14,000 Years of Sediment, Vegetation, and Water-Level Changes at the Makepeace Cedar Swamp, Southeastern Massachusetts

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INTRODUCTION

Water-level fluctuations in many lakes and mires are hydrologic responses to changes in the balance of precipitation and evaporation. If fluctuations among basins are temporally and spatially coherent, they often are indicative of a regional hydrologic response to climate change. Evidence for changes in water level depends on the location and setting of individual basins and changes in conditions over time. Our focus is the northeastern United States (37°–48°N, 80°–67°W), where many fossil-pollen records exist from lakes and mires but few sites have been sampled specifically to record changes in water level. Lake-level studies provide the best information for reconstructing changes in moisture balance that complement regional-scale reconstructions of past climate from palynological and other paleoclimate records.

Initial lake-level compilations in North America (Smith and Street-Perrott, 1983; Harrison and Metcalfe, 1985; Harrison, 1988, 1989) linked continental-scale variations in lake levels with changes in atmospheric circulation since the last glacial maximum. In the northern midwestern United States, Winkler et al. (1986) and Almendinger (1986) used changes in water level to interpret drier conditions than today for the early to mid-Holocene. Harrison and Metcalfe (1985) and Harrison (1988, 1989) showed that lake levels for the eastern United States (23.5° to 60°N, east of 100°W) were high between...
~17,000 and 10,000 cal yr B.P. (14,000 and 9000 14C yr B.P.) and after ~4500 cal yr B.P. (4000 14C yr B.P.), with a predominantly low phase between ~10,000 and 4500 cal yr B.P. (9000 and 4000 14C yr B.P.). Data from the northeastern sites did not match this pattern.

Webb’s (1990) synthesis of 29 late-Quaternary records for the northeastern United States confirmed low water levels at individual sites during the early to mid-Holocene. The regional pattern for the timing of low water intervals, however, was ~8000 to 5000 cal yr B.P. (7000 to 4500 14C yr B.P.) for southern New England and ~13,000 to 6800 cal yr B.P. (11,000 to 6000 14C yr B.P.) for other sites in the Northeast. The 13,000 to 6800 cal yr B.P. (11,000 to 6000 14C yr B.P.) interval for lower lake levels in the Northeast agrees well with pollen response–surface estimates of available moisture and earlier lake-level studies (Harrison and Metcalfe, 1985; Harrison 1988, 1989) that indicate drier conditions ~10,000 cal yr ago (9000 14C yr B.P.). The delayed reduction of water depths in southern New England, however, is inconsistent with pollen response–surface estimates of surface moisture that indicate modern levels of moisture by ~7000 cal yr ago (6000 14C yr B.P.) across the Northeast (Webb, R. S., et al., 1993).

In the absence of sites sampled specifically for changes in water level for the Northeast, Harrison (1989) and Webb (1990) relied mainly on published lithostratigraphic and other evidence to infer changes in moisture balance from the water-level fluctuations of lakes and mires. Webb (1990) added data from Delaware and the Pequot Cedar Swamp in Ledyard, Connecticut (Thorson and Webb, 1991). Our study has added to this work with an analysis of the fossil pollen, spores and sediments from the Makepeace Cedar Swamp (41°56’N, 70°46’W) near Carver, Massachusetts. Our goal was to estimate the timing and the duration of changes in water level during the late Quaternary in southern Massachusetts and thus in southern New England. We followed Winkler et al. (1986) and used the Digerfeldt (1974, 1975) method of multiple cores to correlate variations in sediment patterns and local pollen with fluctuation in water level. From calibrated radiocarbon dates and the regional pollen stratigraphy, we established an age model in the longest core that fits with biostratigraphic and chronostratigraphic information derived from other regional pollen stratigraphies. Changes in pollen stratigraphies were also correlated among some of the cores to date similar intervals and to infer the magnitude of changes in water level across the basin. We reinterpreted the data from the Pequot Cedar Swamp (Thorson and Webb, 1991) and then combined the information from both sites to construct the history of water-level fluctuations for southern New England. Our new data and interpretations indicate that southern New England was drier than present at 10,200 cal yr B.P. (9000 14C yr B.P.). The independent information on water-level changes aid the climatic interpretation of the changes in pollen and vegetation, e.g., the early Holocene maximum of white pine (Pinus strobus), including the classic New England pollen zones first described by Deevey (1939). It also provided an opportunity to gauge the response of lake-level data to short-term climate change, such as the Younger Dryas oscillation, in the Northeast.

**STUDY AREA**

Makepeace Cedar Swamp, a 21-hectare mire at 40 m altitude, is located in sandy outwash along the margin of the Monk’s Hill recessional moraine in southeastern Massachusetts (Fig. 1). The A.D. Makepeace Company owns and uses portions of the site as a water reservoir for nearby cranberry bogs, but our study area was undisturbed. Based on our site survey, altitude across the mire varied only on the order of 1 m. Probing to impenetrable sands every 10 m along two transects (A and B) revealed a 200 × 100 m basin bordering the northeast edge of the mire and extending to the southwest (Fig. 1). The basin is closed, with a high but partially submerged ridge defining the southwest boundary and with upland on the other three sides. Fluvial input was not evident in our reconnaissance of the surface, but the site floods each spring and at other times of high runoff. The hummocky landscape of the moraine dominates the overall shape of the basin, with a series of low relief ridges extending as peninsulas and island chains from the northeastern to the southwestern portion of the swamp. These ridges and islands help to define a mosaic of smaller kettle basins that comprise the entire mire. The present surface is saturated and has abundant grassy tussocks with pools of open water interspersed with dead cedar (Chamaecyparis thyoides) trunks in upright growth positions, as well as partially submerged downed trunks. Beyond the southern edge of the site, open water is visible and live cedars are progressively colonizing the peat mat. The surrounding upland has oak (Quercus), white pine with birch (Betula), red maple (Acer rubrum), hemlock (Tsuga canadensis), and beech (Fagus grandifolia).

