

---

Long-Term Research at the Virginia Coast Reserve

Author(s): B. P. Hayden, R. D. Dueser, J. T. Callahan and H. H. Shugart

Source: *BioScience*, Vol. 41, No. 5, Coastal Barriers (May, 1991), pp. 310-318

Published by: [Oxford University Press](#) on behalf of the [American Institute of Biological Sciences](#)

Stable URL: <http://www.jstor.org/stable/1311584>

Accessed: 21/06/2014 17:21

---

Your use of the JSTOR archive indicates your acceptance of the Terms & Conditions of Use, available at  
<http://www.jstor.org/page/info/about/policies/terms.jsp>

JSTOR is a not-for-profit service that helps scholars, researchers, and students discover, use, and build upon a wide range of content in a trusted digital archive. We use information technology and tools to increase productivity and facilitate new forms of scholarship. For more information about JSTOR, please contact support@jstor.org.



*Oxford University Press* and *American Institute of Biological Sciences* are collaborating with JSTOR to digitize, preserve and extend access to *BioScience*.

<http://www.jstor.org>

# Long-term Research at the Virginia Coast Reserve

## *Modeling a highly dynamic environment*

B. P. Hayden, R. D. Dueser, J. T. Callahan, and H. H. Shugart

**C**onservation in rapidly changing ecosystems is especially difficult, and successful conservation requires knowledge of the dynamics of the systems (Odum 1959). Among the biosphere reserves, the Virginia Coast Reserve—a barrier island and lagoon system on the coastal plain of the trailing margin of the North American Plate (Figure 1)—has one of the most rapid rates of environmental change. The landscapes there are highly dynamic; each year winds, waves, storm surges, and tides return landscapes recently inhabited by man to a more pristine state.

Like several other reserves, the Virginia Coast Reserve has been designated a biosphere reserve by the US Man and the Biosphere (MAB) program, is a National Science Foundation Long-Term Ecological Research (LTER) site, and is managed by The Nature Conservancy. All three organizations are sponsoring research on the reserve.

The research program at the Virginia Coast Reserve focuses on three processes: succession, disturbance,

---

### System-state changes may become the most important dynamic for resource managers

---

and system-state change. Ecologist H. C. Cowles (1899) defined succession as a “variable approaching a variable”—a process with direction and speed following a target that is always on the move. At the reserve, a wide range of marine and terrestrial successional sequences are clearly evident and are confirmed in the historical photographic record. It is not clear that terminal seral stages are ever reached, because the frequency of disturbance is high and succession is often set back to earlier seral stages or diverted along alternate successional sequences.

In addition to succession and disturbance, fundamental transitions of system states have been documented. For example, on the reserve during this century, terrestrial forests and farmland have changed to salt marsh; maritime forests to grasslands; and clear-water lagoons with seagrass meadows to mud-bottomed, turbid-water lagoons.

A fundamental management question is: What is to be protected, saved, or conserved? Odum (1959) posed a dilemma: “It is rather amazing that, in a great many instances, organisms which man most desires to perpetuate are members of early seral

rather than late seral or climax stages.” The Virginia Coast Reserve’s history of disturbance and system-state changes further increases the management problems. Knowledge of succession, disturbance, and system-state changes is essential.

The Virginia Coast Reserve’s extreme rate of landscape change is a compelling attribute for research. In North America, only the Chandeleur Islands fronting the east face of the Mississippi Delta have a more dynamic barrier island coastline (Dolan et al. 1983). The seaward margin of the Virginia Coast Reserve’s coast 18,000 years ago was 100 km east of its current position, and the terrestrial landscape was part of the boreal forest biome of the time (Bonan and Hayden 1990, 1991, Emery et al. 1967). Were the sea level to rise at a rate consistent with global climate models charged with a doubled level of carbon dioxide, these islands would be quickly eroded and displaced toward the mainland of the Delmarva Peninsula.

These landscapes of rapid change are ideal for the study of landscape dynamics and ecosystem processes. The shoreline of the Hog Island research site on the Virginia Coast Reserve is eroding at more than 5 m/year along its southern end and accreting at more than 5 m/year along its northern end. Since 1852, 16% of the total reserve marshes have been lost to rising sea level, and the marsh on the lagoon side of Hog Island, in areas that are not replenished by sands washed across the island from the ocean beaches, has eroded 0.3 m/year

---

B. P. Hayden is a professor and H. H. Shugart is a professor and department chair in the Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22903. R. D. Dueser is a professor and department head in the Department of Fisheries and Wildlife, Utah State University, Logan, UT 84322. J. T. Callahan is associate program director for ecosystem studies at the National Science Foundation, Washington, DC 20550.



for the last 20 years (Knowlton 1971).

The LTER research program, begun in 1987 at the Virginia Coast Reserve, has identified a wide range of spatial and temporal scales appropriate for the study of succession, disturbance, and change of system states. This range is reflected in the diversity of studies under way at the reserve (Figure 2). In this article, we examine the research on the reserve and propose a general research framework for landscape and ecosystem dynamics that will help meet the reserve's research needs for the MAB program.

