985-1989) and the subsequent death of William Odum (project P.I. during 1989-1991). We are acquainted with the difficulties of transfer of administrative and leadership responsibilities. We foresee no further changes in administrative personnel in the future, but the multi-individual structure now in place and working comfortably will insure a smooth transition should a change in individuals become necessary. Cooperative, multi-investigator projects are common in the Department of Environmental Sciences; shared leadership is a project management style with which we are both familiar and comfortable.

Responsibility for the overall VCR research direction is a collective activity. Following our mid-term site review we put in place a program of meetings to articulate better the focus our research program for the coming decade. The VCR renewal proposal is the significant end of that process. The articulation of our focus is also published in Hayden et al., (1991) and Odum and Hayden (1991). The realization of this research focus is achieved through the various sub-organizations of our scientific enterprise (Fig. 24). The research teams outlined in this figure are charged with crafting sub-programs under the common research objective. The lagoon/marsh team is chaired by Blum, the terrestrial team by Young, and the GIS/modeling group by Shugart.

The outside advisory panel includes five distinguished scientists representing disciplines important to the research program:

Dr. John C. Kraft
University of Delaware
Coastal Geology

Dr. Robert C. Harris
University of New Hampshire
Geochemistry

Dr. F. J. Vernberg
Baruch Institute
Estuarine Ecology

Dr. Thompson Webb, III
Brown University
Climatology

Dr. Richard G. Wiegert
University of Georgia
System Ecology

The advisory panel will be kept informed of research progress through annual reports and as invited participants in our annual research symposium held in the Fall of each year. In addition, we plan to have a major review by the committee one year before the NSF mid-term site review.

4.10 NEW PROJECTS AND TECHNOLOGIES

Our use of new technologies is centered in three areas: collection and manipulation of spatially-indexed data, electronic data acquisition systems and innovative approaches to data management. Collection of spatial data uses new technologies at several spatial scales. Remotely-sensed images, obtained from satellites (SPOT, TM, MSS, SAR), airborne scanners (TMS, AVRIS, SAR) and digitized aerial photographs, cover large areas at medium (30 m) to high (<1 m) resolution. ERDAS, GRASS and KHOROS software are used to manipulate this data to create thematic geographical information system (GIS) data layers. At a wide scale, global positioning system (GPS) units are used to obtain accurate geographical reference points (used to register remotely-sensed and manually collected data to a common spatial frame of reference) to a high degree (<5 cm) of resolution in three dimensions. On a local scale, state-of-the-art surveying equipment will be used to extend geographical and topographic controls established using GPS throughout areas of active research. Geographically-indexed data are manipulated using GIS programs (ARC/INFO, ERDAS, GRASS and UNIRAS) to test spatially explicit hypotheses and parameterize spatially-explicit models and display their output.

Electronic data acquisition systems are currently being used primarily to monitor physical processes (tides, weather) at a high level of temporal resolution. Data storage modules and real-time serial links are used for data storage and transfer. Initiation of active experimentation will require the development of additional automated systems, both for monitoring and for control of experimental systems. Portable tidal sensors (using a waterproof data logger in conjunction with a pressure transducer) will be used to densify our network of tidal monitoring stations. Multiplexed cableground-water sensors will allow us to provide real-time monitoring of subsurface water levels at over 50 locations and at 10 depths per location.

Application of new technology to data management takes the form of interactive data access systems and data publication. Currently the majority of research data sets are stored in an archival format on read-write optical or conventional magnetic disks. We are developing systems using sophisticated database and form management tools to facilitate interactive access to data over networks. We also will be actively pursuing data publication using high-capacity CD-ROM disks. Use of this technology will make it possible to make available large quantities of data (both conventional and image data) at a nominal cost to database users. Wide distribution in a widely available medium with excellent archival properties (estimated to be > 100 years) of data will act to safegard its availabilty to future researhers.

