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The Effects of Storms and Sea-level Rise on a Coastal Forest Margin in New Brunswick, Eastern Canada

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ABSTRACT

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Sea-level rise and storms cause a progressive landward shoreline displacement along the coast of the Gulf of St. Lawrence in eastern Canada. Forest edges exposed to the sea tend to decline rapidly. The progression of an erosion scarp into a forest margin caused severe disturbances that were dated by dendrochronology. The dates of formation of reaction wood, narrow ring sequences and tree mortality indicated major disturbances in 1923, 1930, 1938, 1940, 1951, 1959, 1962, 1963, 1971, 1974, 1976, 1977, 1986, 1987, 1988 and 1989, that are related to storms. Sea-level rise leads to the landward displacement of the disturbance zone, causing the forest edge to regress. It is suggested that the forest decline in sites lying close to sea level, but protected by sand barriers, is due to increasing soil water table associated with sea-level rise. According to site microtopography, the stress zone progressed landward into the forest. By crossdating ring-width series from dead trees with those of adjacent living trees, the progressive landward displacement of mortality is estimated to a rate of 3 m/yr horizontally (vertical average: 1.24 cm/yr with a slope $< 5\%$) during the 1985–1991 interval (1 tree/160 m^2/yr). Results highlight the indirect effect of sea-level rise on a tree margin distance of 450 m from water edge.

INDEX WORDS: *Sea level, storm, dendrochronology, forest margin, coast, erosion.*

INTRODUCTION

The effects of sea-level rise on the east coast of North America is a major scientific and economic concern. In this area, tide gauges indicate a rising trend in sea level ranging between 20 and 40 cm/century (GRANT, 1970, 1980; GORNITZ *et al.*, 1982; SHAW and FORBES 1990). Evidences of rapid shoreline recession are abundant: loss of wetlands, disruption of roads and of buildings, salt water intrusion in aquifers and changes in the transport of sediments.

Coastal erosion in the Gulf of St. Lawrence attracted the interest of early researchers (GANONG, 1901; JOHNSON, 1925). Since the 1970's, much research effort along the Gulf of St. Lawrence coasts has been devoted to mechanisms of sediment transport and their causes, and especially to barrier beach dynamics (KRANCK, 1972a; MCCANN and BRYANT, 1972; BRYANT and MCCANN, 1973; GREENWOOD and DAVIDSON-ARNOTT, 1972; BRYANT, 1978; MCCANN, 1979; GREENWOOD and KEAY, 1979; HALE and GREENWOOD, 1980; ORFORD *et al.*, 1991). Sea-level rates of change in the Holocene related to glacio-tectonics were also thoroughly studied (SCOTT *et al.*, 1981, 1987, 1989; QUINLAN and BEAUMONT, 1981; SCOTT and GREENBERG, 1983; BROOKES *et al.*, 1985). Rates of coastal changes depends closely on site exposure and their resistance capacity. For example, in New Brunswick, rocky shores regress to an average rate of 75 cm/yr, sand beaches from 1 to 1.5 m/yr, and peatlands and tidal marshes around 2 m/yr (BÉGIN *et al.*, 1989). Consequently, sea-level rise hastens the landward movement of the shore zone which rates are estimated through various techniques, *e.g.*, delineation of coastlines based on landmarks and comparison of shoreline configurations on multi-year aerial photos (ORFORD *et al.*, 1991).

Among the new techniques available to describe past coastal changes, dendrochronology allows the use of trees as valuable indicators (CLARK, 1986; BÉGIN *et al.*, 1989, 1991; JOHNSON and YOUNG, 1992). The large spectrum of applications of the dendrochronological techniques demonstrate how an approach combining biological and geomorphological aspects can be powerful (SCHWEINGRÜBER, 1988). Coastal adjustment leads forest margins to regress at many locations along the gulf shores. The abundant leaning, uprooted, damaged and dead trees demonstrate the recent impact of the sea on adjacent land ecosystems. We postulated that trees are episodically damaged through the direct influence of salt spray, wave erosion and strong winds during storm events. Forest margin decline (dead and dying trees) is also common at low altitude backshore sites, protected from wave action by sand barriers. Hygrophilous plants (*e.g., Typha angustifolia,* L., *Alnus rugosa* [DuRoi] Spreng. and *Myrica pennsylvanica* Loisel.) establish in these areas submitted to waterlogging associated with the increased soil water table accompanying the sea-level rise. In considering forest margins in different exposures to coastal influences, this study strives to highlight coastal tree-population decline in response to the landward progression of the shore disturbance zone in response to erosion and sea-level rise. Attempts will then be made 1) to date past coastal geomorphic events on the basis of tree record 2) to describe the sequence of events involved in forest margins decline process and 3) to distinguish

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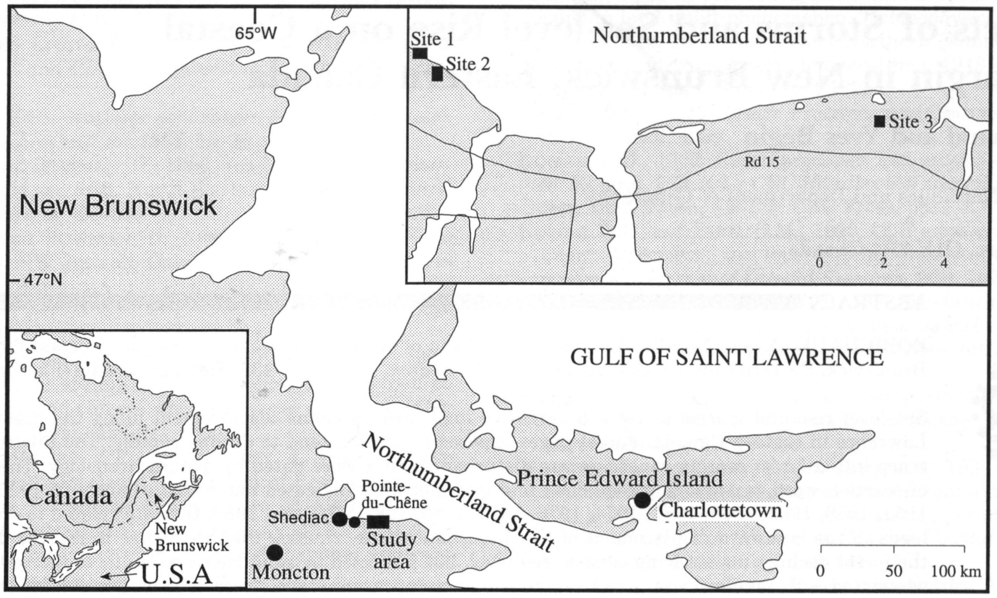

Figure 1. Location of the study area.

between the effect of storms and sea-level rise on coastal forests, along a gradient of exposure to the sea.

