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LATE HOLOCENE VEGETATION AND FIRE HISTORY OF DEVONSHIRE MARSH, BERMUDA, 5000 yBP TO PRESENT

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ABSTRACT

Analysis of palynomorphs and charcoal preserved in a core extracted from the peats of Devonshire Marsh, Bermuda, provides insight into the history of vegetation and fire occurrences, which can be interpreted in terms of a regional climatic history and anthropogenic effects. Changes in pollen spectra in the core indicate two cycles of wet and dry conditions during the past ~5000 years. These changes are similar to those preserved in lake records in the Caribbean region and in marine sediments of the nearby Bermuda Rise, suggesting regional paleoclimatic forcing. Climatic reconstructions are based primarily on proportional changes in the marsh vegetation, reflecting wetter vs. drier environments. Wetter conditions occurred between 3800 and 1750 yBP and the last 60 years.

Over the past 400 years the vegetation in and adjacent to the marsh has been altered anthropogenically due to the introduction of non-indigenous plant species to the island. Prior to colonization, Devonshire Marsh was dominated by arboreal taxa with an understory of ferns and sedges. With the charcoal horizons indicative of the first major fire in the marsh at a depth of 115 cm, the arboreal taxa in the pollen spectra show marked decrease with a coincident rise in fern spores.

Significant increases in charcoal deposition in the last 500 years indicate an increase in fire frequency. Historical data suggests that this is related to permanent habitation of Bermuda beginning in 1609. Major charcoal peaks can be directly related to large fires that impacted the marsh and/or surrounding areas. Charcoal/pollen ratios are highest at 110-115 cm depth and 0-20 cm. Charcoal influx is also high in these intervals. Paucity of charcoal below 120 cm depth indicates fires in Devonshire Marsh are principally related to human activity. Similar increases in fire frequencies are noted in the Caribbean region and are also attributed to anthropogenic impact, but these fires cannot be as well documented as those in Bermuda.

INTRODUCTION

Bermuda consists of a small group of islands situated ~1000 km east of North Carolina in the western Atlantic Ocean (Figure 1). Due to their location, climate is strongly influenced by the Gulf Stream and the Azores-Bermuda High Pressure System which lead to seasonal precipitation patterns. Hence, paleoenvironmental records from peat marshes and lakes on Bermuda provide a unique terrestrial record of local, regional and even hemispheric climatic change. Based on the analysis of palynomorphs and charcoal particulates, Devonshire Marsh, the largest of these sediment-accumulating basins, contains an ~5000 year long record of environmental change.

This terrestrial record of changes in vegetation and fire frequency can be compared to marine records and other terrestrial records from the southeastern United States and the Caribbean region. Since there was no known permanent human habitation on Bermuda prior to colonization in 1609, the peat record also provides insight into the anthropogenic impact on the native and endemic flora of the island.

Prior Peat Studies

There have been few previous paleoenvironmental studies on Bermuda (Watts and Hansen, 1986 and Ellison, 1993). Watts and Hansen (1986) analyzed a core from Mangrove Lake, the largest lake on Bermuda. Based on sedimentological and palynological changes in this core, four zones were identified. These zones represent a change from a freshwater marsh with some marine influence at the base to a fresh water swamp or marsh, to a freshwater lake to a marine lake from 11,000 yBP to present.

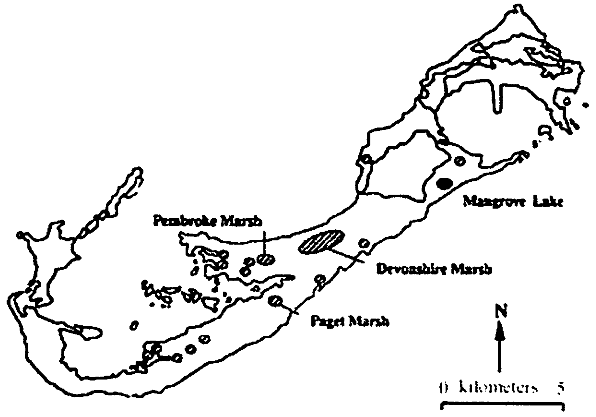

Figure 1. Map of Bermuda illustrating extant peat marshes, wetlands and lakes (designated with the diagonal-line pattern). Devonshire Marsh, the focus of this study, is the largest on the islands. These areas presently represent refugia for several native and endemic plants of Bermuda.

Anthropogenic impact on the flora is noted between 275 and 175 cm depth with the occurrence of *Plantago*, Asteraceae and Apiaceae. Watts and Hansen (1986) found no evidence of the decline of *Juniperus bermudiana* in their analysis. The authors attribute this phenomenon to mixing at the sediment-water interface.

Ellison (1993) in an investigation of mangrove retreat in Hungry Bay, analyzed five cores with basal dates in the range of 4030±110 to 4980±90. The lower portions of four of these cores contained freshwater peat. Overlying the freshwater peat was a mangrove-dominated peat containing pollen of both *Avicennia germinans* and *Rhizophora mangle*, indicating a change from freshwater to marine conditions. The cores also showed the historical decline of *Juniperus bermudiana* (Ellison, 1993).

Other environmental studies on Bermuda focused on reconstruction of sea level changes. Knox (1940) performed the first investigation on peat thickness in Pembroke Marsh. The maximum peat thickness was determined to be 29.6 m

Neumann (1972) undertook the most detailed study of sea level rise using the analysis of peat cores from Devonshire and Pembroke Marshes. Data indicate a sea level rise of 10 m per thousand years from 10,200 to 9000 yBP, 4 m per thousand years between 9000 and 7300 yBP, 3 m per thousand years between 7300 and 3500 yBP. The curve shows an abrupt change and sea level rise slows to 1.6 m per thousand years from 3500 yBP to the present.

Given prior evidence of substantial environmental change during the Holocene, the present study attempts to enhance the paleoclimatic record by combining a detailed analysis of pollen and charcoal in the Devonshire Marsh core with seasonal pollen and charcoal deposition data collected in atmospheric traps over several years.

