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PROJECT DESCRIPTION

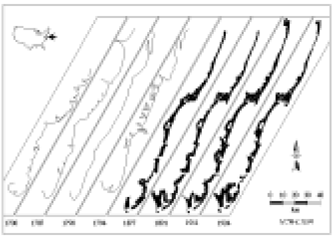
SECTION 1

INTRODUCTION

The central hypothesis of the VCR LTER is that ecosystem, landscape and successional patterns are controlled by the relative vertical positions of the land, sea, and fresh-water table. Large transient and small progressive changes in the position of these free surfaces result in disturbance of ecosystem processes and in physiological stresses that may lead to system state change. Variations in the elevations of these critical surfaces result from local weather or climate change, such as short-term storm-generated fluctuation in sea/land levels or long-term sea level rise. Ecological processes, including species extinctions and invasions that alter rates of erosion and deposition, also affect the positions of these free surfaces relative to one another. In many instances, the joint effects of contemporaneous disturbances at different temporal and spatial scales result in state changes.

The Site

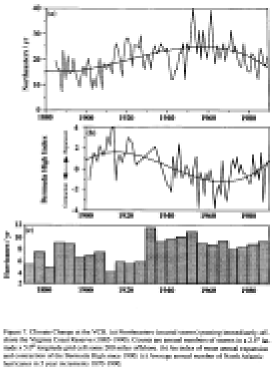
The Virginia Coast Reserve (VCR) is a complex assemblage of 14 barrier islands, associated inlets and beaches, extensive back barrier islands, shallow bays and deep channels, mud flats, expansive salt marshes, and contiguous mainland fringing marshes, deciduous and evergreen forests, and agricultural fields (see Fig. 1 and Fig. 6). It extends 110 km along the seaward margin of the southern Delmarva Peninsula. The low-lying landscape (mean elevation < 2 m) provides an unusually sensitive location for studying and monitoring ecosystem dynamics and the effects of both atmospheric and oceanic climate variability on a range of natural ecosystems. 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%.Where sea level intersects this sloping plain, small changes in elevation of either the land or the sea result in large horizontal changes that determine landscape patterns and ecosystem structure and dynamics.



The vegetation of the islands, marshes, and the mainland-lagoon interface is conspicuously zonal (McCaffrey and Dueser 1990a, b, Ehrenfeld 1990) in character with sub-scale patchiness and sharp transitions between patches. High and low salt marshes, unvegetated mud flats, grasslands, shrub savannas and maritime forests occur in close proximity, with sharp ecotones between adjacent ecosystems. Vegetation heterogeneity is further accentuated by interannual climate variation: precipitation records indicate a range of between 85 and 140 cm yr^{-1} (Hayden 1979; Bolyard et al. 1979). This variation arises primarily from variation in summer thunderstorm rainfall and depends, in part, on local land and sea temperature differences. Further, 45% of late summer and autumn rainfall comes from tropical storms (Hayden 1979).

The VCR is an extremely dynamic, regularly disturbed landscape comprising elements (forests, marshes, sand dunes, grasslands, etc.) that differ in degrees normally associated with biome-level differences. The types of ecosystem changes that occur spatially across continental biomes and temporally 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 produce landscape structure at higher levels of organization. Yet for all of this disturbance and change, or perhaps because of it, the landscape is comprised of repeating units and is seemingly self-ordered. The barrier islands form a gentle arc with the regularity of beads on a string. The morphologies of barrier islands, and their lagoons and mainland interface, repeat in form and dimension. Ecosystem state variables exhibit significant decadal and century-long trends that are driven by extreme perturbations at meteorological and climatological time scales.

The climate of the VCR is dominated by coastal storms or Northeasters (Dolan et al. 1987) (Fig. 7a) and the Bermuda High pressure system (Davis et al. 1994) (Fig. 7b). Each year an average of 38 extratropical storms occur with magnitudes sufficient to rework beach sands and to elevate tides above astronomical norms (Hayden 1976 1981; Dolan et al. 1987 1988). These storms generate waves from the northeast and drive sand southward along the coast. The Bermuda High pressure system generates southeast swell and drives sediment northward along the coast. Like the Northeasters and the size of the Bermuda High, hurricanes have also exhibited long term trends (Fig. 7c). These storms are largely responsible for the production of waves and surges which in turn change the morphology of the islands (Dolan et al. 1979), the associated vegetative cover, and ultimately in combination with sea level rise, the landward migration of islands across lagoonal marshes (Hayden et al. 1980, 1981) and the encroachment of marshes into the forests on the mainland (See Fig. 3B, page RPS 3) (Brinson et al. 1994). In effect, the site is a perpetual experiment in ecosystem disturbance, plant succession and landscape structuring. Harris (1992) 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 (see Fig. 2a, page RPS 2). The extent of marshes throughout the VCR declined 11% from 1852 to 1960 (Knowlton 1971). Farm fences on hypersaline marshes are evidence of the encroachment of saline water into fields and fresh-water marshes along the lagoon mainland interface.



The "Great Halloween Storm of 1991" and its effect on the VCR landscape illustrates the exceptionally dynamic nature of this landscape. On October 30, 1991, the VCR was hit by a storm that evolved from an extratropical storm (a "northeaster") moving eastward to merge with a passing tropical storm, Grace. The resultant Great Halloween Storm (Dolan and Davis 1992) was a major coastal-storm event from Cape Hatteras, N. C. to Kennebunkport, Me. The storm remained offshore and produced considerable damage even at a distance. At the VCR, waves at sea reached heights 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 1447 coastal storms in our LTER data archives (1942-1994). Statistical estimations of its probability indicate a 1000 year plus return interval, i.e., this storm was exceptional. The Great Halloween Storm is comparable to historical disturbance events -- The Great Storm of 1667, The Accomac Hurricane of 1693, the hurricanes of 1749 and 1933. Each produced similar waves and still water levels 3 to 5 m above normal. Immediately following the Halloween Storm, ground and aircraft reconnaissance of the site indicated that in some locations 10s of meters of beach were removed from Hog Island. The inlet between Parramore and Crescent Islands was filled with sand. Marshes behind Parramore Island were buried by as much as 1 m of sand. Large sections of Parramore Island's south end eroded away. Fresh water wells in transects across Hog island became saline. The Halloween Storm and other large storms leave extensive deposits of wrack that appear to be partly responsible for patchiness of marsh vegetation (Brinson et al. 1994). Several new marsh surfaces developed on which we have installed an extensive array of permanent plots and transects to chart the colonization and development of a salt marshes on newly deposited substrates.

Site History

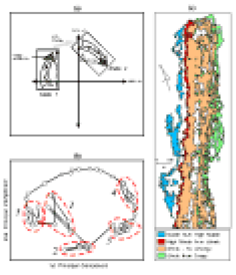
Changes in the states of VCR ecosystems can be dramatic. Tens of thousands of years ago, our site was a maritime boreal forest of *Pinus strobus* and *Picea* sp. (Hayden 1990, Bonan and Hayden 1990a, b; Emory et al. 1967). Seven thousand years ago, what are now open lagoons were forested uplands with stream channel estuaries. Five thousand years ago, these sites changed to tidal channels and marshes (Newman and Munsart 1968). In the last 1500 years the site changed to today's lagoons, marshes and barrier islands perched on the much older surface (Oertel et al. 1989a, c, and Harrison et al. 1965).

The contemporary barrier island-lagoon-mainland complex took form during the late Holocene rise in sea level, although the underlying topographic framework can be traced back to earlier high stands of sea level during the Pleistocene (Oertel et al. 1989a). 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 high as 10-*3* km yr-*1* (Finkelstein et al. 1987). The modern islands typically exhibit shoreline change characterized by lateral accretion and erosion as high as 13 m yr-*1* (Dolan et al. 1979) creating one of the most dynamic coasts in the United States.

While the entire site has undergone a sequence of state changes over the Holocene, landscape/ecosystem elements within the site have undergone equally large state changes within the present century. Mockhorn Island, once agricultural land and formerly forest, has been abandoned and is now a very young salt marsh. At the turn of the century, the salt marshes that now fringe the mainland were fenced, upland pastures.The bay bottoms, which were eel grass meadows at the turn of the century, are now unvegetated bottoms (Hayden et al. 1991). At the time of settlement of Hog Island's town of Broadwater in the mid 1800s, the south end of Hog Island was forested. It is now an overwash-flat grassland (Rice et al. 1976, Fitch 1991, Hayden et al. 1980). The north end of Hog Island was several hundred meters wide and consisted of a narrow beach affronting a marsh in 1852; and, it 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 rates of change exceeded in North America only by the coastal margin of the Mississippi Delta (Dolan et al. 1982).

Succession and 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, transitions between ecosystem states can occur with exceptional abruptness. We envision the ecosystem dynamics at the VCR as having a tendency to be self-ordering or successional within limits. Under certain intensities of disturbance, systems are displaced sufficiently that their dynamics track a different "target" or state (Hayden et al. 1991) (Fig. 8a & 8b). 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, loss of island elevation, and depletion freshwater reserves necessary for forest maintenance. Unless new island building takes place, a replacement forest will not result. Rising sea level is currently forcing state changes on the barrier islands including high marsh replacing shrubs and low marsh replacing high marsh (Fig. 8c).

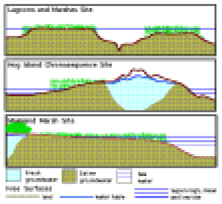


There are two elements to our theoretical conception of landscape dynamics on the VCR LTER. First, there are ecosystem states, in a multivariate Hutchinsonian sense, within which successional dynamics operate. Second, there are events that produce transitions from one of these states to another (Fig. 8a & 8b). At the VCR, one can see both successional dynamics within these ecosystem states and transitional dynamics between given ecosystem states. In spite of this early stage in theoretical development of this notion, we are convinced the observational and multivariate definition of ecosystem states is possible in the sense of Allen et al. (1977), Birks and Berglund (1979), Lamb (1985), and Jacobson and Grimm (1986) (Fig. 8b). Our concept of landscape dynamics (Hayden et al. 1991) is based on 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 can infer such dynamics from field evidence, for example, dead tree trunks in marshes and marsh peats on beaches. We feel this class of dynamics, while frequent and dramatic, is not unique to our site and is relatively widespread in a range of ecosystems. 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.

We view the dominant cause of ecosystem state change at the VCR, and also the initiation of new successional sequences within states, as arising from vertical changes in at least one of three free surfaces: the land, sea, and fresh-water table. We use the term *free surface* rather than simply surface to emphasize that these are not static surfaces. Mass and energy are exchanged across these surfaces and the elevations of these surfaces exhibit long-term trends, periodic oscillations and episodic disturbances. Variations in the elevations of land, sea and water table surfaces arise from relative sea-level rise, storm-generated changes in levels of the sea and the land, and ecological processes including species extinctions. Our long-term experiments and long-term observation and monitoring programs focus on these free surfaces and on the role of they play in ecosystem succession and state changes.