STUDY AREA

This study was carried out on the shores of the Northumberland Strait in New Brunswick (Figure 1). The coast is characterized by a sandstone Pennsylvanian plateau covered by a thin layer of coarse Quaternary marine deposit (HUNTER, 1975; KRANCK, 1972b). According to LOUCKS (1962), shoreline forests of eastern New Brunswick belong to the "Northumberland shore district" ecoregion, an 8 to 32 km wide coastal belt featured by oceanic influences. It is dominated by red spruce (*Picea rubens* Sarg.), but other tree species such as black spruce (*Picea mariana* (Mill.) BSP), white spruce (*Picea glauca* (Moench) Voss.), gray birch (*Betula populifolia* Marsh.) and red maple (*Acer rubrum* L.) are also abundant. Regional climate is temperate with cold, moist winters and mild and foggy summers. Mean annual precipitation is 103.9 cm and mean annual temperature is 5.7 °C (ENVIRONMENT CANADA, 1982a,b).

Tidal regime is microtidal (maximum range: 1.5 m) and semidiurnal. The episodic occurrence of an amphidromic point (randomly moving point with tide = 0) in the area makes the tides difficult to predict. Onshore waves are low because shallow waters prevail offshore (15 to 20 m on average in the strait) and fetches are less than 50 km (BRYANT and MCCANN, 1972). Water levels rise up to 1 m above predicted tides during storm surges and regular storm waves are 1.3 m high with maxima rarely over 2.5 m (HALE and GREENWOOD, 1980). Although it is a seemingly protected environment as compared to the Atlantic coast, storms still have strong effects on coastal dynamics (MCCANN, 1979).

The Northumberland Strait deglaciation occurred *ca.* 13,000 BP (PREST and GRANT, 1969; GREENWOOD and DAVIDSON-ARNOTT, 1972) and was followed by a submergence phase that ended *ca.* 11,000 BP. Afterwards, sea level dropped until 7,000 BP to 35–40 m below present level then started to rise again. Nowadays, coastal transgression affects the whole Maritime coastal region (*i.e.*, New Brunswick, Prince Edward Island and Nova Scotia) (KRANCK, 1972b; GRANT, 1980). Although the causes of the current sea-level rise are still debatable (QUINLAN and BEAUMONT, 1981; PIRAZZOLI, 1986), the Maritime provinces are facing a rapid coastal erosion. According to the closest tide-gauge station at Charlottetown in Prince Edward Island, which has longstanding records (1907–1988), the trend is estimated to be near +31 cm per century (PIRAZZOLI, 1986, 1989; SHAW and FORBES, 1990; GORNITZ *et al.*, 1982) as shown in Figure 2A.

METHODS

Site Selection

The interpretation of the effects of sea-level changes on coastal forests can be complicated by many factors. Seen over decades or centuries, the trend may appear constantly rising at slightly the same rate, but shorter time scale investigations would document many fluctuations, especially storm surges. Also, the reaction of trees to disturbances may be rapid or gradual, differ among species and site exposure, or be delayed in time in response to many regional or local factors (*e.g.*, unfavorable climate, insect infestations, diseases, severe storms, and other site disturbances causing changes in habitat properties). To obtain the best description of the effects of a sea-level rise on trees and to avoid confusion in the different scale factors, a comparative study among different species (*Picea rubens, Abies balsamea* and *Betula populifolia*) was carried out on sites located along a gradient of exposure to disturbance.