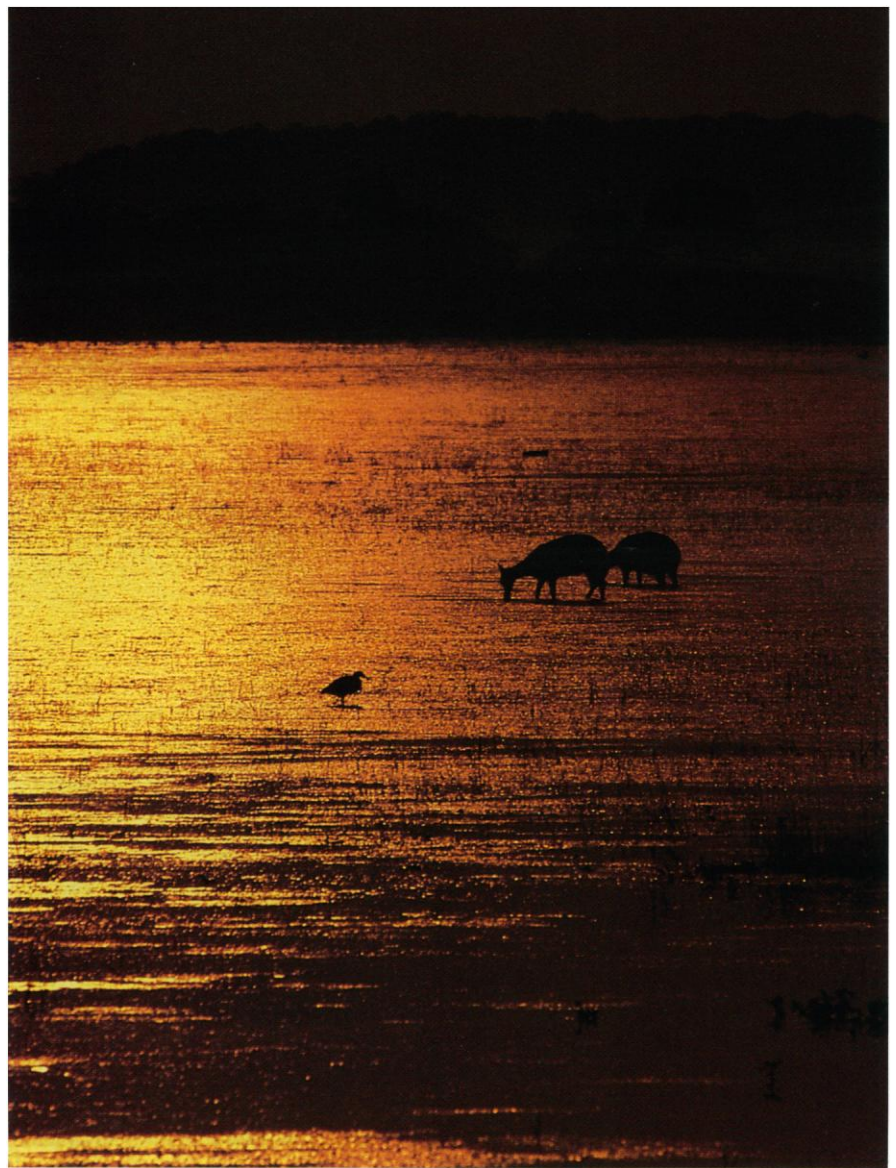
### Human impact and ecosystem functioning

Few places in the middle latitudes are totally free from a history of human habitation and landscape change. In the area that is now the Virginia Coast Reserve, humanity has had an impact on landscape and ecosystem dynamics for more than 300 years. In 1608, 2000 Indians of the Accomac and Accohannock tribes, which were part of the Powhatan Confederacy of mainland Virginia, used the islands and lagoons of the reserve. By 1700, all the Indians were gone. They were lost to the progress of English settlement and to smallpox (Upshure 1900).

English settlers used the barrier islands of the reserve, like many other coastal islands, as pasture and paddock (Badger and Kellam 1989). In the 1680s, most of the islands of the reserve were officially patented by the king of England as pastures, with each managed by a minimum of four herdsmen. The last feral cows were removed from Hog Island in the early 1980s.

The Virginia Barrier Islands were a center of the thriving industry of pirateering from 1680 to 1730. Formal settlements on the islands, especially Hog Island, began in the late 1700s (Badger and Kellam 1989). At that time, the landcover largely reflected grazing practices. During the 19th century, lighthouses, life-saving stations, homes, schools, churches, swank hotels, and elaborate hunt clubs were added as settlements flourished.

In 1903, the town of Broadwater



Above: Sika deer, on Assateague Island off the Virginia shore, feed in a marsh. Below: a newly hatched tern chick on Hog Island in the Virginia Coast Reserve. Photos: Terry Cook.



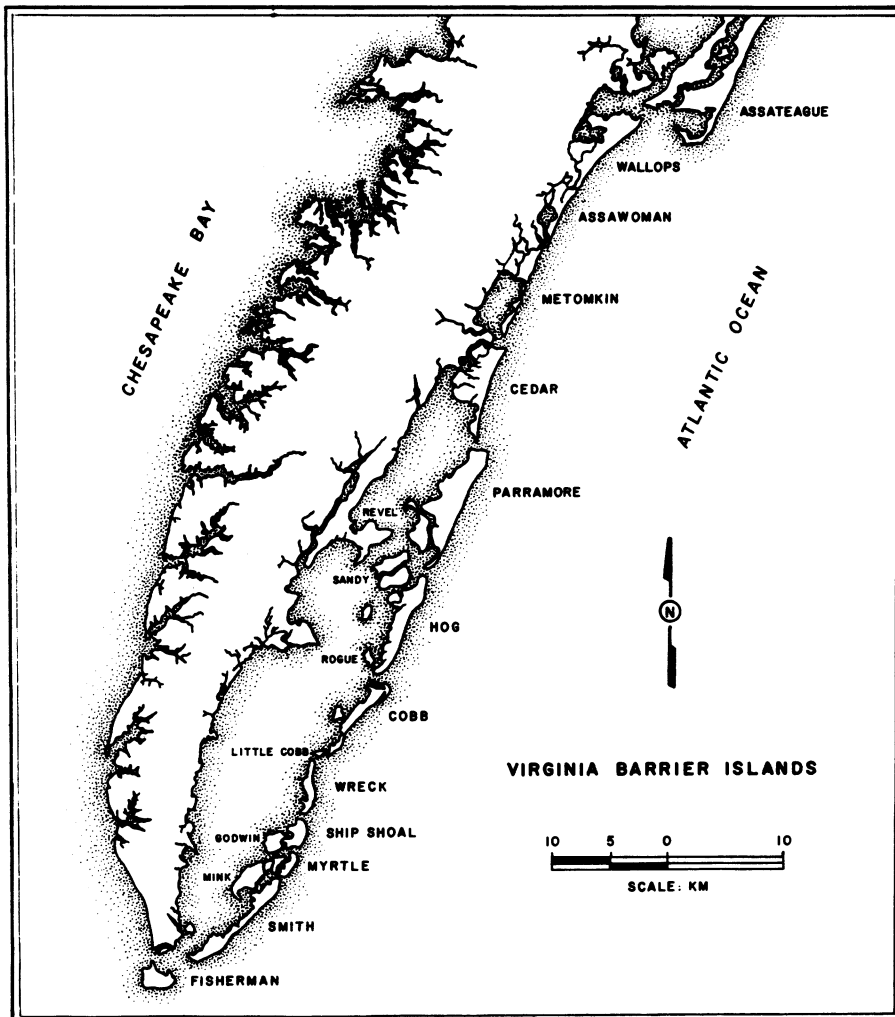


Figure 1. The islands and lagoons of the Virginia Coast Reserve.

on the south end of Hog Island was two miles behind the beach (Sterling 1903). By 1933, the shoreline had reached the town, and the surf washed around the foundations of the buildings (Life 1947). Today, all the land at the south end of the island has been reworked by winds, waves, and tides and is free from anthropogenic disturbance. The site of what was once the town of Broadwater is now hundreds of meters offshore (Figure 3). With these changes, the large dunes on the southern half of the island were eroded away, the freshwater table largely disappeared, and the forest died off. Broadwater was abandoned in the 1930s, and the remaining buildings were moved to the mainland town of Oyster. Today, the south end of the island is a sparse grassland on a sandy terrace with a fringing marsh on the lagoon side of the island. Evolution of

the landscape and its ecosystems is now little influenced by man.

