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Dynamics of an Estuarine Forest and its Response to Rising Sea Level

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ABSTRACT

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To address the impact of rising sea level in a rapidly submerging Maryland estuarine forest, 15 loblolly pines (*Pinus taeda*) were cored for dendroecological analysis. The study area is a pure stand of loblolly pine that extends down an elevation gradient into surrounding marsh where dead stumps and snags indicate a retreating forest margin. Although relative sea level has risen considerably and there are dead trees at the forest-marsh interface, there is no associated decline in ring width, making sea level–induced mortality unlikely. Instead, ring width is correlated positively with annual precipitation and winter temperature and negatively with summer temperatures. Although recruitment of new pines was continuous between 1910 and 1930, there has been no more active recruitment except for a small age class established immediately after regional drought. Because recruitment is failing in the present forest despite abundant seedlings and an open canopy, recruitment ability appears to be limited by saturated soils associated with periods of high sea level. We predict that the forest margin will retreat stepwise, following storm-induced mortality, or continuously, following age-related adult mortality. The position of the forest margin is then a function of sea level position, but it represents the failure to recruit new individuals, not the ability of adults to survive a long term rise in sea level.

ADDITIONAL INDEX WORDS: *Sea level rise,* Pinus taeda, *dendrochronology, storms, hurricanes, Delmarva Peninsula, recruitment.*

INTRODUCTION

Forestland along North America's Atlantic Coast is retreating to higher elevation in apparent response to a rising sea level. Forest retreat is indicated by the remains of relict stands preserved in marshland, and is often accompanied by heavy mortality at the current forest edge. Forest retreat has been identified in at least New Brunswick (ROBICHAUD and BÉGIN, 1997), New York (CLARK, 1986), Maryland (SHREVE *et al.,* 1910; this study), Virginia (pers. obs.), North Carolina (BRINSON, BRADSHAW, and JONES, 1985; HACKNEY and YELVERTON, 1990), South Carolina (GARDNER, SMITH, and MICHENER, 1992), and Florida (ROSS, O'BRIEN, and STERNBERG, 1994; WILLIAMS *et al.,* 1999). Global sea level is projected to rise approximately 50 cm in the next century so understanding the response of these coastal and estuarine ecosystems is an important consideration (IPCC, 2001). The mid-Atlantic coast of North America, and the Chesapeake region in particular, is an ideal study location because regional subsidence in the last century has caused relative sea level to rise at rates similar to global projections for the next century (DOUGLAS, 1997). Many marshes in areas of rapid sea level rise appear unable to vertically accrete quickly enough to maintain themselves and are being replaced by open water (*e.g.,* STEVENSON, WARD, and KEARNEY, 1986). Although the response of marshlands has received considerable attention, the response of coastal and estuarine forests is much less studied.