**FIELD AND LABORATORY METHODS**

**Core Collection and Radiocarbon Dating**

Along transect A (Fig. 1), we collected four sediment cores (A–D) from the present shoreline toward the center of the basin with a 5-cm-diameter, modified Livingstone piston corer (Wright, 1967). Core A came from the deepest portion of the basin, core B from nearest the shore, core C from the steepest slope of the basin (because changes in the shoreline over time could be exaggerated at this location), and core D from the deepest point in the southwest end of the basin. At the base of core D, material jammed the core barrel just above the basal glacial sands. Probing with rods revealed a similar, widespread dense layer that later was identified as spruce wood (Picea spp.). The cores were described in terms of changes in color, texture, lithology, and macrofossil remains. Macrofossils vis-
FIG. 1. (a) Maps showing location of Makepeace Cedar Swamp, Carver, MA, and Pequot Cedar Swamp, Ledyard, CT. (b) Makepeace Cedar Swamp basin showing perpendicular transects A and B that delineate one of the sub-basins. (c and d) Transects A and B depth/bathymetry profiles based on probes every 10 m and the location of four sediment cores along transect A.
bly while making core descriptions were removed by hand, and 20 of 45 samples were selected for identification. Eight macrofossils were identified in seven of these samples. The rest of the macrofossils were inidentifiable. Samples were collected for loss-on-ignition and palynological analysis every 10 cm from cores A, C, and D. Only 49 cm of sediment from the fibrous upper sediments were recovered for the upper meter of core B.

We submitted 10 bulk sediment samples for \(^{14}\)C dating and \(^{13}\)C analysis and two additional sediment samples for AMS dating. The NOSAMS Facility at Woods Hole Oceanographic Institute, Massachusetts, performed the age calculations for dating. The NOSAMS Facility at Woods Hole Oceanographic Institute, Massachusetts, performed the age calculations for the AMS dates (Table 1). The bulk samples were pretreated to remove any rootlets, dispersed in hot acid to eliminate carbonates, and then rinsed and dried before being synthesized to benzene and measured for \(^{14}\)C content. Humic acids were extracted for the AMS dates and sample preparation and analysis followed procedures detailed at www.Colorado.edu/ INSTAAR/RadiocarbonDatingLab. Three of the samples were from the basal sediments of cores A, C, and D, seven were from just before or after changes in sediment type in cores A and C, and the two AMS samples bracketed an oscillation in spruce pollen percentages within the uppermost silts of core A.

**Sediment Analysis**

Loss-on-ignition was used to estimate the percentage organic matter composition of the sediments (Dean, 1974). We inferred the relative concentration of iron from the Munsell color of the loss-on-ignition residue, related to a low, medium, and high scale (T. Damon, personal communication, 1994). Calcium carbonate content for 30 samples (core A) was measured on a gasometric apparatus similar to that described by Jones and Kaiteris (1983). Our system used a differential pressure gauge in place of a vacuum gauge, and carbonate reactions were measured at atmospheric pressure. Replicate analyses of both standards and samples routinely give an analytical precision of better than 0.5% by weight. The percentage humic composition of 45 sediment samples (core A) was measured at 540 nm using a spectrophotometer, then compared with standards of pure humic acid (Aaby, 1986). Humification was used to estimate the percentage humic composition of the sediments. More humified results infer slower peat growth, which may be the result of dry conditions (Aaby, 1986).

**Palynological Analysis**

Samples for palynological analysis from cores A, B, and D (42, 15, and 19 samples, respectively) were prepared using standard laboratory procedure (Faegri and Iversen, 1975); pollen counts ranged between 300 and 1000 grains. We classified a representative number of grains from the undifferentiated pine pollen category from core A into subgenera diploxylon and haploxylon in 30 levels (Bassett et al., 1978). Using ratios of these subgenera, we assigned relative proportions to the total pine pollen percentage, then used ratios of measured diploxylon pine grains to determine the relative proportions of jack/red (Pinus banksiana and resinosa) and pitch (Pinus rigida) pine pollen. For cores B and D, we distinguished pine pollen in appropriate condition into subgenera (only) during initial counts.

We used both the pollen sum of total trees, shrubs, and herbs and a regional pollen sum of 26 taxa to calculate the pollen percentages for cores A, B, and D, to calculate concentrations and accumulation rates for core A, and to zone the pollen data from core A with a constrained incremental sum of squares cluster analysis (CONISS; Grimm, 1987). We assumed that regional pollen events were synchronous among the cores and between Makepeace and other nearby sites, and therefore we used the regional pollen sum to calculate square chord distances between pollen samples in core A and samples in cores B and D (Overpeck et al., 1985). Data for core A were fitted to its age model and used to interpret a sequence of changes for the deepest portion of the basin. Analog matches between samples in core A and those in either core B or D were used to estimate the age of the samples in these cores. Comparisons among cores were then used to infer changes in the magnitude of water levels for selected time intervals of depositional change. Selected pollen samples and analog results from cores B and D that substantiate these inferences are presented in Table 3 and Figure 4. The complete data sets are available from the World Data Center for Paleoclimatology (http://www.ngdc.noaa.gov/paleo/paleo.html).

**RESULTS**

**Lithology and Sediment Analyses for Cores A–D**

The lowermost sediment (792–500 cm) of core A was silt, with low values for percentage of organic matter (7–29%, Fig. 2). Abundant planktonic and epiphytic diatoms indicative of lacustrine conditions were identified in the lowermost coarse sand (>800 cm) between 520–521 cm and 511 cm (M. Winkler and P. Sanford, personal communication, 1993). Between 500 and 439 cm, the silt was slightly fibrous and we identified water lily (Nuphar) seeds at 454 and 448 cm. Between 439 and 424 cm, the silt became more fibrous, as values for both percentage of organic matter (17–54%) and humification (6–21%) increased. Between 424 and 350 cm, peat formed as the sediments increased to >90% organic matter. Between 405 and 370 cm, the peat blackened and changed to a fine texture as values for humification first increased from 20 to a peak value of 84% (370 cm). Just above this (360–350 cm), the peat was mixed with twigs and stem fragments from terrestrial woody plants (unidentifiable), just before a sharp change to less-organic mud (59%) at 346 cm that marked the most abrupt sedimentary change within the core. From 346 to 326, the sediments alternated abruptly between
### TABLE 1