Recent Environmental History of Bermuda

Due to the enclosure of Bermuda by an extensive reef system, continuous human occupation of Bermuda did not occur until the wreck of the *Sea Venture* in 1609. Other than occasional instances of short stays on Bermuda (Wilkinson, 1959 and Zuill, 1946), 1609 represents the beginning of widespread human occupation. Upon arrival, these marooned individuals made extensive use of the main components of the endemic forest vegetation, *Juniperus bermudiana* and *Sabal bermudana*. Since settlement, historical documents provide a record of the effects of colonization on Bermuda and impact upon the native and endemic flora of

Bermuda (Lefroy, 1876; Verrill, 1902; Britton, 1918 and Collett, 1987).

Because colonization is coincident with continuous occupation by humans, Bermuda becomes a significant locale for the evaluation of anthropogenic impact on the native and endemic flora. *Juniperus bermudiana* was used extensively for housing, furniture and construction of ships and small watercraft. *Sabal bermudana* was used for roof thatching on early houses, basketry, woven hats for export, food, and the production of an alcoholic beverage called bibby.

Juniperus bermudiana was consumed to such a degree that legislation was introduced in 1622 limiting its use (Tucker, 1970). Additionally, the *Juniperus* population was also devastated during the decade following 1946 by the introduction, on shipments of ornamental junipers from the U.S., of two scale insects, *Carulaspis visci* and *Lepidosaphes newsteadi*, (Challinor and Wingate, 1971). Without biological controls, the scale insects quickly destroyed 95% of the remaining cedar population, leaving only the hardiest to survive (Phillips, 1984). As Bermudians capture most of their drinking water by collecting what falls on their rooftops, use of pesticides was precluded and the introduction of more than 25 species of ladybird beetles was too late to stop the decimation of the cedar population (Challinor and Wingate, 1971). Naturally resistant individuals were subsequently nurtured and their progeny are being successfully replanted in hospitable environments around Bermuda.

SITE DESCRIPTION

Devonshire Marsh was selected as the focus of this investigation for following reasons: 1) it is the largest marsh on Bermuda (19.6 ha) (Figure 1), 2) the marsh is centrally located and was assumed to contain the most representative pollen assemblages of the surrounding vegetation, and 3) of the other two large marshes (Pembroke, and Paget Marsh), Devonshire Marsh has been the least disturbed by humans (Sterrer and Wingate, 1981) and provided most ready access for coring purposes.

The underlying bedrock is eolian calcarenite, deposited during high stands of sea level correlative to Pleistocene interglacial episodes, as determined by amino acid racemization dating (Hearty and Vacher, 1994). As sea level rose from approximately 121 m below modern sea level (Fairbanks, 1989), sands accumulated on the beaches. This sediment was reactivated and deposited as broad dunes by wind action. At low sea level stands the Bermuda Pedestal was a large forested plateau (Knox, 1940), dune sands became indurated and soils developed. The alternation of dunes and paleosol formation was repeated during major Pleistocene glacial-interglacial cycles (Rowe, 1998).

The three largest marshes on Bermuda, Devonshire, Paget and Pembroke, are freshwater, produced by the intersection of fresh water lenses with interdunal lowlands (Vacher, 1974). Late Holocene development of Devonshire Marsh is tied directly to the rise in sea level beginning 14 kyBP. With the continued rise in sea level, the fresh water lenses on Bermuda rose. Marsh vegetation kept pace with the rise in sea level (Neumann, 1971). Basal peats in Devonshire Marsh have yielded an age of 7200 ± 120 y BP (Neumann, 1971).

Since colonization, the modern vegetation of Bermuda has been severely impacted by humans. Original settlers and early botanists found 17 endemic species and 160 native species. Presently, there are plant species from all over the world and are thought to represent ~1300 species (Phillips-Watlington, 1996).

Prior to colonization, dense forests of *Juniperus bermudiana, Sabal bermudana* and *Cassine laneana*, covered Bermuda. Peat marsh species included *Juniperus bermudiana, Sabal bermudana*, and *Myrica cerifera* as the trees and shrubs in the canopy. The understory included *Osmunda cinnamomea, Osmunda regalis, Thelypteris kunthii, Woodwardia virginica, Cyperus bermudiana* and *Typha angustifolia*. Coastal vegetation was dominated by *Coccoloba uvifera, Yucca aloifolia, Opuntia* *dillenii*, *Solidago sempervirens*, *Conocarpus erecta*, *Rhizophora mangle*, *Avicennia nitida* and *Suriana maritima*. Rockier doline regions included *Trema lamarckiana*, *Dodonaea viscosa*, *Zanthoxylum flavum*, *Cassine laneana*, *Juniperus bermudiana* and *Sabal bermudana*. The native and endemic flora was extremely limited, but each habitat was represented by distinctive assemblages that allowed characterization and identification.

In order to evaluate the representation of the local and regional vegetation in the fossil pollen spectra as well as in the atmospheric trap data, present-day vegetation was quantitatively analyzed. At the coring site, only five plant species, *Cladium jamaicensis*, *Osmunda cinnamomea*, *Myrica cerifera*, *Pteridium aquilinum* and *Schinus terebinthifolius*, were encountered in a 100 m^2 area, indicating low species richness.

Osmunda cinnamomea (55%) and *Cladium jamaicensis* (25%) dominate the study area. *Myrica cerifera* (13%) and *Pteridium aquilinum* (6%) are also relatively abundant. A single specimen of *Schinus terebinthifolius* (1%) was encountered. Peripherally, specimens of *Juniperus bermudiana* and *Sabal bermudana* were observed, as were *Schinus terebinthifolius*, *Ipomoea villosa*, *Nerium oleander*, *Ficus retusa* and *Casuarina equisetifolia*. Shrub species in the vicinity include the endemic *Ascyrum hypericoides*, and the introduced *Lantana camara*.

Coring of the sediment was completed in 1969 near the center of Devonshire Marsh (32°, 18.538' N; 64°, 45.306' W) using a 10-cm diameter irrigation pipe (Neumann, 1971, 1972). Sixteen samples were collected in the field for radiocarbon dates (Table 1). The depth/age relationship for these samples is shown in Figure 2. Samples used for pollen analysis were taken at 5-cm intervals in the upper 200 cm of the core and at 10-cm intervals from 200 cm to the base of the core.