4.11 DISSEMINATION OF INFORMATION

The scientific findings derived from the proposed work will continue to be reported in peer-reviewed publications (see Bibliography A p. 52). We will continue to make presentations on our work at regional, national, international, and LTER-Network scientific meetings. The invstigators will also continue to participate in workshops and other scientific networks (see Section II.F.). We are frequently invited lectures at local citizens group meetings (especially on the Eastern Shore), at primary and secondary schools, and community colleges. Furthermore, we have established scientific and public service contacts with numerous Commonwealth and Federal agencies including the Va. Marine Resources Commision, Va. Environmental Endowment, Va.Hertitage Foundation, Va. Audobon Society, Va. Pesticide Board, Va. State Water Control Board. Va. Department of Transportation, NOAA, U.S. Fish and Wildlife Service, National Park Service, and Coast Guard. The public interest that the presence of the LTER on the Eastern Shore has generated has resulted frequent contact with local business persons, watermen, and farmers. These people consider the investigators of the VCR LTER project to be an important source of information about their relationship with the local environment.

4.12 SUPPLEMENTAL SUPPORT

We have received supplemental funding through the REU, the Technology Supplement, and the ROA programs. We have supported 7 undergraduate students as a result of our REU funding (see Statement on Education and Human Resources). At least three of these students have continued their work during the academic year following their summer field work and have written a senior thesis based on their work at the LTER. Two students who were supported during the summer of 1991 have submitted manuscripts to peer-reviewed journals. The use of the technology supplement funds are described in Section II.J. Don Young (VCU) has recieved ROA funding to study Myrcia thickets at the VCR.

FACILITIES AND EQUIPMENT

Facilities available to the VCR LTER investigators include the Oyster laboratory, the Department of Environmental Sciences laboratories, and two computing facilities (one housed in Environmental Sciences and the other in the Academic Computing Center). The Oyster laboratory is a renovated farm house, leased by the Department of Environmental Sciences from the TNC VCR. The laboratory is located near Oyster, Virginia. This house is suitable for use as temporary housing for 20 people, a field laboratory, and on-site administration. All necessary equipmment for the field stabilization of chemical and biological samples are in place at the Oyster laboratory including: refrigerators, freezers, filtration equipment and pumps, ovens, muffle furnaces, balances, pH meters, salinometers, oxygen meters, and incubators. We also have the capability to analyze water, soil, and sediment for nutrient concentrations on site: A deionized water system and a Hitachi 200 UV-visible spectrophoto-meter have been installed. Three out-buildings at the Oyster laboratory are also available for the use by the VCR LTER. One of the buildings has been renovated and equiped as a shop to provide investigators with on-site ability to construct equipment. Another of the buildings contains ovens, muffle furnaces, and tables for drying samples and specimens. The third building is used for storage of field equipment. The basement of the laboratory has been renovated to provide areas for washing and sorting of field samples, and for storage of herbarium samples. In addition to the Oyster laboratory, the staffed, fully-equipped (electricity, sanitary facilities, kitchen, ets.) Machipongo Station, owned by the VCR TNC, is available for a daily use fee. The LTER has access to this structure to provide shelter for investigators working on Hog Island in case of an emergency.

The Department of Environmental Sciences laboratories are modern and well equipped. These facilities include several analytical laboratories, a clean lab (positive pressure, absolute air filtration, and laminar flow hoods), and a microbiology laboratory.