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Type of date and material</th>
<th>$^{14}$C/AMS</th>
<th>$^{14}$C Adjusted age (yr B.P.)</th>
<th>Calendar age$^a$ (cal yr B.P.)</th>
<th>Calendar range$^b$ ± 1$\sigma$ (cal yr B.P.)</th>
<th>Laboratory number</th>
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<tbody>
<tr>
<td>Core A</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>784–781</td>
<td>conventional, silt</td>
<td>$-30.6$</td>
<td>$11,630 \pm 320$</td>
<td>$13,730^a$</td>
<td>$14,050^f$–$13,190$</td>
<td>Beta-58859$^a$</td>
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<tr>
<td>512–513</td>
<td>AMS, humic acids</td>
<td>$-28.1$</td>
<td>$11,020 \pm 60$</td>
<td>$13,010$</td>
<td>$13,130^f$–$12,990$</td>
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</tr>
<tr>
<td>465–458</td>
<td>conventional, silt</td>
<td>$-29.2$</td>
<td>$10,130 \pm 330$</td>
<td>$11,700$</td>
<td>$12,610^f$–$11,200$</td>
<td>Beta-61394$^a$</td>
</tr>
<tr>
<td>440–441</td>
<td>AMS, humic acids</td>
<td>$-28.5$</td>
<td>$10,040 \pm 55$</td>
<td>$11,480^f$</td>
<td>$11,690^f$–$11,350^f$</td>
<td>NSRL-10791</td>
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<td>410–405</td>
<td>conventional, peat</td>
<td>$-28.9$</td>
<td>$9160 \pm 110$</td>
<td>$10,360$</td>
<td>$10,490^f$–$10,220$</td>
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<td>400</td>
<td>pollen stratigraphic</td>
<td>—</td>
<td>$9820 \pm 50$</td>
<td>$10,800 \pm 110$</td>
<td>$11,240$–$11,190$</td>
<td>—</td>
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<td>352–350</td>
<td>conventional, peat</td>
<td>$-28.3$</td>
<td>$7760 \pm 120$</td>
<td>$8530$</td>
<td>$8650$–$8420$</td>
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<td>351</td>
<td>pollen stratigraphic</td>
<td>—</td>
<td>$8730 \pm 180$</td>
<td>$9720 \pm 160$</td>
<td>$10,050^f$–$9540$</td>
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<td>346–340</td>
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<td>$-29.2$</td>
<td>$7140 \pm 80$</td>
<td>$7960$</td>
<td>$8020^f$–$7880^f$</td>
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<td>290–283</td>
<td>conventional, silt</td>
<td>$-28.6$</td>
<td>$6330 \pm 100$</td>
<td>$7260$</td>
<td>$7420^f$–$7100^f$</td>
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<td>248–247</td>
<td>conventional, peat</td>
<td>$-28.5$</td>
<td>$4860 \pm 130$</td>
<td>$5600$</td>
<td>$5730$–$5480$</td>
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<tr>
<td>032</td>
<td>pollen stratigraphic</td>
<td>—</td>
<td>$250 \pm 100$</td>
<td>$250 \pm 100$</td>
<td>$440^f$–$10^f$</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>530–526</td>
<td>conventional, silt</td>
<td>$-30.5$</td>
<td>$11,690 \pm 270$</td>
<td>$13,690^f$</td>
<td>$14,055^f$–$13,505^f$</td>
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<tr>
<td>264–263</td>
<td>conventional, peat</td>
<td>$-29.5$</td>
<td>$6740 \pm 130$</td>
<td>$7600^f$</td>
<td>$7690$–$7490^f$</td>
<td>Beta-61395</td>
</tr>
<tr>
<td>Core D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>409–403</td>
<td>conventional, silt</td>
<td>$-27.8$</td>
<td>$11,270 \pm 110$</td>
<td>$13,180$</td>
<td>$13,400$–$13,150$</td>
<td>Beta-58862$^a$</td>
</tr>
</tbody>
</table>

**Note.** Italicized dates were not used in core A age-model.

$^a$ Median age for dates with multiple intercepts and an age range >50 yr (see footnotes b, c, and d); mean age for dates with range <50 yr (see footnote e).

$^b$ 13,510 and 13,800 cal yr B.P.

$^c$ 11,370, 11,390, 11,450, 11,550, 11,500 and 11,560 cal yr B.P.

$^d$ 13,550 and 13,800 cal yr B.P.

$^e$ 7590, 7610 cal yr B.P.

$^f$ Extremes of calibrated age ranges.

$^g$ Multiple intercepts.

$^h$ Extended counting time.

Organic mud and silty peat; values for percentage organic matter fluctuated accordingly between 59 and 75%. From 326 to 269 cm, the sediments changed to mottled organic mud that extended to 269 cm, and percentage of organic matter values ranged between 66 and 39%. During this same interval, the red color of the loss-on-ignition ash intensified (310–290 cm) as values for percentage of carbonate rose from 1% to a peak value of 40% (293 cm) and then declined to former low values. No diatoms (M. Winkler and P. Sanford, personal communication, 1993) but abundant cladocera (typical of the littoral zones of lakes among weeds) were reported from 270 to 271 cm.

Between 269 and 249 cm, the sediments again alternated between organic mud and peat, before an abrupt contact (249 cm) to peat deposition which continued to 200 cm. These peats (249–200 cm) contained a stem or root of willow (cf. *Salix*, 224 cm) among other unidentifiable woody remains between 240 and 225 cm, changed to rootlet peat at 32 cm, and then to fibrous, grassy peat that continued to the surface. The values for percentage of organic matter rose from 59 to >90% at the change to peat deposition (249 cm) and then remained high to the top of the core. Values for percentage humification (>40%) were steady, and those for percentage of carbonate remained low (<1%) over the same interval (249 cm, top).

The short sedimentary sequence for core B began with a low-organic (12%) silt mixed with coarse sand grains from 156 to 144 cm, and a layer of sand at 148 cm. From 144 to 140 cm, the sediments increased in organic matter from 12 to 56%, then gradually increased to 72% by 100 cm as sparse grassy fibers appeared and then rootlet material mixed with the silt. From 49 to 20 cm, the sediments were fibrous organic (41–85%) silt that was interspersed with sand below 20% and occasional coarse sand grains. At 20 cm, peat appeared that extended to the top of the core and the sediments increased to >90% organic. At 12 cm, the peat became more fibrous and mossy up to the surface, where living moss was collected.

The general sequence of sediments and loss-on-ignition for core C was similar to those for core A but confined to 550 cm of core. From the bottom to 380 cm, the sediments were low-organic (<20%) silt that was interspersed with sand below 500 cm. A dogwood seed (*Cornus canadensis*) was found at 530 cm, and diatoms, like those from core A, were identified at...
FIG. 2. Sediment stratigraphies, percentage of organic matter, and intervals with identified macrofossils for cores A–D, with percentage of humification, carbonate, and iron content for core A. Intervals of sediment (292–300, 188–200, and 73–100 in core D; 168–200 and 52–100 in core A; 393–400, 182–200 and 60–100 in core C; and 156–175 and 49–100 in core B) are not represented with stratigraphic depths because of compaction during the coring process.
521 cm (M. Winkler and P. Sanford, personal communication, 1993). Between 380 to 280 cm, the sediments became more fibrous and changed to peat as organic matter increased to >90%. Like core A, core C contained a layer of woody plant fragments from 352 to 350 cm that included an ovulate (female) cone of white pine. Above 280 cm, organic matter decreased and dropped to 31% by 250 cm, marking the change to mottled, organic mud deposition up to ~220 cm. Within this mud (264 cm), a birch twig, sedge (Cyperaceae) achene, and rush (Juncus) seed were identified. After 220 cm, values for organic matter rose from 31 to >87% and remained high to the top of the core as the sediments changed from organic to more-fibrous mud at 182 cm, to a silty peat at 139 cm, and finally to a more-consolidated, rootlet peat to the top of the core.