In addition, an atmospheric fallout trap was positioned on a 1.5 m post in close proximity to the original coring site. The trap was changed and analyzed seasonally for palynomorphs and charcoal to determine composition and influx of these particulates and allow comparison with the core data (Rueger, 2002).

MATERIALS AND METHODS

Sample processing followed standard palynological extraction techniques (Faegri et al., 1989) and are detailed in Rueger (2002). Prior to processing, three tablets containing *Lycopodium* spores were added to each sample to calculate palynomorph and charcoal influx, using radiocarbon ages. Terrestrial pollen sum (Σ) was based on the sum of nonarboreal palynomorphs (NAP) and arboreal palynomorphs (AP). Pollen content was determined as total content per unit mass per year (Rueger, 2002). From total concentration values, pollen influx in grains/gm/mm/yr was also determined (Rueger, 2002).

Sample	Depth (cm)	Age (yBP)	Accumulation Rate (mm/yr)
D-1	5	0	
D-2	81	100±80	8.1
D-3	135	775±80	0.8
D-4	173	1185±85	0.9
D-5	234	1400±85	2.8
D-6	259	1995±85	0.4
D-7	357	2355±90	2.7
D-8	485	2910±90	2.3
D-9	589	3725±95	1.3
D-10	699	4065±100	3.2
D-11	705	4569±100	0.9
D-12	747	4730±100	0.7
D-13	805	5380±100	0.9
D-14	850	6010±100	0.7
D-15	945	6240±110	4.1
D-16	1030	7200±120	0.9

Table 1. Samples taken from the Devonshire Marsh core with radiocarbon dates for the core and corresponding depths, ages, and accumulation rates (Neumann, 1971, 1972).

Swain (1973) demonstrated that charcoal preserved in sediments realistically represented the nearby fire history. Charcoal present within the processed residue from Devonshire Marsh

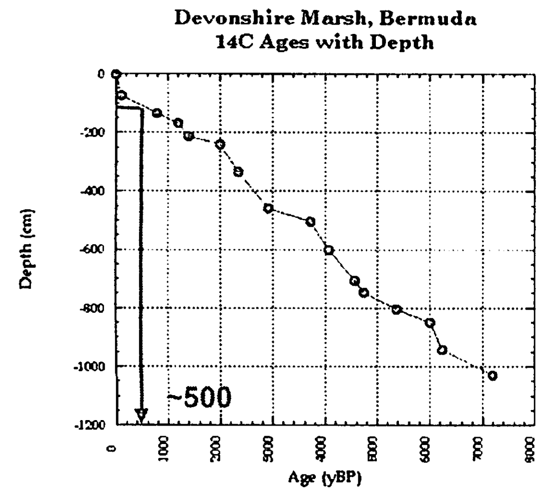

Figure 2. Diagram illustrating the accumulation of peat in Devonshire Marsh over the past 7,200 years (Neumann, 1971, 1972).

was counted simultaneously with the palynomorphs using a standard optical microscope with a mechanical stage to evaluate the history of fire events in the marsh. Charcoal size counted in this investigation was in the range between 10 and 50 μm. This size fraction is similar to palynomorph grain sizes, which according to Mehringer et al. (1977) is most indicative of local fires.

Charcoal concentration was determined as total content per unit mass of sample as in Davis (1967), Mehringer et al. (1977), Singh et al. (1981) and as influx per unit area per year or depositional rate as in Byrne et al. (1977), Green (1981) and Tolonen (1986). From total concentration values, charcoal influx in grains/gm/mm/yr was determined and charcoal deposition rate was determined (Rueger, 2002) (Figure 3).

The charcoal/pollen ratio for each level (Figure 4) was determined following the methodology of Blackford (2000). Charcoal/pollen ratios in the samples will be higher where fire has occurred near to the coring locality. Charcoal/pollen ratio is used as it is a recommendable index of "true" fires, because it apparently minimizes effects of different rates of sedimentation and false peaks of reworked charcoal (Swain, 1973, Tolonen, 1986). Taxonomy used in this investigation follows that of Britton (1918) and Phillips-Watlington (1996).

RESULTS

Sediment Composition and Accumulation Rates

The upper 100 cm of the core was composed principally of peat, dominated by undecomposed fern rhizomes and grass roots. Below that, to a depth of 620 cm, the core was relatively homogeneous, composed of partially decomposed woody peat with abundant plant remains. From 620 cm to 1055 cm, the peat was highly decomposed with much less root material preserved. Bedrock in the form of calcarenite limestone was encountered at a depth of 1055 cm. The changes at 100 cm and 620 cm may reflect the transition from a persistent swamp-forest peat to an herbaceous marsh peat.

The lower-most radiocarbon sample at 1030 cm yielded a date of 7200±120 yBP (Figure 2). Unfortunately pollen was not preserved between 1030 and 755 cm. Nine ^{14}C dates were obtained from the interval of the core in which palynomorphs are preserved (Figure 2). Average accumulation rate for this interval was 1.7 mm/yr. Accumulation rates between the dates are variable and are shown in Table 1. The slowest rates are near the top of the core and faster rates deeper. These data suggest that peat accumulation is tracking sea level rise. This conclusion is substantiated by comparing the dates obtained from the Devonshire Marsh core with elevation of sea level at corresponding times provided by Fairbanks (1989) from Barbados.

Pollen Records in the Core

Pollen analysis of the core showed continuing presence of seven major taxa (Figure 3): *Juniperus bermudiana, Myrica cerifera, Sabal bermudana, Osmunda cinnamomea, Polystichum adiantiforme, Woodwardia* *virginica/Thelypteris kunthii, Pteridium aquilinum,* and *Cyperaceae*. The most common *Cyperaceae* species in the modern flora is *Cladium jamaicensis*. *Woodwardia virginica* and *Thelypteris kunthii* could not be separated morphologically and are plotted as one taxon. In reference specimens, both were approximately the same size, were monolete, psilate and thick-walled, making differentiation extremely difficult at the species level. Also, *Juniperus bermudiana*, a thin-walled, spherical and inaperturate pollen grain with scattered gemmae, was not always easy to identify.