Free Surfaces

The concept of free surfaces, as we use it, is the same as used in hydrology and meteorology. Our hypotheses focus on the relationships of three free surfaces: fresh-water table, land and sea level (Fig. 9). While other free surfaces exist, e.g., the free surface characterized by the sediment oxic/anoxic interface, we focus on these three because studies over the last 6 years suggest that the VCR LTER site is structured to a large extent by these surfaces. At the VCR small variations in elevations or slopes of the fresh-water table, land or sea level surfaces can result in ecosystem and landscape changes equivalent to continental biome transitions . Aeolian transport of sand inland from the beach may result in higher base island elevations and in the formation of dunes. It is the base elevation of the land above the extremes of the astronomical tides that permits significant trapping of rainwater and the development of a perched freshwater lens which is the confined fresh water resource for terrestrial vegetation (Bolyard et al. 1979). The storage capacity for this resource depends upon the difference between the elevation of the fresh-water table and on the elevation of the land free surface (Ghyben-Herzberg principle) and on local precipitation and evaporation. Where the fresh water storage capacity 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 level of high tides and where 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.



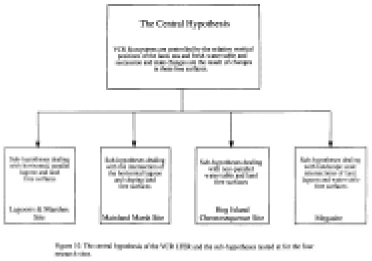
Neither the level of the land nor the level of the sea is stationary (Table 2). At the south end of the VCR, the land is subsiding around 2 mm yr-*1* and the eustatic level of the sea is rising at about 1 mm yr-*1* giving a relative sea level rise of 3.0 mm yr-*1* (Emory and Aubrey 1991). Oertel (1989b) places the relative rate of sea level rise (eustatic rise + land subsidence) between 2.8 to 4.2 mm yr-*1*. The rate of relative sea level rise decreases toward the mainland as well as southward and northward for hundreds of kilometers (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 deposition (Ray and Hayden 1992; Kastler 1993) or unless biogenic accretion can keep pace with the rising sea (Brinson et al. 1994). Land level and eustatic sea-level surfaces, measured locally as the single parameter relative sea level, are important free surfaces for VCR ecosystems. When changes in land and sea level elevations exceed a threshold, system state change occur (Ray et al. 1992). The characteristic temporal variability of these critical state variables is summarized in Table 2.

Locally, the elevation of the land free surface is controlled by sedimentation and erosion of marine and terrestrial mineral sediments and organic matter accumulation (Hackney and Cleary 1987; Brinson et al. 1994). For VCR ecosystems, increases in elevation due to sedimentation may offset the regional subsidence of the land and eustatic rise of the sea. Additionally, because most of the inorganic sedimentation above mean sea level is transported hydraulically, water levels during northeasters and tropical storms are the critical agents of change raising the land surface elevations above the levels of the astronomical tides (Dolan and Godfrey 1973). Below ground organic matter accumulation (Blum 1993) 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.

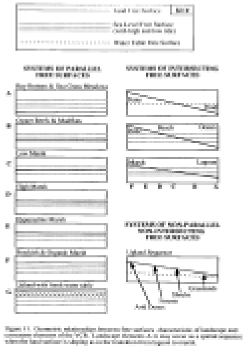
These considerations have led us to begin long-term experiments which manipulate critical free surfaces. The first two involve direct manipulation of the pattern of inundation frequency and magnitude for two types of marsh (fringe and insular-lagoon), using approaches appropriate for the marsh type, to provide insight into the response of marshes to sea level rise. The third experiment employs a long-term manipulation of the unconfined freshwater lens on a coastal barrier island to study state changes arising from climate change and to study ecosystem-level water relations. These experiments are designed to build on and to focus our earlier research findings, and to emphasize the free surface controlling factors of water table, land, and sea elevations and to understand the biogeographic organization of the VCR.

VCR RESEARCH PROGRAMS

The Hypotheses. The research programs of the VCR LTER are focused on understanding the relationships between slow, long-term changes in critical free surfaces and rapid, short-term disturbances in these same surfaces that trigger ecosystem state changes and set in motion or alter successional sequences (Fig. 10).



The central hypothesis of the VCR LTER is that ecosystem, landscape and successional patterns are controlled by the relative vertical positions of the land, sea, and fresh-water table. Large transient and small progressive changes in the position of these free surfaces result in disturbance of ecosystem processes and in physiological stresses that may lead to system state change. Variations in the elevations of these critical surfaces result from local weather or climate change, such as short-term storm-generated fluctuation in sea/land levels or long-term sea level rise. Ecological processes, including species extinctions and invasions that alter rates of erosion and deposition, also affect the positions of these free surfaces relative to one another. In many instances, the joint effects of contemporaneous disturbances at different temporal and spatial scales result in state changes. Several types of relationships between the three free surfaces occur at the



VCR (Figure 10 and Fig. 11). An understanding of these relationships goes directly to the theoretical basis for the sub-hypotheses that guide our field studies. Nine relationships are detailed below. At any one location within the VCR a subset of these relationships apply. We do not refer to these relationships as hypotheses as, in their general formulation, they are not the object of our field studies. Nonetheless, the sub-hypotheses of our central hypothesis are founded from these relationships.

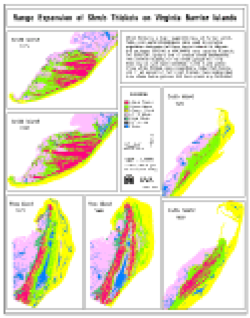
Relationships Between Free Surface Dynamics and VCR Ecosystems

1. 1. Long-term (> 1 yr) changes in the mean elevation of a horizontal free surface intersecting a sloping free surface causes associated ecotones to shift position horizontally.
2. 2. Long-term (> 1 yr) changes in the mean elevation of a free surface parallel to a static free surface causes an ecosystem state change.
3. 3. Short-term (<= 1 yr) periodicities in the elevation of a free surface relative to parallel, static free surface gives rise to a characteristic ecosystem type which depends on the frequency of surface elevation variation, the amplitude of the free surface elevation change, and the relative position of the static free surface.
4. 4. A horizontal gradient in the mean elevation of one free surface relative to a horizontal second free surface results in horizontal zonation of ecosystems. A change in magnitude of the gradient in elevation compresses or expands the zonal arrangements of ecosystems. A change in the elevation of the horizontal surface displaces the zonal system of ecosystems horizontally.
5. 5. Long-term maintenance of ecosystem structure, in an environment with free surface elevation changes, requires parallel changes in at least one of the other free surfaces. If these conditions are not met, an ecosystem state arises, a results that could not be achieved by autogenic succession.
6. 6. Patchiness in community structure arises from a spatially commensurate variation in the elevation of one or more free surfaces. The land free surface elevation heterogeneity is a primary source of patchiness at a number of spatial scales at the VCR.
7. 7. Disturbances that change the geometry of free surfaces may cause ecosystem state change. A disturbance that does not change the geometry of the free surfaces does not cause an ecosystem state change, but may set the system back to an earlier successional stage.
8. 8. Nutrient cycling, above and below ground production, decomposition, and local trophic structure are directly or indirectly dependent on positional inter-relationships of the free surfaces associated with the specific ecosystem.
9. 9. Keystone species at the VCR are those that have the capacity to alter the elevations of the three free surfaces. *Ammophila* on islands, *Spartina* on marshes, oysters on mudflats, and sea grass on bay bottoms all influence the deposition or erosion of sediments.

Our research program is designed to investigate relationships between the three free surfaces and the ecosystems that depend on them. We have also begun three long-term manipulative experiments that directly alter critical free surfaces. We will monitor the long-term ecosystem changes at each experimental site. Additionally, we have paired each experiment with landscape units which have, over the last several decades, experienced natural variations in the same free surfaces. Our approach during the past 6.5 years has been to study the controls on succession and state changes at four research venues within the Virginia Coast Reserve: the VCR Megasite, the North Hog Chronosequence Site, the Hog Island Bay Lagoon and Mainland Marsh Site. At each site we are engaged in core-area work that tests our research hypotheses, specifically supports our experimental efforts, provides critical data for models, and provides useful information for the management of the site by our host, The Nature Conservancy. At our research locations, we are investigating the nine aspects of our central hypothesis. At the VCR Megasite we focus our research on the intersections of the three free surfaces at large geographic and long time scales. At the North Hog Chronosequence Site we focus on the non-parallel fresh-water table free surface and its elevation variations relative to the land free surface across a 120 year chronosequence of ecosystems. The marsh-land surface and its interactions with the parallel yet oscillatory lagoon water free surface is the focus of research at the Hog Island Bay Lagoons and Marshes Site. At the Mainland-Marsh Site we focus on the oscillatory free surface of the level of the lagoon intersecting the sloping land and water table free surfaces. We rely on imagery, networks of sensors and permanent plots, wide-area surveys, transects, and reconnaissance programs as well as sediment coring programs to deal with historical and paleoecological variations in VCR landscapes.

VCR Megasite

The Megasite consists of The Nature Conservancy\qs Virginia Coast Reserve and the lands westward to the watershed divide of the Delmarva Peninsula (see Figure 1). The major boundaries of this strikingly zonal and patchy landscape arise from the separation between free surfaces and intersections of two or three critical free surfaces and gives rise to rapidly changing ecosystems (Fig. 12). The zones and patches which comprise the VCR have characteristic relationships among the three free surfaces. The central hypothesis as applied to the Megasite is as follows:



Long-term progressive and short-term disturbance-driven changes in the intersections of land, lagoon and water-table free surfaces of the VCR cause changes in the spatial (10s m to 10s km) organization of VCR ecosystems and shifts in ecotones. Sub-hypotheses being studied at the Megasite (MS) include:

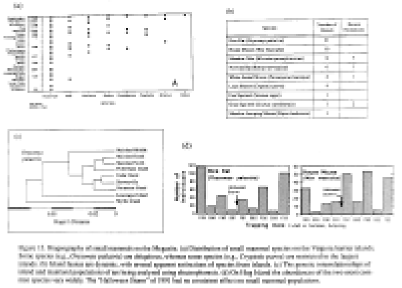
1. The sedimentary layer produced by the 1933 hurricane that buried then-existing marshes is present throughout Hog Island Bay and is thickest where sea grass meadows and were extensive before 1933.(Zieman and Hayden)
2. The shorezone of the barrier islands switches from accretional to erosional with a return period of approximately 80 years. We further hypothesize that the transition from accretion to erosion patterns is an Atlantic Coast-wide phenomenon that is caused by changes in winter storm(s) climate and long-term changes in the subtropical anticyclone of the North Atlantic. (Hayden and Dolan).
3. Seaside vegetation composition on the barrier islands is a response to winter storm overwash disturbances (changes in land free surface elevation) and marine flooding; the effects vary depending on whether sections of the island are erosional or accretional. (Hayden and Shugart).
4. Elevation of the land free surface above sea and fresh water surfaces are major determinants of the capacity of an island to support viable populations of vertebrates. Extinctions of vertebrate populations may result from changes in one or more of these surfaces. (Dueser, Porter and Moncrief).
5. Reworking of regressive strandplain land free surfaces during the late Holocene transgression produced a characteristic stratigraphy due to the release of "fines" into the water column which increased lagoonal turbidity. The "fines" are preferentially deposited in wave-protected areas, and the marshes of small watersheds on the lagoon margins. (Oertel)
6. Lagoonal waters are presently light-limited and turbid as the result of both inorganic and organic (high C/N values) particulate suspension. Increased primary production by phytoplankton and an increase in macroalgae will reduce organic turbidity in lagoonal waters. It is further hypothesized

that this increase in clarity will be a key factor in the return of seagrasses to the VCR. (Zieman and Hayden).