In core D, the lowermost material (414–409 cm) was a broken section of spruce trunk and branch, overlain by (409–300 cm) organic silt, followed by fine, fibrous peat (300–260 cm). A lens of coarse, angular sand with abrupt contact above and below was recorded between 277 and 275 cm. Values for organic matter increased from <10% (409 cm) to 69% at 280 cm, dropped to their lowest values (20%) at 270 cm, and then increased again to 43% at 290 cm. Between 260 and 219 cm, the sediments were organic mud; values for organic matter varied from 43 to 76%. From 219 to 43 cm, the sediments changed to peat, then to a finer, rootlet peat to the top of the core with high values for organic matter (86–95%).

**Calibrated Age Model and Sediment Accumulation Rates for Core A**

The first age-model for core A was based on the nine 14C dates obtained from the core (Fig. 3) and the estimated age for the rise in ragweed (Ambrosia) pollen at A.D. 1700 that corresponds with land clearance by English settlers in the Plymouth/Carver, Massachusetts, area (Fries, 1962; Patterson and Backman, 1988). The 14C dates were calibrated by interpolating between dates given in the IntCal98 data set (Table 1; Stuiver et al., 1998) using the CNVTAGE interpolation program (Leduc, 1996). Sample ages were estimated by linear interpolation between these calibrated 14C dates.

To determine the accuracy of the age-model, we compared the estimated ages for seven pollen changes at Makepeace with the same pollen stratigraphic changes at three nearby sites in southern New England (Table 2). The dates for these seven events were similar among the three nearby sites because of the regionally synchronous nature of climate change (Gaudreau and Webb, 1985) and the hemlock decline (Allison et al., 1986; Bhiry and Filion, 1996; Davis, 1981) within this small area. The seven distinct pollen events included (1) the lowest value for spruce pollen before its peak during the Younger Dryas interval, (2) the highest value for spruce pollen before values decline to ≤5%, (3) the midpoint for the rise in pine pollen percentages after the decline in spruce pollen abundance and the mean of the age between the two pollen samples when (4) oak pollen rises above 10% for the first time, (5) pine pollen declines to ≤15% after the peak at (3), (6) beech pollen first rises above 3%, and (7) hemlock pollen decreases the most in abundance (Fig. 3; Table 2).

Our results showed good agreement between the Makepeace age model and the associated ages from the other sites except for the ages from the interval of highly humified peat between 407 and 351 cm that is bracketed by two 14C dates and is immediately below an abrupt transition from pine to oak pollen that is not matched at the other sites (Fig. 3). When compared to their regional counterparts, these two dates are significantly younger at Makepeace: 10,360 cal yr B.P. at 407 cm was 440 yr younger and stratigraphically below the regional age for the rise in oak pollen percentages to >10% (10,800 cal yr B.P., 400 cm; Table 2), and 8530 cal yr B.P. at 351 cm was ~1190 yr younger than the regional age for the decline in pine pollen (9720 cal yr B.P.; 351 cm, Table 2). These dates, in the humified peats, may be younger because of root penetration. Our revised age model, therefore, used the regional dates for this interval (Table 2) and indicates a period of extremely slow accumulation between 9720 and 7960 cal yr B.P.

As an additional check on the age-model and our interpretation of the sediments, we calculated sedimentation rates for intervals in core A by linearly interpolating between pairs of dates (Fig. 3) and compared them to the average rates compiled by Webb and Webb (1988). The sediment accumulation rates for the lowermost silt (800–512 cm) were initially rapid at 380 cm/103 yr, but during the Younger Dryas interval (13,000 to 11,700 cal yr B.P.), the rate slowed to 37 cm/103 yr, which is below the mean for the late Pleistocene (52 cm/103 yr; Webb and Webb, 1988).

At the beginning of the Holocene (512–351 cm; ca. 11,700 to 9720 cal yr B.P.), the estimated rates of sediment accumulation increased to 89 cm/103 yr and slowed again to 45 cm/103 yr after 10,800 cal yr B.P., as peat began to accumulate in the basin. These rates were first faster, then just less than the estimated rate of continuous sediment accumulation in mid-latitude basins during the Holocene (65 cm/103 yr; Webb and Webb, 1988). Above 351 cm, the estimated sediment accumulation rate was slow (5 cm/103 yr) that it indicates intermittent to almost no sediment accumulation annually (Webb and Webb, 1988). This interval (351–343 cm; 9720 to 7960 cal yr B.P.) overlapped the abrupt change from humified peat to organic mud (Fig. 3). From 343 to 32 cm (ca. <7960 to 250 cal yr B.P.), the estimated rates of sediment accumulation again varied within the normal range for continuous organic sedimentation, especially when peat formed (Webb and Webb, 1988). Above 32 cm, the estimated rate of sediment accumulation increased to 128 cm/103 yr but was slower than that estimated for midlatitude basins during the Historic Period (298 cm/103 yr; Webb and Webb, 1988).
Pollen Stratigraphy for Core A

The sediment accumulation rates and analysis for core A indicate that silt deposition began about 13,750 yr ago and peat deposition after ~11,200 cal yr B.P., followed by an interval of little accumulation between 9700 and 8000 cal yr B.P. After 8000 cal yr B.P., organic mud accumulated until 5600 cal yr B.P., and the sequence ended with peat formation from 5600 cal yr B.P. to present. Four local pollen zones, MCSA 1-4 (Fig. 4), fit within this sequence and indicate both regional and local changes in vegetation. They mark the same changes from spruce to pine to oak pollen-dominated assemblages as do the regional zones T/A, A, B, and C (Deevey, 1939), and they also indicate local changes in vegetation. Both regional and total pollen accumulation rates were calculated (Fig. 5).

