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An Integration of Remote Sensing and GIS to Examine the Responses of Shrub Thicket Distributions to Shoreline Changes on Virginia Barrier Islands

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ABSTRACT

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The high-water-shoreline positions in 1852, 1871, 1910, 1919, 1943, 1955, 1967, 1980, and 1990 for Hog Island, a barrier island located at the eastern shore of Virginia, were determined with the NOS T-sheets and aerial photographs. Shrub thicket distributions for northern Hog Island were extracted from black/white and infrared color aerial photographs for the years of 1949, 1962, 1974, and 1989. The overlay operations between shrub age and land age data layers indicated that shrub coverage on Hog Island was closely related with shoreline changes. By examining 138-year shoreline changes on 50-m-interval transects of Hog Island, it was found that the sine function could describe shoreline change patterns better than earlier used simple models. The overlay between old NOS T-sheets and 1993 TM satellite image suggested that there would be at least three types of shoreline changes for different barrier islands. All these three types of shoreline change patterns could be interpreted with the sine function model. The potential distribution of shrub thickets on Hog Island was simulated based on the shoreline change model. The shrub line and shoreline positions were closely related with each other, but there were time lags between shrub thicket expansion and shoreline accretion.

ADDITIONAL INDEX WORDS: *Virginia Coast Reserve, landscape dynamics, modeling, spatial change.*

INTRODUCTION

Changes in shoreline position and vegetation pattern on barrier islands can be observed at almost any temporal scale. The longer they are observed, the more complete the pattern. However, geographically referenced historical records and maps of shoreline change rarely exceed 140 years (CROWELL *et al.*, 1993). There are many factors that drive shoreline change, such as drift trend and site-specific indicators, but the influences of vegetation are not among those important factors (TAGGART, 1988). A lot of work has been done regarding the shoreline changes and predictions, and vegetation dynamics on barrier islands (*e.g.*, CROWELL *et al.*, 1993; FENSTER and DOLAN, 1994; FENSTER *et al.*, 1993; EHRENFELD, 1990; HAYDEN *et al.*, 1991; TAGGART, 1988). The interactions between shoreline changes and vegetation dynamics were also examined at different temporal and spatial scales (GODFREY *et al.*, 1979; ROMAN and NORDSTROM, 1988; ZAREMBA and LEATHERMAN, 1986). Should the shoreline changes and vegetation dynamics be related, shoreline changes are normally the cause, while changes in vegetation patterns and composition are the result.

The Virginia Coast Reserve Long-term Ecological Research program addresses the geomorphologic controls on barrier island ecosystems of Virginia, USA (HAYDEN *et al.*, 1995). Shoreline position over the last century has changed dramatically on Hog Island, a typical barrier island in Virginia (HAYDEN *et al.*, 1991). The spatial distribution of shrub thickets (*Myrica cerifera*) on northern half of Hog Island have both expanded (SHAO *et al.*, 1993; Young *et al.*, 1995b) and died back in the past decades as the shoreline has accreted and eroded, respectively (Young *et al.*, 1995a). Shoreline changes in the past 40 years (from 1950 to 1990) can be simulated with a quadratic polynomial model (FENSTER and DOLAN, 1994); however, long-term (> 100 years) Modelling of shoreline change, as well as the processes of shrub thicket dynamics in response to shoreline changes have not been attempted. In order to better understand the complex dynamics of barrier island, examining the long-term shoreline and vegetation changes at landscape scales becomes one of the most helpful approaches. Remote sensing and GIS (geographic information systems) facilitate the extraction and standardization of spatial data layers, and make effective spatial analysis. In this paper, we will use remote sensing and GIS technologies to examine dynamic distributions of shrub thickets and the changes of shoreline position on barrier islands; interactions of shoreline changes and shrub distributions on Hog Island will be examined in detail.

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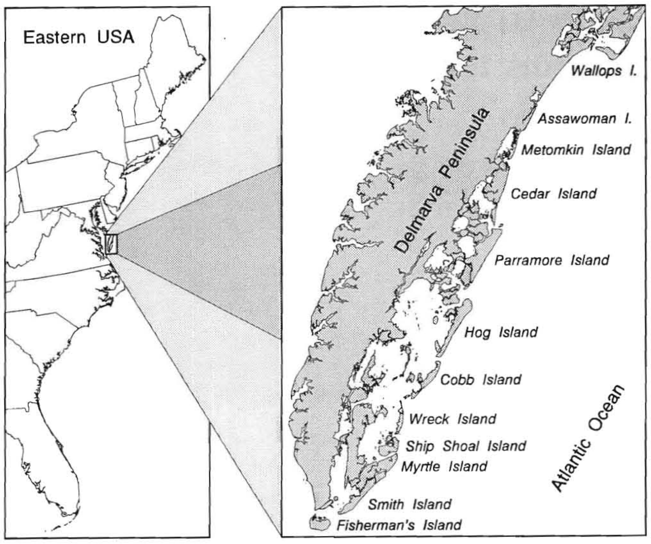

Figure 1. The study site location.