Megasite studies depend upon repeated synoptic surveys and measurements across a wide geographic area and at time intervals appropriate to determining the long-term dynamics. The benchmark Megasite inventory is Dueser et al (1976). Time intervals for such surveys range from 1 to 5 years, depending on our understanding of the dynamics of the system under study and the occurrence of significant disturbances. Spatial density of sampling depends on the type of data and the structure of the landscape. An inventory of long-term records is provided in Section 2: Long-term Data Sets. We are initiating an extensive survey of marsh surface coring to measure the thickness and position in the stratigraphic column of sedimentary deposits that we hypothesize were laid down in 1933 (MS Ho-1). We have dated carbon from this layer using high-sensitivity accelerator mass spectrometry radio-carbon dating and place it in the 1930s. The survey of this stratigraphic surface will provide a widespread time marker for many studies.

Megasite programs focus on recording elevations of critical free surfaces and ecosystem attributes. Studies of land surface elevations focus on measurements of changes in the shorezone. Within this zone, island building and destruction, and the reworking of the island sediments are driven by storm waves and surges. Surveys of the shorezone, the intersection of the sea-level and land free surfaces, rely on aerial photography (1949-1993). Beginning in 1994 we will use GPS surveys to determine shoreline and ecotone positions. This will permit improved schedules for surveys and reduce post-processing requirements. Storm and wave climate data from the National Weather Service is added to our data archives monthly(1885-1994). Studies to date, have shown that the shorezone of Hog Island has undergon fundamental reversal in the direction of change in 1967 (Fenster et al. 1994)(MS Ho-2). Reversals have occurred once or twice per century for the last several hundred years (Harris 1992). Our current interpretation is that winter storms and summer swell from the Bermuda high pressure cell (see Fig. 7, page PD 2) have changed systematically over the last century (Hayden 1981, 1982; Davis et al. 1994). The specific mechanism involved is hypothesized to be a change in the net along-the-coast direction of movement of sediments (MS Ho-2). Along the island where the shorezone is widest, seaward terrestrial environments are flooded with saline water during coastal storms, and may be buried by sands transported from the beach. We have mapped the probabilities of such burials on Hog Island and have determined for each probability class the plant species which survived in that disturbance zone (Fahrig, Hayden and Dolan 1993)(see Fig. 5, page RPS 5). During the renewal period we will verify the results of this work (MS Ho-3) on other islands and will use this survival vs. disturbance probability information in our model ISLAND (see Section 2: Models and Synthesis page PD 23).

Work on MS Ho-4 examines the causes of extinction and immigration by linking multiannual surveys of multiple islands (varying in elevation), semi-annual censuses of small mammal populations on four transects on Hog Island (varying in availability of fresh water and probability of overwash), intensive observations of inter-island movements (Forys and Dueser 1993) and genetic (mitochondrial DNA, allozyme and microsatellite DNA) analyses (Fig. 13). Extensive multi-island surveys were completed in 1988-1989 and 1993. We are examining relationships between insular populations using genetic analyses of samples from 11 islands sampled in 1993. Aerial photo and map surveys indicate an 11% loss of lagoon and back-barrier marshes since 1852 (Knowlton 1971). More recent surveys covering the last 30 years (Kastler 1993), found that loss of island marsh exceeds development of new marsh while mainland marsh has increased uby 8%. We hypothesize (MS Ho-5) that the lagoons are enriched in low-nitrogen carbon particles winnowed from of the eroded marshes. We will quantify loading of lagoon waters with low quality carbon and new sediments from marshes. In conjunction with the US MAB program, we have initiated, a study of the role of nutrient enriched groundwater from the mainland which may be the source of the high levels of nutrients in the creek and lagoon

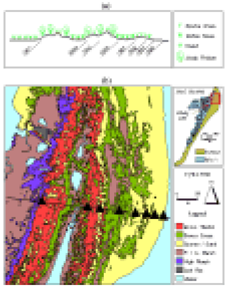


waters. General observations indicate that lagoon bottoms that were seagrass meadows prior to the extinction of the eel grass in the early 1930s are becoming especially rich in macro-algae (MS Ho-6). Transects, used in preliminary work, together with new central lagoon permanent plots will be established and used to measure changes in macroalgal biomass and community composition.

Research infrastructure of the VCR Megasite includes: 1) a 60-monument, cm-level GPS network, 2) a system of dated landscapes, 3) a network of surveyed overwash terrace, 4) a network of sediment cores, 5) a benchmark system of vegetation plots, 6) a system of mammal transects on 23 island and marsh surfaces, 7) remote sensing calibration facilities, 8) a mm-level set of benchmarks at research sites, and 9) a geo-rectified, 50-meter interval VCR-wide base map system for shorezone landscape studies. These on-site resources for site-wide research are supported by a remote sensing laboratory in Charlottesville.

North Hog Island Chronosequence Site

The water-table free surface and the land free surface are neither parallel nor horizontal on the barrier islands. The spatial and temporal variations in relationships of these two free surfaces control ecosystem structure, dynamics and long-term changes. The central hypothesis applied to the North Hog Island Chronosequence site

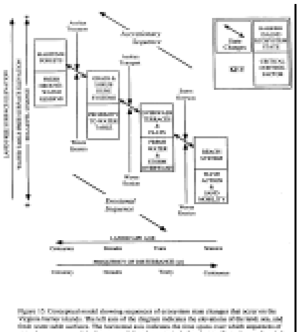


(Fig. 14) is:

Terrestrial vegetation on coastal barrier islands is limited primarily by the relationship of the non-parallel land and water table free surfaces. The relative elevation of the fresh-water table and the magnitude of the reserve of fresh water available structures the vegetation of the barrier islands. Working sub-hypotheses for North Hog Island (HI) Chronosequence include:

1. The depth of the fresh water table below the surface of the island depends on the elevation of the land above mean sea level. (Kochel, Hayden, Furman, and Porter)
2. In stable or accreting regions of the islands, species composition of the vegetation is determined by island elevation, depth to the freshwater table, and variations in water table elevation due to rainwater input and evapotranspiration losses. (Brinson, Porter and Hayden)
3. In unstable regions of the island, plant species composition and successional processes are determined by depth to the freshwater table, climate variations and by the frequency and magnitude of disturbance from coastal storms. (Young and Hayden)
4. Accreting regions of the islands have landscapes ordered in age from the sea landward. Along this chronosequence the relative positions of the land and water-table free surfaces have been in place for periods ranging from less than one year to about 120 years. Within the chronosequence, autogenic succession accounts for biogeochemical variations. (Day, Young, Porter, and Shugart)
5. Above and below ground production are limited by proximity to the fresh water and available nitrogen. (Young and Day)
6. Decomposition rate is a function of soil moisture and thus proximity to the water table. (Day)
7. Nutrients (primarily N) are derived from either N-fixation by *Myrica* or atmospheric deposition and spatially are a function of exposure to oceanic influences and soil moisture and thus proximity to the water table. (Young, Macko and Galloway)
8. Utilization of the island landscape by small mammals varies with age and complexity of the landscape and vegetation type. (Dueser and Porter)

9. Mammalian consumers affect the composition and structure of vegetation which, in turn alters the rates of change of free surfaces through alteration of aeolian deposition and evapotranspiration (Dueser, Young and Porter)
10. A change in the mean level of the water table free surface will result in a change in vegetation composition and productivity. (Hayden, Porter, Furman, and Young)



Our model for state changes on the barrier islands is shown in Figure 15. On these islands state changes arise from both erosional and accretionary processes and are driven by disturbances and long-term changes in sea level. The landscape of the northern tip of Hog Island consists of a series of beach ridges (dunes) and swales that have built seaward over the last 120 years or so. We have dated the landforms of this landscape using survey maps and aerial photographs in conjunction with field excavations. We have established a chronosequence transect with permanent plots and network of groundwater wells that record spatial and temporal variations in the elevation of the fresh water-table. In addition, we have established productivity, decomposition and nutrient cycling study plots along this Chronosequence transect (Conn and Day 1993a, b). We will install large mammal exclosures at the same locations in 1994. Chronic nitrogen-addition experiments have been performed along the transect for the last three years. Using groundwater wells, we are evaluating the relationships among land surface elevations, water table free surfaces and island vegetation patterns (HI Ho-1, 2, 3, 4). In addition, we have established a water-table manipulation experiment (see page PD 16) on isolated dunes located in a saline and hypersaline marsh (HI Ho-1, 2, 3, 4). The fresh-water effectively "floats" in these sand masses which are perched on a sea-water flooded, saline matrix of fine grained marsh sediments. Hypothesis HI Ho-3 focuses the role of disturbance in modification of the water table controlled pattern of vegetation on barrier islands. Along the chronosequence, we are also examining the hypotheses that proximity to the water table free surface is a principal controller of above and below ground production (HI Ho-5), decomposition (HI Ho-6) and nutrient availability (HI Ho-7). The utilization of landscapes of varying age and productivity by small mammal populations will be determined through long-term censuses coupled with structural habitat measurements (Dueser and Shugart 1978, Dueser and Porter 1986 and Scott and Dueser 1992) (HI Ho-8) mammal exclosures will be used to establish the effects of herbivorous mammals on vegetation composition and structure (HI Ho-9). The water table draw-down experiment will test the hypothesis that a change in water table elevation will result in changes in species composition and primary productivity (Hi Ho-10). This work is also a direct test of climate, i.e., free surface controls on vegetation through precipitation climate change.