The silt sediments of regional Zone T/A (MCSA-1) (792-722 cm; 13,750 to 13,570 cal yr B.P.) were dominated by

### TABLE 2

<table>
<thead>
<tr>
<th>Site</th>
<th>(1) Low % between spruce pollen peaks</th>
<th>(2) 2nd spruce pollen peak</th>
<th>(3) 1st rise in pine pollen</th>
<th>(4) Rise in oak pollen &gt;10%</th>
<th>(5) Decline in pine pollen</th>
<th>(6) Rise in oak with beech pollen</th>
<th>(7) Decline in hemlock pollen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rogers Lake</td>
<td>12,950</td>
<td>12,530</td>
<td>10,820</td>
<td>10,750</td>
<td>9540</td>
<td>8110</td>
<td>5320</td>
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<td>Winneconnet Pond</td>
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<td>12,690</td>
<td>12,050</td>
<td>10,920</td>
<td>9790</td>
<td>7740</td>
<td>5370</td>
</tr>
<tr>
<td>Duck Pond</td>
<td>13,140</td>
<td>12,900</td>
<td>11,880</td>
<td>10,720</td>
<td>9820</td>
<td>8510</td>
<td>5470</td>
</tr>
<tr>
<td>Regional average</td>
<td>13,260</td>
<td>12,770</td>
<td>11,580</td>
<td>10,800</td>
<td>9720</td>
<td>8120</td>
<td>5390</td>
</tr>
<tr>
<td>Makepeace Cedar Swamp</td>
<td>13,010</td>
<td>12,550</td>
<td>11,480</td>
<td>10,110</td>
<td>8530</td>
<td>8080</td>
<td>5420</td>
</tr>
<tr>
<td>Difference</td>
<td>250</td>
<td>220</td>
<td>100</td>
<td>690</td>
<td>1190</td>
<td>40</td>
<td>30</td>
</tr>
</tbody>
</table>

*Note. Columns 4 and 5 show intervals with significant differences between regional average age and Makepeace Cedar Swamp age. Italicized entries are AMS dates. Pollen sites with estimated ages for biostratigraphic events are listed from west (Rogers Lake, Connecticut) to east (Duck Pond, Massachusetts). Chronologies are from age-basis tables in NAPD (1999) that were calibrated using the IntCal93 calibration data set (Stuiver and Reimer, 1993) and the CNVTAGE interpolation program (Leduc, 1996). The biostratigraphic pollen events (1–7) are shown on the Makepeace pollen diagram in Figure 3 and are described in the text.*
spruce pollen with birch, willow, and *Myrica* (Myricaceae) pollen. The accumulation rates for both regional and total pollen were >60,000 grains/cm$^2$/yr. As the silt graded to peat in Zone A (MCSA-2) (722-425 cm; 13,570 to 11,200 cal yr B.P.), spruce pollen (62%) remained dominant. Just before 13,000 cal yr B.P., oak pollen values increased to 6%, and hickory (*Carya*) pollen and pollen from other thermophilous taxa were recorded in low abundance just before a second peak in spruce pollen percentages associated with the Younger Dryas interval (Peteet *et al.*, 1993). Around 12,100 cal yr B.P., values for local types rose, particularly aquatic pollen. Before the Younger Dryas interval, both total and regional pollen accumulation rates were well above 21,400 grains/cm$^2$/yr. These rates then dropped dramatically to ~7000 grains/cm$^2$/yr at the onset of the Younger Dryas interval, and they remained low (<10,000 grains/cm$^2$/yr) until ~11,300 cal yr B.P. Hem-

**FIG. 4.** Pollen stratigraphy for Makepeace Cedar Swamp cores A (upper), B (middle), and D (lower). CP for core B indicates interval of sediments compacted during core extrusion. Asterisks indicate pollen types used in the regional pollen sum that also includes ash (*Fraxinus*), basswood (*Tilia*), elm (*Ulmus*), hackberry (*Celtis*), hazel (*Corylus*), holly (*Ilex*), ironwood/hornbeam (*Ostrya/Carpinus*), larch (*Larix*), mulberry (*Morus*), poplar (*Populus*), walnut (*Juglans*), and wormwood (*Artemesia*).
FIG. 5. Paleohydrologic summary diagrams for Makepeace (core A, upper) and Pequot Cedar Swamps (core B, lower) comparing lithology, sediment analyses, and a shared sequence of local and fossil palynological and paleoenvironmental indicators to show similar trends toward dry conditions during the maximum of white pine (P. strobus) pollen ca. 10,200 cal yr B.P. (9000 yr B.P.). Total (solid line) and regional (dotted line) pollen accumulation rates are shown for core A. The same taxa are shown for both sites, but stippling indicates that a taxon was not used for the paleohydrologic interpretation for that site.
lock and white pine pollen (<3%; 12,150 cal yr B.P.) appeared in Zone A for the first time.

The peat interval associated with Zone B (MCSA-3) (425–350 cm; 11,200 to 9720 cal yr B.P.) was dominated by pine pollen, with high values for white pine pollen throughout the zone. Values for total aquatic pollen declined abruptly in the middle of the zone. At the top of the zone, a peak value for total pine pollen (78%) coincided with the lowest regional and total pollen accumulation rates (<2600 grains/cm²/yr) in the core. These rates are consistent with peat forming and the absence of wash-in pollen (Jacobson and Bradshaw, 1981).

Zone C (MCSA-4) (350 cm-top of core; 9720 cal yr B.P. to present) is dominated by oak pollen and has three subzones. The organic mud of subzone MCSA-4a (350-250 cm; 9720 to 5600 cal yr B.P.) was distinguished by sharp increases in both oak (10–58%) and grass (Poaceae) (7–52%) pollen percentages. Other local types included blackgum (Nyssa), alder (Alnus), and buttonbush (Cephalanthus) pollen. The accumulation rates for both regional and total pollen remained low (<2600 grains/cm²/yr), then diverged and fluctuated to the top of the subzone. Total rates exceeded regional rates for pollen accumulation, with a peak value of 39,000 grains/cm²/yr at 3200 cal yr B.P.

The MCSA-4b (250-32 cm; 5600 to 250 cal yr B.P.) subzone boundary was marked by renewed peat deposition and a decline in hemlock pollen. Grass pollen still dominated, then declined from 40 to 15% as buttonbush, St. John’s Wort (Hypericum), and sedge pollen percentages increased in the middle of the zone. Total pollen accumulation rates, with values from 8750 to 39,000 grains/cm²/yr, were higher than those for regional pollen throughout the subzone. The fibrous peats of the uppermost subzone MCSA-4c (32-top; 250 cal yr B.P. to present) were characterized by increased values for ragweed (3%), spruce, hemlock, birch, and chestnut (Castanea) pollen. Local types included sharp increases in heath (Ericaceae), ragweed, sedge, and aster (Asteraceae) pollen at the top of the subzone. The accumulation rates for regional and total pollen increased to >26,200 grains/cm²/yr, but then they dropped to 12,000 grains/cm²/yr at the top of the core.