STUDY SITE AND DATA SOURCES

This study examined the barrier islands along the Eastern Shore peninsula of Virginia, with an emphasis on Hog Island and both Parramore and Smith Islands (Figure 1). Hog Island consists of two distinct landscapes. On the bay side, there is an expanse of marsh (*Spartina alternilora*); on the ocean side, there are sand dunes and swales covered with grasses (*Ammophila breviligulata* or *Spartina patens*) and shrub thickets (*Myrica cerifera*). Patches of forest (conifers and hardwoods) occur on other islands, including Parramore and Smith. For the last six decades, most of the barriers islands including Hog Island have been protected from human interference. Thus, current vegetation patterns have been influenced primarily by natural forces.

Based on the 1852 or 1871 NOS T-sheets (National Ocean Service Topographic Map) and 1993 Landsat TM imagery, the island boundary lines and the marsh-upland boundary lines were defined for Parramore, Hog, and Smith Islands. These data were projected into the UTM geographical coordinates. For Hog Island, high-water-shoreline positions were extracted from the NOS T-sheets for 1852, 1871, 1910, and 1919, and from aerial photographs for 1943, 1955, 1967, 1980, 1990. These data cover 138 years and may represent the long-term shoreline changes based on the definition by CROWELL *et al.* (1993). The shoreline positions were measured at 179 east-west 50-m interval transects from south to north on the island. The shoreline positions were recorded using the X coordinate values of the UTM geographical projection.

Shrub thickets (*Myrica cerifera*) on Virginia barrier islands are evergreen and usually bordered by grasslands (McCAFFREY and DUESER, 1990a; b), and are easily distinguished with remote sensing technology. Black/white and infrared color aerial photographs covering the northern part of Hog Island were used to determine shrub thicket patterns. The black/white aerial photographs taken in 1949 and 1962 were manually interpreted under stereoscopes and the boundary lines of shrub thickets were digitized with ARC/INFO GIS software. The infrared color aerial photographs taken in 1974 and 1989 were scanned and interpreted using ERDAS software. The 1993 TM satellite image for the entire barrier system was also interpreted using ERDAS software. Following a raster to vector conversion, spatial overlay analyses were accomplished using the ARC/INFO. The interpretation of 1989 aerial photography was field checked in the summers of 1991 and 1992. The interpretation of 1974 aerial photography was cross-checked with the vegetation maps of McCAFFREY and DUESER (1990b). Classification of 1993 TM image was checked by sampling points for the entire Eastern Shore peninsula of Virginia, Maryland and Delaware. The 4-time shrub thicket data layers were overlaid in order to determine spatial shrub thicket age pattern. The 5-time island boundary data layers for 1871, 1919, 1943, 1967 and 1989 were also overlaid to generate land age patterns on Hog Island.

RANGE EXPANSION OF SHRUB THICKETS

As a result of rapid spatial spreading, shrub thickets had a clear pattern of age structure on the northern portion of Hog Island (Figure 2). The oldest shrub thickets (>40 years) were located along the marsh-upland boundary line. The younger shrub thickets appeared to the south, east and north of the oldest thickets, but not to the west in the marsh. The northern half of Hog Island has become much wider since 1871 (Figure 3). The age of landscape elements ranged from 1 to 118 years old, or older. The linear pattern of old shrub thickets (>27 years) were parallel to the oldest shoreline (Figure 2). Though landscape elements were much older than thickets, thickets were found only on certain older areas (Table 1). The >27-year-old shrub thickets occurred only on sites older than 118 years. The <27 years shrub thickets were found on both the oldest area and 70–118 year-old area. The ground cover of shrub thickets accounted for 0% of upland area (no thickets) on the youngest sites, 4.9% on 22–46 year-old sites, 11.7% on 46–70 year-old sites, 22.3% on 70–118 year-old sites, and 47.5% on the oldest sites. As the landscape aged, more thickets were observed; but the older area was not always more suitable than the younger area for thicket expansion. For example, 65.3% of the <15 yr shrub thickets occurred in 70–118 year-old area, while 27.2% occurred in the oldest area; the <15 yr shrub thickets took about 20% of 70–118 year-old land but only 14.6% of the oldest land.

The close relation between thicket distribution and landscape age may have resulted from the dynamic environment. Newly deposited sands are nutrient limited, so it takes about 30 to 40 years for pioneer shrubs to replace dune grasses. Due to *Myrica cerifera-Frankia* symbiosis for N-fixation, the intrusion of the thickets can raise soil N content (YOUNG *et al.*, 1992). This symbiotic association may promote growth for *Myrica* thickets (YOUNG, 1992). However, it would be difficult for *Myrica* to grow if destructive high-energy storm frequency was less than 30 years (HAYDEN *et al.*, 1991) or if overwash were frequent (FAHRIG *et al.*, 1993). If land age is greater than 100 years, maritime forest species would gradually in-