### Coastal-barrier and ecosystem functioning

Barrier islands, like those of the Virginia Coast Reserve, make up 8% of the shoreline of North America (Dolan et al. 1975). Most of these areas are along the US Atlantic, Gulf, and Arctic coastlines.

The coastal plain of the Delmarva Peninsula slopes gently seaward to a broad submarine continental shelf. The shore zone, or interface between the land and sea, has a series of barrier islands 3 to 20 km offshore. The islands are 2 to 14 km long, 1 to 2 km wide, and 1 to 9 m elevation.

Vegetation on the islands is primarily grasses and shrubs; there are maritime forests of pine and oak on the

wider, higher islands and in sheltered areas (McCaffrey and Dueser 1991). The lagoons or bays behind the islands are shallow, and many have large tidal mud flats and marshes. Tidal range, the difference between high and low tide, is approximately one meter. Average daily wave heights are low, ranging from 0.5 to 1 m. Winter extratropical storms generate deep-water waves, which are the principal agents of landscape change; these storms can produce deep-water waves up to 10 m in height. In addition, storm winds may elevate water levels (storm surge) by as much as 2 m. Hurricanes (tropical storms), which occur less frequently, also cause major landscape changes, especially near their landfall.

Landward of the lagoons or bays is the mainland of the Delmarva Peninsula. The rural terrestrial watershed draining into the Virginia Coast Reserve lagoons is 2 to 24 km wide.

The barrier islands of the reserve, like those elsewhere along the Atlantic Coast, are migrating landward (Fisher and Simpson 1979, Kraft et al. 1973). Tree stumps and peats, remnants of island forests and bayshore marshes, are found on ocean beaches and are evidence of the landward movement of the sands that make up these islands.

Beach sands washing across the islands during severe storms and inlet formation are the two main means of moving sand from the beaches landward to the lagoons and thus in the transgression of the islands landward. During severe storms, the beach zone and seaward dunes are overtopped by high water levels and waves. As this sediment-charged mass of water spills across the beach and flows overland to the bayshore, a layer of sediment is removed from the beach and added to the island's interior—a process that transforms the shape and position of the island but conserves its total sediment mass. During storms, beach and nearshore sediments are carried through the inlets and into the lagoons. These inlet shoals may then be invaded by marsh grasses to form new marshes.

### Succession, disturbance, and system-state change

System concepts such as equilibrium, quasi-equilibrium (steady state), and



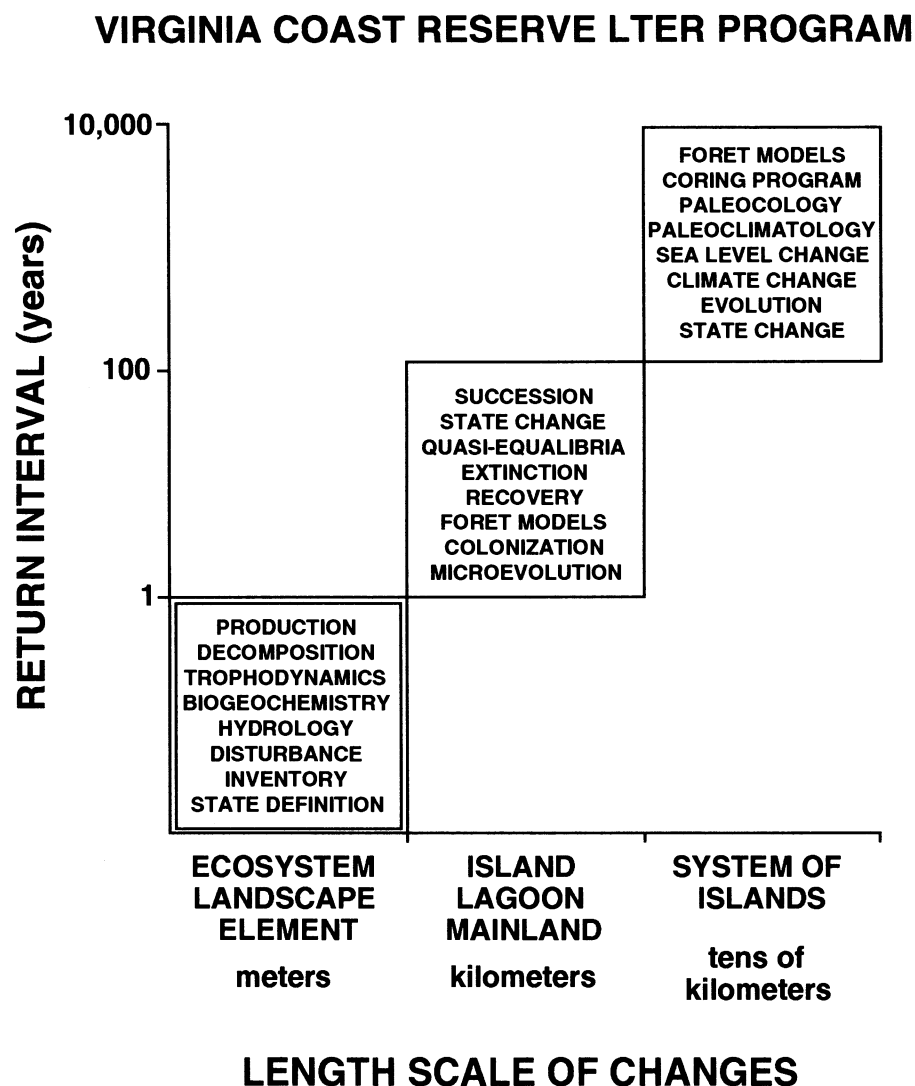
perturbation have utility only when the temporal and spatial scales of the system under study are specified. Quasi-equilibrium identified at one space-time scale may not hold at smaller or larger scales. This scaling distinction is especially important in system modeling and field verification.

We view ecosystems as being observationally defined by a set of selected state variables of the system. This multivariate set constitutes the observational hyperspace of the ecosystem. With statistical ordination procedures, the great dimensionality inherent in all ecosystems can be reduced to a smaller number of composite variables (Lamb 1984), and the dynamics of the system can be studied. The time history of an ecosystem in its reduced hyperspace is schematically illustrated in Figure 4. In this frame of reference, succession, quasi-equilibrium, disturbance, and state change can be viewed in a Euclidian fashion.