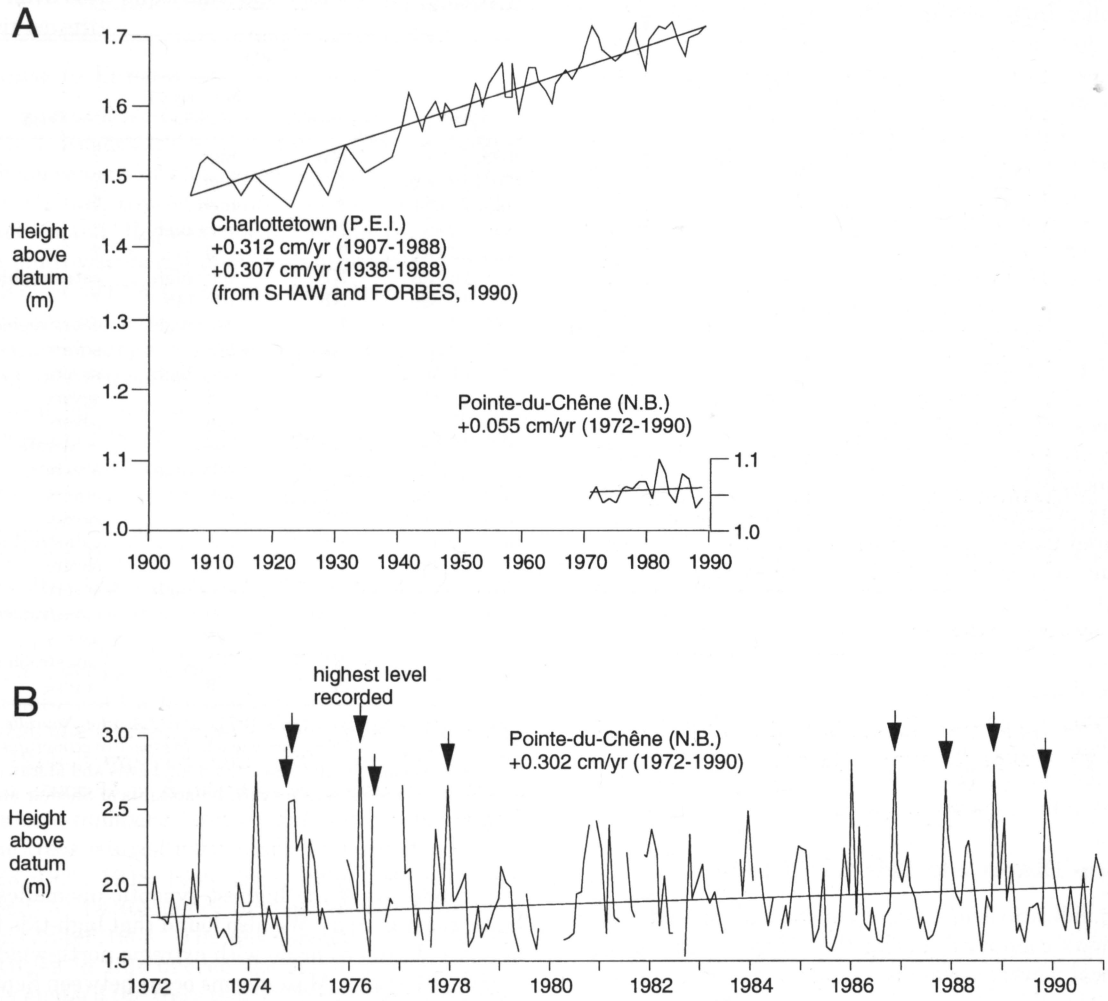

Figure 2. (A) Mean annual tide-gauge records from two Northumberland Strait stations. (B) Monthly maximum tide level at Pointe-du-Chêne. Arrows indicate the major storm events from Table 1. Datum: 0 is the local lowest normal tide.

Sites were selected (a) to date the recent storms by means of tree-ring analysis of *Picea rubens* and *Abies balsamea* leaning in response to wind pressure and wave erosion on a directly exposed shoreline (Site 1), (b) to study trees in an intermediate situation of exposure to disturbances, showing a landward decline of a *Betula polulifolia* stand whose backshore position exposes trees to salt spray and washover during extreme storm surges, but is far enough to prevent direct physical damage (Site 2), and (c) to determine the rate of a forest decline in a site 450 m from the shore's active zone behind a freshwater marsh dammed by a barrier beach, where the water table level seemingly fluctuates with sea level (Site 3).

Survey of Damaged or Stressed Coastal Trees and Tree-Ring Analysis

Three aspects pertaining to the tree response to sea-level rise were studied in each site: (a) the degree of exposure of trees according to their position relative to the water's edge, (b) the level of disturbance reflected in growth form anomalies (leaning or lying trees, stem deformation, breakage) and (c) signs of stress indicated by irregular patterns found in population age structures and tree-ring curves.

Trees were exhaustively plotted in quadrats or transects (Site 1: 40 × 40 m, Site 2: 10 × 35 m, Site 3: 45 × 45 m) perpendicular to the coast. In Site 1, only trees with a diameter >10 cm were cored to consider only the oldest individuals. For other sites, all trees in stands were sampled for population age structure analysis. Tree elevation was then carefully positioned by means of a network of measurements (a 2 m-interval grid) using an electronic levelling device (Type G.D.D.™, precision of ±1 cm per meter of elevation). Isobases were delineated using the IBM-PC software Surfer™ which interpolates a network of elevation data with x-y references by means of surface polynomial (2nd or 3rd degree) regression techniques. The network of elevation data was standardized relative to the datum defined by the Canadian Hydrographic Service (FISHERIES and OCEANS, 1993) described as the lowest normal tide.

Growth-form anomalies were studied by gathering the following specifics from each individual: tree tilting (direction and angle), direction of crown asymmetry (Krumholz effect due to wind exposure), gross description and general state of health estimated through the proportion of living branches (5 categories: dead tree, dying tree with <20% of living branches, severely affected tree with 20–50% of living branches, stressed tree with >50% of living branches, and healthy tree showing little or no external sign of stress).

All trees were cored close to the collar using a standard increment borer (Pressler type) in two opposite directions. Annual rings were counted under a lens microscope and sequences of reaction wood were dated. Reaction wood is an overproduction of lignin in wood-cell walls that give strength along one face of the stem structure to compensate the mechanical stress induced by tilting (Scurfield, 1973). In gymnosperms, reaction wood (called "compression wood") develops spontaneously below a leaning stem and is easily recognizable by its contrasted yellow-brownish color. Ring widths were measured using a Henson™ micrometer to a precision of ±0.01 mm. A mean ring-width curve was derived using the two radii for each tree. Mortality dates of dead trees were determined by cross-dating their outer rings with those of reference living trees further inland by means of linear correlation procedures. Such cross-dating allowed the detection of missing rings in some trees, that is, trees with unequal cambial activity along their stem. Incomplete and eccentric rings were also dated. They usually develop when environmental stress conditions prevail.

Recent Storm History and Tide Gauge Data

Dates and indications of intensity of storms were gathered from interviews conducted among the eldest residents and perusal of local newspaper archives. Storm classification (ordinal classes) was based on mentions of the degree of damage to infrastructures, erosion markers, level of coastal immersion, and records of wave height and wind velocity. The most significant events were deemed to validate results obtained from the tree records. Storm analysis conducted in the Atlantic provinces by Lewis and Moran (1984) and Brown *et al.* (1986) yield a useful synoptic description of some of these extreme climatic events. The published weekly data on storm winds have also been used (Environnement Canada, 1980–1990). Extreme water levels were analyzed through data sets (daily means and monthly maxima) from the closest gauging station located at 10 km west of the studied sites (Pointe-du-Chêne, 1972–1990).

RESULTS

Recent History of Coastal Storms

Meteorological records from the Moncton station (Figure 1), newspaper archives and interviews gave consistency to a chronology of recent major storms that had a significant effect on the coastline (Table 1). Storm surges are also depicted in water-level records at Pointe-du-Chêne station since 1972 (Fig. 2B). Although the survey may be incomplete, it closely corresponds with the descriptions of Brown *et al.* (1986) from the standpoint of the highest synoptic anomalies in the Atlantic coastal areas. We also found that high-tide levels of 2.3 m above datum coincide with extreme north-wind speeds exceeding 81 km/hr. Most storms occur between September and December (Table 1). Subsequent events in winter do not have significant effects on the coast because of the protection afforded by the ice-foot, 1 km wide on average and attached to the shore (January to late March–early April, Owens, 1976). Storms are rather rare during the rest of the year, but exceptional events may occur.