Dendroecological techniques are an effective tool for measuring the response of forests to changing environments, including air pollution (ASHBY and FRITTS, 1972), elevated carbon dioxide (LAMARCHE *et al.,* 1984), and lake level changes (BÉGIN and PAYETTE, 1988). In coastal environments, tree rings have been observed to respond to storms on the barrier islands of Virginia and the coastline of New Brunswick (JOHNSON and YOUNG, 1992; ROBICHAUD and BÉGIN, 1997). Dendrochronology techniques have also been used to document failure of forests to regenerate in saturated soils associated with rising sea level along the coasts of New York and Florida (CLARK, 1986; WILLIAMS *et al.,* 1999), and a general decline in ring width was observed to follow sea level rise in New Brunswick (ROBICHAUD and BÉGIN, 1997). However, no full dendroecological analysis has been attempted to determine the direct effect of sea level rise on tree growth and survival. The objective of this research is to correlate both ring width variations and recruitment patterns to a rising sea
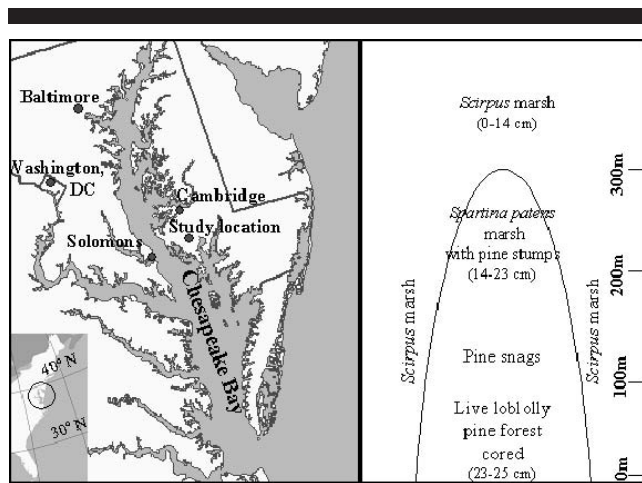
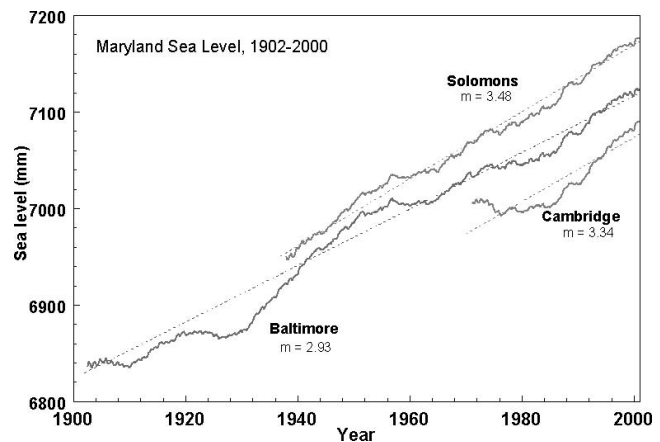Figure 1. Map and schematic diagram of study area. Elevation above lowest marshland is in parentheses.

Figure 2. Maryland sea level, 1902–2000. Three tidal gauge records of monthly sea level. Data have been smoothed with a 12-month moving boxcar filter. Numbers below curves are linear fit trends in mm per year.

level in an effort to explain a retreating forest margin in a rapidly submerging estuarine environment.

STUDY AREA

Relative sea level is rising in the Chesapeake Bay region at nearly twice the global average because of land subsidence from glacial rebound, groundwater extraction, and sediment loading (DOUGLAS, 1997; KEARNEY and STEVENSON, 1991). Sea level rise is faster than marsh accretion rates, resulting in severe marsh and land loss (KEARNEY and STEVENSON, 1991; STEVENSON, KEARNEY, and PENDLETON, 1985; STEVENSON, WARD, and KEARNEY, 1986). Soils at the forest-marsh interface are rapidly submerging and becoming more anoxic. Soils underlying both the marsh and forest are described as saline within 30 inches (BREWER, DEMAS, and HOLBROOK, 1998). The amount of cations and salts distributed throughout the soil profile, potentially detrimental to tree growth, is increasing with inundation frequency (HUSSEIN and RABENHORST, 1999, 2001). Although the effects of rising sea level on forests in this region have not been studied, SHREVE *et al.* (1910) observed remains of a loblolly pine (*Pinus taeda*) forest near Chesapeake Bay that extended great distances beyond the present forest margin, and inferred that the forest edge was retreating. Rapid sea level rise, protection from storm erosion, and early observations of forest retreat make the numerous submerging estuarine forests in this region ideal locations to study the direct effects of rising sea level on tree growth, mortality, and regeneration.

The study area is a small stand of loblolly pines (*Pinus taeda*) located in Dorchester County, Maryland, USA, on the Chesapeake bayside of the Delmarva Peninsula in close proximity to the Blackwater National Wildlife Refuge (38.377°N, 76.058°W; Figure 1). The landscape is dominated by brackish marshland, with nearly pure loblolly pine forest occupying slightly higher elevations along a series of ridges that gradually descend into the marsh. Elevation in the interior of the

stand, where trees were cored, is 2 cm above the forest-marsh border and 25 cm above the lowest marshland. Previous survey work, within 5 km of the study area, indicates that "upland forest" dominated by loblolly pine extends to elevations less than 10 cm above mean high tide, which we assume is a good estimate for the elevation of the trees cored in this stand (HUSSEIN and RABENHORST, 2001). Sea level, as recorded at two tidal gauge stations within 35 km of the site, has risen approximately 3.4 mm/yr between 1938 and 2000 (Figure 2).