Pollen Stratigraphies, Analogs, and Age-Models for Cores B and D

We used (1) dates estimated from the square chord distances calculated between all the pollen samples in cores B and A and in cores D and A, (2) the basal ¹⁴C date for core D (13,180 cal yr B.P.; 406 cm), and (3) the biostratigraphic date for the ragweed rise (250 cal yr B.P.) to establish age models for cores B and D. For core B, the top analog matches (Table 3) dated the lowermost sample (150 cm) between 3200 and 7790 cal yr B.P. Because the values for hemlock pollen are declining in the lowest three samples, we chose the two best analog matches that are closest in age to the regional hemlock decline (5300 ± 3000 cal yr B.P.; Webb, 1982) for the lowermost sample. The best analog match dated the next higher sample in core B (130 cm) to 2490 cal yr B.P., so we infer that consistent peat accumulation began after ~3200 cal yr B.P. in core B. Increased values for ragweed pollen above 25 cm indicate a historic age (250 cal yr B.P.) for the uppermost sediments of core B. The sediments of core B, therefore, represent the interval from ~3200 cal yr B.P. to the present (Fig. 4). We selected the top analog matches (Table 3) for ten pollen samples between cores A and D to display key changes in the pollen stratigraphy used to interpret changes in water level. Other analyses showed that pollen samples from 280 and 270 cm bracketed a coarse sand lens (277–275 cm) that coincided with the lowest values for organic matter (20%) in core D. The analog results showed that the lower pollen sample (280 cm), with spruce, jack pine (<5%), and abundant white pine pollen was substantially older than the sample just above (270 cm), which had predominantly pitch pine, beech, and oak pollen (Fig. 4). From this combined evidence, we inferred an interval of nonconstant accumulation for core D (270 and 280 cm; 10,680 to 7790 cal yr B.P.) similar to that for core A (351 and 343 cm; 9720 to 7960 cal yr B.P.). Higher up in core D, the top analog matches dated the sample at 210 cm to the same ages as the lowermost sample in core B and the next higher sample (181 cm) to 3200 cal yr B.P. Over 20% ragweed pollen near the top of core D (10 cm) indicates a historic age for these upper sediments (Fig. 4).

### Table 3: Analog Results and Interval Correlation for Selected Fossil pollen Samples

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Square chord distance</th>
<th>Age cal yr B.P.</th>
<th>Depth (cm)</th>
<th>Square chord distance</th>
</tr>
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<tr>
<td>&lt;70.0</td>
<td>0.15</td>
<td></td>
<td>&lt;25.0</td>
<td>0.10</td>
</tr>
<tr>
<td>181.0</td>
<td>0.06</td>
<td>250</td>
<td>130.0</td>
<td>0.10</td>
</tr>
<tr>
<td>210.0</td>
<td>0.09</td>
<td>150.0</td>
<td>150.0</td>
<td>0.10</td>
</tr>
<tr>
<td>210.0</td>
<td>0.07</td>
<td>150.0</td>
<td>150.0</td>
<td>0.09</td>
</tr>
<tr>
<td>210.0</td>
<td>0.07</td>
<td>240.0</td>
<td>150.0</td>
<td>0.07</td>
</tr>
<tr>
<td>250.0</td>
<td>0.07</td>
<td>330.0</td>
<td>150.0</td>
<td>0.08</td>
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<td>330.0</td>
<td>150.0</td>
<td>0.08</td>
</tr>
<tr>
<td>270.0</td>
<td>0.10</td>
<td>310.0</td>
<td>7520</td>
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</tr>
<tr>
<td>280.0</td>
<td>0.06</td>
<td>394.5</td>
<td>10,680</td>
<td></td>
</tr>
<tr>
<td>290.0</td>
<td>0.06</td>
<td>394.5</td>
<td>10,680</td>
<td></td>
</tr>
<tr>
<td>300.0</td>
<td>11,480 cal yr B.P.</td>
<td>440.0</td>
<td>11,480</td>
<td></td>
</tr>
<tr>
<td>312.0</td>
<td>0.13</td>
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<td>472.5</td>
<td>11,960</td>
<td></td>
</tr>
<tr>
<td>&lt;406.0</td>
<td>13,000 cal yr B.P.</td>
<td>512.0</td>
<td>13,010</td>
<td></td>
</tr>
<tr>
<td>&lt;406.0</td>
<td>13,180 cal yr B.P.</td>
<td>570.5</td>
<td>13,170</td>
<td></td>
</tr>
</tbody>
</table>

Note: Italicized entries are ¹⁴C dates.

* Age-model and lithology used to correlate ages between cores D and A.
Changes in Water Level at Makepeace Cores A, B, and D

Using the local pollen stratigraphy, other paleoenvironmental indicators, sediment analyses, and regional and total pollen accumulation rates from core A, we interpreted how its changing depositional regimes related to changes in water level (Fig. 5). We then used data from cores B and D to broaden our interpretation to basin-wide changes in water level, focusing on 13,750, 13,000 to 11,500, 9720 to 7960, 5600, and 3200 cal yr B.P. to show how changes at these times relate to changes in the regional and local vegetation (Fig. 6). For the estimations, we assumed that water was at least +1 m above lake sediments.

Data from core A indicated open water at the beginning of sedimentation 13,750 cal yr B.P. that became shallow enough to accumulate peat after ~11,200 cal yr B.P., and then intermittently dried out from 9700 to 8000 cal yr B.P. (Fig. 5). This interval of slow accumulation was followed by a rise in moisture as mud accumulated from 8000 to 5600 cal yr B.P., when peat began collecting again, to present. This onset, at 5600 cal yr B.P., may indicate a second period of shallowing. Abundant quillwort (Isoetes) spores and diatoms in the lowermost silts and high (>19,000 grains/cm²/yr) total and regional pollen accumulation rates indicate a deep lake from initial deposition to ~13,000 years ago. After 13,000 cal yr B.P., simultaneous drops in total and regional pollen accumulation rates were likely related to the onset of cool Younger Dryas climates. Toward the end of this period, water lily (Nymphaceae) and then water shield (Brasenia) pollen appeared. By 11,500 cal yr B.P., more fibrous sediments, water shield pollen, and water lily pollen and seeds represent water depths that were likely between 2 and 4 m (Sinden-Hempstead and Killinbeck, 1996; Warrington, 1980). Several water lily seeds found in the sediments show the local source area for these plants. Between ~11,500 and 11,200 cal yr B.P., the organic content of the sediments rose, sediment accumulation rates increased, quillwort spores disappeared, and water lily pollen and leaf-hair bases (microscopic remains of water lily plants; Adam, 1967) dramatically increased in abundance. We infer a trend toward a reduced area of open water at this time. However, more abundant aquatic vegetation, such as water lilies, may also result from increased water level due to the expansion of the shallow, littoral zone. Whatever these conditions represent, after ~11,200 cal yr B.P., the steady increase in organic matter and continued low values of both regional and total pollen accumulation rates indicate the rapid formation of a floating peat mat (Jacobson and Bradshaw, 1981), followed by peat accumulation. At ~10,800 cal yr B.P., the abrupt decline of all aquatic pollen and indicators indicates the switch to mire conditions just as abundant fungal material and peat moss (Sphagnum) spores rise, coinciding with highly humified peat and the lowest rates for total and regional pollen accumulation in core A. These low rates match those in mires that have no wash-in component (Jacobson and Bradshaw, 1981). During this same interval, white pine pollen, which first appeared in low abundance around 12,150 cal yr B.P., increased and remained high. By ~9700 cal yr B.P., increased surface exposure and dry conditions are inferred from the layer of terrestrial woody plants directly above the highly humified peats, after which there was little to no accumulation for ~1700 yr.