Table 1. *Chronology of storms with severe coastal impact built from various sources.*

	Wind			
Date	Direction	Max. speed (km/hr)	Flood	Hurricane
1899, 7 Sep.	NW	high	?	
1904, 15 Sep.	?	high	?	X
1917, 20 Oct.	?	high	?	
1923, 1 Oct.	?	very high	?	
1930, 25 Oct.	?	70	?	
1938, 25 Nov.	NE	very high	catastrophic	X
1940, 17 Sep.	NE	130–145	?	X
1951, 27 Nov.	?	very high	catastrophic	
1959, 19 Jun.	NE	102	severe	
1962, 31 Mar.	?	very high	severe	
1962, 8 Oct.	?	128	severe	X
1963, 30 Oct.	?	136	severe	X
1963, 19 Dec.	?	160	moderate	
1971, fall	N	very high	severe	
1974, 20 Oct.	NE	130	severe	
1974, 26 Nov.	?	112	severe	
1976, 17 Mar.	NE	?	catastrophic	
1976, 12 Jun.	?	high	severe	
1977, 7 Dec.	?	very high	severe	
1986, 22 Nov.	NNE	130	catastrophic	
1987, 12 Nov.	NE	85	severe	
1988, 21 Nov.	NE, N	101	catastrophic	
1989, 21 Nov.	N	89	severe	

Sources: *L'Évangéline* (1900–1974) and *L'Acadie Nouvelle* (1984–1990), daily newspapers of New Brunswick; *Perspective climatique* (1980–1990), Canadian weekly climate news and data; Lewis and Moran (1984); Brown *et al.* (1986); and interviews with inhabitants of Shédiac and Cap Pelé

Table 1 summarizes the descriptions of the major storms depicted. Because of the variety of the sources, storm description is neither exhaustive nor akin. According to newspaper sources, two recent catastrophic coastal storms are often cited: November 27, 1951 and November 21, 1988. In both cases, the center of the low passed directly over the area leaving large amounts of snow. The fall 1951 snowstorm was one of the most memorable, probably because part of the town of Shédiac was flooded (Figure 1). The newspapers mentioned that numerous fallen trees were found in the area. The late-fall 1988 snowstorm was similarly windy, with gusts reaching 100 km/hr. Heavy damages to trees and infrastructures were recorded along the coast. The tide gauge station of Pointe-du-Chêne measured a peak of 2.8 m, which is 1.3 m above the predicted high-tide level. The storms thought to have affected the coast the most severely occurred in the following years: 1923, 1930, 1938, 1940, 1951, 1959, 1962, 1963, 1971, 1974, 1976, 1977 and 1986–1989. Earlier events—1899, 1904 and

1917—may have been important, but data are insufficient to confirm their severity.

Tree Response to Erosion and Storm Winds

Forest margins exposed to erosion were deeply destabilized during the last decades (Site 1, Figure 1). The progressive landward displacement of an erosion scarp, now located at the upper beach limit, caused the directly exposed forest edge to move back inland. Regional mean erosion rate, as estimated from multi-year aerial photo measurements spanning the 1945–1982 period, is 1.1 m/year. Most trees lean landward (Figure 3A) and have an asymmetric crown as a result of wind exposure. Younger trees near the erosion scarp were all dead and recruitment was restricted to further inland zones. The mean age of studied spruces was 69 years and the oldest tree was only 98 (65 and 96 respectively for fir trees) at the time of survey. Crossdating of outer rings in dead trees indicates that a large number of individuals died recently (55%: 42 out of 76, *i.e.*, up to 4.7/100 m^2).

After a clearcut, tree colonization of Site 1 started around 1894 (Figure 3B). According to the current rate of shoreline displacement, the erosion scarp was probably at about 100 m seaward from its present position at that time. The frequency of tree falls, as indicated by reaction wood initiation, reflects the episodic nature of the destabilization events (Figure 3C). Although some of the trees showed reaction wood sequences starting in 1915, it was only until 1923, when the erosion scarp was at about 75 m seaward from its current location, that a significant number of trees began a stepwise destabilization. The trees reacted particularly to a series of severe storms: 1923, 1930, 1938, 1940, 1951, 1959, 1962 and 1963. However, only a low frequency of trees recorded the most recent events (after 1963). The development of strong subaerial structures in this uneven-age stand (diameters >12 cm) probably enabled the trees to withstand wind stress since the 1960's (mean tree age at that time: 30 years, 2 modes centered on 25 and 55 years). Thereafter, the sheltering effect of the big trees on others located further inland has limited the extent of the forest fringe's wind stress zone.

Trees that are now within a zone 5 m from the actual erosion scarp show a marked decline in ring widths beginning in 1972 (Figure 3D, trees "d", "e" and "f"). Four major storms occurred in the 1970's: 1971, 1974, 1976 and 1977. We estimated by aerial photo measurements that the erosion scarp was about 20 m seaward from its current position in 1972. A low storm activity period followed during the next 7 years (1978–1985), when a growth spurt was recorded by most of the trees. Another period of low growth began in the mid-1980's, but this time in all of the sampled individuals, with eventual mortality for most trees remaining near the present scarp. Contrasting with a reference curve based on unaffected red spruce trees located inland (n = 15), the stressed trees show a drop in growth in which initiation seems to be delayed in time according to the distance of the tree to water edge (Figure 3D, trees "a" to "f") and following storm periods.

Recent Decline of a Shoreline Birch Stand

A gray birch (*Betula populifolia*) stand lying at a backshore position episodically exposed to the sea showed several decaying features (Site 2, Figure 1). Crown deterioration seems to start with leaf chlorosis and early abcission. Apical buds on the main stem and upper branches die and are soon followed by lateral buds developing long shoots. Dead branches dry up and fall off the main stem, leaving scars. Although pruning is a natural feature often associated with the shading effect in growing stands, it took an unexpected extent in the forest margin studied. Most seaward exposed birches were left only with a clump of branches in their crown. A gradient in stress according to the distance from the water is suggested by the frequency distribution of birch in classes of vigor. The proportion of healthy trees by classes of distance from water vary accordingly (bar diagrams in Figure 4A). The most seaward zone sampled is episodically submerged during storm surges over the uppershore ridge which marks the beach limit. The decaying birch trees nearby are surrounded by a dense fringe of alder (*Alnus rugosa*) and expanding mats of hygrohaline plants (*Myrica pennsylvanica* and *Lathyrus japonicus*). Many birch tree stumps and logs were also found in this zone. Above the critical altitude of 3.2 m above datum, healthy trees dominate.

