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Impact of Human Activity on Regional Forest Composition and Dynamics in Central New England

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ABSTRACT

Historical and ecological data from north-central Massachusetts suggest that widespread and intensive human disturbance after European settlement led to a shift in forest composition and obscured regional patterns of species abundance. A paleoecological approach was required to place recent forest dynamics in a long-term context. Pollen and charcoal data from 11 small lakes in north-central Massachusetts were used to reconstruct local vegetation dynamics and fire histories across the region over the past 1000 years. The sites are located across an environmental gradient. Paleoecological data indicate that prior to European settlement, there was regional variation in forest composition corresponding to differences in climate, substrate, and fire regime. Oak, chestnut, and hickory were abundant at low elevations, whereas hemlock, beech, sugar maple, and yellow birch were common at high elevations. Fire appears to have been more frequent and/or intense at lower elevations, maintaining high abundances of oak, and archaeological data suggest Native American populations were greater in these areas. A change in forest composition at higher elevations, around 550 years before present, may be related to the Little Ice Age (a period of variable climate), fire, and/or activity by Native Americans, and led to regional convergence in forest composition. After European settlement, forest composition changed markedly in response to human disturbance and there was a sharp increase in rates of vegetation change. Regional patterns were obscured further, leading to homogenization of broad-scale forest composition. There is no indication from the pollen data that forests are returning to pre-European settlement forest composition, and rates of vegetation change remain high, reflecting continuing disturbance on the landscape, despite regional reforestation.

Key words: paleoecology; human disturbance; forest dynamics; New England; rates of change.

INTRODUCTION

Paleoecological, historical, and ecological studies have demonstrated the dramatic impact of European settlement on vegetation in North America over the past 300 years (Harper 1918; Spurr and Cline 1942; Siccama 1970; Webb 1973; Brugam 1978a, 1978b; Russell 1980; Burden and others 1986a, 1986b; McAndrews 1988; Williams 1989; Russell and others 1993; Whitney 1993; Foster 1995; Schneider 1996; Foster and others 1998). In the eastern United States, disturbances such as forest cutting, altered fire regimes (burning to clear land, or suppression of the natural fire regime), agricultural activity, introduction of alien species (including pests and disease), alteration of herbivore populations, urban development, and atmospheric pollution have had a marked influence on vegetation composition and dynamics (Brugam 1978a; Russell and others 1993; Whitney 1993; Foster 1995; Foster and others 1998), as well as terrestrial and aquatic ecosystem processes (Engstrom and others 1985; Aber and others 1991; Brush 1994; Foster 1995; Sullivan and others 1996). In particu-

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lar, several studies have shown that regional vegetation patterns at the time of European settlement were related to climate, physiography, or natural disturbance regime, and that these patterns have been altered or obscured by human disturbance since settlement (Egler 1940; Whitney 1990; White and Mladenoff 1994; Palik and Pregitzer 1992; Abrams and Ruffner 1995; Foster and others 1998). Detailed studies (using historical and ecological data) in New England document that the history of deforestation for agriculture in the 18th and 19th centuries, followed by natural reforestation in the late 19th and early 20th centuries, has resulted in regional homogenization of forest composition and a loss of correlation between the distribution of tree taxa and regional climatic gradients (Foster and others 1998).

The process of broad-scale vegetation dynamics and regional homogenization of vegetation has important consequences for ecological studies, conservation, and management planning, and it has implications for interpretation of current and prospective vegetation relationships to climate. Because of their limited temporal perspective, however, modern and even historical studies are inadequate to interpret these major forest and landscape changes. Paleoecological studies, when designed to record local and regional forest dynamics with high temporal resolution, provide an opportunity to interpret historical dynamics over long time periods (for instance, the last millennium). For example, a long-term perspective enables us to compare pre-European vegetation, disturbance histories, and rates of vegetation change with postsettlement dynamics, to identify the timing and processes involved in the homogenization of regional vegetation patterns, and to assess the responsiveness of vegetation to changes in the disturbance regime.