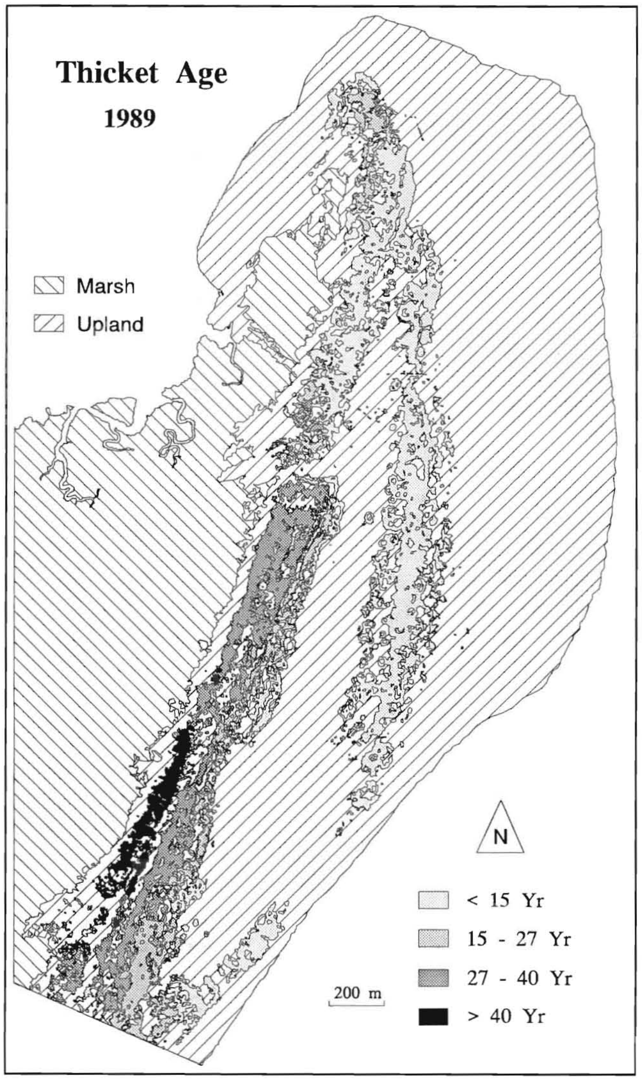

Figure 2. The spatial pattern of shrub thicket age structure on northern Hog Island.

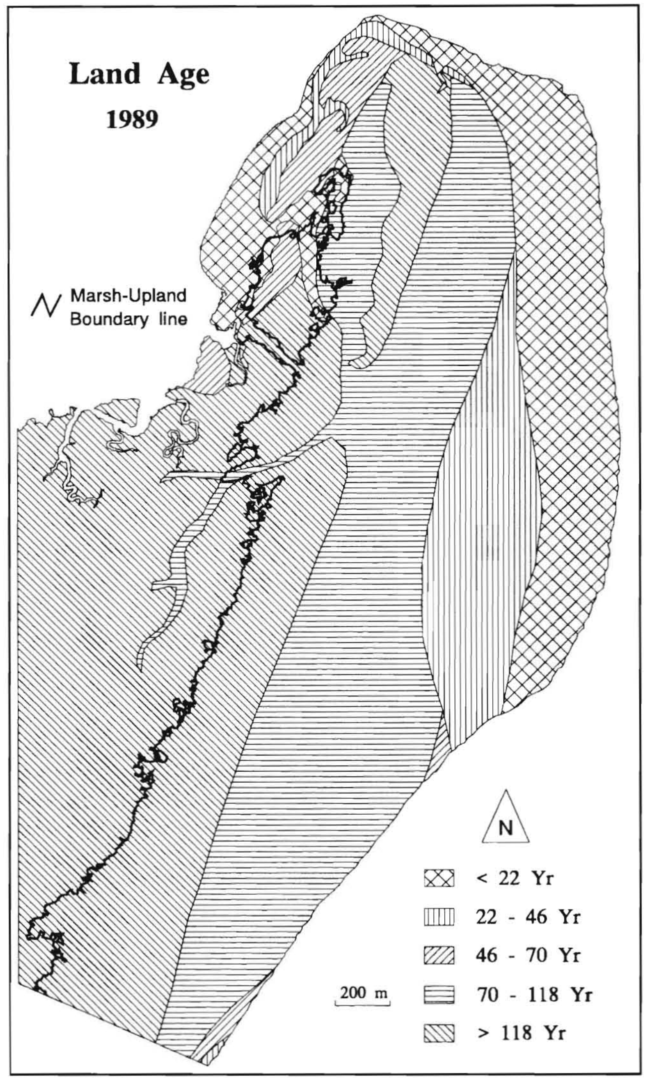

Figure 3. The spatial pattern of land age structure on northern Hog Island.

vade into the thicket (LEVY, 1983). Because the frequency of storms is so high, succession on Hog Island rarely progresses past the stages of grassy or shrub terrace (HAYDEN *et al.*, 1991). The spatial distributions of shrub thickets depend on land age, which, in turn, depends on shoreline changes. Accurate prediction of shrub thickets distributions on barrier islands would depend on reliable modeling of shoreline changes.