Among the 40 trees cored, 32 were considered for tree-ring analysis, the other 8 having rotten heartwood. Dating of surrounding stumps and logs was made impossible for the same reasons. The frequency of trees according to years of establishment indicates an uneven-age distribution showing an interruption in colonization after 1952 (Figure 4B). Growth ring patterns of birches show highly sensitive and consistent growth between trees (Figure 4C). Trees reacted similarly to a series of storms, but the fall 1951 event seems to have been the most significant (a growth reduction for 3–4 years was recorded in almost all the sampled trees, Figure 4C). Aerial photos clearly show the disappearance of a frontal marsh during the early 1950's. A long lasting sequence of narrow rings starting in 1972 coincides with the beginning of a major storm period (1971–1977). In 1972, the upper beach limit was at 15 to 20 m seaward from its present location. Since the 1970's, a high frequency of birch trees exhibit incomplete rings, especially around 1975–1976, 1983 and 1986–1990 (Figure 4D). The highest frequency of trees showing such incomplete rings is in 1976, which is precisely when the highest water level was recorded since the opening of the Pointe-du-Chêne gauging station (March 17th, 1976, Figure 2B). High tide levels recorded range between 2.5 and 2.9 m above datum during major storms, and the birch trees studied lie at altitudes of 2.9 to 3.3 m. The latest storm activity period (Table 1, 1986–1989) seemed to have an irreversible effect on the shoreline birch population.

Sea-Level Rise, and Decline of Spruce Forest Margins

A stand of *Picea rubens* at 450 m from the shoreline (Site 3, Figure 1) indicated a possible link with sea-level rise. It showed a recent decline along a topographical gradient; the stressed and dead trees were concentrated in the lower elevations at the edge of a freshwater marsh (Figure 5A). Healthy trees occupy higher elevations (lighter areas on Figure 5A). All trees are still in an upright position and have a fairly symmetric crown, suggesting that wind effects are neg-

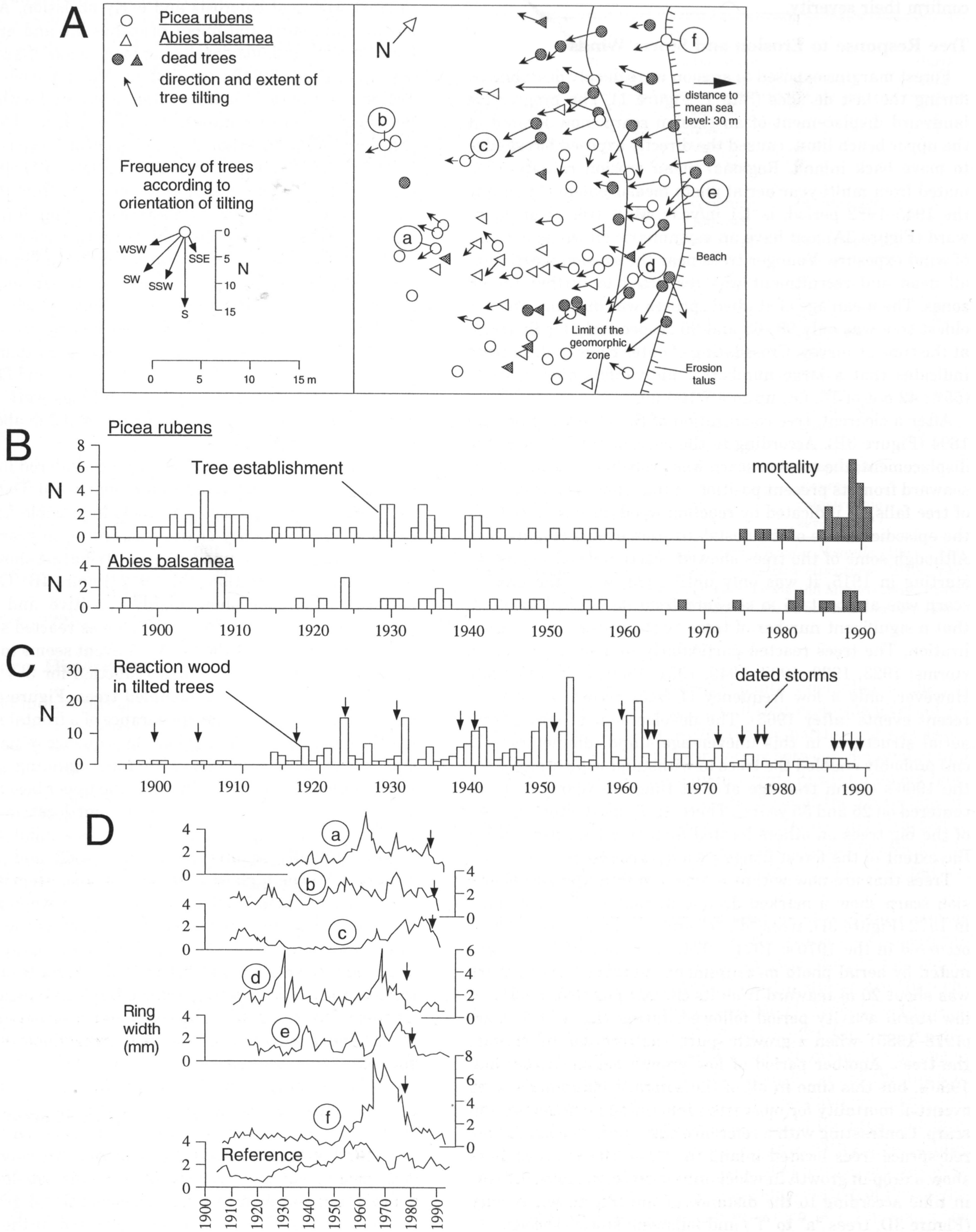

Figure 3. (A) Extent and orientation of tree tilting in 1990 on Site 1. Circled letters correspond to selected trees of Fig. 3D. (B) Age structure of sampled red spruce and balsam fir. (C) Reaction wood initiation frequency on trees. Arrows indicate major storm events from Table I. (D) Radial growth of selected red spruce trees of Site 1 compared to a reference curve. Arrows mark the beginning of the recent decline.