In this study, we sought to use paleoecological methods to understand the vegetation and environmental dynamics of the New England landscapes, and to place historical changes [compare Foster and others (1998)] within an ecological framework. Specific questions include: How do recent forest dynamics, within a period of intensive human activity, relate to long-term changes in forest composition driven by climate, natural disturbances (fire, wind, disease) and activity by Native Americans? What was the impact of widespread and intensive human disturbance on regional patterns of vegetation? Was the nature of the disturbance associated with European settlement unique or have there been analogous events in the presettlement period (Raup 1981)? Are the rates and extent of vegetation change in pre-European settlement forests comparable to those in the postsettlement period? Following a major decrease in regional disturbance since the end of the 19th century, have regional patterns of forest composition and dynamics reverted to those of presettlement forests?

Historical evidence suggests that European settlement in central Massachusetts resulted in a major change in forest composition, abundance, and structure (Foster 1988, 1992, 1995; Foster and others 1992, 1998). Large tracts of forest were cleared after European settlement (between AD 1700 and 1750) largely for agricultural purposes and timber (Foster and others 1998). Natural reforestation has taken place throughout the region as agricultural activity was abandoned at the end of the last century (Cronon 1983; Foster 1995). Changing levels of human disturbance in central Massachusetts provide the opportunity to investigate the impact of recent variation in disturbance frequency and intensity on forest composition and dynamics.

Wind and fire are the predominant natural disturbances in New England. Although little detailed information is available on pre-European settlement fire frequency, intensity, and impact on vegetation, fire resulting from natural processes and activity by Native Americans appears to have been important locally (Patterson and Sassaman 1988). New England is prone to hurricanes, which are infrequent but occasionally catastrophic (Foster and Boose 1992; Boose and others 1994), and pathogenic outbreaks are also a rare but important disturbance factor (Patterson and Backman 1988; Orwig and Foster forthcoming). For instance, paleoecological evidence suggests that hemlock (*Tsuga canadensis*) populations in eastern North America were decimated by an insect pest approximately 5000 years before present (Davis 1981; Allison and others 1986; Bhiry and Filion 1996; Fuller forthcoming). Forest vegetation in New England, therefore, is adapted to periodic and occasionally catastrophic disturbances (Raup 1981). After European settlement, the disturbance regime changed from being dominated by episodic natural processes (for example, wind and fire) to one dominated by widespread and ongoing human activity that varied in intensity over a 300-year period. The main focus of this paper is to place the recent history of regional forest dynamics in response to human disturbance into a long-term perspective.

Study Area

Central Massachusetts is divided into three broad physiographic regions based on elevation, relief, and differences in geology, soils, climate, and land use: the Central Uplands, the Eastern Lowlands, and the Connecticut River Valley (Figure 1). Relief in the