The study area is bounded by marshland on three sides. The resulting peninsula of trees descends into the marsh following a very slight elevation gradient. Vegetation along the gradient appears to be controlled by moisture and/or salinity; with the loblolly pine stand yielding to a wax myrtle (*Myrica cerifera*)–marsh elder (*Iva frutescens*) shrub thicket, which in turn yields to a high *Spartina patens* marsh, which in turn yields to a low *Scirpus robustus* marsh (Figure 1). Tidal inundation, flooding, and salt spray are cited as controlling factors for the composition and distribution of similar pure loblolly pine "tidewater forests" in the region (BRUSH, LENK, and SMITH, 1980; LEVY, 1983; SHREVE *et al.,* 1910; TOLLIVER, MARTIN, and YOUNG, 1997).

Dead loblolly pine stumps and snags are abundant throughout the upper marsh, indicating that the forest previously extended at least to the modern *S. patens–S. robustus* border, 250 m from the modern forest edge. Stump height and preservation quality, relative indicators of the date of tree death, gradually decrease away from the live forest, suggesting a forest margin that has been actively retreating at least since Shreve's 1910 observation. Loblolly pine is the only tree species present in the interior of the stand and its diameter at breast height (DBH) is 20–40 cm for all trees. The canopy is relatively open and supports an understory of poison ivy (*Toxicodendron radicans*) and small loblolly pine seedlings. No hardwood trees or seedlings of any kind are present. Forests further inland are characterized by the addition of hardwoods: willow oak (*Quercus phellos*), basket oak (*Quercus michauxii*), sweetgum (*Liquidambar styraciflua*),

and red maple (*Acer rubrum*), and are actively recruiting new individuals (BRUSH, LENK, and SMITH, 1980). Vegetation structure and composition gradients between this forest and those further inland, and early observations of retreat, all indicate that water level has an important influence on the dynamics of this stand.

METHODS

Fifteen trees were randomly selected for coring in the living portion of the forest, representing more than half of the stand. Special attention was given to avoid sampling on the edge of the stand to ensure that all sampled trees were the same elevation and exposed to identical inundation and salt spray regimes. Trees with excessive deformities were avoided, but we gave no consideration to tree diameter and height. Two perpendicular cores were extracted from every tree at stump height (<0.5 m) to ensure an accurate age of the tree.

All cores (*n* = 30) were dried, mounted, and sanded. Cores were visually cross-dated by identifying and listing signature years of narrow ring width to prevent dating errors associated with partial, missing, or double rings (YAMAGUCHI, 1991). After cross-dating, cores were measured for annual radial growth to the nearest 0.002 mm with the TA Unislide Tree-Ring Measurement System (Velmex Inc., Bloomfield, New York). The COFECHA quality data control program was then used to verify visual cross-dating (COOK *et al.,* 1997). Four cores were discarded because they had complacent growth patterns and did not cross date well. The ARSTAN program detrended cores using a spline 30% of the length of the chronology to remove tree age and microsite factors, and then averaged the detrended chronologies to create a master chronology of 26 cores (COOK *et al.,* 1997). The detrending process will not remove any environmentally caused decline signal, but rather will verify that any decline within the data is not age-related (COOK and PETERS, 1981; ZEDAKER, HYINK, and SMITH, 1987). The residual chronology was used for all dendroclimatic analysis because the standard master chronology had high autocorrelation and using the residuals eliminates problems of autocorrelation.