MODELING OF SHORELINE CHANGES

Rates of change in shoreline positions are frequently employed to summarize historical shoreline movements and to predict future shoreline positions based on the perceived historical trends. For the purpose of predicting the future of shoreline positions for Virginia barrier islands, simple methods or models have been used, such as the End-Point Rate

Table 1. *Overlay results of thicket age data layer (Figure 2) and land age data layer (Figure 3) for Hog Island (ha).*

	Land Age (yr)					
Thicket Age (yr)	<22	22–46	46–70	70–118	>118	Total
<15	0	2.54	1.20	32.28	13.40	49.42
15–27	0	0	0.27	3.79	11.49	15.55
27–40	0	0	0.01	0.18	17.44	17.64
>40	0	0	0	0	4.64	4.64
Total	0	2.54	1.48	36.25	46.97	87.24
Upland area	84.0	51.6	12.6	162.5	98.6	409.3
Proportion of thickets	0%	4.9%	11.7%	22.3%	47.6%	21.3%

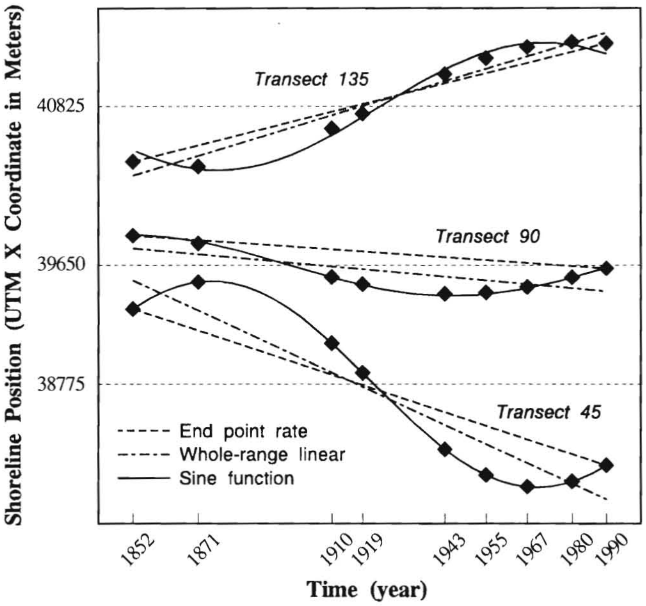

Figure 4. Comparisons of three different models for simulation shoreline changes with time on Hog Island.

method (EPR), whole-range linear regression (WLR), or partial-range linear regression (FENSTER *et al.*, 1993). It is clear that shoreline changes from 1852 to 1990 on Hog Island do not show the simple linear patterns but cyclic patterns for Hog Island (Figure 4). In this case, the existing linear models and the nonlinear quadratic polynomial model used to model Hog Island shoreline changes from 1950 to 1990 (FENSTER and DOLAN, 1994) appear to be too simple to simulate the long-term cyclic shoreline change patterns. Therefor, the 4-parameter sine function was found relatively more suitable (Figure 5). The 4-parameter sine function is expressed as

$$X(T = a \sin(bT + c) + k \quad (1)$$

where, X is shoreline location on each transect (m); T is the time (year); a, b, c, and k are parameters. The parameter a defines the amplitude of the sinusoid; b defines the period (the period $= 2\pi/b$); c and b define the phase (the phase $= c/b$); and k defines the axis location (Figure 5). Thus, if the temporal scale is longer than centuries, the parameter k should be considered as a variable. For Hog Island, the period was treated the same for the entire island. The values of the four parameters were determined with the numerical technique of the least-square method.

The simulation results show that the values of the amplitude (a), and the phase (c/b) are different from south to north on Hog Island (Figure 6). The amplitude for the southern part of Hog Island is larger than that for the northern part; the amplitude for either end of Hog Island is larger than the middle of the island; the phase of the northern portion of Hog Island delayed about a half of the period compared with that on the southern part; the value of period was determined to be 190 years. The characteristics of these parameter combinations lead to a clear dynamic shoreline change pattern: erosion occurs on the north when accretion occurs on the south, or in the reverse order. Thus, the cyclic processes of shoreline change would repeat very 190 years on Hog Island. Recent observations indicate that Hog Island may be at the end of a cycle, with the northern portion now just ending the accretion phase and the southern portion just ending the erosion phase.

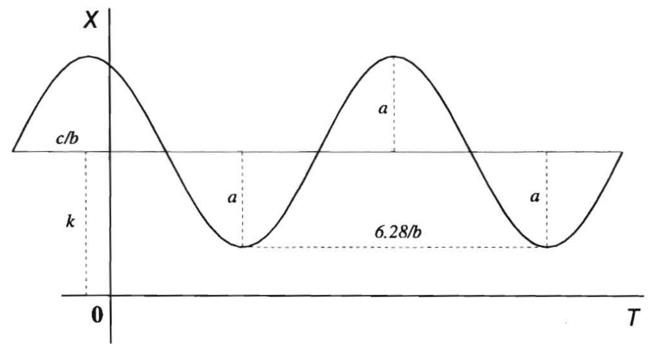

Figure 5. The four parameters of the sine function used for modeling cyclic shoreline changes.