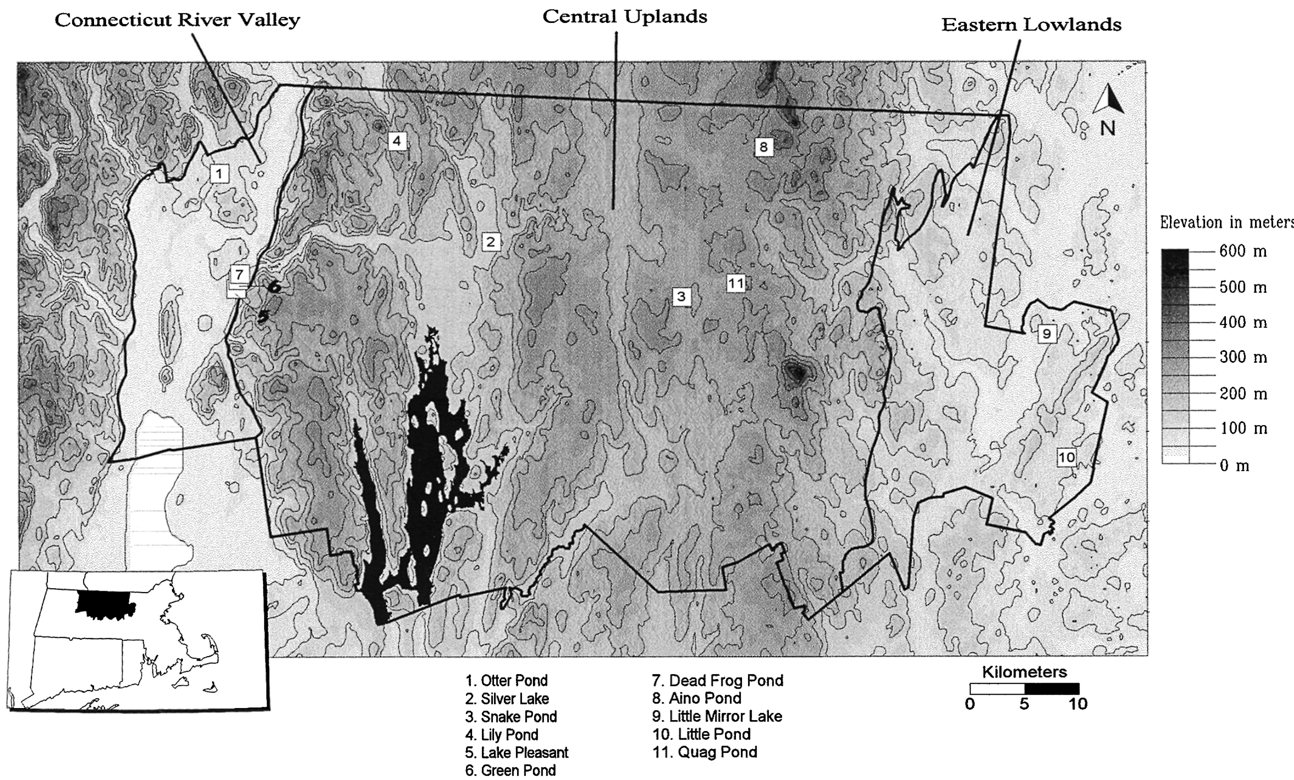

Figure 1. Topographic map of central Massachusetts showing the location of the lake basins analyzed and physiographic regions.

Central Uplands varies from 150 to 430 m above sea level across an area dominated by north–south-trending ridges. Soils (in the Monadnock, Tunbridge, Lyman, and Beckett series) are generally acid, sandy loams underlain by acidic, Paleozoic bedrock and a cover of thin glacial till (Taylor and Hotz 1985). The Connecticut River Valley, an area of lower elevation to the west (Figure 1), is underlain by sedimentary siltstone, sandstone, shale and conglomerate, and relatively thick deposits of outwash, alluvium, and glacial lake-bottom sediments. Soils in this area include the well-drained, coarse-silty Hadley, poorly drained Limerick, and excessively drained sandy soils of the Hinckley series (Mott and Fuller 1967). Three sites studied are located on the Montague Sand Plain in the Connecticut River Valley, an extensive area of sandy outwash with a distinct vegetation of pitch pine and scrub oak (Motzkin and others 1996). The Eastern Lowlands are part of the coastal lowland area of New England (Denny 1982). This area of varied relief (40–200 m above sea level) is underlain by granite, schist, and gneiss of Proterozoic age, and overlain by glacial till, large areas of stratified deposits, and lesser amounts of alluvium.

The climatic gradient across the region primarily reflects variation in elevation (Ollinger and others 1993). The Eastern Lowlands and Connecticut River Valley have milder climates than the Central Uplands (Foster and others 1998). Surficial geology also varies across the region. Glacial till dominates the Uplands; lake deposits, outwash, and alluvium are widespread in the Connecticut River Valley; and stratified deposits and till occur in the Eastern Lowlands (Heeley 1972).

Regional vegetation in central Massachusetts is typical of the transition hardwood–hemlock–white pine forest region (Spurr 1956; Westveld 1956). Important hardwood species include red maple (*Acer rubrum*), beech (*Fagus grandifolia*), yellow birch (*Betula alleghaniensis*), oak (*Quercus rubra, Q. alba*, and *Q. velutina*), paper birch (*B. papyrifera*), black birch (*B. lenta*), and sugar maple (*A. saccharum*). The coniferous species, hemlock (*T. canadensis*) and white pine (*Pinus strobus*), are also common, with some red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*). Most of the study region has reforested since agricultural abandonment in the late 19th century, although the Connecticut River Valley and Eastern Lowlands have more agricultural land than the Central Uplands (Foster and others 1998). Vascular plant nomenclature follows that used by Gleason and Cronquist (1991).