Ring width index (RWI) from the ARSTAN-generated residual chronology was compared to historical climate data monitored at the Blackwater and Vienna weather stations, 5 and 25 km from the stand, respectively (NOAA, 2001). Climatic variables included mean temperature and total precipitation for every month between 1942 and 2000. Mean monthly tidal gauge measurements, archived at the Permanent Service for Mean Sea Level (PSMSL, 2002), were compiled and smoothed with a 12-month boxcar filter to generate a sea level history. Reported trends are the result of a linear fit between dates specified. Ring width was correlated to mean annual sea level at Solomons Island, Maryland (35 km from study site) between 1938 and 2000. The tidal gauge record from Cambridge, Maryland, (20 km) was used to generate a more local sea level chronology between 1981 and 2000. This period was selected because it features 9 of the 10 highest annual sea level positions and an extremely rapid rate of sea level rise (5.9 mm/yr). Records of monthly and annual sea level position with missing daily measurements, interpolated
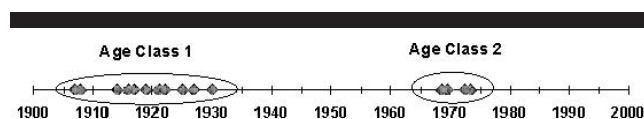

Figure 3. Recruitment history. Years of establishment in a loblolly pine estuarine forest.

and flagged by PSMSL, were removed prior to correlation to ring width. Seasons were divided as follows: winter, January through March; spring, April through June; summer, July through September; fall, October through December. Correlation to ring width was calculated using the Pearson product-moment correlation method. The year of establishment for each of the 15 trees was estimated by using the earliest ring of each core pair. Because the trees were cored very close to the ground, recruitment years are likely older by no more than a few years.

RESULTS

The stand likely has at least two distinct age classes (Figure 3). The oldest cohort includes trees recruited between 1907 and 1930. Eleven of the 15 cored trees were established in this period, and recruitment appears to have occurred continuously throughout. No recruitment took place between 1931 and 1968. Following this 37-year period, a second cohort was established between 1969 and 1973 in which more than a quarter (4 of 15) of the stand was recruited. Although a small sample size prevents certainty and discussion about regeneration patterns, it appears that no recruitment into the larger size classes has taken place since 1973, even though there is an open canopy and abundant pine seedlings in the understory at present.

The master tree ring chronology for 14 loblolly pines reveals above-average radial growth between 1907 and 1930 before a gradual decline through 1940, possibly representing stand closure (Figure 4). Extremely high growth between 1948 and 1952 (RWI > 1.4) is followed almost immediately by extremely low growth (RWI = 0.4) between 1958 and 1964. The severity and abruptness of radial growth change suggests a major, stand-wide disturbance. Growth fluctuates greatly after 1970, with significantly above-average growth in the mid to late 1970s and early 1990s. Periods of significantly below-average growth occur in the early 1970s, early 1980s, and mid-late 1990s.

Correlation coefficients (*r*) of climatic variables with the ARSTAN residual chronology are shown in Figure 5. Growth was positively correlated with winter temperature and negatively correlated with summer temperature. Correlation with precipitation was stronger than with temperature and was positive for spring, summer, and mean annual precipitation. Ring width variation was not significantly correlated to either monthly or seasonal sea level position.

DISCUSSION

Estuarine Forest Dynamics

For much of the stand's 94-year history, radial growth has fluctuated in response to climatic variables. In particular, pe-
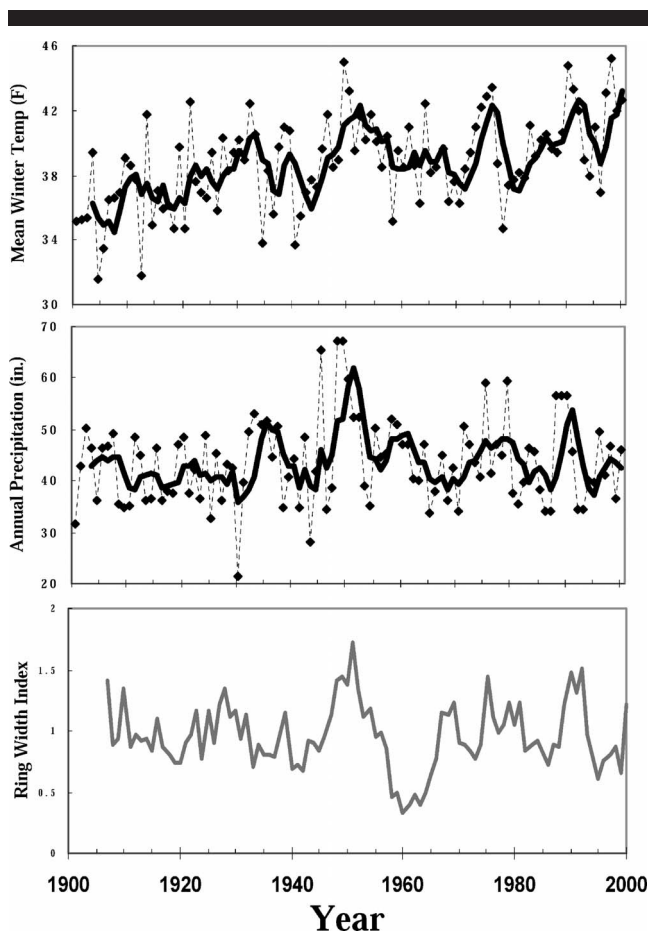
Figure 4. Radial growth and climate. Standardized ring width index of 14 loblolly pines in an estuarine forest. Mean winter temperature and total annual precipitation were recorded in Vienna and Cambridge, Maryland.