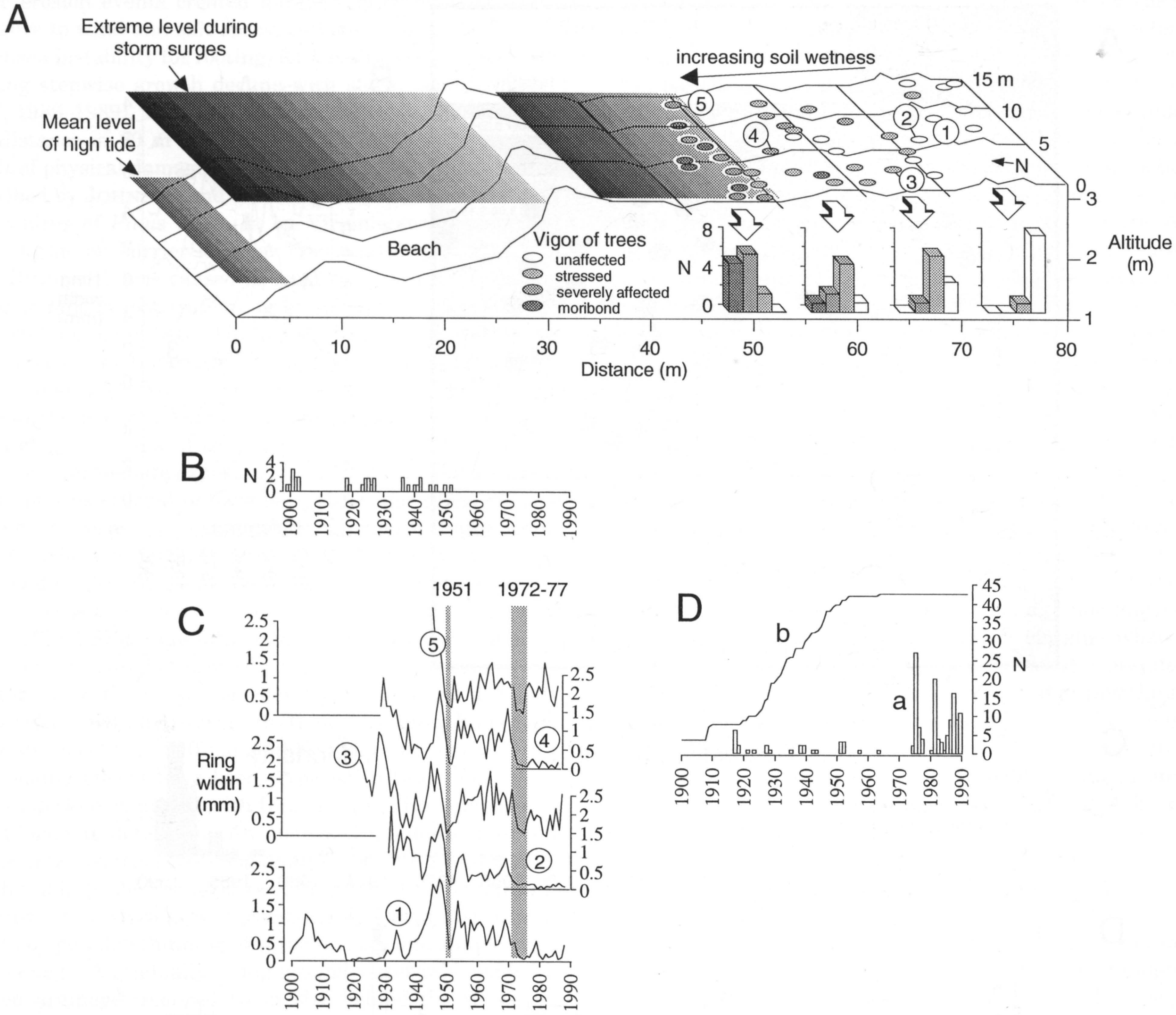

Figure 4. (A) Position and vigor of birch trees on Site 2. Circled numbers correspond to selected trees of Fig. 4C. (B) Age structure of birch trees. (C) Radial growth of selected birch trees. Shaded vertical lines correspond to two major storm events. (D) a: Frequency of incomplete rings in studied trees, b: cumulative frequency of tree age.

ligible. The age structure of spruce shows cohorts of survivors spanning less than 20 years, established after clearcutting in the late 1920's (Figure 5C). Regeneration virtually stopped in the late 1940's, progressive growth decline started for marginal trees in the early 1950's and many trees died in the last decade. Disturbed tree growth is generally characterized by a gently decreasing ring width curve (contrasting with the trend in earlier growth periods) suggesting gradual decay (Figure 5B). This tree-ring pattern differs largely from those of spruce trees in an unexposed reference stand situated farther inland (Figure 5B, bottom diagram). Sequences of very narrow rings are present in all the trees close to the marsh. However, dating the onset of disturbance on the sole basis of radial growth pattern is hazardous. In this site, the distribution of tree mortality dates according to their topographical position is certainly the best indicator to depict a trend in forest decline (Figure 5A). Since 1985, mortality has clearly moved landward, following closely the site topography (isochronic lines of mortality shown on Figure 5A) at a mean rate of 1.24 cm/yr according to the measurements of the absolute altitude of the dead trees. The advance of the mortality front was of 20 m during the 1985–1991 interval, an average of close to 3 m/yr (1 tree/160 m^2/yr). Abrupt drops in the radial growth may correspond to storm events. As a matter of fact, since the 1940's, years showing the highest frequency of trees with narrow rings correspond to those of high frequency of major storm surges in the area (Figure 5D).