Table 1. List of Lake Basins Analyzed[a]

Site	Elevation (m)	Area (ha)	Water Depth (m)
Central Uplands			
1. Aino Pond	354	1.8	2.5
2. Quag Pond	332	0.8	2.6
3. Snake Pond	282	5.0	8.0
4. Lily Pond	269	0.8	1.3
5. Silver Lake	161	7.1	2.0
Connecticut River Valley			
6. Otter Pond	107	3.1	2.6
7. Green Pond	80	5.0	5.7
8. Lake Pleasant	80	20.0	11.4
9. Dead Frog Pond	80	0.2	1.0
Eastern Lowlands			
10. Little Pond	99	5.0	3.2
11. Little Mirror Lake	73	5.0	8.5

[a]*The sites occur in three broad physiographic regions: Connecticut River Valley, Eastern Lowlands and the Central Uplands. See Figure 1 for locations.*

Native American populations were present and active on the landscape prior to European arrival, but there is little agreement on the extent of their impact, if any, on vegetation (Day 1953; Pyne 1982; Russell 1983; Mulholland 1984; Winkler 1985; Patterson and Sassaman 1988; Dunwiddie 1989; Williams 1989) and few studies combining archeological and paleoecological data to test hypotheses. Archaeological evidence suggests a regional gradient of aboriginal population density in southern New England that parallels that of fire frequency; decreasing from coastal and southern regions to the north [reviewed by Patterson and Sassaman (1988)]. In central Massachusetts, Native American settlements were more abundant at lower elevations, along the Connecticut River Valley and in the Eastern Lowlands (Patterson and Sassaman 1988; M. Mulholland unpublished data). In central Massachusetts, European settlement took place mainly between AD 1700 and 1750 (Foster and others 1998).

METHODS

Site Selection and Description

To examine vegetation dynamics over the past 1000 years, a transect of 11 lakes located across north-central Massachusetts was selected for paleoecological investigation (Figure 1 and Table 1). Selection criteria included small surface area (less than 5 ha) and no inflowing or outflowing streams, to ensure that the lakes had a mainly local pollen source area [within about 5 km of the lake (Jacobson and Bradshaw 1981)]. One site (Lake Pleasant) is considerably larger than 5 ha in area but has adjacent small lakes (Green Pond and Dead Frog Pond) that we also studied to determine the local signal. By comparing the records among sites, we can assess regional versus local vegetation dynamics. The lakes are located across an elevational and climatic gradient (Figure 1), and the areas surrounding them have been subjected to different types of land use.

Paleoecological Methods

Sediment cores (5 cm diameter) were taken at the deepest point in each lake basin by using a modified, Livingstone piston corer (Livingstone 1955; Wright 1967). To capture the sediment–water interface, the uppermost, unconsolidated sediment was obtained using perspex tubing (10 cm diameter) with a piston, constructed such that the sediment could be extruded vertically in the field. Cores taken with the Livingstone were wrapped in plastic film and aluminum foil, and stored, with the surface samples, in the dark at 4°C.

Subsamples of sediment were taken at 1- to 2-cm intervals to achieve fine temporal resolution, and analyzed for fossil pollen, spores, and charcoal by using standard methods of preparation (Berglund and Ralska-Jasiewiczowa 1986; Faegri and others 1989). At least 500 arboreal pollen grains were counted for each sample. Pollen percentages were calculated based on a pollen sum of all terrestrial pollen grains and spores. Microscopic charcoal was tallied for each core by the point-intercept method (Clark 1982). *Eucalyptus* pollen suspension of known volume and concentration was added to each sample during preparation and *Eucalyptus* pollen grains were counted simultaneously with charcoal to estimate charcoal–pollen ratios.

Numerical zonation was used to aid description of the pollen data from each site using the program Psimpoll version 2.25 (Bennett 1994,1996). Pollen assemblage zones were determined by optimal splitting based on information content (Bennett 1996). The number of statistically meaningful zones was determined by a Broken Stick Model, a routine in Psimpoll (Bennett 1994, 1996). This method tests whether the number of zones accounts for a greater proportion of variance than predicted by the Broken Stick Model (Bennett 1996).

Chronologies for each site were obtained by radiocarbon (^{14}C) and lead (^{210}Pb) radiometric dating methods. Bulk sediment samples (1–4 samples per site) were submitted to Beta Analytic and Woods Hole Oceanographic Institution facilities for conventional and accelerated mass spectroscopy radiocarbon dating. Radiocarbon age determinations were converted to calendar years by the program Calib version 3.0, based on a combination of bidecadal tree datasets and marine coral datasets (Stuiver and Reimer 1993a, 1993b).