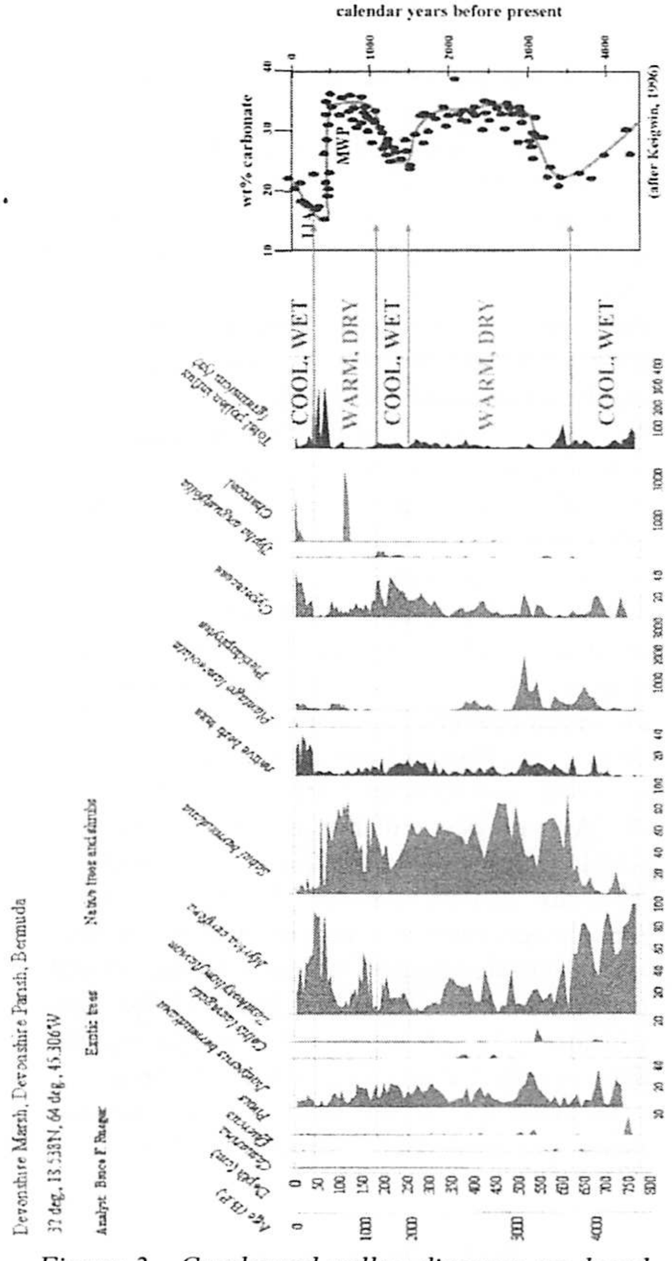

Figure 3. Condensed pollen diagram produced from the core taken from Devonshire Marsh compared with the deep marine sediment record obtained from the Bermuda Rise.

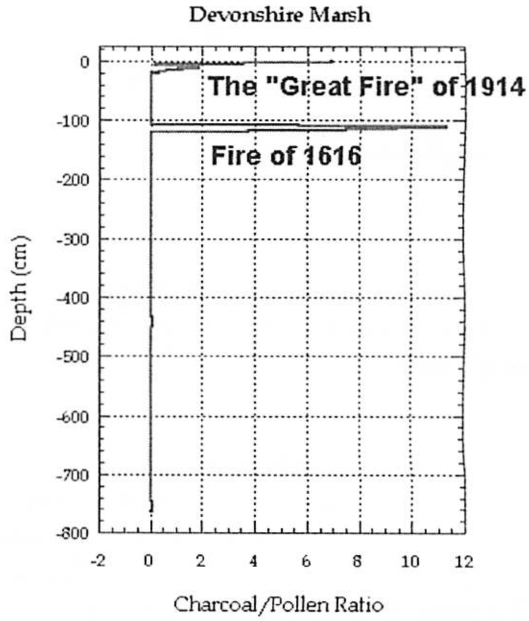

Figure 4. Charcoal/pollen ratios determined for samples from the Devonshire Marsh core.

Analyses of the distribution of pollen and spores throughout the Devonshire Marsh core, revealed several major changes and trends (Figure 3):

1) The base of the core, below 755 cm, contained only poorly preserved palynomorphs. Grains encountered possessed thick walls, and were predominantly those of *Myrica cerifera*.

2) The lowest interval in which palynomorphs were well preserved was between 4750 yBP and 3880 (755 to 640 cm depth). *Myrica cerifera*, *Juniperus bermudiana*, pteridophytes and Cyperaceae are the most abundant taxa in this interval. *Sabal* is particularly sparse. The flora in this interval is dominated by nonarboreal pollen.

3) Between 3880 and 1750 yBP (640 to 250 cm depth), native trees and shrubs were most abundant and included *Juniperus*

bermudiana, *Sabal bermudana* and *Myrica cerifera*. Native herbs are uniformly present. Cyperaceae and pteridophytes were also present showing high variability. Sediment accumulation in this interval was higher than that found in the interval below; palynomorph influx was moderately high, but in general was lower than the underlying interval (Figure 2).

4) Peat between 1750 and 1210 yBP (250 and 180 cm depth) was characterized by abundant Cyperaceae. *Typha angustifolia* also reaches its maximum abundance in this interval. Also found in this interval is *Juniperus bermudiana* and *Myrica cerifera*. *Sabal bermudana* is present, but abundance decreases relative to the underlying section. This interval also has one of the higher accumulation rates observed in the core and pollen deposition is moderate.

5) Between 1210 and 60 yBP (180 and 50 cm depth), *Sabal bermudana* again becomes the most abundant taxon. *Myrica cerifera*, *Juniperus bermudiana*, *Typha angustifolia*, and Cyperaceae experience significant decreases in abundance. The highest occurrence of charcoal particulates occurs in this interval at approximately 520 yBP (115 to 110 cm depth). This represents the largest fire event(s) preserved in the core and is immediately followed by an increase in pteridophyte spore abundance (Figure 2).