DISCUSSION

On the east coast of New Brunswick, tree reactions to disturbance depend on the site's exposure to sea influences and

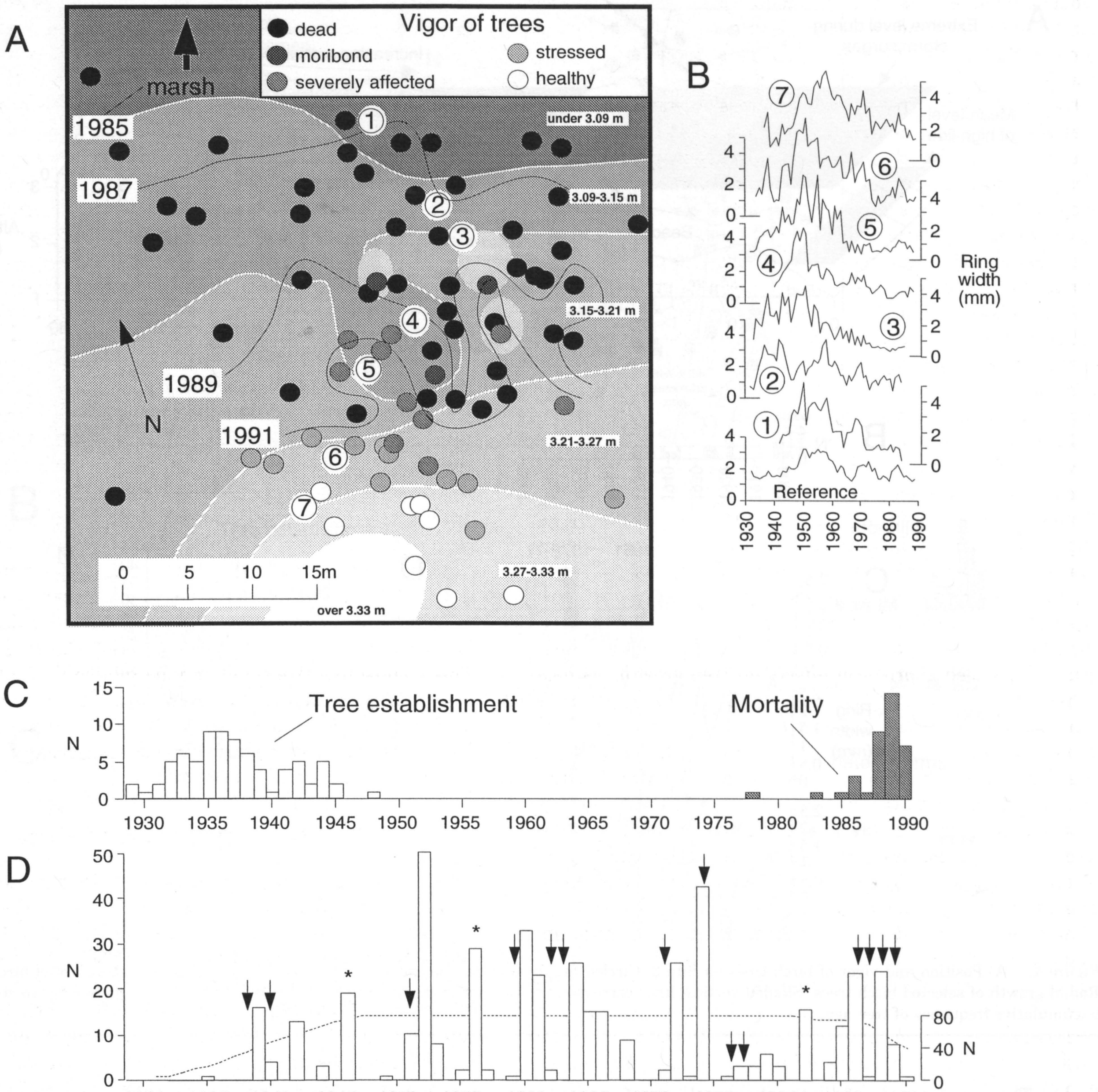

Figure 5. (A) Topography of Site 3 (shaded surfaces: altitude ranges are indicated by small numbers within each zone at right) with position and vigor of trees (dots), and mortality isochrone limits (lines with corresponding years indicated by big numbers). Circled numbers correspond to selected trees of Fig. 5B. (B) Radial growth of selected red spruce trees compared to a reference curve. (C) Age structure of red spruce and dates of mortality. (D) Frequency of abrupt drops in radial growth of trees. Arrows correspond to the major storm events from Table 1. *: Unknown or other causes of growth suppression.

wind stress. Similarly, FOSTER and BOOSE (1992) showed that in central Massachusetts inland forests, the pattern of tree damage was closely dependent on site exposure to catastrophic winds. In coastal sites, however, tree responses differ in nature, length of time, severity and frequency according to a combination of disturbance factors such as sea-level rise and storms.

At the most exposed study site (Site 1), changes in the forest margin are strongly related to storm effects on the coastline. As the shoreline receded through erosion, trees once located further inland experienced increasing exposure to winds. Storm wind pressures caused substantial tree tilting and synchronized reaction wood phases in a relatively high proportion of samples starting at an estimated distance of 75 m from the erosion scarp (Figure 3A). This effect was reduced when trees became strong enough to withstand such winds.

Moreover, as recorded by ring-width curves (Figure 3D), episodic erosion events created harsher conditions (increased exposure to wind and salt spray, changes in the water table, increased instability for rooting) for trees farther inland, thus causing stepwise growth decline with storm periods (1971–1977, 1986–1989). Tree-growth suppression started at a critical distance of 20 m from the forest's edge, probably as a result of physical damage. Such growth suppression has been described by JOHNSON and YOUNG (1992). The reduced tree-ring widths of *Pinus taeda* L. on Virginia coasts coincided with storms on barrier islands. Tree mortality at Site 1 in New Brunswick was caused in most cases either by erosion (undermining of root system), or by storm winds (blowdown), or a combination of both. Afterward, storm waves drifted the fallen trees along the beach. The highly exposed coastal forest margin may experience changes mostly through storm periods, but these modifications are also dependent on stand density and age (*i.e.*, size of trees).

In the intermediate exposure site (Site 2), washover during severe storms seemed to have been the major cause of birch decline. Retrospective examination of gauged water levels from Charlottetown (SHAW and FORBES, 1990) showed a rising trend in sea level, which has probably exacerbated storm surge effects as shown on the birch trees studied. The extreme 1951 storm event, although affecting the forest margin (recruitment ceased afterwards, Figure 4B) and having a major impact on the coast (considerable erosion and flooding), has only caused short-term effects on tree growth, as have other storms of the 1950's and 1960's. Since the early 1970's, long-lasting effects have been recorded in tree rings. Birch growth decline coincided with that of Site 1. Reasons for this are difficult to determine. An increased influence of storms can be inferred from tree-ring analysis on Site 2 and may be attributable to the sea-level rise, but also to the increase in exposure to washovers with coastline recession and to wind effects by possible thinning of stand density and simple physical damage. A gradually rising ground-water table added to slowed drainage (reduced basin size behind the retreating small barrier) may also have created unfavorable conditions for birch growth with time, reaching a critical point in the early 1970's. Increased soil moisture led to a hygrophilous succession through introduction of *Alnus* thickets competing with birch trees. In this case, because of the intermediate exposure of the stand as compared to the other two sites, and because washovers are influenced by storms and sea levels, both phenomena have effects on trees and are difficult to discriminate.