Contiguous sediment subsamples (1 cm^3) were taken from each core to estimate "unsupported" and "supported" ^{210}Pb activity in order to date the recent sediments by using the ^{210}Pb dating method (Olsson 1986). The ^{210}Po activity (in equilibrium with ^{210}Pb) was measured with an alpha spectrometer and ages determined using the constant rate of supply (CRS) model (Binford 1990). Samples were prepared to extract ^{210}Po by using a method developed by D. R. Engstrom (personal communication). A 20-μL spike of ^{209}Po of known activity was added in order to estimate the activity of ^{210}Po, and thus ^{210}Pb, within the sediments.

To determine the organic content of the lake sediments (percent mass loss on ignition), samples (1 cm^3) taken at regular intervals (1–2 cm) were combusted at 550°C for 6 h in a muffle furnace (Bengtsson and Enell 1986).

Numerical Analysis

To determine patterns of vegetation change at a local level, the pollen data for each site were ordinated by Correspondence Analysis (CA) using the program Canoco version 3.11 (ter Braak 1992). Only arboreal taxa 3% or greater of the pollen sum were used in this and subsequent analyses, and all the data were subjected to square-root transformation. Rates of palynological change (a measure of rates of vegetation change) were estimated for each of the pollen records using the program Tilia version 2.0. The pollen data were smoothed with a three-point moving average, and positions along the smoothed curves were interpolated to obtain equal time intervals [25 years (Jacobson and others 1987)]. Chord distances were estimated between samples (as a measure of dissimilarity) to determine rates of change (Jacobson and others 1987; Bennett 1996).

To examine subregional patterns of vegetation change, the pollen data from each of the Upland sites (Central Uplands) were combined and ordinated using CA, as just described. This was repeated for the lowland sites (Eastern Lowlands and Connecticut River Valley), and Detrended Correspondence Analysis (DCA) was used in a similar way to determine regional patterns of change through time on the entire dataset from all 11 sites.

CA was also used to compare climate–vegetation relationships between pre- and post-European settlement forests across the region. CA was performed on the presettlement and postsettlement samples separately for all the sites combined. Linear regression was used to examine the relationship between forest composition and climate. CA first-axis scores of the presettlement samples (at 1000 years bp and 300 bp) were regressed on to modern growing degree days (GDD). Estimates of GDD were obtained from a regression model developed by Ollinger and others (1995) that is based on empirical data, elevation, latitude, and longitude. This was repeated for the modern pollen samples from each site. We assumed that although GDD have changed with climate over the past 1000 years, the differences between sites (based on lapse rates, elevation, location, and so on) should not have changed. We chose to use GDD because this parameter of climate is correlated with vegetation composition.

Results

Time Scales

Chronologies were constructed for the pollen records from each site using calibrated radiocarbon ages and, for some sites, ^{210}Pb time scales (see the Appendix for details). To make the calibrated radiocarbon ages (determined as years before AD 1950) comparable with the ^{210}Pb age estimates (years before present), each calibrated radiocarbon date was increased by 40 years and converted to years before present, where present was taken as AD 1990. Radiocarbon and ^{210}Pb ages are therefore expressed as years bp (before present) in the subsequent results and discussion. European settlement was inferred from the pollen records by an increase of ragweed (*Ambrosia*), grass (Poaceae), and sorrel (*Rumex*) pollen percentages. This increase was determined objectively by numerical zonation (see below). According to historical data, settlement occurred between 300 and 250 years before present (Foster and others 1998). A date of 250 years bp was assumed for the European settlement horizon for each site. Linear interpolation was used to determine ages of undated samples. Due to erosion from cleared land, sediment accumulation rates increased significantly after European settlement at most sites, and thus estimation of pollen or charcoal accumulation rates was not attempted.

With the exception of Green Pond, most of the sites have records that extend from roughly 1000 bp to the present day. The truncated Green Pond pollen record, with high percentages of chestnut in the uppermost sample, indicates that about the top 100 years of sediment were not obtained; 100 years bp was taken as the uppermost age of this sedimentary record.