At the end of this interval around 8000 cal yr B.P., dramatic transformations occurred in the local vegetation and character of the basin. Peat deposition ceased and inorganic sediment increased, indicating standing water, which may have supported seasonal growth of aquatic grasses with total and regional pollen accumulation rates above 10,000 grains/cm²/yr, water must have covered the coring site. Between 7240 and 6850 cal yr B.P., increased values for carbonates and iron content indicate floodings and/or increased surface flow, likely from seepage water or water flowing over the peatland, leached water from surrounding deposits, or an aquifer farther away.

After 5600 cal yr B.P., peat formed and has continued until present. An abrupt sediment contact marked the change from mud (~247 cm) to more fibrous deposition, and the sediments that accumulated during this time contain wood fragments (like the top of the lower peats). This return to a nonlacustrine interval may indicate dry conditions beginning about the time of the hemlock decline (5300 ± 200 yr B.P.).

Additional data from cores B and D indicate a sequence of within-basin water levels that began high, became low, and then rose again and were highest, relative to the modern, after ~3200 cal yr B.P. (Fig. 6). At initial deposition (13,750 cal yr B.P.), a lake formed with an estimated minimum water depth ranging between 4 and 5 m. Before 13,000 cal yr B.P., coarse sand mixed with silt below 5 m in core C may indicate shore displacement from rising water level. By correlating intervals in cores A and D, we estimated that the minimum water depth at the onset of the Younger Dryas interval (13,000 cal yr B.P.) and at ~11,500 cal yr B.P. was ~2.5 m. This estimated depth fits well with our inference of shallow conditions at ~11,200 cal yr B.P., based on the presence of the aquatic plants and indicators in core A. These data do not constrain the maximum and/or changes in water level that may have occurred between 13,000 and 11,500 cal yr B.P. However, by 10,800 cal yr B.P., peat overlay the uppermost lake sediments in both cores; at 9720 cal yr B.P., the peat horizon in core A (350 cm, surface of the basin) existed below (>50 cm) the elevation of the earlier lake sediments at 11,480 cal yr B.P. (300 cm) in core D. Therefore, the water level dropped ~1.5 m by 9720 cal yr B.P. because the exposed peat “surface” of the basin was lower (350 cm) than the elevation of the earlier lacustrine sediment (300 cm) in core D. We infer increasingly dry conditions after 11,200 cal yr B.P., as the area of open water diminished, peat formed, and accumulation slowed or became nonconstant first near core D by 10,680 cal yr B.P., and then near core A by 9720 cal yr B.P. A sand layer occurs at this interval in core D, when abundant wood fragments in these levels of proximal
FIG. 6. (a) Correlations based on analog matches among fossil pollen data (dotted lines) and dated sediments (solid line). Italicized ages are $^{14}C$ dates. (b) Estimated water level for Makepeace Cedar Swamp at 13,700, 13,000 to 11,400, 9720 to 7960, 5600, and 3200 cal yr B.P. Boxes indicate that $^{14}C$ dated intervals were used to estimate the water level for each time period, and lines indicate analog and/or stratigraphic correlation was used.
cores A and C indicate that vegetation, which included white pine, colonized the surface sometime between ~9700 and 8000 cal yr B.P. This vegetation grew there in response to continuing dryness as the former surface stabilized (Cameron, 1970; Moore and Bellamy, 1974).

After the interval of slow, intermittent accumulation ended at 7960 cal yr B.P., a basin-wide rise in water level is indicated by the deposition of organic mud over the former peat surface in all the cores except for B. We estimated that the maximum water depth was <2 m, with a minimum range of less than ~1 m. A period of dry or stable conditions likely existed from 5600 to 3200 cal yr B.P., because this organic mud became overlain with peat. Peat began accumulating near core A after 5600 cal yr B.P., at core D between 5400 and 3200 cal yr B.P., and at core B by 3200 cal yr B.P. We infer that the peat accumulation by 3200 cal yr B.P. resulted from an increase in water level because (1) the basin expanded to its greatest (recorded) extent out to cores B and D; (2) low values for humification and high values for percentage of organic matter (core A) indicate peat accumulation that had little opportunity to decompose before being buried, and (3) total pollen accumulation rose dramatically at this time.

Changes in Water Level at Pequot Cedar Swamp, Ledyard, Connecticut

The pattern of lake-level changes mapped by Webb (1990) for southern New England differs from that for the rest of the Northeast in emphasizing an interval of low water after, not at or before, ~10,000 cal yr B.P. (9000 yr B.P.). This pattern is based mainly on the interpretation of data from Pequot Cedar Swamp (Webb, 1990; Thorson and Webb, 1991; Fig. 1), a complex mire system 105 km west of Makepeace. Because few sites have been analyzed specifically for changes in water level in southern New England, and because of the strategic difference in the timing of low water at these proximate mires, we reexamined the data for Pequot.

Like the data from Makepeace, those from Pequot document the transformation of an open-water basin during the late Pleistocene to a mire in the late Holocene, marked by slow, possibly nonconstant accumulation that began during the transition from a pine- to an oak-dominated pollen assemblage (Thorson and Webb, 1991). The interval of dry conditions and slow accumulation at Makepeace occurred, however, between ~10,000 and 8000 cal yr B.P. and at Pequot between 8400 and 5000 cal yr B.P. (Fig. 5). The key interval for our reexamination of Pequot are the data between 13,000 cal yr B.P. and the hiatus at 8400 cal yr B.P. During this interval, Thorson and Webb (1991) inferred that the water level rose, stabilized, and then rose again before deposition became intermittent, in contrast to the progressive shallowing that led to peat formation and nonconstant accumulation prior to wet conditions (by ~8000 cal yr B.P.) at Makepeace. The water-level histories for both sites are similar after ~5600 cal yr B.P. The water level was low at both sites about the time of the hemlock decline, but sometime between 5000 and 3000 cal yr B.P., the return of peat deposition at both sites related to rising water levels.