A model of barrier island morphology (see ISLAND, SECTION 2: page PD 24), water table, and vegetation is based on understanding the controls on the elevation of the fresh water table free surface and depends on 1) elevation of the land above spring tide, 2) precipitation input, and 3) evapotranspiration losses (Rasteter 1989). Shao, Shugart, Young (1994) have developed a new evapotranspiration model for the North Hog Island Chronosequence (see Fig. 21, page PD 24) that will be tested at our water-table manipulation experiment site. We are also developing a maritime forest FORET model that will be made spatially explicit by means of a water table driver in the model. Input data to parameterize this model are being derived from a set of 100 benchmark vegetation plots on Parramore Island. At the Chronosequence Site we are measuring decomposition, primary production, and nutrient cycling and interpreting the observations in terms of depth to the water table and landscape age. We are dating the landscapes of other barrier islands of the VCR, which will permit replication sites for findings from Hog Island studies.

The research infrastructure of the VCR North Hog Chronosequence Site includes: 1) a photo- and map-dated 120-year chronosequence of landscapes, 2) 5 transects and mammal associated permanent plots, 3) a system of

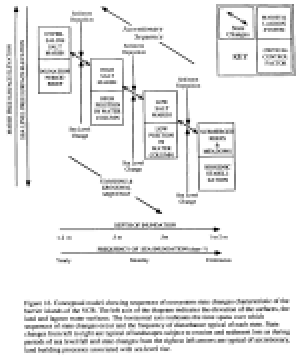
32 minirhizotron tubes (Brown and Upchurch 1987), 4) a surveyed network of groundwater wells, 5) a tide station, 6) an LTER minimum standard meteorological station, 7) a solar powered experimental groundwater pumping station for fresh-water table manipulation, and 8) permanent plots with and without nitrogen amendments.

Hog Island Bay Lagoons and Marshes Site

VCR land and lagoon free surfaces are horizontal and parallel. The lagoon surface is a complex oscillator and the mean level of the land relative to the lagoon surface differentiates landscapes within the lagoon and marsh system. The central hypothesis as applied to the lagoons and marshes site is:

The type of community and level of productivity of emergent marsh vegetation on lagoonal marshes is controlled by the relative elevations of the parallel marsh land free surface and the parallel, oscillatory lagoon water free surface. Working sub-hypotheses for Hog Island Bay Lagoon and Marshes Site (LM) include:

1. *Spartina alterniflora* growth form and productivity vary as a function of the difference between marsh surface elevation and mean sea level. Lowering the marsh land surface will increase productivity and promote dominance by the tall form of *S. alterniflora*. (Zieman and Hayden)
2. VCR Marshes that were buried during the 1933 hurricane are elevated and relatively flat, and are therefore dominated by the short form of *S. alterniflora*. (Zieman and Hayden)
3. Hypersaline marshes are restricted to regions where the marshland-surface is level at elevations between mean high tide and spring tide. (Zieman)
4. Storm-derived marine sediments deposited below mean high tide level develop a chemistry and texture compatible with marsh colonization and succession. (Furman and Zieman)
5. Reduction of pore water salinity by infiltration of precipitation and the activitiy of invertebrates enhances *Spartina altinaflora* productivity. (Zieman and D. Smith)
6. Exchange of water between ocean and lagoon is accomplished by a standing tidal wave and tidal currents moving through well-developed antecedent valleys. The exchange is very efficient, and the resulting lagoonal water body maintains a relatively constant salinity at 30-32 ppt. Exchange is determined by water-mass trajectory path, not diffusion of stratified flows (Oertel).
7. Water mass boundaries in lagoons are determined by differences in current "drag" created by bottom friction and fluctuating water levels. (Oertel, Porter, and Hayden)



Our model for state changes on the lagoonal marshes of the VCR is shown in Figure 16. On these marshses state changes arise from both erosional and accretionary processes and are driven by disturbances which deposite large quantities of sediment and by long-term changes in sea level. Lagoonal water and land surfaces are parallel or nearly parallel. Productivity and height of *S. alterniflora* varies according to its position in the water column (LM Ho-1). We are testing this hypothesis through our experiment on marsh lowering and through extensive mm-resolution surveying of marshes in the lagoons. Exceptions to parallel water and land levels occur along the marsh edges where the land is steeply sloped and along the marsh-island and marsh-mainland interfaces where a shallow but significant sloping land surface is encountered. The marshes of Hog Island Bay vary in elevation relative to mean sea level. Due to these variations the position of marsh plants in the water column varies considerably. These spatial variations constitute an analog of the sea level rise effects on marshes (LM Ho-2) and to our experimental marsh lowering. The high marshes, where evapotranspiration is high, are prone to hypersalinity. Where the marsh slope becomes shallow, salt flats develop within a range of tidal elevations, but if the slope is steeper, salt flats never develop, regardless of the elevation (LM Ho-3).

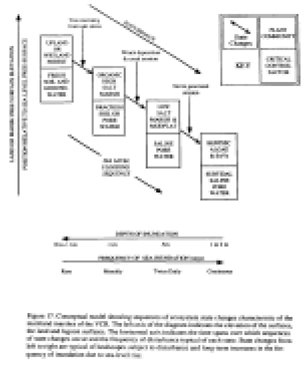
Along the seaward and landward margins of Hog Island Bay, sediment supply is adequate for the formation of new marshes. We are monitoring these new marshes to determine if sediment chemical conditions typical of marshes develop before plant colonization or if sediment chemistry is a consequence of marsh succession (LM Ho-4). Using remote sensing, we have identified marshes that formed in each of the last 7 decades. These marshes constitute a chronosequence that will permit us to use a space-for-time substitution to detail long-term succession of marshes and to guide our long-term monitoring of newly formed marshes. Along this chronosequence, marsh elevations and plant productivity vary systematically as a function of marsh age.

Preliminary studies indicate marsh primary productivity is highly correlated with porewater salinity. Porewater salinity is reduced directly by rainfall during low tide. Rainwater access to a thick layer of the marsh surface depends on invertebrate burrows (macropores). We will test the hypothesis that fiddler crabs play a primary role in regulating primary productivity (LM Ho-5). We recognize that, in the long-term, we will need to know a great deal more about tidal volumes, tidal velocities and tidal residence times. Such information will be necessary to calculate nutrient fluxes and adequately model marsh and lagoon systems. We hypothesize that the relatively constant salinity in Hog Island Bay arises from the lagoonal nature of the system including low fresh water input, the shallow embayments and nearly complete tidal flushing through deep channels (LM Ho-6 and 7)

Research infrastructure developed for the Hog Island Bay Lagoons and Marshes Site includes: 1) a series of experimentally lowered marsh surfaces, 2) a system of marsh surfaces with different positions in the water column, 3) an array of marsh mm-level benchmark monuments for surveying, 4) a GPS/Digital Fathometer System for hypsometric surveys, and 5) a sequence of marshes of known ages for pseudo-chronological studies.

Mainland Marsh Site

As sea level encroaches on mainland surfaces at the VCR LTER, the transition from upland to subtidal environments encompasses four ecosystem states: forested upland, organic high marsh, mineral low marsh and intertidal mud flat, and subtidal lagoon (Fig. 17). The central hypothesis stated for this landscape is:



The vertical position of the mainland-marsh ecotone is a function of the interaction of the non-intersecting, sloping free surfaces of the saline lagoon water, fresh ground water table, and land surface. Within the ecotone structured by these sloping free surfaces, multiple states are ordered along a gradient maintained by storm-generated disturbances against a background of chronic sea level rise. Changes in state along the gradient are caused by mechanisms which are characteristic of each change of state (Brinson et al. 1994). Sub-hypotheses for the Mainland Marsh Transition Site (MM) include:

1. The forest to high marsh transition is induced by storm-generated influxes of saline water that stresses and kills trees, tree mortality is primarily a result of salt

induced water-stress and not water-logging. (Brinson and Christian)

2. Tree mortality allows light penetration to the forest floor and is followed by replacement of forest by marsh. (Brinson and Christian)
3. The transition from organic high marsh to mineral low marsh is facilitated by erosion of tidal creeks headward and/or along creekbank margins resulting in subsidence of the surface of the organic high marsh. (Christian, Brinson, Blum, and Wiberg)
4. Increased oxidation of sediment organic matter contributes to subsidence of the organic high marsh surface. Increased oxidation is a result of better drainage created by the steeper hydraulic gradient between the marsh water table and the creek at low tide. (Christian and Anderson)
5. The organic high marsh surface subsides in part because of decreasing accumulation of below ground organic matter and in part as a result of decreased allocation of resources for root and rhizome growth. (Blum and Christian)
6. Inundation and salinity by themselves are insufficient to cause species replacements in organic high marsh communities. Disturbance due principally to wrack deposition must be involved to maintain within state heterogeneity (although fire, trampling, and ice scouring may be additional disturbances). (Christian and Brinson)
7. Sediment deposition on mineral low marsh surfaces is facilitated by the frictional resistance (i.e., baffling effects) of marsh plants and /or infiltration of water through the marsh surface on falling tides. Erosion of marsh sediment is inhibited by the presence of vegetation and sediment particle aggregation by invertebrate fauna (Wiberg and D. Smith).
8. Nutrient transfers from the mainland into the mainland-marsh tidal creeks depends on the distance of transport and the number and type of marsh zones through which the flow must pass. (Macko, Anderson and Blum)

Our model for state changes on the mainland marshes of the VCR is shown in Figure 17. On these marshses state changes arise from both erosional and accretionary processes and are driven by disturbances and long-term changes in sea level resulting in increased frequency of inundation of uplands by saline waters.Work at the Mainland Marsh Site has focused on the position of marshes in the coastal landscape as a function of the recent history of rising sea level and existing upland geomorphology (see Fig. 3b, page RPS 3). We have simplified the mainland-marsh-tidal creek landscape to 4 states (Fig. 17), and have proposed mechanisms responsible for state changes that could be expected as a result of sea-level rise (Brinson et al., 1994). While our model for the changes resulting from sea level rise has some similarity to that of Dame et al. (1992) our focus is mostly on the marsh surfaces rather than the tidal creek changes. Our previous work in assessing these state changes (and maintenance of the states) has been both observational and experimental. Most of the observational studies are long-term and ongoing at the Phillips Creek marsh. This will remain our reference site for mainland-marsh ecotone state changes and dynamics, while Mill Creek marsh will be the focus of our proposed long-term experimental simulation of tidal creek headward erosion. In the organic high marsh, we track the movement of the interface between patches of *Juncus roemerianus* and its neighboring plant species (short-form *Spartina alterniflora* and *S. patens*/*Distichlis spicata* association) at different locations reflecting different states and flooding regimes. Further, we examine aspects of both above and below ground dynamics inside and outside these patches (Blum, 1994). We also use aerial photographs to examine transitions from forest to marsh and marsh to mud flat (Kastler 1993 and Fig. 3b, page RPS 3), and will use similar techniques to monitor tree mortality as a result of storm-induced upland flooding (MM Ho-1) and to track headward erosion of tidal creeks (MM Ho-3).