6) The uppermost interval, from 60 yBP to the present (50 to 0 cm depth), is characterized by the highest variability in palynomorph abundance. In this interval, tree and shrub pollen shows a significant decrease with *Sabal* exhibiting its lowest abundances. In contrast, pteridophytes and Cyperaceae increase. Decreases in *Juniperus bermudiana* and *Sabal bermudana* are in response to human-induced fire event(s). Charcoal is abundant throughout the uppermost part of this interval. Pteridophytes *Osmunda cinnamomea* and *Woodwardia virginica/Thelypteris kunthii* increase towards the top of the core. In the last 40 years (upper 35 cm), *Pteridium aquilinum* is the most abundant fern spore taxon. *Myrica cerifera* increases in abundance in this interval. Other minor taxa noted here include *Lippia nodiflora*, Asteraceae, *Casuarina* sp., Apiaceae, and *Plantago lanceolata*. Pollen depositional rate within this interval is the highest observed in the core. Changes in pollen distribution in this analysis are similar in the uppermost intervals to those noted in a core taken in 1991 which set the groundwork for this investigation (Rueger and von Wallmenich, 1996).

Results from the Atmospheric Particle Trap

Samples from the atmospheric traps are dominated by spores and pollen of pteridophytes and herbs representative of the local wetland flora (Rueger, 2002).

Juniperus bermudiana was the only tree with substantial pollen accumulation, originating from isolated specimens near the marsh. *Myrica cerifera* and *Sabal bermudana* are common shrubs in the marsh and are well represented.

Pteridophytes and *Cyperaceae* make up the majority of the vegetation in the marsh and their presence is reflected in the pollen collected in the traps. *Osmunda cinnamomea* and *Woodwardia virginica/Thelypteris kunthii* were the most abundant fern species.

The trap data is quite representative of the modern flora in the marsh as the most abundant plants in the marsh today are members of the *Cyperaceae* (*Cladium jamaicensis*) and the *pteridophytes* (*Osmunda cinnamomea* and *Pteridium aquilinum*). The dominant shrub in the marsh is *Myrica cerifera* and pollen from this plant is well represented in the trap flora. Pollen and spores of the plant taxa collected in the traps are representative of the plants observed in close proximity to the trap locality (Rueger, 2002).

The atmospheric palynomorph influx from the Devonshire Marsh trap was compared with the fossil pollen record to assess how representative the fossil pollen spectra in the peat are in terms of local and regional vegetation.

DISCUSSION

Comparison of Modern Vegetation and Fossil Record

On Bermuda, native and endemic plants have been classified according to the habitats in which they are most commonly found (Britton, 1918 and Phillips-Watlington, 1996). These habitats include shallow sandy bays, mangrove swamp-tidal lagoon, brackish marsh, beach and dune, coastal hillsides and rocks, upland hillsides, upland valley, dolines and peat marshes. In this investigation, these habitats were combined to make five categories: 1) coastal, (shallow sandy bays, mangrove swamps-tidal lagoon, brackish marsh, beach and dune, and coastal hillsides and rocks); 2) inland, (upland hillsides and upland valley); 3) dolines; 4) peat marshes; and 5) introduced taxa.

Comparisons of the actual percentages of plant taxa in the field with the percentages of pollen and spore taxa in the traps and in the surface sample from the core are shown in Figure 5. The distribution of plants in the modern vegetation of the marsh compares well with the pollen and spore types collected in the traps and the surface sample of the core. This comparison supports the idea that the fossil record is accurately representing the flora of the marsh. Consequently, the fossil record can be used to interpret changes in the vegetation of the marsh through time. It also supports the conclusion that very few pollen and spore types are arriving on Bermuda by long-distance transport mechanisms.

The pollen from introduced plants, such as *Pinus*, *Picea*, *Quercus* and *Schinus terebinthifolius*, are more likely to be found in the traps due to the anemophilous nature of pollen dispersal. Most of the native and endemic plants on Bermuda rely on vector pollination. With anemophilous pollination mechanisms, pollen production in these plants increases and consequently may be over represented in the traps. Introduced species, in general are also able to exploit their new environment and out-compete the native and endemic flora, again altering distribution values in the traps and in the modern marsh vegetation.

The occurrence of pollen from *Quercus* and *Pinus* in the core and *Quercus*, *Pinus* and *Picea* in the pollen traps were thought originally

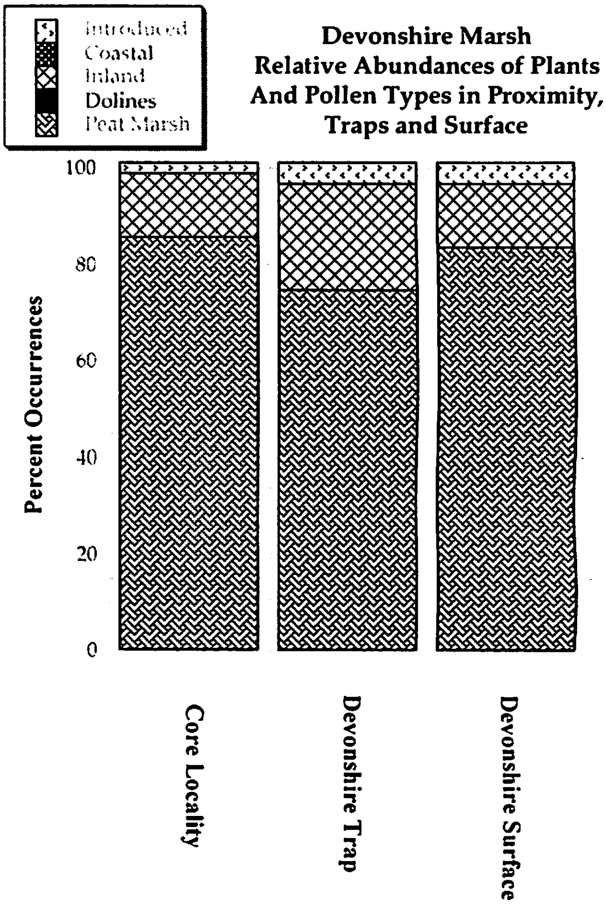

Figure 5. Comparison of percent occurrence of plants from the various habitats in the local vegetation in proximity to the coring locality, the percentages of pollen and spore types in the atmospheric fallout traps collecting in the marsh and the percentages of pollen and spore types in the surface sample from the Devonshire Marsh core.