riods of slow growth appear to be strongly correlated with cool winter temperature and low annual precipitation (Figures 4, 5). Although JOHNSON and YOUNG (1992) identified individual hurricanes as a major controlling factor on loblolly pine ring width on Delmarva barrier islands, their impact on this bayside forest is less apparent. The hurricanes of 1933, 1958, and 1960 do generally coincide with periods of slow growth, but hurricanes in 1944, 1953, 1979, and 1985 show little to no impact.

A collapse in radial growth during the 1950s deviates sharply from the normal growth pattern. Responding to favorable climatic conditions, radial growth reached an extreme high in the early 1950s before declining dramatically to its extreme low in 1958. Although slow growth of loblolly pine in the early 1960s was attributed to regional cool and dry climate at a similar latitude in Virginia (ABRAMS and BLACK, 2000), the extreme nature of decline in this forest likely represents a very significant stand-wide disturbance.

Beginning in 1958 with Hurricane Daisy, a hurricane passed nearby in each of the following five years, including the particularly damaging Donna in 1960. In addition to hur-

ricanes, the total number of storms per year that passed over a location on the southern Delmarva reached a peak in 1958 (JOHNSON and YOUNG, 1992); this presumably indicates increased storm activity at our study site as well. Severe storms can alter loblolly pine growth by several pathways, including wind and flooding. Wind reduces growth by causing crown damage (GRESHAM, WILLIAMS, and LIPSCOMB, 1991) and by increased salt spray (LEVY, 1983). Long-term freshwater flooding reduces loblolly growth because of soil anoxia (PEZESHKI, 1992). Short-term flooding causes a reduction in stomatal conductance after just nine days of low salinity inundation (JOHNSON and YOUNG, 1993; TOLLIVER, MARTIN, and YOUNG, 1997).

Extremely low radial growth rates persisted through the mid-1960s, not returning to average until 1968, 10 years after the collapse. Slow recovery following hurricane disturbance was also observed in a New England forest, where radial growth rates were reduced for 5–10 years after canopy damage by wind (FOSTER, 1988). The cool and dry climate may have also slowed recovery in our study area.

Whereas we have proposed multiple storms, climate and slow recovery as an explanation, the cause of the 1960 collapse is speculative and alternative explanations exist. The stand could have been stressed from the cool, dry climate and susceptible to insect attack. It seems doubtful, however, that a pine bark beetle infestation could suppress growth so dramatically without mortality, of which there is no evidence in the stand's interior. Given the forest's proximity to the northern extent of loblolly's range, ice storms could possibly damage the crown enough to reduce growth rates. A survey of ice damage in southeastern Virginia, however, suggests that crown damage of any sort is rare in the forest interior (ELSTNER and WARE, 2001). Finally, fire is thought to play an important role in Delmarva forests (KIRWAN and SHUGART, 2000) and is a common marsh management technique. Although nearly all the sampled trees had charcoal on the outer bark, no fire scars were observed, indicating that fires were of low intensity and did not cause bole damage. Moreover, property owners and local trappers report that the marsh has been, and continues to be, actively managed by fire over the entirety of the study period, resulting in a fire regime that has not been significantly changed.