Our long-term research design capitalizes on links between the temporal and spatial scales in ecosystem and landscape dynamics (Figure 2). Spatially, the reserve has a hierarchy of three levels: the chain of islands and lagoons, the islands and their lagoon watersheds, and the landscape elements that compose the islands and their watersheds. We deal with the time domain in terms of return intervals. For example, high tide has a return period of slightly less than 0.5 days, daily thermal maximum has a return period of one day, and synoptic weather disturbances have a return period of approximately seven days. Three regions of a space-time domain are shown in Figure 2 to classify studies under way at the reserve. The lower-left region includes the long-term core-monitoring programs required at all LTER sites.

### Quasi-equilibrium

Most of our LTER monitoring, observational and experimental research, and deterministic modeling focus on quasi-equilibrium, or steady-state, dynamics. The state variables that have been monitored during this century include above-ground net primary production, below-ground organic carbon accumulation, seasonal



**Figure 2.** Summary of the Virginia Coast Reserve LTER research program in terms of the spatial and temporal scales of the dominant system processes. Ongoing research activities are indicated in the diagram. The double-framed box indicates core-area monitoring requirements for all LTER sites.

and longer-term floristic changes, elevations of fresh and saltwater tables, and biogeochemical fluxes. All LTER sites are required to monitor these five variables.

Experimental studies are also focused on quasi-equilibrium ecosystem processes. It is as important to know how ecosystems are maintained as it is to know why and how they change. In essence, these research activities identify essential state variables of the system. These same variables are used in the computer models now being developed. We assume that the state variables we are measuring reflect quasi-equilibrium conditions at the decadal time scale and that we can

thus define the contemporary state of the systems under study. From this baseline succession, disturbance and state changes are examined.

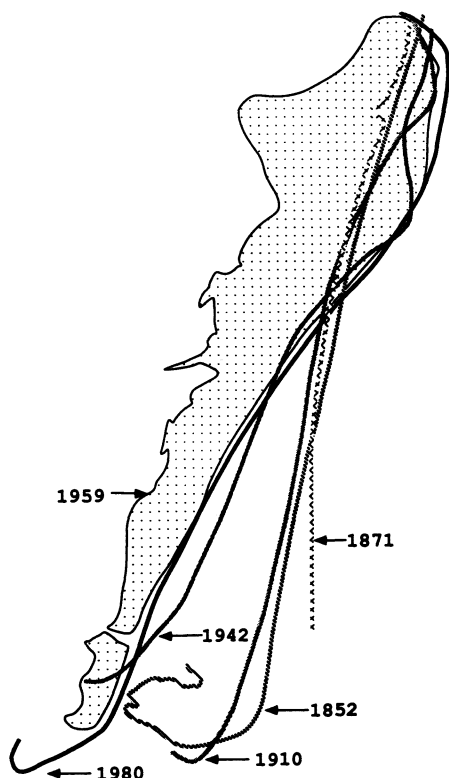
### System perturbations

Perturbations arising external to the systems are of three types: periodic, episodic, and trend. Periodic perturbations in our studies largely are those with return periods of less than one year and include the annual, diurnal, and tidal cycles. Much of our routine monitoring focuses on system-state variables and their variation on these time scales.

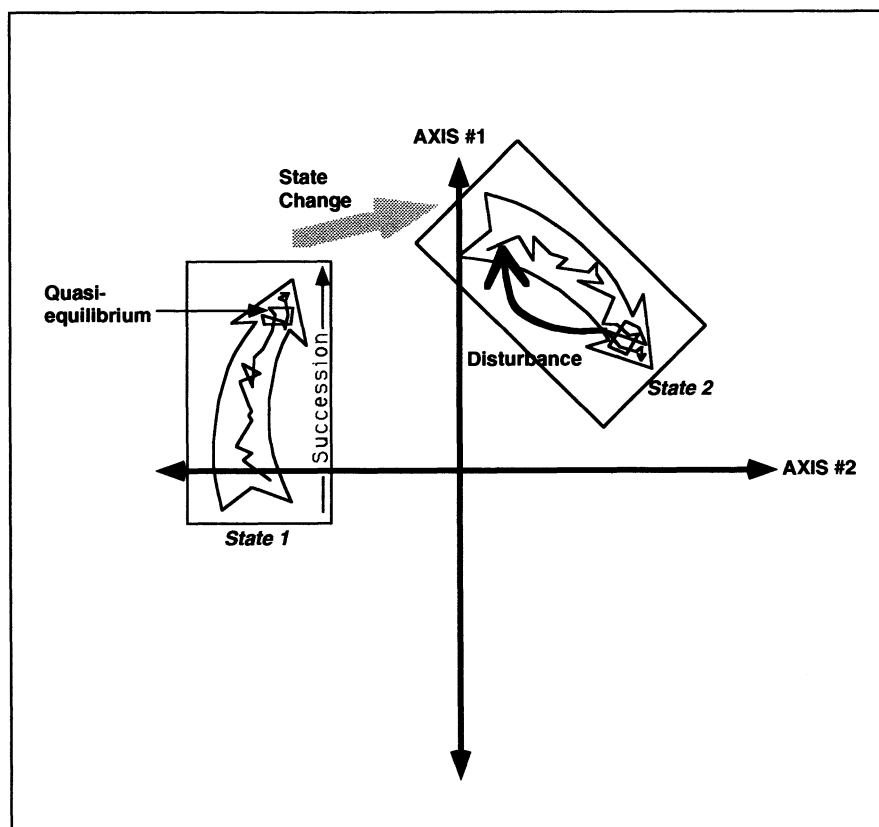
Episodic perturbations often cause

major changes in system dynamics, including alterations in successional sequences and system-state changes. Recent history of the reserve indicates that episodic perturbations of three types are important: severe weather, species extinctions, and alterations in land-use practices. The Ash Wednesday storm of March 1962, the extinction of the sea grasses in the reserve lagoons in the 1930s, and the initiation and termination of agricultural land-use policies by The Nature Conservancy are episodic phenomena that have recently led to fundamental changes in landscape and ecosystem pattern, structure, and dynamics.

Most of our emphasis to date has been on recurring extratropical and tropical storms. The two dominant geophysical trend perturbations being studied are relative sea-level rise and systematic changes in storm frequency. Sea-level rise and the action of individual coastal storms are responsible for the transgressive nature of the reserve barrier islands.