An experiment that increases inundation frequency by pumping creek water onto marsh plots was initiated in summer 1993 (see Section 2, Mainland Marsh Inundation Experiment, page PD 18). This experiment examines the role of inundation and wrack deposition, separately and in combination, in maintaining organic high marsh plant diversity in *Juncus roemerianus* dominated and *Spartina patens*/*Distichlis spicata* co-dominated associations (MM Ho-6). Primary productivity, species displacement, sediment chemistry (primarily salinity, redox potential, and species of N and S), and trace gas fluxes (CH_4, CO_2, N_2, N_2O) are monitored during these pumping experiments (MM Ho-8). We propose to begin experiments during winter/spring 1995 (seasons of peak storm frequency and intensity) in salt loading and tree girdling to observe 1) thresholds of salt effects on stress symptoms and mortality (MM Ho-1) and 2) response of the ground cover to increased light penetration (MM Ho-2). Experiments to address MM Ho-3, 4, 5, 6, and 7 will be done in a long-term manipulation experiment in another marsh as described in Section 2 of the Project Description: Marsh Mainland Inundation Experiments.

Other proposed studies include determination of 1) the primary sediment transport mechanisms from marsh surfaces, both depositional and erosional (MM Ho-7), 2) the role of the biota in modifying sediment transport by altering marsh surface frictional resistance and particle aggregation (MM Ho-7), and 3) the movement of agricultural chemicals in groundwater to forested buffer strips, marshes, and tidal creeks (MM Ho-8). Hypotheses concerning mechanisms of sediment deposition onto and erosion from marsh surfaces will be tested on a mineral low marsh located proximally to tidal channel and lagoon sediment sources and to faster moving water in tidal creeks and channels. Effects of plant stem density and marsh elevation on sedimentation will be investigated through measurement of flow velocity, suspended sediments, and marsh elevation on natural and lowered marsh surfaces (see Section 2: Long-Term Experimentrs, page PD 16). In addition, we will begin studies to examine the relationship of marsh surface invertebrate fauna abundance, biomass, and species composition (Yozzo et al. 1994) to the intensity of sediment aggregation and aggregate properties (size, settling velocity, and durability) (Kastler 1993).

Stable isotope studies to characterize nutrient transfer across the land, fresh-water table, and sea-level free surface interfaces were begun in 1993 at the Mainland Marsh Site. The site is ideal for this type of study because large quantities of fertilizers are applied to the highly permeable upland soils of this area. Isotopic fractionation of nitrogen and carbon species and flux measurements of CO_2, CH_4, N_2O, and NO_xwill be used to identify biogeochemical processes that lead to losses of inorganic nitrogen and carbon (Macko et al. 1987) due to anthropogenic disturbances (Anderson and Levine 1987) (MM Ho-8). We will also measure rates of nitrification and denitrification using an ^{15}N dilution technique to complement our stable isotope measurements (as non-LTER funds become available).

Research infrastructure of the Mainland Marsh Transition Site includes: 1) transects across the marsh and into the neighboring forest of known elevation, distance from tidal water source, flooding regime, and related physical and chemical variables, 2) a network of water-level recorders and tide gages, 3) a solar-powered meteorological station , 4) experimental plots augmented with lagoon water using a solar-powered pumping system, 5) a network of ground water wells, and (6) a series of permanent plots to monitor changes in the interface between *J. roemerianus* and neighboring marsh plant associations.

PROJECT DESCRIPTION

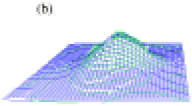
SECTION 2

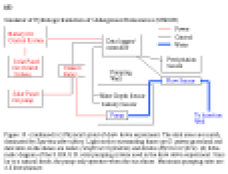
LONG TERM EXPERIMENTS

VCR long-term experiments consist of manipulations of critical free surfaces: land level, sea level and fresh water-table level. Elevations of these free surfaces are critical state variables in ecosystem dynamics. Our general hypothesis is that changes in elevation will bring about transitions to new states that are either self-maintaining or successional. We propose long-term low-level manipulations of free surfaces rather than singular disturbance and recovery experiments.We will alter tidal inundation in marshes using 3 approaches to test different hypotheses and the level of the fresh water table on a section of a barrier island. Each experiment will be paired with a spectrum of natural analogs that have experienced variation in that critical free surface in the last several decades. In addition, we will use the results of the experiments and observations from the natural analogs to parameterize a model of each system. The measurements to be taken in each experiment are summarized in Table 3.

Water Table Draw Down Experiments

The terrestrial surface of the VCR is a mosaic of discrete patches, with abrupt edges between communities dominated by different plant assemblages. A well developed dune-swale unit exhibits segregated communities (i.e., grass-dominated ridge vs. shrub-dominated swale) related to elevation of the water table. Young (1992) has demonstrated that the dominant shrub on the islands, *Myrica cerifera*, occurs in close proximity to ground water reserves (i.e., swales) because of drought sensitivity. Our proposed experiment to reduce the size of the confined fresh water lens by pumping should lead to drought stress, reduced production, and increased mortality. By comparison, experimental addition of water to the more xeric grass-dominated dunes should enhance water availability and lead to successful establishment of *Myrica* and other woody species. The edge or ecotone between the two associations will change through time in response to the manipulation of the fresh water lens.





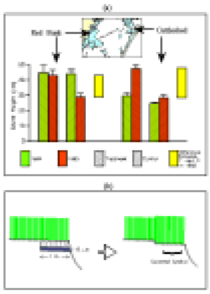
Parramore (Fig. 18a) and Hog Islands have round sand masses (Fig. 18b) with isolated freshwater reserves perched atop sand flats and surrounded by saline and hypersaline salt marshes. In 1993, we proved we can control the level of the water table in these pimples by pumping. We have selected three similar pimples (Fig. 18c on next page) for our initial draw down experiments in 1994. One will be a draw-down treatment in which the water table is lowered at a rate equal to an increase of 1 mm d-*1* of evapotranspiration. A second pimple will receive the removed water as a supplement equivalent to an increase in rainfall of 1 mm d-*1* added to the system below the surface of the sand. The third pimple is our control. In 1994 will will add wells, pumps and recorders to two additional replicates of each treatment and control. In 1995 two more replicates will be installed and bringing the total sample size to five. We expect to continue these experiments for at least the next decade. Pumping studies in 1993 did not involve a manipulation of the water table (Fig. 18d). Pumped water was re-injected below ground at the same location. We established that we can pump at a rate of 1 to 3 mm d-*1* and can record mm level changes in the water table. We also demonstrated that we can record community level evapotranspiration within each day and can record the seasonal draw down and recharging of the water table (see Fig. 4b, page RPS 4).

Experimental hypotheses include: 1) increases/decreases in the elevation of the water table free surface in the pimples will result in reduced/increased grass cover on the pimples, increased/reduced woody plant establishment and growth, expansion/contraction of the *Iva* and *Baccharis* shrub, and *Spartina patens* grass zone around the pimples at the expense of the surrounding salt marsh, 2) fluctuations in the elevation of the water table free surface will lead to significant variations in nutrient budgets, especially nitrogen input via *Myrica* N-fixation, and 3) differential responses to changes in water table free surface will lead to shifts in species composition within the pimple community. Over the long-term, these experiments will constitute a climate change experiment. We anticipate that the pimple from which water is extracted will experience the equivalent of a 25% rainfall reduction, the receiving pimple a 25% effective increase in average annual rainfall. The control pimple will have no manipulation of the water table free surface other than that arises from year to year variation in rainfall.

Analog sites to the experiment. Depth to the fresh water table free surface depends on the elevation of the pimple surface. In that the pimples are quite variable in elevation, they differ a great deal in the water resource available to terrestrial vegetation and, as such, the vegetation cover across the spectrum of pimples includes several biome-level vegetation types, e.g., open dunes, grasslands and forests. The smallest, lowest elevation pimples are entirely *S. patens* grass covered systems. Pimples with slightly higher elevation are entirely covered with shrubs (*Iva* and *Baccharis* or *Myrica*). Larger pimples have mature *Juniperus virginica* and *Pinus taeda* forests with a grassland/desert center in the pimple. Using surface wells, we will initiate water table monitoring of dozens of pimples in order to determine community wide evapotranspiration rates from different communities and the role of rainfall variation on pimple community structure over time. Measurements of *18*O content will be used to extimate in water turnover rates in the pimples. These isolated freshwater systems will permit us to study biome level evapotranspiration differences in a common climate regime. Comparisons of pimples with and without *Myrica* aided by *15*N measurements will facilitate the assessment of the significance of *Myrica* nitrogen-fixation to the nitrogen budget. We will use the data from these monitoring programs to further parameterize our evapotranspiration model (see Section 2: Models and Synthesis page PD 23).

Lagoon Marsh Surface Lowering Experiment

In 1992 we began a program of experimental manipulation of the land free surface elevation along the margins of salt marshes to artificially bring about changes in the position of the marsh in the tidal water column. This experiment is prompted by two observations. First, compared with other marshes in the region, the lagoon marshes of the VCR seem to be higher and flatter (LM Ho-2), and less productive, and second, when large blocks of these elevated marshes are undercut by natural erosion forces and drop 10-20 cm onto the creekbank, the plant biomass and productivity greatly increase. From this we hypothesize that modest accelerated sea level rises will result in increased *Spartina alterniflora* biomass and productivity. Preliminary tests indicate that the height and standing biomass of the *Spartina* increased even in the first year (LM Ho-1).



The experiment involves undercutting a large block of creekbank marsh (Fig. 19a) and severing its attachment at the sides and back so it remains in place laterally, but is lower in the water column (LM Ho-1). This will allow increased flushing by tidal water. In 1992, we used hoe-like implements to remove sediment from beneath the root zone and hand saws to sever the connections. This procedure was very difficult and often yielded an uneven surface. In 1994, we will use a hydraulic pressure washer to remove sediment from beneath the root zone. The back and edges will then be severed with a pressure cutting head (3500 psi) and a hand saw, and the block allowed to settle into place. The result is a lowering of the marsh surface in the water column of approximately 5 cm.