to represent long-distance transport from North America. However, *Quercus* and *Pinus* were both introduced to Bermuda in the last 100 years, but *Picea* is not known to exist on Bermuda (Lisa Greene, personal communication, 2001). Specimens of *Pinus* are, in fact, located not far from Devonshire Marsh as ornamentals. Consequently, *Quercus* and *Pinus* cannot with certainty be regarded as indicative of long-distance transport. However, in the core, below depths of 125 cm, *Quercus* and *Pinus* can be attributed to long-distance transport to Bermuda.

Any grains of *Picea* pollen have arrived from allochthonous sources, most likely North America, as *Picea rubens* currently grows in the central Appalachians (Petrides, 1972).

In the fossil record, higher influx rates were found in the younger sediments (Figure 3). This is related to at least two factors: 1) the fact that the sediment is not as well decomposed at surface as it is at depth. With longer exposure time, peat has also been subjected to greater amounts of organic decay, and 2) with depth comes greater sediment compaction.

These factors also account for the fact that pollen concentration is lower in the upper part of the core (Figure 3). With less decomposition of the peat the concentration of palynomorphs should be lower. Conversely, compacted, more highly decomposed lower parts of the core, will have higher concentration of palynomorphs. However, concentration and deposition rate is greatly affected in close proximity to the carbonate bedrock. Proximity increases alkalinity of the groundwater which is highly corrosive to the palynomorphs and detrimental to their preservation.

Holocene Vegetational History and Environmental Changes

Environmental interpretation of the pollen diagram from the Devonshire Marsh core allows delineation of five distinct zones. The oldest zone, between 4750 yBP and 3880 yBP represents an interval of wetness in the marsh (Figure 3). The abundance of pteridophytes and Cyperaceae attest to high water table in the marsh.

The next interval, between 3880 and 1750 yBP, is characterized by increased abundance of *Sabal bermudana* and pteridophytes and decreased relative abundances of *Myrica cerifera, Juniperus bermudiana* and Cyperaceae. This indicates that conditions were getting drier.

Wettest conditions in the marsh are reflected in the third zone in the diagram (Figure 3) between 1750 and 1210 yBP. Abundant Cyperaceae and the only significant occurrence of *Typha angustifolia* are indicative of standing water. *Myrica cerifera* and *Juniperus bermudiana* are present but these species are tolerant of a wide variety of moisture conditions. Decrease in abundance of *Sabal bermudana* supports the interpretation of increased moisture content as it is not common today in areas of standing water, preferring uplands and marshy areas.

Dry conditions resume between 1210 and 60 yBP, where *Sabal bermudana* becomes the most abundant taxon (Figure 3). Cyperaceae, pteridophytes and *Myrica cerifera* decrease in abundance. *Typha angustifolia* abundance decreases significantly, indicating the absence of standing water. *Juniperus bermudiana* gradually decreases, perhaps as a result of fire occurring at ~520 yBP. The slight increase in pteridophyte abundance may also be attributed to fire event(s).

The uppermost zone, which encompasses the last 60 years, is characterized by the most significant anthropogenic impact on Devonshire marsh (Figure 3). Recurrent fires and agricultural impacts have greatly modified the flora. Decrease in *Juniperus bermudiana* is attributed to a sequence of marsh fires that began in 1914 and the scale insect infestation in the late 1940s-early 1950s. *Sabal bermudana* becomes a minor component of the marsh flora. Its demise may be related to the fires in the 20th Century. With the loss of canopy vegetation, *Myrica cerifera* exploited the openness of the marsh, as do many of the pteridophyte species. *Pteridium aquilinum*, well adapted to bright sunlight, also made use of the newly created habitat. Herbs and introduced weedy taxa also take advantage of the newly created, highly disturbed marsh surface. Introduced species increased in abundance in the very upper part of the core as new tree species were brought to Bermuda in an attempt to replace *Juniperus bermudiana.*

Devonshire Marsh Fire History

The most significant accumulations of charcoal in the core occurred at approximately 520 yBP (110 to 115 cm depth) (Figure 3). Coincident with these charcoal accumulations is a marked change in pollen spectra within the arboreal and shrubby species *Juniperus bermudiana*, *Sabal bermudana* and *Myrica cerifera*. Immediately above 520 yBP (110 to 115 cm depth), relative abundances of these pollen types show significant decreases, while those of *Osmunda cinnamomea* and *Woodwardia virginica/Thelypteris kunthii* increase (Figure 3). Pteridophytes increase in abundance due to the lack of cover. Decreased shade may also account for the more widespread occurrence of *Pteridium aquilinum* which is also coincident with the fire event(s). These trends continue in the marsh for the following ~ 400 years.

Since the islands of Bermuda were colonized in 1609, and there is a paucity of charcoal below 520 yBP, this fire event(s) must be attributed to anthropogenic causes. This charcoal horizon probably corresponds to a 1616 fire event which is recorded in several sources, such as diaries, local newspapers and the national archives.

During 1614, a captured Spanish frigate arrived in Bermuda loaded with a cargo of grains and meal (Craven, 1990). Along with the meal came a great many rats. Due to the lack of natural predators, the rats quickly colonized the islands and proceeded to multiply at such a rapid rate that they soon became a plague (Wilkinson, 1959 and Ives, 1984). Lefroy (1876) stated that many attempts to eliminate the rats were tried, including the importation of cats from England in 1615. When this failed, more drastic measures were deemed necessary.