**Figure 3.** Hog Island shoreline positions at various survey dates between 1852 and 1980. The main street of the town of Broadwater on the south end of Hog Island was located along what was the position of the 1942 shoreline.



**Figure 4.** Succession, disturbance, quasi-equilibrium, and state change viewed in ecosystem hyperspace. Axes 1 and 2 are linear combinations of system-state variables obtained by statistical ordination procedures. The boxes indicate states of the system with the direction and pace of succession to a quasi-equilibrium condition.

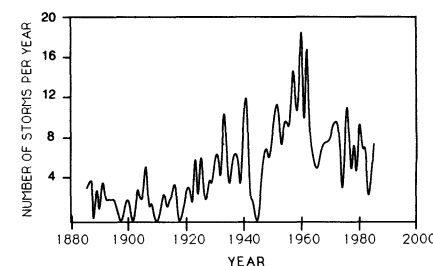
We have assembled a detailed record of hurricanes since 1620. Each extratropical storm since 1885 has been recorded, and the wave climates of more than 1200 storms since 1942 have been calculated. Erosion rates associated with these storms, the depth of flooding of the islands by oceanic waters, and the sand transport across the islands due to these storms are being extracted from historical aerial photographs. Vegetation cover changes in response to storm surges for last 50 years are being tabulated from historical aerial photographs.

The Holocene history of the reserve's environments (marshes, tidal deltas and inlets, and subaerial beach deposits) is being reconstructed by using data from a sediment-coring program. The results of the coring program are being related to the history of relative sea-level rise and also are used in the construction and evaluation of simulation models of the islands. Future sea-level changes can

be simulated and predictions made. Besides the current relative sea-level rise along this section of the Atlantic Coast of 1.5–2 mm/year (Braatz and Aubrey 1987, NAS 1987), the frequency of coastal storms has changed during the last century (Figure 5).

### Succession disturbance and state change on Hog Island

The succession sequences on the Lake Michigan dune identified by Cowles



**Figure 5.** The frequency of coastal storms off the coast of Virginia's Eastern Shore (1885–1988).

(1899) are similar to those of the past 90 years on the north end of Hog Island. The north end of Hog Island is accreting seaward at more than 5 m/year. New dunes and interdunal ponds develop as the shoreline moves seaward. Through detailed analysis of historical aerial photographs and survey charts, a time-space cross-section of the island has been constructed (Figure 6). The oldest terrain on the north end of the island dates to the 1870s. Since 1871, the shoreline has moved seaward almost a kilometer. The pace and direction of succession are documented for this system.

The south end of Hog Island is eroding at more than 5 m/year. *Spartina* and *Anemophila* grasslands are buried, and the succession sequence common at the north end of the island is terminated. The grasses begin encroaching seaward after the storms. The frequency of storms is such that succession rarely progresses past the stages of grassy or shrub-and-grass sand terrace. In this case, a seral stage is maintained by storms and sediment redistribution.

In the second half of the 1800s, the south end of Hog Island was accreting seaward, much as on the north end of the island today. Substantial dunes and forests existed on the south end of the island at that time. Before the turn of the century, the north end of the island was but a narrow strand of beach with a grassy sand terrace and a fringing marsh on the lagoon side. It was eroding rapidly, much as the south end of the island is today. Apparently, around 1900 the state of the system changed in a fundamental way. The direction and relative stability of successional sequences at the two ends of the island was reversed. We view this transition as a system-state change. The south end of the island had considerable high ground, with a sufficient resource of fresh

groundwater to sustain a pine and oak maritime forest. Today the forest is gone, replaced by a sandy grassland.

Succession, disturbance, and system-state change have been going on simultaneously on Hog Island during this century. System dynamics at the decade time scale need to be studied as a whole. A long-term program of monitoring and experimentation is needed to study these contemporary processes. On longer time scales in both the past and into the future, modeling and model testing is an essential research tool. Three model-based studies are under way at the Virginia Coast Reserve.

## FORET model applications

After the last Ice Age (18,000 years ago), sea level was more than 100 m lower than today, and the shoreline in the region of the reserve was approximately 100 km seaward of its current position. Peat deposits found by scallop fishermen at this distance offshore contain freshwater sphagnum peat with a decidedly boreal forest pollen assemblage (Emery et al. 1967).

At some point since the last Ice Age, there was a system-state change at the biome level. We have estimated the periglacial climatic conditions for the Virginia coastal area for 18,000 years ago and used these climatic estimates to drive a boreal forest FORET model (Bonan 1988, Bonan and Hayden 1990, in press). The model forests proceed through a successional period (Figure 7) to a quasi-equilibrium condition after approximately 300 years. Quasi-equilibrium model forest output statistics were then verified against the pollen assemblage in the freshwater peats found on the continental shelf off the Virginia coast.

Mean monthly air temperatures for the area 18,000 years ago were taken

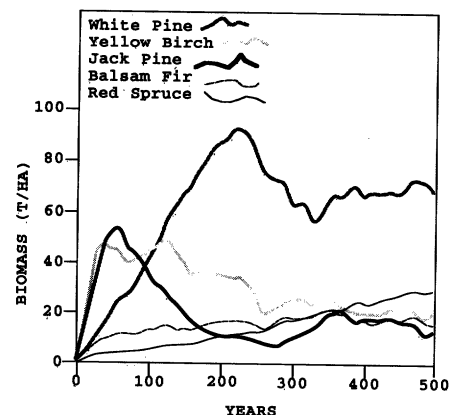


Figure 7. Model output statistics of a FORET model for the Eastern Shore for the end of the last Ice Age (18,000 years ago). Model equilibrium was reached after approximately 300 years, as a white pine-dominated boreal forest. Biomass is given in tons per hectare for each species.

from Moran (1972). Summer temperatures were approximately 10° C cooler than they are today, but winter temperatures were similar. These moderate winter temperatures precluded the existence of permafrost on the reserve. Periglacial precipitation was estimated to be the same as today, except average rainfall was less due to the lack of tropical storms and hurricanes (Wendland 1977). Because the fronts and frontal storms now experienced in the fall through the spring would also have been present in summer due to the cold, glaciated high latitudes, modern October-through-April cloudiness values were used for all months of the year. Monthly total radiation was not adjusted to account for orbital variations but was adjusted for cloudier summertime conditions. Given these climate conditions and a pool of boreal and transition-forest tree species, Bonan's FORET model was run with 50- and 200-year fire-disturbance return intervals for 500 model years.