Response to Sea Level Rise

The lack of correlation between tree ring width and sea level position was unexpected, because species composition and recruitment history clearly indicate that the stand is being influenced by sea level (see Study Area section and below). Radial growth as late as 1990 is higher than at any other time period with the exception of the early 1950s. The lack of correlation within the period of highest sea level position and most rapid rise, 1981–2000, suggests that a critical position has not been reached and that the rate of sea level rise is an unimportant determinant of radial growth in this stand. Furthermore, if sea level or its effect on groundwater salinity significantly influenced growth, then correlations to certain seasonal climate data might be expected. Specifically, negative correlation with annual precipitation and tempera-
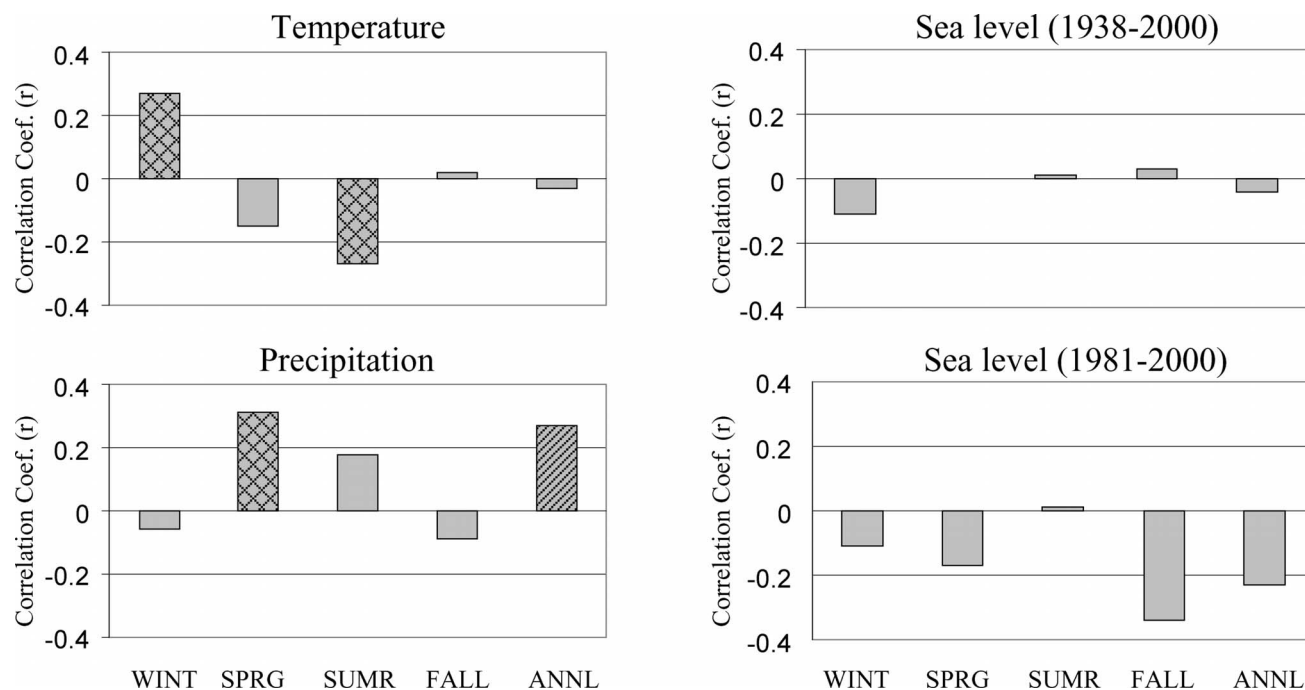
Figure 5. Correlation of annual ring width to climatic variables. Correlation coefficients of ring width to temperature, precipitation, and sea level. $p < 0.05$ is denoted with crosshatching; $p < 0.01$ is denoted with slashes.

ture (increasing groundwater level), and positive correlation with summer precipitation (diluting salinity) might be expected. We did not detect any of these trends, and in some cases detected exactly the opposite, reinforcing the notion that sea level alone has not influenced the growth of these pines.