In both years of the experiment to date a 3- to 5-fold increase in plant biomass in the lowered plots compared to control sites on the mainland and island marshes was observed. In the first year, the primary source of biomass increase at the mainland sites was stem density, while it was largely plant height on the island marshes (Fig. 19a). In the second year both factors had increased at all sites.

Two adjustment scenarios are planned: acute and chronic. In the acute scenario, the marsh will be lowered by 15 cm creating a marsh surface equivalent to the 1930s marshes. In the chronic scenario, the marsh will be lowered about 5 mm every other year, thus approximating the current rise in sea level at the VCR. Above ground marsh productivity (Morris et al. 1990) and peak standing crop will be monitored yearly and total biomass (above and below ground) will be measured every second year. We hypothesize that secondary production will also increase with increasing relative sea level. Specifically, we expect increases in juvenile fish and crustacean utilization of the treated sites. Sedimentation and marsh elevation will be carefully monitored on test and control plots and local marshes.

Marsh manipulations will be performed along the margins of mid-lagoon marshes. Each manipulation will result in the lowering of 4 m2 of marsh surface and will be paired with an adjacent control surface the same size. Both treatment and controls will have 5 replicates. To assess the possibility that the experiment records simple edge effects we will also survey marshes in Hog Island Bay with different relative elevations and test the hypothesis that relative marsh elevation results in the same effects as in the experiments.

Throughout the VCR there are hundreds of natural examples of the creation of high productivity low marsh habitat from the erosion and slumping of the perched short-form *Spartina* marshes. Many of these do not survive because they do not readily develop a prograding marsh face and are rapidly eroded by wave action in the tidal creeks. Where such an interface develops the new tall-form marshes can last many years. We will document these slumps on our GIS system, label the sites, and follow them on an annual basis to track their long-term fate. In addition, because marsh burial in the 1930s varied considerably in depth of burial, present-day marshes vary in elevation. We are surveying marsh elevations at the mm level in order to identify a natural gradient in marsh submergence that will serve as an alternate source of information equivalent of that to be experimentally determined.

Mainland Marsh Inundation Experiments

As sea level rises and the frequency and intensity of disturbances increase, a sequence of state changes occurs in the mainland-marsh ecotone (Fig.17, page PD 13). We propose experiments to simulate headward erosion of tidal creeks that occurs as a result of sea-level rise (MM Ho-3, 4 and 5) and to simulate the effect of increased inundation frequency and disturbance (specifically, wrack deposition) in the organic high marsh (MM Ho-6).

Inundation Experiment: In our experiment to test MM Ho-6, currently in place at Phillis Creek, we alter inundation by pumping water into experimental plots with a battery-operated submersible pump charged by solar power. The pumping occurs when water in the creek rises above a designated water stage. The water is distributed throughout 3 x 4 m wood-framed plots which allow ponding on the surface during pumping followed by slow infiltration and exit of the flood water. It takes approximately 45 min. to cover a plot with water. Inundation plots are positioned so that each contains two different plant associations (e.g., 2 x 3 m in a *Juncus roemerianus* patch and the other 2 x 3 m is in an area of *Spartina patens* and *Distichlis spicata*). Pore water samplers (sippers) to assess sediment chemistry are located inside and outside of the plots (Table 3). Further, half of the plot stretching across both plant associations is covered with *Spartina alterniflora* wrack. We are using a randomized block design of 3 blocks each with 3 plots. Each block consists of one plot with increased inundation and two control plots (Fig. 20a). One block is represented in Fig.20a. A prototype installations were completed during 1993. The additional blocks, each located in the organic high marsh, have been established and are currently fitted for 1994 when inundation frequency will be increased and the plots disturbed by additon of wrack. This design tests disturbance effects from wrack deposition with and without associated inundation increase (MM Ho-6). We will include further testing of this hypothesis at the Mill Creek Experimental marsh as part of the tidal creek headward erosion simulation experiment described below.

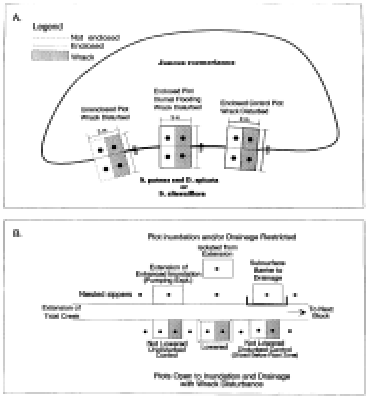


Figure 20. Mainland marsh long-term experiments. Each panel represents treatments in one block. Treatments will be randomly assigned to plots within replicate blocks. (a) Pumping experiment. (b) Headward erosion of tidal Creeks Experiment.

Tidal Creek Headward Erosion Simulation: Mill Creek marsh, like the Phillips Creek marsh, is in the Machipongo drainage system and is located landward of Fowling Point marsh. In addition, Phillips and Mill Creeks are connected by the Eastern Lead, an important tidal channel. The Mill Creek marsh site selected for manipulation is approximately 8 ha, bordered on two sides by small sandy islands or "necks", partially blocked at one end by a causeway, and connected to Mill Creek via a short tributary. A randomized block design will be used of at least 5 blocks with elevation and disturbance nested within exposure to increased tidal flooding will be used. One block is represented in Figure 20b. The two plots adjacent to the extension will receive enhanced flooding in contrast to the third "isolated" plot (MM Ho-3, 5). One of these two plots will have a plywood barrier embedded into the soil near the extension to restrict drainage such that comparison with the other "adjacent" plot tests MM ho-4.

The plots below the extension in Fig. 20b provide alternate testing of MM Ho-3, 5, and 6. the design is similar to that used in the pumping experiment with disturbed and undisturbed controls, a plot with enhanced inundation (this time by lowering the marsh surface as previously described), and nesting within each treatment for the influence of wrack deposition. The lowering will enhance inundation beyond that achieved by extending the creek alone. Plots will be 2 m long by 3 m wide, oriented with the widest portion of the plot parallel to the ditch (Fig. 20b). With this method of simulating sea-level rise there is less control of hydrology than with pumping but greater ability to mimic sediment transport and rising sea-level effects in upper tidal creeks. This will allow us to directly address MM Ho-3 through 7 by monitoring changes in the biological, chemical, and physical characteristics of the manipulated areas (Table 3).

Connection to modeling: Part of our effort on marshes is to identify and quantitatively model depositional and erosional mechanisms on marshes in response to tidal and storm-induced flows (Wiberg). We have also developed a mechanistic model of salt marsh organic matter accumulation based on plant production and decay and constrained by sediment physical/chemical properties (Nuttle and Blum). Results from the proposed experiments and continuation of experiments at the Mainland Marsh Site will allow us to test the validity of our model for differing sediment properties that are determined by differences in tidal inundation frequencies. In the long-term, we propose to link the sediment transport and organic matter accumulation models to allow us to predict patterns of marsh accretion and loss (Nuttle, Wiberg, Blum, Brinson, and Christian).

LONG-TERM DATA SETS

The holdings of the VCR long term data sets are presented in Table 4a&b.

THE FIVE CORE AREAS

The five core areas provide a common currency with which to compare the four main VCR LTER research sites, as well as other LTERs and LMERs. Additionally, the core-area work provides a long-term set of reference measures for comparison with our long- and short-term experiments. At each of the four research sites, we measure primary production, organic matter accumulation, and trophic structure within the context of large transient and small progressive changes in the position of the the free surfaces that result from disturbance, the fifth core area. The core area measurements we make are dictated by the characteristics of the site and the hypotheses being addressed at each of the sites and thus are not necessarily the same at all research sites since the variety of states at the VCR is so diverse. As a preamble to the discussion of our work in the five core areas, an overview of activities is provided in Table 5 and Table 6 lists the hypotheses that directly appply to core area measurements.

Primary Production

Primary production on the VCR Megasite is assessed on large spatial and temporal scales using remote sensing techniques. Aerial photography and satellite imagery are used to examine landscape-level vegetation responses to changes in the intersections of the three free surfaces over time. With our library of high resolution aerial photographs, we can map important landscape elements back more than 45 years. Approximations of long-term net production are based on differences between area-based biomass estimates for various land-cover types. In order to use remote sensing to "scale up" site-based studies of primary production, we are collaborating with NASA on the use of advanced satellite and airborne scanners (TM, AVIRIS, and MODIS) to estimate primary production over wide areas for short time frames. MODIS, AVIRIS, and TM data, along with data from a ground based sun photometer (for atmospheric correction) were collected as part of the SCAR-A campaign during the summer of 1993. We intend to extend this collaboration in a joint LTER/NASA proposal aimed at calibrating MODIS-based remote sensing techniques for measuring land cover, primary production and leaf-area index.

At the North Hog Island Chronosequence Site, we have established permanent vegetation plots across the dune-swale chronosequence where the dominant plants are *Myrica* and *Ammophila*, a keystone species (see Relationships, page PD 6). We measure above ground biomass annually as peak standing stock and leaf area index in the *Myrica* thickets. Above ground production *Myrica* is measured as a relative index based on number and length of new shoots produced each year and root turnover is measured using mini-rhizotrons for all plant associations along the chronosequence. These measures focus on the relationship of primary production to dune age, depth to the fresh water table and nitrogen availability (see page PD 21).

The approach used for the Hog Island Bay Marshes and Lagoon Site includes 1) a series of permanent *Spartina alterniflora* (also a keystone species) plots in recently deposited substrate (< 20 years) and older sediments (> 60 years, but estimated to be > several hundred years) and 2) a transect of permanent water column stations from mainland tidal marsh creeks, across the lagoon, in barrier island marsh creeks, to an ocean inlet. The positions of the marsh vegetation plots are stratified based on the relative position of the land and sea water free surfaces and include high and low marsh plots. Above ground production in the lagoon and barrier island marshes is measured using the method of Morris and Haskin (1990). Peak standing stock is also measured in four marshes in the lagoon. Along the water column transect, phytoplankton standing stock is measured monthly as chlorophyll-a concentration. Beginning in summer 1994, we plan to measure phytoplankton production on a quarterly basis using radiolabeled bicarbonate incorporation (Malone 1982).

In the mainland marshes, we have established a series of permanent vegetation plots in the organic high marsh and mineral low marsh where we measure both above and below ground plant production to study the role of disturbance in maintainance of plant diversity and the relationship between frequency of tidal inundation and allocation of biomass to above and below ground portions of the plants. These plots include the keystone species, *Spartina alterniflora*, as well as *Spartina patens*, *Distichlis spicata*, and *Juncus roemerianus*. For above ground production of *S. alterniflora* we use the Morris and Haskin (1990) method, of *J. roemerianus* the method of Christian et al. (1990), and of *S. patens*/*D. spicata* association a sequential clip plot method. For below ground production we use the method described in Blum (1993).