MODELING OF SHRUB THICKET DYNAMICS

Based on Equation 1 (Figure 5), shoreline change can be divided into two stages: accretion and erosion. Each stage covers a half period (*e.g.* 95 years for Hog Island). With such cyclic pattern, any expansion within a year on a transect is called a segment, the age of any segment on a transect can be determined according to the value of the phase parameter. If the phase value is ¼ of the period, the shoreline is at starting point of erosion. In this case, there are 95 (½ period) seg-

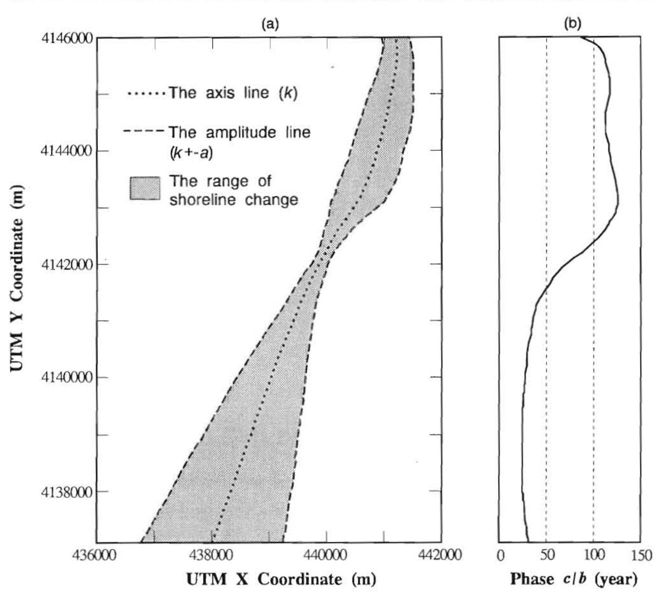

Figure 6. Parameters values of a sine model for Hog Island.

ments on a transect, and the oldest segment of the transect is 95 years of age and the youngest segment is 1 year of age; if the phase value is ¾ of the period, the shoreline is at the starting point of accretion. Under this situation, there is no segment yet (the narrowest situation). For a given phase value P (in years), the age A_{max} (in years) of the oldest segment of a transect is calculated as

$$A_{max} = P - \pi/2b \tag{2}$$

where, P is the phase calculated as c/b (c and b are same as in Eq. 1).

Then the number of segments (N) of a transect is determined with

$$N = \begin{cases} A_{max} & \text{when } A_{max} \leq \dfrac{\pi}{b} \\ \dfrac{2\pi}{b} - A_{max} & \phantom{\text{when }} A_{max} \geq \dfrac{\pi}{b} \end{cases} \tag{3}$$

where, A_{max} and b are same as in Eq. 2 ($2\pi/b$ is the period as defined in Eq. 1).

The oldest segment of a transect is located on the bay side, and the youngest is located on the ocean side. The age distribution along a transect can be expressed by a vector ($\boldsymbol{A}$):

$$\boldsymbol{A} = (A_{max}\; A_{max} - 1\; A_{max} - 3 \ldots A_N) \tag{4}$$

where, A_N is the age for the youngest segment, and A_{max} is same as in Eq. 2.

For Hog Island, the age vectors are expresses as:

$$\boldsymbol{A} = \begin{cases} \leftarrow \text{Bay side} \qquad\qquad\qquad\qquad \text{Ocean side}\rightarrow \\ (\;1\;) \\ (\;2\;\;1\;) \\ (\;3\;\;2\;\;1\;) \\ \;\vdots\;\;\;\vdots\;\;\;\vdots \\ (\;94\;\;93\;\;92\;\;91\;\cdots\;3\;\;2\;\;1\;) \\ (\;95\;\;94\;\;93\;\;92\;\cdots\;4\;\;3\;\;2\;\;1\;) \\ (\;96\;\;95\;\;94\;\;93\;\cdots\;5\;\;4\;\;3\;) \\ \;\vdots\;\;\;\vdots\;\;\;\vdots \\ (\;187\;\;186\;\;185\;) \\ (\;188\;\;187\;) \\ (\;189\;) \end{cases} \tag{5}$$

where, $\boldsymbol{A}$ is a vector representing the ages for transect segments (year).

Based on Eq. 1, the length of a segment on a transect is

$$L(T) = X(T + 1) - X(T) \tag{6}$$

where, $L(T)$ is the length of a segment on a transect when time is T, and the X is same as in Eq. 1.

The segment length vector ($\boldsymbol{L}$), similar to Eq. 4, can be written as:

$$\boldsymbol{L} = (L_1\, L_2\, L_3 \ldots L_N) \tag{7}$$

where, L_i is the length for the ith segment on a transect (i = 1, 2, 3, . . . , N from the bay side to the ocean side).