Our findings are also unexpected given the gradual ring width decline and mortality observed to follow recent sea level rise (3.1 mm/yr) in a Canadian spruce forest (ROBICHAUD and BÉGIN, 1997). Their stand was located in a very similar estuarine environment where dead trees along the edge of a freshwater marshland were protected from storm erosion. There, ring width and mortality were influenced primarily by sea level rise at distances greater than 450 m from the shoreline and at altitudes 3.2 m above the normal low tide. Because the stands' environments are similar, red spruce may be considered more susceptible to sea level rise than loblolly pine.

Because sea level position does not appear to directly affect the growth of loblolly pines in this forest, we consider its gradual rise to be a poor explanation for the mortality of dead trees preserved in the high marsh. Although we cored living trees with no sign of ill health, the cored trees are at essentially the same elevation as the dead trees. Additionally, observations of growth rings in stumps from dead trees show relatively rapid growth throughout and no long term decline, although significant decay prevented their measurement. Like measurements from the cored living trees, this suggests that mortality was a sudden event. We believe storm surges are the most likely disturbance to cause mortality in this

stand, as they have been documented to cause mortality in other costal and estuarine forests (ROBICHAUD and BÉGIN, 1997; WILLIAMS et al., 1999).

An alternative hypothesis is that sea level causes little to no effect on ring width until soil conditions reach a threshold, shortly after which mortality occurs. This could explain the abruptness of mortality in the observed dead trees, but does not fit well with mortality patterns identified by ROBICHAUD and BÉGIN (1997), who noted mortality following either long term (20–50 years) declines in ring width or specific storm surges. This explanation is also inconsistent with the observation of marshland, dead, and living trees all occupying essentially the same elevation.

Regeneration in this Chesapeake estuarine forest does, however, appear to be affected by hydrologic changes associated with sea level fluctuation, as recruitment patterns are similar to those in submerging coastal environments of New York and Florida (CLARK, 1986; WILLIAMS et al., 1999). The present forest interior contains abundant loblolly seedlings, but none reach substantial height despite readily available light in an open canopy. Seedling density decreases down an elevation gradient to complete absence in the *Spartina patens* marsh, apparently in relation to salinity or water table elevation. Although a limited sample size prevents more detailed conclusions, it appears that regeneration has generally failed since about 1930 despite favorable canopy conditions. The only exception to this observed recruitment failure is a short period around 1970 when prolonged dry conditions in the 1960s and below-average sea level position may have caused the local water table to drop below a critical level nec-

essary for recruitment. The presence of a recruitment class immediately following drought, when soil salinity would be highest, suggests that soil moisture, rather than salinity, is the primary stressor, though a limited sample size hinders a definitive separation of cause. Disturbance in the 1960s may have contributed to this period of recruitment if storm damage resulted in more light to the understory, but we note that recruitment is failing in the present forest despite a relatively open canopy. As with recruitment failure in submerging coastal forests of New York (CLARK, 1986) and Florida (WILLIAMS *et al.,* 1999) we conclude that excessively saturated soils associated with a high sea level position are responsible for recruitment failure in this estuarine forest.

CONCLUSIONS

Though dead trees at the forest-marsh interface and stumps throughout the high marsh indicate forest margin retreat, radial growth has not responded to the gradual historical rise in sea level, making it an unlikely source of mortality. Instead it appears that the retreat is in response to episodic storm surge–induced mortality and the inability of loblolly pine to recruit new individuals in highly saturated soils associated with sea level rise. Because the current forest margin is not actively recruiting, retreat will occur with death of the overstory. The margin may retreat stepwise, following storm- and other disturbance-induced mortality (CLARK, 1986; WILLIAMS *et al.,* 1999) or continuously, following age-related natural mortality. The position of the forest margin is then a function of sea level position, but it represents recruitment failure, not the ability of adults to survive a long-term rise in sea level.

ACKNOWLEDGMENTS

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