The FORET model boreal forest of 18,000 years ago for the Virginia coastal plain was dominated by white pine (Figure 7). Red spruce, balsam fir, jack pine, and yellow birch were subdominants. Percent composition at the genus level (pine, spruce, fir, and birch) for the model and the fossil peat pollen observations are excellent matches with no more than a 5% deviation. The notion of a white pine-dominated boreal forest is sur-

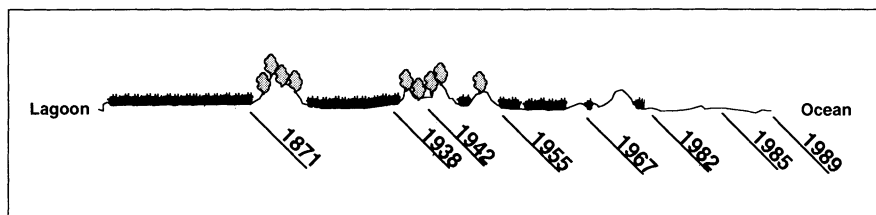


Figure 6. Cross-section of the north end of Hog Island indicates the location of the shoreline at eight dates between 1871 and 1989. Current vegetation is schematically indicated.

prising, because white pine is not a dominant in modern boreal forests.

As a further check on the model, Bonan adjusted the periglacial climate conditions by using typical atmospheric lapse rates (temperature change with altitude) for an altitude of 1000 m to simulate periglacial temperatures in the Blue Ridge Mountains to the west. The quasi-equilibrium model output forest for this run was a more typical spruce, jack pine, and birch boreal forest with little white pine. The colder climate at 1000 m altitude in the Blue Ridge Mountains was sufficient to generate a more typical boreal forest.

The FORET model results suggest that the Virginia coastal plain boreal forest of 18,000 years ago was of a substantially different composition compared with modern high-latitude boreal forests. FORET models for the current pine-oak maritime forests of the reserve are under development, so historical and projected climate

changes can be assessed in terms of contemporary barrier island forests. Efforts to model the change of state from boreal to pine-oak maritime forest remain as future work.

### Island, lagoon, and mainland marsh dynamics

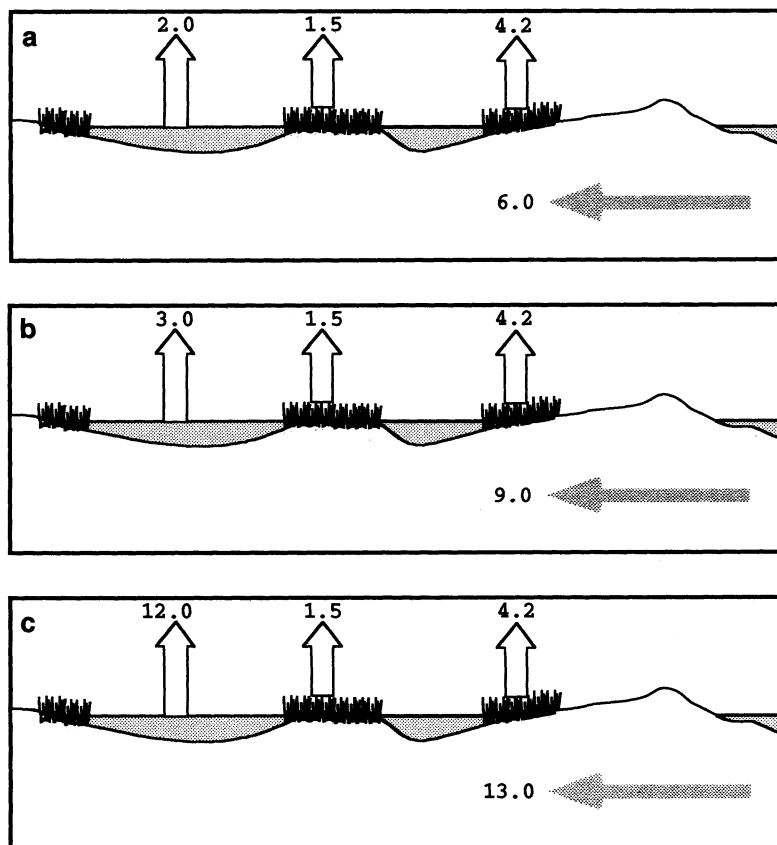
The lagoons of the reserve are open waters containing marshes of three types: mainland-fringing marshes, barrier island-fringing marshes, and marsh islands. Between 15,000 and 8000 years ago, relative sea-level rise was approximately 8.4 mm/year, largely resulting from the melting of the polar ice caps (NAS 1987, Ray et al. in press). Little is known about the status of the lagoons or even if they existed at this early date.

Between 6000 and 2000 years ago, the relative rate of sea-level rise was approximately 3 mm/year resulting from land subsidence and eustatic sea-level rise, and the lagoons were

open-water environments with little evidence of marsh islands (Harrison et al. 1965). After 1200 AD, land subsidence slowed, sea-level rise declined to a low rate of 1.3 mm/year, and marsh islands flourished from Assateague Island southward to the entrance of the Chesapeake Bay (Harrison et al. 1965). Since then, the rate of sea level rise has increased slightly to approximately 2 mm/year and marsh area has diminished.

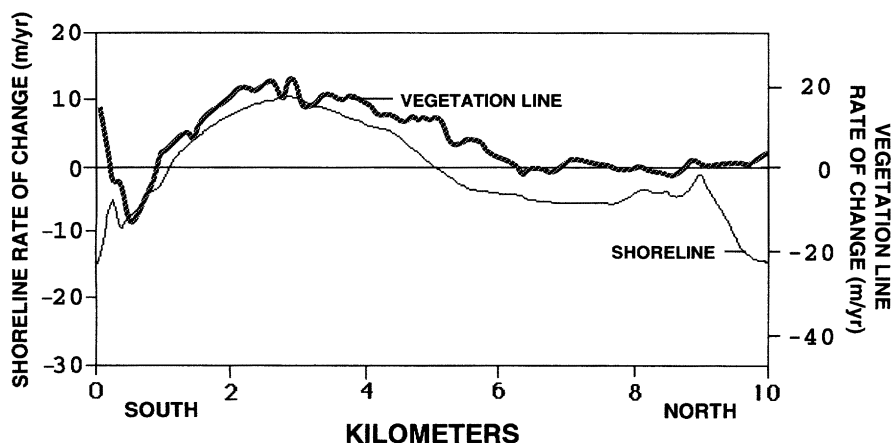
Marsh islands generally lack a ready supply of inorganic sediment, so their upward growth rate resulting from deposition of organic litter is approximately 1.5 mm/year (NAS 1987). For the reserve, there is now an annual net loss of marshes as they are being converted to mud flats and open waters. Analysis of survey maps shows there has been a 16% loss of marsh in the lagoons between 1852 and 1968, most of which involved island-marsh loss (Knowlton 1971). In contrast, the barrier fringing marshes of the seaward side of the lagoon, where sands are transported from ocean side beaches by overwash across the island, easily keep up with current relative sea-level rise. Estimates for their upward growth rates are 4.2 mm/year (NAS 1987). Where beach sands are not washed across the island, the marsh-lagoon shore-line is eroding at 0.3 m/year.