Pollen from the floating aquatic plant, water shield, indicates that a shallow lake was present at Pequot by 15,450 cal yr B.P. (Warrington, 1980; Keddy, 1983). Around 12,950 cal yr B.P., the sediments change from silt to silty peat as values for percentage of organic matter and humification increased with greater deposition of detrital sediment (270–200 cm). Thorson and Webb (1991) inferred a rising water level for this interval, which is possible if basin infilling outpaced increasing water level. In this scenario, infilling must equal or exceed water-level increase; otherwise, rising water level would prolong or renew water-open water conditions. These data indicate, however, that a reduction in water level is also possible for this period, because the sedimentary sequence from silt to peat matches changes expected as peat develops in lakes from floating mats to peat accumulation. At Pequot, we infer that open, likely shallow, water at 12,950 cal yr B.P. changed into woody peat by 11,350 cal yr B.P. The open water during this interval, documented by water lily pollen, leaf-hair bases, and silt grading to silty peat, was replaced at 11,350 cal yr B.P. by a woody peat mat without aquatic pollen (PCS-3) at the same time that maximum values for white pine pollen were recorded. These changes in sedimentation and pollen closely match those at Makepeace.

In the woody peat (200–160 cm) and the next-higher sedimentary unit of complex peats (160–100 cm; 11,350 to 8400 cal yr B.P.), pollen and spores characteristic of marsh fringe and wet woods dominate the local stratigraphy (PCS3–4), beginning with shield-fern (Dryopteris) spores (PCS-3; 11,350 cal yr B.P.) and followed by holly (Ilex), heath pollen (PCS-3; 10,000 cal yr B.P.), and abundant cinnamon fern spores (Osmunda) just before the hiatus (PCS-4; 8400 cal yr B.P.). For the same interval, values for percentage of organic matter are high (>90%) throughout, and after an initial drop (170 cm), values for humification are >80%. For this interval, Thorson and Webb (1991) inferred stabilization (11,350 cal yr B.P.), followed by rising water level (after 10,000 cal yr B.P.) that resulted in the deposition of complex peat before the hiatus. In this scenario, we would anticipate that after the interval of stable water conditions, values for humification would be consistent and low as (1) peat continued to accumulate within the saturated surface and (2) previously deposited peats compacted (with little decomposition) below the new surface growth. Instead, values for humification remain high and then peak just before the hiatus at 8400 cal yr B.P. We interpret this trend to indicate that the water level was lower than before this interval. The highly humified peats probably resulted from slow or reduced peat accumulation as plant matter remained at the surface longer, causing increased decomposition to occur (Aaby, 1986; Aaby and Tauber, 1975). The mire surface probably became dry at times. Enough water was eventually present to allow complex peat to accumulate above the layer of decomposed woody peat (a recurrence horizon). After the hiatus,
peat deposition resumed and the local pollen stratigraphy shows a red maple swamp (70 cm; 5000 cal yr B.P.), followed by the establishment of a peat wetland (40 cm; 2580 cal yr B.P.). Our revision of water-level history at Pequot raises the possibility that water level fell by 11,350 cal yr B.P., with indications of slow or reduced peat accumulation between 11,350 and 8400 cal yr B.P. when peat accumulation ceased. This history is in good agreement with the record at Makepeace. Records from both sites show a similar shift from deep water to increasingly abundant aquatic vegetation and the first appearance of white pine during the Younger Dryas period. After the Younger Dryas interval, aquatic vegetation quickly diminished and white pine quickly rose in abundance.

The data for Makepeace and Pequot indicate low water levels (~10,200 cal yr B.P.) when white pine pollen is abundant in the pollen stratigraphies of both sites. The oldest dates for white pine pollen in these pollen stratigraphies (ca. 13,000 and 12,150 cal yr B.P.), therefore, provide a reasonable constraint for the beginning of the regional drying of southern New England. When these dates are compared with the onset of drier-than-modern conditions in the Northeast (13,000 to 6800 cal yr B.P.), the records at Makepeace and Pequot correlate with those from sites across the region. Regional moisture conditions were therefore generally drier than present throughout the Northeast when white pine pollen was at its peak. Local effects, however, determine the differences in timing for the driest conditions at each site. The Makepeace and Pequot data indicate that the early Holocene pattern in northern and southern New England sites is consistent with the timing of dry conditions inferred from lake-level records for Delaware (Webb, 1990).

CONCLUSIONS

From this detailed record at Makepeace, we have interpreted higher or rising water level before 13,000 and after 3200 cal yr B.P., with an interval of low water level between ~10,000 and 8000 cal yr B.P., which fits well with the patterns that R. S. Webb et al. (1993), Harrison and Metcalf (1985), and Harrison (1989) mapped for the Northeast. We have documented that the hydrologic balance of individual basins throughout southern New England changed at about the same time (~500 yrs) as the abundance of white pine pollen increased within the regional vegetation. Previously, this linkage between vegetational and hydrological changes had been demonstrated along the prairie–forest ecotone in the northern Midwest (Watts and Bright, 1968; Winkler et al., 1986; Webb, T., et al., 1993). In our study, we have been able to demonstrate a similar link between hydrologic change and changes in the structural and taxonomic composition of forests in the Northeast.

The closely associated changes in the moisture balance and the regional vegetation change provide a plausible explanation for the long-recognized early Holocene maximum in abundance and spatial coverage of white pine throughout the area (Davis, 1969; Gaudreau and Webb, 1985; Jacobson et al., 1987) and the delayed (relative to oak) appearance of beech populations. As climate warmed and the regional hydrologic conditions became drier (as shown from the water-level evidence within individual basins), the vegetation shifted from more boreal and less drought-tolerant spruce to more temperate and drought-tolerant white pine. Maps tracing this history for spruce, pine, oak, beech, birch, hemlock, and other taxa support the inference of dry conditions in New England, southern Quebec, and the Maritime Provinces when white pine dominated throughout the region (Webb, 1988; Webb, T., et al., 1993; Webb, 1992). Our results imply that a changing combination of temperature and moisture conditions can explain the major changes in pollen and vegetation first described by Deevey (1939). The independent information about water-level changes, along with regional mapping of the pollen, is key to this interpretation.

Our assessment of significant vegetation response to changes in regional moisture balance may provide insights into potential vegetation changes in areas of North America that are moist and temperate today. Under most scenarios for increased greenhouse gas concentrations, many climate-model simulations show a shift to drier conditions in northeastern North America over the next 100 yr (IPCC, 1992, 1996). If our evidence of past vegetation response to drier conditions in a moist, temperate region is an indication of how vegetation might change in response to similar shifts in the hydrologic balance, then we would expect a compositional change from dominantly mesic to more xeric taxa in the future, if the environment becomes drier than it is today (Overpeck et al., 1991; VEMAP members, 1995; IPCC, 1996).

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