In 1616, Governor Tucker of Bermuda initiated island-wide burning of large tracts of wooded areas and marshes to destroy habitat (Smith, 1624; Smith, 1950; Wilkinson, 1959; Lefroy, 1876; Ives, 1984; and Craven, 1990). This destroyed such large quantities of valuable cedar and palmetto timber that it led to strict regulations on harvesting and exporting cedar wood. The fires did little to end the plague of rats (Lefroy, 1876) which was finally eased by the occurrence of a solid month of rain and cold temperatures in 1618 (Craven, 1990).

During the interval following this early conflagration, the occurrence of *Sabal bermudana* pollen increases in the Devonshire Marsh core, illustrating the resiliency of this species to fire. However, it never regained the dominance it held prior to the fire (Figure 3). *Juniperus bermudiana* never appears to recover and open space is utilized by *Myrica cerifera*, which has increased over the past 100 years (Rueger, 1999).

Over the past 60 years (0 to 50 cm depth), charcoal is a common constituent in the organic residue extracted from the core (Figure 3). Extremely high charcoal influx, is again noted in this interval (Figures 3 and 4). This charcoal reflects fires of anthropogenic origin, with the first occurring in 1914, known locally as the "Great Fire of 1914" (John Cox, personal communication of an interview with Ms. Dora Smith, 1900-1992). Ms. Smith recalled traveling by Devonshire Marsh area one night in late spring or summer of 1914, and observing the entire marsh ablaze.

Following the fire of 1914, the marsh was burned multiple times in the early 20th Century for a variety of reasons, including cattle grazing and celery farming (Wingate, 1997). A sequence of fires in the late 1940s and early 1950s were intentionally set on a regular basis by a Mrs. Jackson of Lime House, to keep trespassers and itinerants away (John Cox, personal communication).

The marsh also burned on 28 March, 1957 (Anonymous, 1957a; 1957b) and 27 April, 1971 (Seymour, 1971). The most recent fire event occurred as a sequence of three fires that burned the marsh on 5-7 December, 1996 (Anonymous, 1996a; 1996b; 1996c; Hainey, 1996 and Deacon, 1996 and 1997). The 1996 fire occurred in three major outbreaks that burned 80-90 percent of the marsh. By the end of January, 1997, a lush bloom of ferns had covered the marsh almost immediately. This was followed by the recovery of *Sabal bermudana* and *Myrica cerifera* (Rueger, 2002).

Prior to 520 yBP (> 115 cm depth), charcoal particulates in the core are absent or extremely sparse (Figures 3 and 4). Charcoal/pollen ratios in the core indicate that fires have been common only over the past 500 yBP and support the conclusion that the major fires affecting the vegetation in Devonshire Marsh are anthropogenic in origin (Figure 4).

Consideration of and comparison with records of charcoal in the southeastern United States illustrates significant differences with those observed in Devonshire Marsh on Bermuda. Fire frequency at lakes in the southeastern US, over the past 5,000 yBP, is common and charcoal is found at all levels (Watts and Hansen, 1988, Hussey, 1993 and Watts et al., 1996).

In the Caribbean region, including Haiti, Puerto Rico and the Bahamas, large quantities of charcoal are found between 5400 and 2500 yBP (Burney et al., 1994, and Higuera-Gundy et al., 1999). Kjellmark (1996), at Church's Blue Hole on the Bahamas, reported the highest charcoal concentrations over the last 740 years. At these sites, high charcoal concentrations are attributed to human occupation of the areas surrounding the lakes.

Extraregional Paleoenvironmental and Paleoclimatic Comparison

Comparisons of vegetational changes on Bermuda with those in the southeastern United States and the Caribbean region show similar patterns. In the southeastern US, the vegetation began to change from oak to pine dominance at approximately 5000 yBP in Florida (Grimm et al., 1993, Watts, 1969, 1970, 1971, 1975a, 1975b, 1980a, 1980b, Watts et al., 1996, and Watts and Hansen, 1988) and between 8000 and 6500 yBP in Georgia (Watts, 1969 and Watts, 1980a), South Carolina (Watts, 1980b and Hussey, 1993), and North Carolina (Whitehead, 1973). This is interpreted to represent a change from a dry, savannah-like environment with oak forests to a moister, modern-like pine forested environment (Rueger, 2002).

Few sufficiently detailed paleoenvironmental studies exist from the Caribbean region allow comparison to the Bermuda record. One record is from Lake Miragoane on Haiti (Hodell et al., 1991; Higuera-Gundy et al., 1999 and Fritz et al., 2001) and shows changes from wet (5200 to 3200 yBP) to dry (3200 to 2400 yBP) with a very wet interval at ~1200 yBP. Increases in charcoal concentration during this interval indicate greater fire frequency (Higuera-Gundy et al., 1999). The uppermost zone, from 180 yBP to the present, contains a record of substantial human impact on the region. The area was deforested and sediments record the resulting soil erosion.

Kjellmark (1996) in his analysis of Church's Blue Hole in the Bahamas found evidence of a late Holocene dry period between 3200 and 1500 yBP. Following this dry interval, more wet and humid conditions are evidenced by palynomorphs of mesic tropical hardwoods in proximity to the pond. A change from these conditions to one dominated by *Pinus* occurs at approximately 740 yBP and may be related to anthropogenic impact on the flora.

High-resolution paleo-oceanographic studies of sediments from the Bermuda Rise, show changes attributed to variations in sea-surface temperatures (SST) and production of North Atlantic Deep Water (Keigwin, 1996). Specifically, Keigwin (1996) found three distinct sediment cycles over the past 4500 years (Figure 3). Between 4500 and 3250 yBP, carbonate production decreased significantly in the western North Atlantic Ocean (Figure 3). At this time, sea surface temperature (SST) decreased and precipitation increased producing an interval of cooler and wetter conditions. From 3250 to 1700 yBP, warm, dry conditions were prevalent in the western North Atlantic Ocean. Carbonate production decreased at 1700 yBP when conditions were warm and dry during and continued until 1200 yBP. At 1200 yBP, carbonate production again rose and until 400 yBP conditions were warm and dry conditions during the Medieval Warm Period. Carbonate production has decreased from 400 yBP to the present, indicating a return to cool, wet conditions, which are thought to represent the Little Ice Age

Changes similar to those in the southeastern US and the marine sediments of the Bermuda Rise are preserved in the peat of

Devonshire Marsh (Figure 3). The lowermost unit from 3880 to 4750 yBP suggests conditions were quite wet on Bermuda. Cooler intervals such as this may also have had associated increases in storminess, which would explain increased precipitation on Bermuda (Lamb, 1979 and Hass, 1993).