The dynamics of the lagoons and marshes of the reserve must be studied on recent, historical, and paleoecological time scales. Although the rate of relative sea-level rise has slowed in recent decades (Hicks and Hickman 1988), there remain concerns about an accelerated sea-level rise that may result from greenhouse warming. Given such concerns, it is useful to extend lagoon-marsh research findings to conditions in a warming world. Figure 8 illustrates our estimates of lagoon-marsh landscape status for current conditions and for two rates of accelerated sea-level rise (3 mm/year and 12 mm/year). Under both scenarios, marsh islands would be lost at an accelerated rate, but losses of fringing marshes would be increased only for the higher rate of rise. Our research suggests that the reserve would change under the conditions of a greenhouse-warmed Earth, but that the changes expected are not without



**Figure 8.** Barrier island, marsh, and lagoon dynamics under (a) the current rate of rise of sea level (2 mm/year), (b) a 3 mm/year sea-level rise, and (c) a 12 mm/year sea-level rise. The vertical arrows over the lagoon and fringing marshes indicate the upward rates of rise of the marsh surface due to organic and inorganic deposition. The horizontal arrows indicate the rates of westward transgression of the barrier island in millimeters per year for each sea-level-rise scenario.





**Figure 9.** The rates of change of the shoreline and the vegetation line (grass to open-sand transition) at 50-meter intervals along Hog Island (1942–1987). Positive numbers indicate a landward displacement of the line (erosion), and negative numbers a seaward displacement of the line (accretion).

historical precedent there (Harrison et al. 1965, Ray et al. 1991).

Aerial photographic monitoring of marshes of the reserve is under way. Every three to six years, aerial photographs are taken and used to update marsh shoreline erosion statistics. Through such research monitoring, reserve managers can place landscape changes in proper perspective. Studies of marsh productivity, biogeochemistry, and upward and inland growth rates are also in progress.

In the contemporary record, two marsh system-state transitions have

been identified. The first is a change from forest and agricultural land to salt marsh. One of the islands, Mockhorn Island, along the western margin of the lagoon was farmed until the early 1930s. It is now a salt marsh. With the current relative rise of sea level in the area, periodic flooding due to astronomical and wind tides is expected to become progressively more common, and agriculture or forest maintenance will become impossible on other islands along the western margin of the lagoon and on the necks of the mainland extending

out into the lagoon, which are now primarily forested or used for agriculture. The second marsh state transition also is due to the rise in sea level. In some areas of the lagoon, this rise exceeds the rate at which the marsh islands grow upward, so the salt marsh becomes a tidal mud flat.

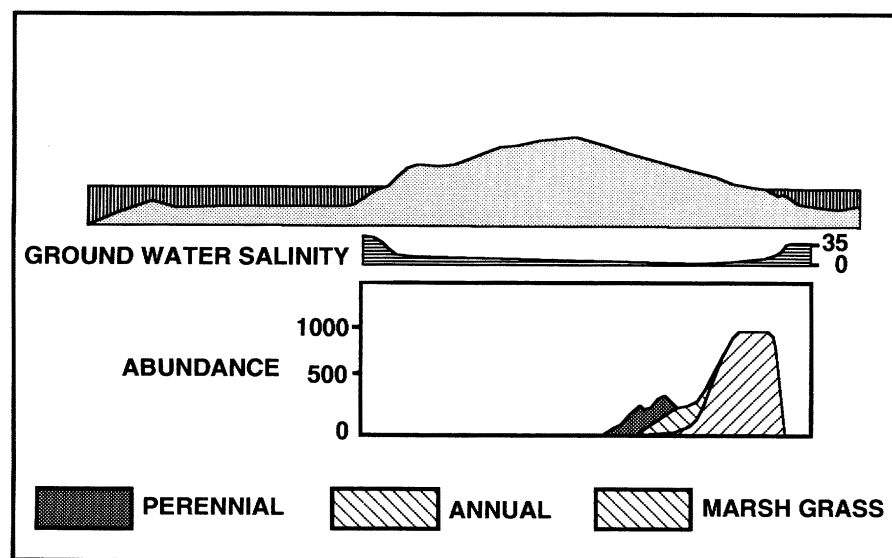
## Contemporary island dynamics

The barrier islands of the reserve are sand islands whose height above sea level depends on the height of highest storm surges and on the redistribution of sand by the winds to form dunes. Vegetative cover is closely coupled to elevation, local topography, and water-table salinity. The presence or absence of saline groundwater, the depth to fresh groundwater, and the distribution of aeolian sea salts and overwash marine waters are all controlled by sand elevations.

To understand a barrier island ecosystem, it is essential to have a clear understanding of the sedimentary budget of the island. To this end, an extensive monitoring program using historical and metric aerial photography is proceeding, and a stochastic/deterministic model (ISLAND) of island geomorphology, hydrology, and ecology has been constructed (Rastetter in press).

Historical photographs of the barrier islands of the reserve are available at five- to ten-year intervals from the early 1940s to the present. From this metric photography, we have measured the position of the high-water shoreline and the line separating active, mobile shore-zone sands and vegetation-stabilized sands. The rates of change and the standard deviations of these two lines are now known at 50-meter intervals along the 100-kilometer shoreline of the reserve (Figure 9). Mean erosion rates for the entire reserve are approximately 6 m/year. Local erosion rates as great as 12 m/year are common. In erosional areas, the active sand zone is encroaching landward at similar rates. Island grassland communities are buried as sands are transported inland during storms.

In a world warmed by greenhouse gases and having a 50% increase in rate of sea-level rise (3 mm/year), we estimate from our analysis of marsh



**Figure 10.** Schematic of the output of the model ISLAND at 30 years after the extinction of the dune grasses. New island topography (top; shaded area is sand and striped area is ocean and bay), groundwater salinity (middle), and abundance of vegetation cover (bottom) are shown. The island in this model is 2 km wide.

dynamics that the average erosion rate for the reserve will be 9 m/year. Should the relative sea-level rise be 12 mm/year, an average shoreline erosion of 13 m/year is expected (Figure 8).