The study of the spruce stand protected from the direct effect of sea erosion (Site 3) has shown its sensitivity to the indirect effects of the rising sea level. Trees died when soil wetness reached a critical level. This assertion is supported by other studies. For example, LORIO *et al.* (1972) showed that on flat, wet sites, a deficient root system developed in *Pinus taeda* trees compared to neighbors on mounds in response to a water regime that increased water stress. They concluded that tree metabolism on wet sites is modified considerably by variations in microrelief. GARDNER *et al.* (1992) also observed along a forest salt-marsh transect in South Carolina that the boundary between the low-lying coastal forest and the high marsh moves upslope with sea-level rise. Local site configuration prompts salinization as well as flooding at the position of the forest margin studied. We noted that the water table of Site 3 in New Brunswick is not yet contaminated by sea salt. NUTTLE and PORTNOY (1992) stated that the elevation of the coastal water table is controlled by mean sea level through hydrostatic equilibrium at the shore. A rising sea level in areas above the high water mark but not too far above the water table (as in Site 3), produces a water table rise that concentrates runoff near the surface. An increasing frequency of forest soil saturation can cause tree growth suppression and, when becoming frequent, may be responsible for forest edge decline. A similar increase in average soil wetness is thought to be the major cause of the gradual landward progression of growth decline and mortality in the spruce stand studied. However, the progression of the spruce mortality front was four times greater than the rising trend in sea level (1.24 cm/year compared to 0.31 cm/year). A storm sequence such as during the 1986–1989 period (Table 1) may have exacerbated the level of stress, causing recent spruce mortality beyond that attributable to intolerance to waterlogging. Sudden drops in tree growth coincided with high coastal water levels induced by storm surges (Figure 5D). As observed in the field during a minor storm event in fall 1990, the lower edge of the forest margin—where dead trees dominate—was submerged in freshwater despite very low precipitation in the previous weeks and during the storm. This water-table rise could only be related to the temporary storm-induced sea-level rise. Elevation of the water table created excess water in this already poorly drained environment, and the flooding may persist, exacerbated by subsequent precipitation.

SUMMARY AND CONCLUSION

This study made it possible to examine storm and marine transgression effects on coastal tree margins through dendrochronology. Most of the severe storms (Table 1) were reflected in reaction wood phases (Figure 3C) and growth drops in tree-ring series (Figures 4C and 5D) in the following years: 1917, 1923, 1930, 1938, 1940, 1951, 1959, 1962, 1963, 1971, 1974, 1976, 1977, 1986 and 1988. Tree-ring study shows differing sequences of changes for each site according to their exposure to the sea. In the highly exposed Site 1, tree tilting in reaction to storms started very early in the spruce stand's history. It was the major effect and lasted from 1917 until the early 1960's, when trees became sturdy enough to withstand storm winds. Growth decline began in the early 1970's for marginal trees and in the mid-1980's for inland trees, when they were 20 m from the erosion scarp. It followed erosion periods during storms. Mortality affected only marginal trees and started in the mid-1980's with the last storm-erosion sequence. Birch trees of the moderately exposed Site 2 showed periodic growth drops from the late 1910's and may be associated with washover during storm surges. The 1951 event was recorded by most sampled trees, but major growth declines have been recorded only since 1971, probably prompted by a rising sea level and by increased exposure to winds and washover flooding. Protected Site 3 experienced a very gradual growth decline eventually reaching trees further inland with time. Decline closely followed site topography, suggesting a rising water table controlled by a sea-level rise. A threshold was attained in the mid-1980's when many trees gradually died off. It reflects rapid site deterioration outpacing the actual rate of sea-level rise.

Because of differing site exposure, storm and marine transgression could be distinguished with some accuracy. Site 1 trees record mostly changes through erosion and storm wind effects, Site 2 is influenced by a combination of storm and sea-level rise impacts, and Site 3 shows mostly indirect water table fluctuations from sea-level rise and storm surges. Sites showing only sea-level effects will have to be protected from storm-surge influences on the water table.

This paper exemplifies the use of tree markers in the analysis of the effects of past disturbances on coastal ecosystems. Although most studies interpret large-scale coastal changes using multi-year aerial photos, dendrochronology yields a close insight into the spatial and temporal dimensions of processes affecting the dynamics of shoreline forest margins.

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☐ RÉSUMÉ ☐

Effets des tempêtes et de la transgression marine sur les marges forestières du Nouveau-Brunswick, Est du Canada. Les tempêtes et la transgression marine dans le golfe du Saint-Laurent dans l'est canadien provoquent une transgression rapide du rivage sur les terres et un dépérissement des forêts bordières. Les perturbations du milieu forestier ont été étudiées par l'analyse dendrochronologique. Les dates des séquence de bois de réaction (bois dense formé en réponse à des stress mécaniques dans les tiges déstabilisées) et des épisodes de cernes étroits indiquent la chronologie suivante des périodes de perturbation majeure liées aux tempêtes: 1923, 1930, 1938, 1940, 1951, 1959, 1962, 1963, 1971, 1974, 1976, 1977, 1986, 1987, 1988 and 1989. La hausse progressive du niveau marin a comme effet direct de déplacer la zone de perturbation vers les terres au sein des franges forestières. Sur les sites protégés par des plages barrières et occupant une altitude voisine du niveau marin, le dépérissement forestier est dû à une hausse du niveau de la nappe phréatique suivant celle du niveau de base. Les stress reliés á l'humidité décrivent un gradient suivant la microtopographie au sein des massifs forestiers. Par l'interdatation des séries de largeurs de cernes tirées d'arbres morts avec celles des arbres vivants voisins, le déplacement d'une vague de mortalité au sein de la forêt a été estimé à 3 m/an horizontalement et à 1.24 cm/an verticalement (pente moyenne de la zone forestière étudiée < 5%) de 1985 à 1991 (mortalité de 1 arbre/160 m^2/an). Les résultats indiquent des effets indirects de la hausse du niveau marin sur une frange forestière éloignée du rivage (jusqu'à 450 m).—*Translated by the authors.*