Warmer and drier conditions on Bermuda existed during the interval between 3880 and 1750 yBP. This interval is followed by an interval extending from 1750-1210 yBP in which conditions in Devonshire Marsh were the wettest recorded.

Also coincident with the end of this interval, is a corresponding change in rate of sea level rise that occurs at approximately 2000 yBP (Rueger, 2002). This change in rate of sea level rise is the only one of significance noted in the record and occurs at a depth of 250 cm in the Devonshire Marsh core. This indicates that both sea level and marsh vegetation responded to global and/or regional climate forcing which resulted in a decrease in sea level rise and a coincident increase in moisture availability to the marsh (Figure 3).

As indicated by the Devonshire Marsh pollen record, during the Medieval Warm Period between 1200 and 600 yBP conditions on Bermuda were also warm and dry at that time (Figure 3).

The Little Ice Age signal is not as obvious or as well defined in the peat record of Devonshire Marsh, probably because anthropogenic impacts begin to appear at that time, including fires and the importation of exotic plant species (Figure 3).

The close relationship between paleoenvironmental changes on Bermuda and changes in marine conditions suggests that both the terrestrial and the marine systems, are responding to the same force. The changes in Devonshire Marsh appear to be driven by moisture which is linked to the amount of rainfall on Bermuda. When winter rainfall increases during the cooler, wet interval, marsh vegetation adapts to those conditions.

CONCLUSIONS

The relationship between the palynomorphs preserved in the sediments of Devonshire Marsh and those collected in atmospheric fallout traps shows strong correlation. This can be attributed to the fact that most palynomorphs do not travel far from the point of production. This relationship suggest that accurate interpretations of changing vegetational parameters in the marsh can be based on changes in pollen and spore abundances in the fossil record.

Long-distance transport of palynomorphs from either the southeastern United States or the Caribbean region cannot be well documented. Only a few pollen grains of *Pinus*, *Picea* and *Quercus* were observed in the sediments of the marsh or in the traps. Of these three genera of trees, *Pinus* and *Quercus* have been introduced to Bermuda since colonization. Only the presence of *Picea* pollen in the traps can be conclusively attributed to long-distance transport to Bermuda. The occurrence of *Pinus* and *Quercus* in the sediments of Devonshire Marsh deposited prior to colonization, must be the result of long-distance transport. *Pinus*, *Picea* and *Quercus* occur in the southeastern United States and this would be the most logical source of these pollen grains. Regardless, long-distance transport of palynomorphs to Bermuda has not occured in great quantities or had a great impact. Most of the palynomorphs found in the peats of Devonshire Marsh and in the traps are of local origin and have not been moved great distances from their origin.

In the palynomorphs collected in the atmospheric fallout traps, seasonality in rates of deposition was noted. The majority of palynomorphs collected in the traps deposited in the spring with contributions during the summer and winter collecting intervals. Palynomorph production and dispersal rates were greater in the winter and spring intervals as this is the time of year when there is greater moisture available to the plants.

The record of charcoal deposition in the peats is also similar to that in the Caribbean region based on analyses of lake sediments in Haiti, Puerto Rico and the Bahamas. In this region, large-scale occurrence of charcoal in lake deposits is attributed to the first arrival of humans in close proximity. Since the colonization of Bermuda was known to have begun in 1609, and the largest occurrence of charcoal is recorded in the peat at approximately this time, most of the fires in Bermuda that have affected Devonshire Marsh can be ascribed to anthropogenic impact. On Bermuda, since the time of colonization is known and the record of charcoal is initiated at the same time, the relationship between these fires to human occupation is conclusive. Historical records document the occurrence of all the major fires that have affected the marsh and all are attributed to human cause.

The palynomorph analyses indicate that sea level rise and regional climatic changes over the past 5000 years have both influenced the vegetation in the marsh. As sea level rose, vegetation was able to maintain growth at a similar rate. Since sea level rise was relatively constant, with only one change in rate noted at a depth of 250 cm in the core and the palynomorphs indicate that water salinities in the marsh basin were fresh or only slightly brackish over the last 5000 yBP, the observed changes in marsh vegetation are attributed to regional climatic influence. As climate changed, vegetation in the marsh changed and these changes were recorded in the palynomorphs preserved in the peats.

Between 4750 and 3880 yBP, when marsh development began, the palynomorphs indicate that the conditions on Bermuda were moist, much like at present. Abundance of palynomorphs from pteridophytes, Cyperaceae and *Myrica cerifera* support this interpretation. Between 3880 and 1750 yBP, the local climate became drier as evidenced by the decrease in palynomorphs from the pteridophytes and Cyperaceae, and increases in pollen abundances from *Juniperus bermudiana* and *Sabal bermudana*. The wettest conditions recorded in Devonshire Marsh occur between 1750 and 1210 yBP as evidenced by increases in abundance of palynomorphs from the Cyperaceae, *Myrica cerifera* and especially *Typha angustifolia*. Drier conditions resume in the marsh between 1210 and 60 yBP. Over the past 60 years, anthropogenic impacts have masked the climate record signals that could have been preserved.

The Devonshire Marsh climatic history can be readily correlated with similar records found in the southeastern United States, the Caribbean region and with the marine record found east of the Bermuda pedestal. The higher resolution noted in this investigation can be attributed to the lack of sediment mixing or turnover in peat deposits that is observed in the records of lakes and ponds and oceanic sediments.

Changes in the peats of Devonshire Marsh reflect two of the three climatic cycles defined by Keigwin (1996) in the sediments of the Bermuda Rise. These changes were influenced by fluctuations in sea-surface temperature and production of North Atlantic Deep Water. The changes in these conditions are recorded as an alternation between wet and dry conditions in the peats of Devonshire Marsh.

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