The predictions of the ISLAND model now under development are in part driven by the rate at which sea level rises. By using these rates in the model ISLAND, we will generate a new morphology of the island and a groundwater table surface. By using elevations and depth to fresh water, we then estimate the vegetation covers using empirically derived vegetation transition probabilities in a Markov model (Rastetter in press). These same vegetation transition probabilities have been correlated with the historical record of disturbance frequency due to severe storms. The model can thus be used for both near-term disturbance studies and for long-term trend studies.

Figure 10 shows the results of an ISLAND model simulation of ecosystem changes 30 years after the extinction of dune grasses. Because systematic data from aerial photographs is available for the past 40 years, it will be possible to test our simulation models against these data.

Such simulation models should be useful to reserve research managers. For example, several species of nesting birds need the open, active sand zone just inland from the beach and seaward of the zone of vegetation-stabilized sand. The areal extent of this environment is a critical variable in the maintenance of breeding populations. The existence and width of the zone of suitable habitat depends on the frequency and magnitude of winter storms and the rate of sea-level rise. Model output statistics from ISLAND will be useful in developing stochastic estimates of suitable colony habitat extent under various scenarios of environmental change.

## Research and conservation

A central tenet of the biosphere-reserve concept is the requirement for ongoing, long-term research. The Nature Conservancy began its stewardship of the Virginia Coast Reserve with an extensive inventory research

program and has maintained a selective monitoring and research program. The LTER research program at the reserve is driven not by the needs of conservation agencies but by the need to resolve fundamental questions about the origin, maintenance, and change of pattern and structure in ecosystems. Although its goals are different, LTER research can still serve the cause of conservation by providing knowledge of the ecosystem's dynamics.

Reserve managers are aware that succession and disturbance are fundamental, essential ecosystem processes. Seral succession stages are recognized as ephemeral. Disturbance regimes such as fire and windfalls are now viewed as constructive rather than destructive and as system-maintaining rather than system-destabilizing. The notion that state changes are also valuable, when entire systems are considered, is not yet an entrenched notion. However, should the predicted global environmental changes be realized, system-state changes may become the most important dynamic for resource managers.

## Acknowledgment

This work was supported by National Science Foundation Grant BSR 8702333-02.

## References cited

- Badger, C. J., and R. Kellam. 1989. *The Barrier Islands: A Photographic History of Life on Hog, Cobb, Smith, Cedar, Parramore, Metompkin and Assateague*. Stackpole Books, Harrisburg, PA.
- Bonan, G. B. 1988. Environmental processes and vegetation patterns in boreal forests. Ph.D. dissertation, University of Virginia, Charlottesville.
- Bonan, G. B., and B. P. Hayden. 1990. Using a forest stand simulation model to examine the ecological and climatic significance of the late-Quaternary pine-spruce pollen zone in eastern Virginia, U.S.A. *Quat. Res.* 33: 387–415.
- . 1991. Forest vegetation structure on the eastern shore of Virginia circa 18,000 years BP. *Va. J. Sci.* 41(4A): 307–320.
- Braatz, B. V., and D. G. Aubrey. 1987. Recent relative sea-level change in eastern North America. Pages 29–46 in D. Nummedal, O. H. Pilkey, and J. D. Howard, eds. *Sea-level Fluctuation and Coastal Evolution*. Society of Economic Paleontologists and Mineralogists, Special Publication No. 41.

- Cowles, H. C. 1899. The ecological relations of the vegetation of the sand dunes of Lake Michigan. *Bot. Gaz.* 27: 95–117, 167–202, 281–308, 361–391.
- Dolan, R., B. P. Hayden, and S. May. 1983. Erosion of United States shorelines. Pages 285–299 in *Handbook of Coastal Processes and Erosion*. CRC Press, Boca Raton, FL.
- Dolan, R. D., H. Lins, and B. Hayden. 1988. Mid-Atlantic coastal storms. *J. Coastal Res.* 4: 417–433.
- Emery, K. O., R. L. Wigley, A. S. Bartlett, M. Rubin, and E. S. Barghoorn. 1967. Freshwater peat on the continental shelf. *Science* 158: 1301–1307.
- Fisher, J. J., and E. J. Simpson. 1979. Washover and tidal sedimentation rates as environmental factors in development of a transgressive barrier shoreline. Pages 22–34 in S. P. Leatherman, ed. *Barrier Islands*. Academic Press, New York.
- Harrison, W., R. J. Malloy, G. A. Rusnak, and J. Terasmar. 1965. Possible late Pleistocene uplift Chesapeake Bay entrance. *J. Geol.* 73: 201–229.
- Hicks, S. D., and L. E. Hickman. 1988. United States sea level variation through 1986. *Shore and Beach* July: 3–7.
- Knowlton, S. M. 1971. Geomorphological history of tidal marshes, Eastern Shore, Virginia, from 1852–1966. Masters dissertation, University of Virginia, Charlottesville.
- Kraft, J. C., R. Biggs, and S. Halsey. 1973. Morphology and vertical sedimentary sequence models in Holocene transgressive barrier system. Pages 321–354 in D. Coats, ed. *Coastal Geomorphology*. State University of New York, Binghamton.
- Lamb, H. F. 1984. Modern pollen spectra from Labrador and their use in reconstructing Holocene vegetational history. *J. Ecol.* 72: 37–59.
- Life Magazine. 1947. The best of Life. Jan. 27, 1947.
- National Academy of Sciences (NAS). 1987. *Responding to Changes in Sea Levels: Engineering Implications*. Marine Board, National Research Council, National Academy Press, Washington, DC.
- Odum, E. P. 1959. *Fundamentals of Ecology*. W. B. Saunders, Philadelphia.
- Rastetter, E. B. In press. *A Spatially Explicit Model of Vegetation-Habitat Interactions on Barrier Beaches*. Springer-Verlag, New York.
- Ray, G. C., B. P. Hayden, A. J. Bulger, and M. G. McCormick-Ray. In press. Effects of global warming on marine biodiversity. In R. Peters, ed. *Consequences of Greenhouse Effect for Biodiversity*. Yale University Press, New Haven, CT.
- Sterling, C. A. 1903. *Hog Island Virginia*. Charles A. Sterling, Norfolk, VA.
- Upshure, T. T. 1900. Eastern Shore history. *Virginia Magazine of History and Biography* 9: 93.
- Wendland, W. M. 1977. Tropical storm frequencies related to sea surface temperatures. *Journal of Applied Meteorology* 16: 477–481.
- Williams, L. H. 1937. *Pirates of Colonial Virginia*. Dietz Press, Richmond, VA.