Organic Matter Accumulation

At the Megasite scale, we have completed a synoptic survey of the percent organic matter in forested barrier island soils, in sediments of Hog Island Bay, and in barrier island fringe, lagoon, and mainland marshes. We will repeat this survey every 5 years: the next survey is scheduled for fall 1997. To understand the factors controlling organic matter accumulation, we measure 1) below ground production and decay at the Hog Island Bay Marsh/Lagoon and Mainland Marsh Transition Sites as described in Blum (1993); and at the North Hog Island Site, 2) root turnover and decay as described in Day (1993) and Weber and Day (1993) and 3) leaf litter fall and decay (by M. Harmon, Andrews LTER LIDET program). Additionally, at the Mainland Marsh Site we are working to determine the relative contribution of new vs. old organic matter to sediment organic matter accumulation by comparing organic matter in plots where organic matter produciton is prevented in comparison with untreated, adjacent plots.

We have been using wooden dowels to measure relative above and below ground decay rates at three marsh locations for three years. We will expand this effort to all of our main research sites and 3 long-term experiments during the summer of 1994. Through the use of this technique we will be able to compare relative decay rates among locations at the VCR LTER as well as with those LTER\qs and other long-term experiment projects that are participating in the LIDET study (see Intersite Activities, page PD 27).

Nutrient Movements and Transformations

Nutrient movement among landscape elements at the VCR occurs via groundwater transport and general circulation of lagoon water. To understand nutrient transport at the Megasite scale, we are examining the exchange of water between the ocean and the lagoon and characterizing the lagoon\qs hypsometery. Also, we have established a transect across Hog Island Bay where we measure N and P standing stocks (as well as other chemical/physical parameters) at 10 permanent stations. To understand the effect of disturbance and constraints on both primary production and organic matter accumulation, we monitor nutrient standing stocks of N and P in all of our primary production and organic matter accumulation plots at three of the main research sites (not the Megasite). Nitrogen pools and fluxes in both sediments, porewater, and plans are measured on the Lagoons and Marshes Site. We also measure salinity in a series of groundwater wells at the North Hog and Mainland Marsh research sites because of our concern with the relationship between the fresh-water and sea-water free surfaces. Many of our sites have anaerobic substrates which have a signficant impact on nutrient transformations; thus, we also monitor indicators of anaerobiosis such as dissolved oxygen and sulfide concentrations.

Nitrogen cycling is especially important at the North Hog Island Chronosequence and the Mainland Marsh Transition sites. Because plants along the North Hog Island Chronosequence are nitrogen limited (Day 1993, Weber and Day 1993), we measure N mineralization rates, symbiotic dinitrogen-fixation by Myrica, and collect data on atmospheric inputs of nitrogen in addition to standing stock measures. Mainland marsh sediments have elevated nitrogen concentrations with respect to lagoonal and island marshes. These differences may reflect the influence of agricultural practices on adjacent uplands or differences in the source of marsh sediments (i.e., flooded upland soils vs. recent oceanic deposits). We use a system of groundwater wells at the Mainland Marsh Site to monitor stable N isotope composition of upland groundwater, sediment pore water, and tidal creek water to elucidate sources of nitrogen input into the tidal creeks and lagoon. Because of the importance of marshes in nitrogen cycling, we have been measuring nitrogen mineralization, denitrification, nitrification, and dissimilatory nitrate reduction using *15*N-pool dilution techniques. Additionally, we will begin measurement of nitrogen gas fluxes to quantify N losses from the marsh.

Trophic Structure

The complex juxtaposition of free surfaces which characterize the VCR Megasite provides a unique opportunity to test theories which contrast the roles of isolation, habitat sufficiency and population processes in determining the composition of island faunas. In partnership with the Virginia Museum of Natural History, allozyme analyses of small mammals collected during multi-island surveys are being used to examine the effects of isolation on the genetic diversity of populations to attempt to reconstruct the colonization history of the islands and to identify population sources for the island populations. In Hog Island Bay, we are using stable isotopes to trace aquatic foodwebs and are comparing the VCR foodwebs with those of nearby Chesapeake Bay. At the scale of the North Hog Island Chronosequence we examine the relationship between the complexity and age of the vegetation and small mammal (consumer) populations using long-term census techniques coupled with structural habitat measures. At the Hog Island Bay Marsh Lagoon and Mainland Marsh Transition Sites we examine marsh surface utilization by sub-adult and adult nekton and the role of invertebrate burrowing activities on primary production. Total nekton abundance, microhabitat selection, size-frequency distribution, and species composition of resident and non-resident nekton are compared in regularly and irregularly flooded marsh areas. Preliminary work to examine the effect of fiddler crab burrow density on *S. alterniflora* production was done during the past summer. Similar experiments will be done in conjuction with the Tidal Creek Headward Erosion experiment.

Recently (Spring 1993) we began studies to determine the contribution of microorganisms to higher trophic levels and have been developing techniques (Garland and Mills 1991) to assess functional and structural differences in the microbial community of mainland marsh tidal creeks. We plan to initiate studies as part of the North Hog Island Chronosequence, in which we establish exclosures to assess the effects of herbivory on the compostion and structure of insular vegetation.

Disturbance

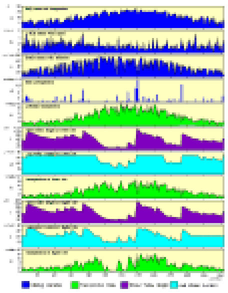
Understanding the role of disturbance in system dynamics is a critical part of our research program. It is our view that disturbance 1) is essential to the maintenance of certain system states, 2) regulates succession, 3) changes system states, and 4) is responsible for the VCR\qs diverse landscape. Disturbance occurs mainly in the form of coastal-storm related phenomena. Regular, predictable fluctuation of the sea water free surface is commonplace throughout the system, and includes 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. Superposed on these patterns are the aperiodic disturbances such as storm surge flooding, sediment and wrack depostion, erosion, and fires. Although tropical storms are infrequent -- several landfalls at the VCR per century since 1650 -- the magnitude of their disturbance is great. Overwash events move tremendous volumes of sand and salt water resulting in saline intrusions into fresh water stores of the islands and mainland. We have installed a system of measurement stations at the VCR Megasite scale that, when coupled with appropriate aerial and satellite images, permits long-term monitoring of both regular relatively high frequency fluctuations, and aperiodic, lower frequency disturbances. In addition to continued monitoring disturbance events, we collect supplemental information at the North Hog Island Chronosequence, Hog Island Bay Marsh and Lagoon, and Mainland Marsh Transition Sites to determine the extent of disturbance (erosion, shore-line change, salinity changes, etc.) and to establish new baselines.

SYNTHESIS AND MODELING

VCR modeling efforts brings a diverse array of modelers and modeling approaches includeing state variable change models, disturbance frequency models, material flux model, and sediment dynamics models, to bear on the central problem of understanding state change and dynamics on the VCR LTER.

Ecosystem State Models

Individual-based models (Huston et al. 1988) have been developed to simulate succession to a quasi-equilibrium or ecosystem steady state for the VCR and Luquillo LTERs, respectively, Bonan and Hayden 1990a, b; O'Brien et al. 1992) and are being developed 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 and parameterized with data collected in 1993 for 100 permanent plots on Parramore Island. This model will emphasize water balance and will be controlled, in part, by the "natural lysimeter" aspect of the VCR islands land and water table free surfaces and will be tuned using data collected in our water table draw down experiment (see Long-term Experiments page PD 16). 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 rainfall and little of the rainwater is lost as runoff because of the high hydraulic conductivity of the soils. 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 (ET) and evaporation from small ponds. Maximum LAI and life form vary with rainfall input and island topography (Eagleson 1982, Woodward 1987). We have developed an ET model for barrier island vegetation (Shao et al. 1994 (Fig. 21).



We will develop a FORET type model (Shugart 1984) of island vegetation "perched" on a barrier island "lysimeter" and parameterized using draw-down experiment data. 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 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 forested LTER sites (often in cooperation with the modeling group at the VCR LTER), the development of this model will also promote LTER intersite comparisons.

Threshold State Variable Change Models

A key tenet of the VCR research program is that when an ecosystem state variable(s) exceeds a threshold, 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 ISLAND 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. Rastetter's model ISLAND is a Markov model of vegetation on cell based transects across an island with a specified topography controlled by ocean delivery of sand and trapping of sand by plants (see also Noest 1991). These state variable change models will be parameterized with data from our Megasite surveys and form data collected at the Chronosequence Site.

We will determine temporal transition probabilities for ISLAND using a series of aerial photographs, collected at ~5 year intervals and with 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 (see Fahrig et al. 1993b). 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 us to test 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 rise rate 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 implications for a 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) met 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.

Wetland Models

A salt marsh model for use at the Lagoons and Marshes and mainland Marshes Sites is being developed to examine the effects of sea level rise and differential sedimentation on the growth, biomass, and species succession on the VCR salt marshes. The basis of this model is a refined version of the MARSH model developed by Zieman et al. (1977) for predicting salt marsh succession on natural and created marsh sites. Plant growth and succession are controlled primarily by physical variables such as tidal height and range, salinity, temperature, and light. These variables mirror the control postulated to dominate in such situations. Our sampling of long-term plots for biomass and productivity will serve to refine the parameters for local marshes.The model now simulates a series of points along a transect from the mudflats to the uppermost edge of the marsh. Future refinements will include the addition of nutrient dynamics and linkages to the sediment deposition models described below.

Disturbance Frequency Models

For the Chronosequence Site, Fahrig (1990a, b) determined that Markov transition probabilities for occurrence of Hog Island plants were strongly dependent on: (1) their proximity to and variability of the shoreline and (2) 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 km 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). Recently, we have written a statistical simulation model for both 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 to use the model to produce the null statistics against which the observed state changes since 1977 period can be compared and used as a model test. We 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. 1993).

Material Flux Models

Below ground organic matter is particularly important in marshes because it is the 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 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 focuses on net primary production, turnover, and decomposition of 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, 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 parameterization) 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.

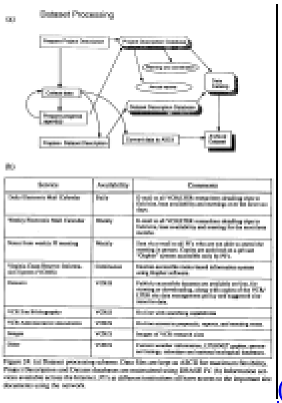
Sediment Deposition Model for Marsh Surfaces

We are developing a model of sediment deposition on marsh surfaces that will provide quantitative model relationships between flow events (storms) of various magnitudes and frequencies and resultant sediment erosion and deposition. We have added a co-PI Wiberg with the ability to develop this type of model. The model will consist of three linked models for flow and sediment dynamics in an intertidal marsh environment. A model will describe sediment deposition from a flow over a vegetated marsh surface like those at the Mainland Marsh Site. This depositional model will be linked to a second model that will provide initial flow and sediment conditions for the marsh deposition model based on flow and sediment transport conditions in the tidal creeks dissecting the marshes. The third component model will simulate combined channel and flood plain flow (e.g. Knight and Demetriou 1983). The conjunction of the three models will provide an integrated view of flow and sediment dynamics for the VCR LTER marsh systems. By combining these models with historical data on the frequency and magnitude of storm events, we will examine the recurrence times and magnitudes of depositional and erosional hydrodynamic events.