Laboratory instrumentation includes a SpectraMetrics SpectraSpan IIIA direct current plasma emission spectrophotometer, a Dionex Model 14 ion chromatograph system for routine anion and weak organic acid analyses, a Dionex ion chromatograph system with post-column reactor and a Knauer UV-vis detector for transition metal analyses, a high-performance liquid chromatography pump used in conjunction with the UV-vis detector for analysis of dissolved organic compounds, a Dionex gradient eluent ion chromatograph system for the analysis of cations, Varex ROSA-1 automated sample injectors and Hewlette-Packard integrators for the ion chromatographs, an Instrumentation Laboratories model 751 dual-beam atomic absorption/atomic emission spectrophotometer equipped with a model 755 flameless atomizer (graphite furnace) and a model 254 automated sample injector, a Perkin-Elmer/Hitachi 200 UV-visible spectrophoto-meter, a dual-channel Technicon AutoAnalyzer II, and two Radiometer auto-titrator systems. Standard lab equipment includes pH meters, strip chart recorders, conductivity bridges, analytical balances, refrigerators, fume hoods, drying ovens, centrifuges, temperature-controlled shaker/water baths, and a muffle furnace.

The Department also maintains a completely equipped lab facility for microbial ecology. All necessary routine equipment for the proposed work may be found there, including autoclave, incubators, balances, ovens, centrifuges, spectrophotometers, pumps, etc. Specialized equipment includes two Zeiss Model 14 research microscopes with epifluorescence illumination, a Varian Model 3800 gas chromatograph with both flame ionization and electron capture detectors, a Beckman LS7500 liquid scintillation counter, an American Research Products HPLC, a Dohrmann TOC analyzer, and a Carlo-Erba C/N analyzer.

Additional facilities in the department include the mineralogy lab which houses powder and singe crystal Philips X-ray diffractometers, research petrographic microscopes, and sample and thin section preparation equipment. Field equipment maintained by the department includes pH meters, flow cells, conductivity bridges, peristaltic sampling pumps, thief samplers, filtering apparatus, and flow meters. There is a complete shop for wood and metal working with a full-time engineer for design and fabrication of unique field and laboratory equipment.

The field and laboratory equipment required by investigators associated with other insitutions will be provided by their respective Universities.

The Department of Environmental Sciences has a Remote Sensing and Geographical Information System (GIS) Laboratory which consists of 4 Sun SparcStation 1 workstations each of which is equipped with 16 MB of memory and a 600 MB hard disk and a 80386-based PC. The PC and two of the SUN systems are equipped with 24-bit color displays (the other SUNs have 8-bit color displays). These support ERDAS, GRASS, KHOROS and UNIRAS raster-based GIS and remote-sensing system and the ARC/INFO vector-based GIS system. Peripheral equipment includes an Eikonix 4Kx4K color scanner, three digitizing tablets (up to 36x48"), a Calcomp 1026 pen plotter, and a Tektronix 4696 color printer. Digital output and storage is available via a Pinnacle read-write optical disk drive (capacity 500MB), an Exobyte 8mm video-tape drive (2.3 GB), a SUN cartridge tape drive (60MB) and a Cipher 9-track, 6250 b.p.i. tape drive (200 MB). All systems are networked to share resources. Systems are available 24-hours/day, 365 days per year and are backed up on a daily basis.

Support for statistical analyses and other software needs are derived from the Academic Computing Center. Accounts for LTER researchers are available on an IBM 3090, running VM/CMS, 9 RS-6000 computers running AIX and a PRIME 9950 computer. Supercomputer accounts are available on the Pittsburg supercomputer via a consortium arrangement. Sun workstations are also available in ACC computing laboratories. In addition, the center provides language and statistical software for PC's via a Novell network. Software packages available through the ACC include: SPSS, SAS and MINITAB statistical packages, C, Pascal, FORTRAN and C++ languages, and IMSL and Matlab numerical analysis packages. Graphics support includes NCAR graphics, spreadsheets and SAS GRAPH. All computers are networked via a system of connected Ethernets to NSFNET (Internet), providing full electronic mail, read news, telnet and ftp support.

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This list of publications is comprised of only those by VCR Faculty & Staff (bold) and students (italics).

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Barr, L. 1989. Sedimentation and Fallout Cesium-137 Cycling in a Virginia Salt Marsh. MS Thesis. Univeristy of Virginia, Charlottesville, Va.

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