For Hog Island, using the transect #45 (Figure 1) as an example (a = 757.8, b = 0.03305, and c = 0.8164), the segment length distribution along a transect is expressed by one of the following vectors:

$$\boldsymbol{L} = \begin{cases} \leftarrow \text{Bay side} \qquad\qquad\qquad \text{Ocean side}\rightarrow \\ (\;0.8\;) \\ (\;0.8\;\;1.7\;) \\ (\;0.8\;\;1.7\;\;2.5\;) \\ \;\;\vdots\;\;\;\;\vdots\;\;\;\;\vdots \\ (\;0.8\;\;1.7\;\;2.5\;\;3.3\;\cdots\;3.3\;\;2.5\;\;1.7\;) \\ (\;0.8\;\;1.7\;\;2.5\;\;3.3\;\cdots\;3.3\;\;2.5\;\;1.7\;\;0.8\;) \\ (\;0.8\;\;1.7\;\;2.5\;\;3.3\;\cdots\;3.3\;\;2.5\;\;1.7\;) \\ \;\;\vdots\;\;\;\;\vdots\;\;\;\;\vdots \\ (\;0.8\;\;1.7\;\;2.4\;) \\ (\;0.8\;\;1.7\;) \\ (\;0.8\;) \end{cases} \tag{8}$$

where, $\boldsymbol{L}$ is a vector representing the length for transect segments (m).

Based on Equations 1 to 8, land age, distance to shoreline, and island size can be readily derived. But relative elevation is still unknown. We define that the occurrence of shrub thicket that is controlled by land age, distance to shoreline and island size as the potential distribution for shrub thicket. The potential distribution of shrub thicket is determined with the following three conditions: a) shrub thicket cannot grow on lands younger than 30 years old because of slow natural succession (Table 1); b) shrub thicket cannot grow within distance of 50 m to the shoreline position because of frequent disturbances; and c) shrub thicket cannot grow if upland width (transect length) is less than 100 m because of insufficient storage of ground water (SHAO *et al.*, 1995).

The modeling results show that shrub thicket distribution is controlled by shoreline changes (Figure 7). In 1850, the southern Hog Island just ended accretion phase, and there were time lags in shrub response to the shoreline accretion. In the beginning of this century, northern Hog Island started to expand while the southern portion was rapidly eroding. By 1950, southern Hog Island has became so narrow and the potential shrub line very close to the shoreline position. The northern Hog Island has started expansion since 1900. During the first 50 years (1900–1950), the shrub thicket had significant spreading as a result of shoreline accretion, but the distance between shrub line and shoreline became much greater on the northern portion of Hog Island. From 1950 to 1990, the shoreline accretion rate slowed down but the potential shrub thicket distribution area still kept rapid expansion on northern Hog Island. By the middle of 1990s, the shrub thickets have reached the broadest distributions on northern portion of Hog Island because the shoreline position has become relatively stable. The 1949–1989 rapid expansion of the shrub thickets observed *in situ* on northern Hog Island verified the simulation result (SHAO *et al.*, 1993; YOUNG *et al.*, 1995b). Simulated shrub thicket dieback resulted from shoreline erosion in the upper middle position of Hog Island was verified by YOUNG *et al.* (1995a). The future of the shrub thickets on northern Hog Island will depend on the direction and speed of shoreline movements. There would be two possibilities: 1) If shoreline comes back following the same pattern as before, the northern portion of Hog Island will be washed away within 100 years. In this case, shrub thickets will lose their landforms to grow; 2) the shoreline changes on northern Hog Island may have greater period values than the

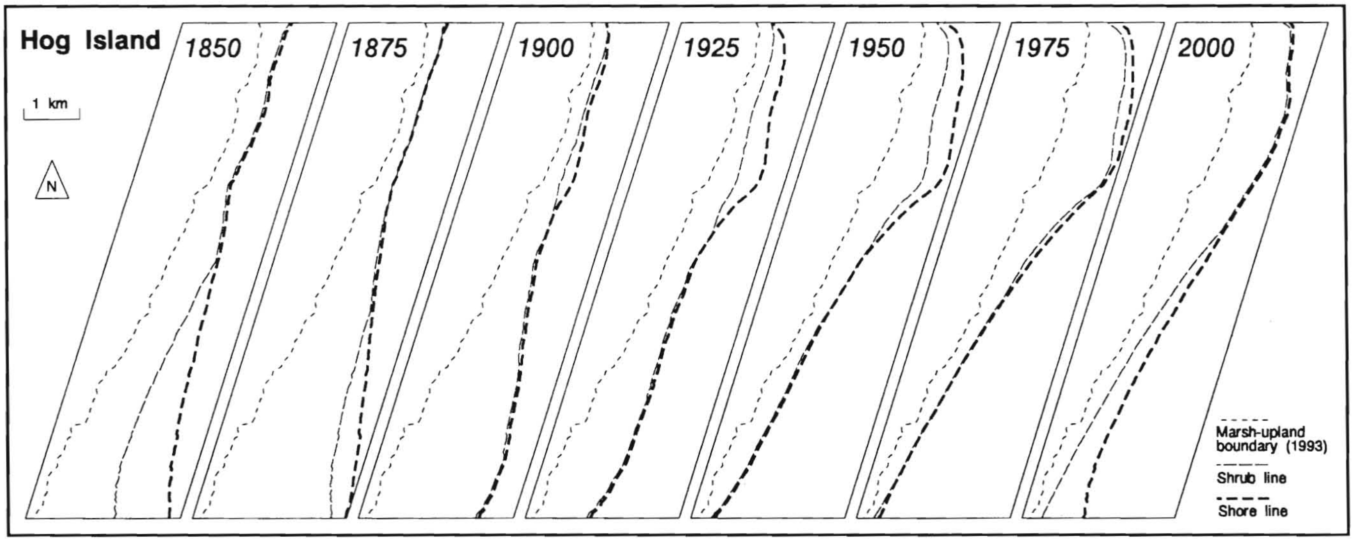

Figure 7. The temporal changes and interactions of shoreline and shrub line positions on Hog Island.

southern portion (Figure. 4, transect #135). Under this situation, shrub thickets would have better chance to grow longer on northern Hog Island, but the tree species may gradually invade into this vegetation (LEVY, 1990).