The model for sediment deposition and erosion on a vegetated marsh is currently being formulated. Sata and analyses are available from (experimental) studies of flow resistance due to vegetation (e.g., Turner and

Chanmeesri 1984; Pasche and Rouve 1985; Kadlec 1990). However little has been done to relate vegetation to erosion, transport, and deposition of sediment. Data to constrain and test our model of sedimentation on vegetated marsh surfaces will be collected on a low marsh in the Mainland Marsh Site. Previous work in this area includes characterization of sediment texture on the marsh surface and in cores, long-term accumulation rates from lead isotope dating, and an indication of the level of perennial sediment activity on the low marsh (Kastler 1993). Future measurements will include flow velocities and suspended solids associated with tidal flows on natural and lowered vegetated marsh surfaces (see Table 3).

DATA MANAGEMENT



The VCR LTER has a centralized data management system (Fig. 24a) which is the responsibility of a full-time data manager and a student assistant. The data manager is a project PI 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.

The data management system has four general objectives. The first is to provide archival storage of data. To accomplish this objective, on-line 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. We facilitate such access using Gopher and World-wide Web-based on-line information systems. Public data sets are available for downloading, along with suggested citations crediting specific researchers and the VCR LTER. The Virginia Coast Reserve Information System (VCRIS) also includes information on research calendars, current weather forecasts, personnel and bibliographic citations.

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. 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. 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 data sets 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.

INTERSITE AND NETWORK ACTIVITIES

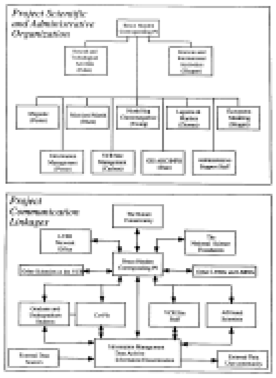
Network and Intersite activities of PIs are tabulated in Table 7.

RELATED RESEARCH PROJECTS

The funding history for LTER PIs for VCR related projects is presented in Table 8. In total, research support not provided by the LTER Core grant or from associated supplemental funding amounted to $2,811, 399 Some of these funds (e.g. to Galloway-NSF, Dolan-FEMA, and Hayden-NOAA) supported data collection on the site an addition to VCR data archives. Other funds went to improve technology used by VCR scientists at the site and in laboratory development (e.g. Blum-Va Mines, Hayden & Shugart-NASA, Macko-NSF, and UVa). The majority of the projects went to support question-driven research at the site. It is noteworthy that $56,000 of the related research projects came from proposal-based graduate student research and fellowship awards. As most of the VCR PIs get little or no money for summer stipend support, these external research projects are often the source of such stipends. Where the research missions of the external research and the LTER are compatible this relationship is highly synergistic. The research staff for many of the related research projects brings new scientists to the VCR research site. This expansion of the research community is significant and has resulted in the establishment of ESRA (Eastern Shore Research Association). This association is being developed with the assistance of the Virginia Marine Sciences Consortium. It will hold an annual scientific meeting, maintain an electronic bulletin board and maintain a GOPHER information system. This association will permit us to fully identify the wider research community that is interested in the Virginia Coast Reserve and Virginia's Eastern Shore.

DISSEMINATION OF INFORMATION

Information from the VCR/LTER has been distributed to individual scientists, governmental organizations, non-profit organizations and the general public (Fig. 24b and Fig. 25). A primary mode of distribution to the scientific community is via the Virginia Coast Reserve Information System (VCRIS), an Internet accessible information system using Gopher software. Since its initiation in the fall of 1992 it has been accessed in over 11,000 individual sessions from over 1,000 individual computers, including access from Germany, Great Britain, Japan, Austria, Switzerland and Australia. Data on shoreline change and water quality have been provided to Accomac and Northampton Counties. We have provided The Nature Conservancy with up-to-date aerial photography and collaborated with them on the development of vegetation and bird-nesting maps.



Communication of research results to the public has been through several avenues. Brochures describing LTER research were developed in conjunction with The Nature Conservancy and the Virginia Museum of Natural History. Articles outlining LTER research were published in the LTER Network News. Additionally, VCR researchers (especially Randy Carlson, our site manager) have been active in presenting talks to local groups. Members of the general public with Internet access have also been able to use VCRIS.

ARCHIVES AND INVENTORIES

The VCR LTER maintains a number of 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 using either 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 of the VCR are summarized in Table 9.

LEADERSHIP, MANAGEMENT AND ORGANIZATION

The signatory PIs of the VCR LTER are Bruce Hayden, John Porter and Herman Shugart. Hayden is the lead PI and is responsible for project management and administration (Fig. 25). Other than academic duties, all of Hayden's funded research is focused on the VCR and his time is fully invested in LTER duties. John Porter is full time on the LTER program and is fully versed in project management and administration and can serve in that capacity if called on. Shugart has served as lead PI and is able to serve if required. John Porter is the VCR data manager and is in charge of our GIS laboratory. Shugart is our leader in modeling and synthesis. The signatory PIs have primary responsibility for network and international activities.

During the academic year PIs in Charlottesville meet weekly and in the summer biweekly to deal with general administrative issues, advice and consent regarding policy and procedures and response to NSF, Network and Intersite activities. The minutes of these meetings are distributed through e-mail the following day and archived in the project GOPHER VCRIS which is open to all VCR Scientists. In academic year 1993, we began monthly project-administrative meetings with the graduate students. Quarterly, we hold meetings of all PIs. The location of this meeting varies according to needs. In addition to the PIs, officials of The Nature Conservancy are invited to attend these meetings. The winter quarterly meeting is our *All VCR Scientists* meeting. At this meeting oral research presentations (including REU presentations) are made and short written versions are subsequently collected, reprinted and bound for general distribution.

VCR scientists are classified as Signatory PIs, Co-PIs, Subcontracting PIs, and Affiliated PIs. Signatory PIs as indicated on the cover-sheet of this proposal have management and administrative responsibilities and oversight and coordination of research. Significantly, these PIs have the additional responsibility to insure project communication including, timely reports to the National Science Foundation, annual scientific meetings, intersite and international activities, weekly and quarterly administrative meetings, and long-term research planning sessions (Figure 25). Hayden serves as Corresponding PI and is the main contact with NSF and with the LTER Network Office (Figure 25). Co-PIs are scientists with a long-term research commitment to the VCR LTER research program and are responsible for the conduct of the research outlined in this proposal. Sub-contracting Co-PIs have part of their research financed by the Core VCR LTER grant through subcontracts with UVa. Affiliated PIs are scientists whose research is independently funded and have research missions consistent with the VCR LTER, support our data and reporting protocols and contribute to the data archives of the project including long term-data sets. Logistics support for their research is provided where possible. The scientists in each category are listed in Table 1 following the last page of the Results of Prior NSF Support section of the proposal.

In past years we used a committee of 5 outside scientists (Dr. John C. Kraft , Dr. Robert C. Harris, Dr. F. J. Vernberg, Dr. R. G. Wiegert, and Dr. T. Webb III) as an oversight committee.We intend to continue to rely on this committee eventhough we had to rely on substitute on occassion. For the renewal period, we propose to invite these 5 outside reviewers to our annual VCR All Scientist meeting and each year invite two reviewers to evaluate specific LTER activities, e.g. data management, modeling, marsh productivity, decomposition. In the year before our mid-term review and in the year before our next renewal we will bring our 5 external reviewers in for intensive reviews. We intend to invite experts from other LTERs and LMERs to help us in our internal reviews. These individuals know the requirements of the LTER program, have served on site review panels, and NSF LTER renewal panels. Project leadership will select the reviewers asked in each year to evaluate activities and move research programs forward. We will ask of these reviewers to submit a written set of recommendations.

NEW PROJECTS AND TECHNOLOGIES

GPS Kinematic Hypsometry

In 1994 we will begin a new long-term data acquisition program to determine water volumes in Hog Island Bay. The bay is comprised of extensive areas of shallow water, for which no existing depth profiles are available. Our boats will be rigged with digital fathometers and GPS units so that systematic bathymetric surveys can be conducted. These data sets collected will be used to determine long-term trends in bathymetry and estimate the horizontal fluxes of nutrients and sediment fluxes. Surveys of opportunity resulting from general boat traffic will also be added to bathymetric data sets. With this data, water volumes as a function of tide stage can be determined. Oertel, Porter, Hayden and Kochel will conduct these surveys.

GPS Kinematic Ecotone Surveys

The shoreline and the seaward margins of terrestrial vegetation are currently determined by occasional aerial photography. In 1994, we plan to begin mapping these ecotones using kinematic GPS equipment. The resolution of these new data (< 1m) will be better than possible using photographs (2 m) and can be done on short notice. This kinematic survey capability will permit accurate mapping of ground-visible ecotones and critical landscape margins. Kinematic surveys will be repeated from time to time to determine long term trends in ecotone positions. Hayden, Porter, Dolan and Kochel will conduct this work.

Chronosequence Exclosure Project

Animal exclosures are planned for the Summer and Fall of 1994. Exclosures will be placed at 4 locations along the North Hog Chronosequence. The exclosures will be placed on 10 yr., 35, yr., 70 yr. and 120 yr landscapes. Exclosures will be 5 m on a side and will be designed to exclude deer, rabbits and muskrats. Young, Dueser, Porter, and Moncrief will conduct these experiments.

Nitrogen Budget Project

In 1994, a nitrogen budget project will be started on Hog Island. The sites for this study are a series of vegetated pimples some of which have nitrogen fixing Myrica vegetation and others have no nitrogen fixers. An NADP station is located within a mile of these pimples and nitrogen fixing and dry and wet deposition data will be available. There are no runoff losses or losses to groundwater that are not recoverable. Galloway, Young, and Macko will conduct this project.

SUPPLEMENTAL SUPPORT

Supplemental support for the period 1988-1994 was used to 1) support undergraduate students (REU program), 2) develop technical capabilities and meet LTER network standards for emerging technologies (Technical Supplements), and 3) meet special research opportunities (SGER). The specific history of our supplemental support is given in Table 10.

Next chapter