THREE TYPES OF SHORELINE CHANGES

Through spatial data layers overlay operations, at least three types of shoreline change were observed for the barrier islands of Virginia. For example (Figure 8a), Hog Island experienced large changes on both the southern and northern portions; the changes were simultaneous but in opposite directions. For Smith Island, the entire island has shifted to the west and the shoreline changes were almost synchronous from south to north. The shoreline of Parramore Island changed dramatically on the southern half, but little change was evident on the northern portion. Based on these different shoreline change behaviors, three types of shoreline change are *crisscross*, *parallel*, and *one-end*, respectively.

These forms of shoreline change for barrier islands were determined by the different parameter combinations of the sine model; the cyclic shoreline changes are not obvious (i.e. observable) for Parramore and Smith Islands because the time span is not long enough. The shoreline change data indicate that the period values for Parramore and Smith must be much larger than that (190 years) for Hog Island. The crisscross-type change results from large amplitude values and half-period phase differences from south to north; the parallel-type change results from large amplitude values and small differences in phase values from south to north; the one-end-type change results from small amplitude values on one end but large amplitude values on another end of a barrier island.

Due to the different shoreline change features on the three barrier islands, the land age structure is also different from each other. On either northern Parramore or southern Smith Island, a table portion of upland was found (Figure 8), which must be older than northern Hog Island. The woody vegetation was also found on northern Parramore and southern Smith Island (Figure 8b), but there were more trees or forests on Parramore and Smith Islands than on Hog Island (MCCAFFREY and DUESER, 1990a; b). The differences in vegetation structure results from the difference in land age, which, in turn, is controlled by the period values of shoreline change cycles. On barrier islands it takes longer for trees to migrate and grow than for shrub thickets (EHRENFELD, 1990). Because TM satellite data used for mapping shrub thicket distributions have a spatial resolution of 30 m, a lot of young-aged shrubs on northern Hog Island were missed. Therefor a large distance between the shrub thicket edge and the shoreline position was observed on northern Hog Island (Figure 8b). The upper middle portion of Hog Island, where the shrub thicket is nearest shoreline, has been experienced the most severe erosion for the last decade (YOUNG *et al.*; 1995a). This is because that the phase value is smaller from north to south. More erosions would be expected in the northern portion of Hog Island in the near future.

DISCUSSION AND CONCLUSIONS

Regulated by cyclic shoreline changes, the changes in vegetation distributions on barrier islands also have cyclic patterns. The longer shoreline change cycle is, greater proportions of woody species in barrier ecosystem. The fast growing feature of *Myrica* shrub is just suitable for the frequent changes in shoreline positions and landforms.

It is obvious that old shrub thickets can be found only in old sites, but young shrub thickets can be observed from both young and old sites on Hog Island. Shrub thickets develop from grassland, which, in turn, has developed from

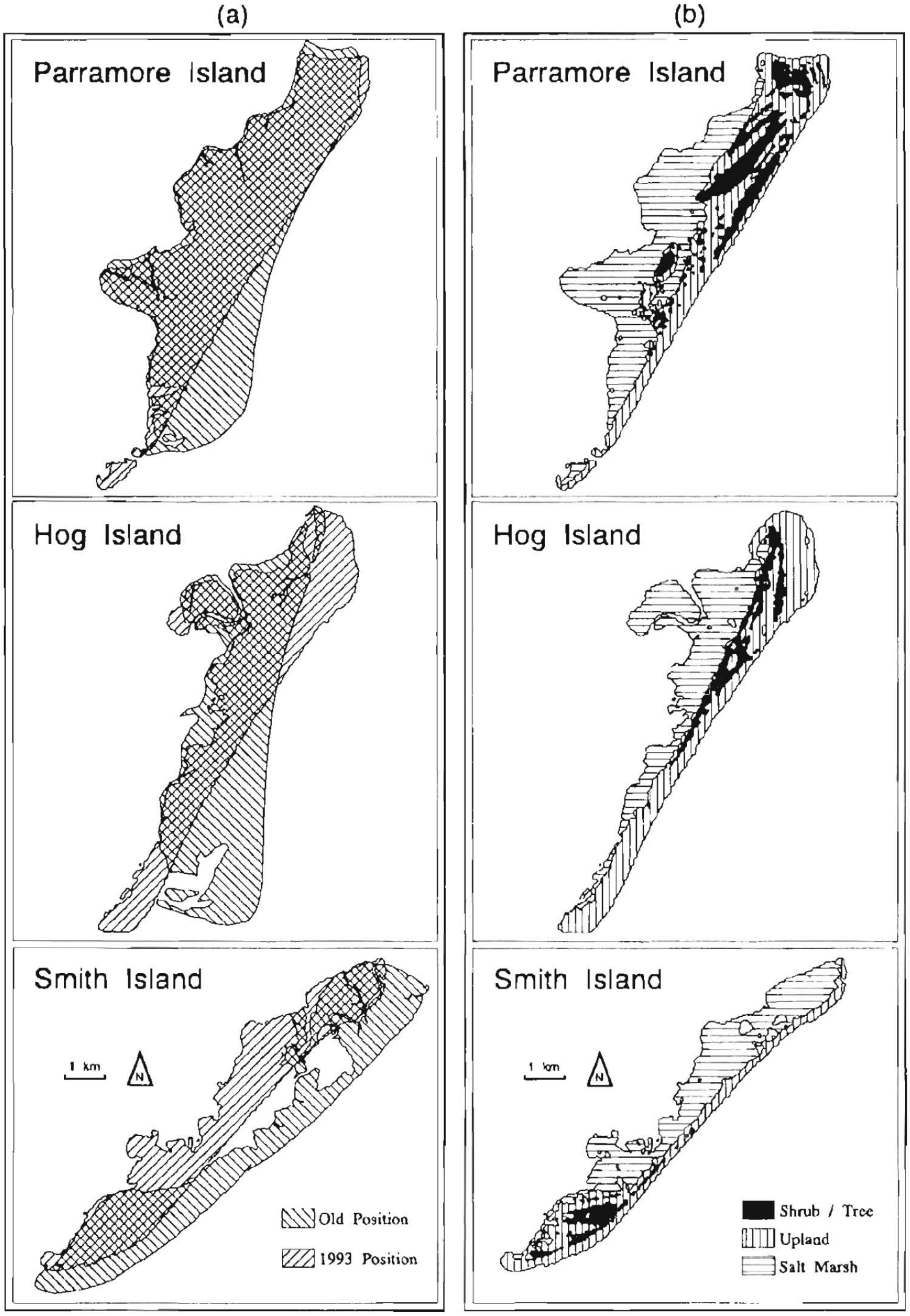

Figure 8. The comparisons of 1993 shoreline positions with 1852 (Smith) or 1871 (Parramore and Hog) shoreline positions (a) and the distributions of shrub thickets/forests on the three barrier islands of Virginia (b)

bare sand dunes (EHRENFELD, 1990; YOUNG *et al.*, 1995b). The overlay analysis showed the natural development from primary bare sands to shrub thickets takes at least 30 years on Hog Island. Shrub thickets are not able to disperse and grow rapidly enough to track the island expansion during some period of shoreline accretion. Thus, a time lag exists between shrub thicket/forest expansion and shoreline accretion. The faster shoreline accretion is, the greater the distance from shrub thicket/forest edge to shoreline. In comparison, if the shoreline is eroding, the vegetation on that portion of barrier island will be washed into the ocean. This phenomenon is often observed in the field and is helpful to evaluate and predict the short-term trends of shoreline position movements.

Even though both historical NOS T-sheets and aerial photographs are used to measure shoreline change, the time span normally cannot exceed 140 years for the barrier islands of Virginia. Such a "long-term" data set for shoreline change still cannot show the cyclic shoreline change patterns for every barrier island. Because more trees are found from Parramore and Smith Islands, the period for these two islands is much longer than Hog Island. Therefore, we did not find the sinusoid shoreline changes for Parramore and Smith Islands. If longer time-span shoreline movement data were available, similar or alternative cyclic models could be developed for other barrier islands. This modeling task should be able to be accomplished in the future.

We found that there are at least three types of shoreline changes for Virginia barrier islands (crisscross, parallel and one-end change). Other types of shoreline changes may also exist for other barrier islands. For example, the barrier islands along the Gulf Coast of the United States, especially the Chandeleur island, which are among the most mobile barrier islands in the world (OTVOS, 1979). All these types of shoreline changes are of cyclic patterns and can be explained with the sine-function shoreline change model. The different combinations of the amplitude, phase, and period values lead to various shoreline change patterns. This is an important advantage of the sine function shoreline change model. If the period value is much higher than observation time spans, the investigation may mislead to a linear or other simple shoreline change patterns. More field observations are needed to make the sine model more reliable in other situations.

The simulation of potential shrub distribution is controlled mainly by three conditions: succession stage, overwash disturbance and ground water. The simulation results can show the interactions between the shrub line and shoreline positions, but cannot tell the exact shrub coverage on a barrier island. Shrub thicket distributions are controlled by water availability, which, in turn, are sensitive to little changes in topographical conditions (SHAO *et al.*, 1995). If topographical information were available at landscape scales, the modeling of shrub distribution would become much more specific or exact. Because the simulation of dune formation and movement on barrier islands at landscape scales is even more difficult, extra efforts should be made in order to consummate vegetation dynamics modeling for barrier islands.

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