Pollen, Charcoal, and Sedimentary Data

Pollen and charcoal records from the upland (Central Uplands) and lowland areas (Connecticut River Valley and Eastern Lowlands) are discussed separately below with the sedimentary results. Pollen diagrams are presented with pollen percentage data plotted against time, in calendar years bp (Figure 2). Each of the sediment cores was composed primarily of algal lake mud (gyttja) and had a high organic content (50%–90%). Charcoal abundance is expressed as charcoal–pollen ratios. Microscopic charcoal is thought to record mainly regional landscape fires (Clark 1988). However, the variation between charcoal–pollen values among sites located close together (for example, Little Pond and Little Mirror Lake) suggests that much of the charcoal may have a local source area (that is, within the lake catchment).

Uplands

Pollen profiles from each of the Upland sites were divided into three pollen assemblage zones by numerical zonation to aid description of the records (Figure 2a–e).

Zone 3 (1000–600/500 years bp). At all the Upland sites, 1000 bp, hemlock and beech were relatively abundant (20%–25% and 15%–20% pollen, respectively). They probably occurred in association with sugar maple (2%–3%; underrepresented in pollen assemblages) and yellow birch (birch sp. 10%–20%). Although the species of birch cannot be distinguished in the pollen record, yellow birch has intermediate shade tolerance and is often associated with hemlock and/or beech (Nichols 1935; Stearns 1951; Erdmann 1990). White pine, some chestnut, and oak were also recorded along with low abundances of spruce. Herbaceous pollen abundances were low, indicating the closed nature of the canopy. Charcoal–pollen ratios were also low (less than 100), suggesting infrequent fires and/or low intensity fires.

Zone 2 (around 550–250 years bp). There appears to have been a subtle change in forest composition, starting between 600 and 500 years bp, at each of the Upland sites, which characterizes the beginning of zone 2. Although there was variation in the timing of this change, at each site there was a gradual decline in the abundance of hemlock, beech, and sugar maple, and there was also variation in the response of other taxa. White pine pollen percentages generally increased to 5%–10%. In most cases, percentages of oak pollen did not change although they increased at Aino Pond. Chestnut pollen percentages increased at some sites, except Quag Pond and Silver Lake. Birch pollen frequencies remained the same or increased slightly. At Silver Lake, this change in forest composition appears to have occurred about 800 years bp, approximately 2 centuries earlier than at the other Upland sites. This may indicate that there is a problem in the chronology at this site or that the change occurred earlier in this location.

Herbaceous pollen abundances began to increase during this period, presumably as a result of an opening up of the canopy. In particular, bracken fern (*Pteridium*) spores increased at most sites to reach their highest levels (2%–4%). In general, there was a gradual increase in the charcoal–pollen ratio (especially at Lily Pond, up to 200); however, overall charcoal levels remained relatively low and erratic (less than 100).

Zone 1 (250–0 years bp). There was variation in the timing of European settlement across the region, but it occurred between around 300 and 250 years bp (AD 1700–1750) (Foster and others 1998). After European settlement, there was a marked change in forest composition as hemlock and beech declined sharply in abundance (5%–10%), and herbaceous pollen types increased rapidly, indicating forest clearance. White pine increased at Snake and Lily Ponds and, initially, at Aino Pond. Birch pollen percentages increased gradually to reach 20%–30% as did those of oak (15%–30%). The increase in birch and oak occurred primarily in the last century as reforestation and forest maturation was taking place across the landscape. Red maple increased at all sites although its pollen values were low due to poor representation in the pollen record. Because of the chestnut blight (*Cryphonectaria parasitica*), chestnut pollen percentages declined at the beginning of the century. Herbaceous pollen types such as grasses, sorrel, and ragweed initially increased sharply, but generally declined as forest cover increased in the last 100 years. Bracken fern spore values declined after European settlement.

Charcoal–pollen ratios increased at Quag Pond and Silver lake, decreased at Lily Pond, and remained erratic at Snake Pond and Aino Pond. After forest clearance, there was a drop in the organic content of the sediment, indicating the inwash of inorganic material from erosion in the watershed.

Lowlands

Numerical zonation indicated that the pollen records from each of the Lowland sites (Connecticut River Valley and Eastern Lowlands) could be divided into two zones (Figure 2f–k). The Lowland areas were combined for discussion as they showed similar patterns among sites.

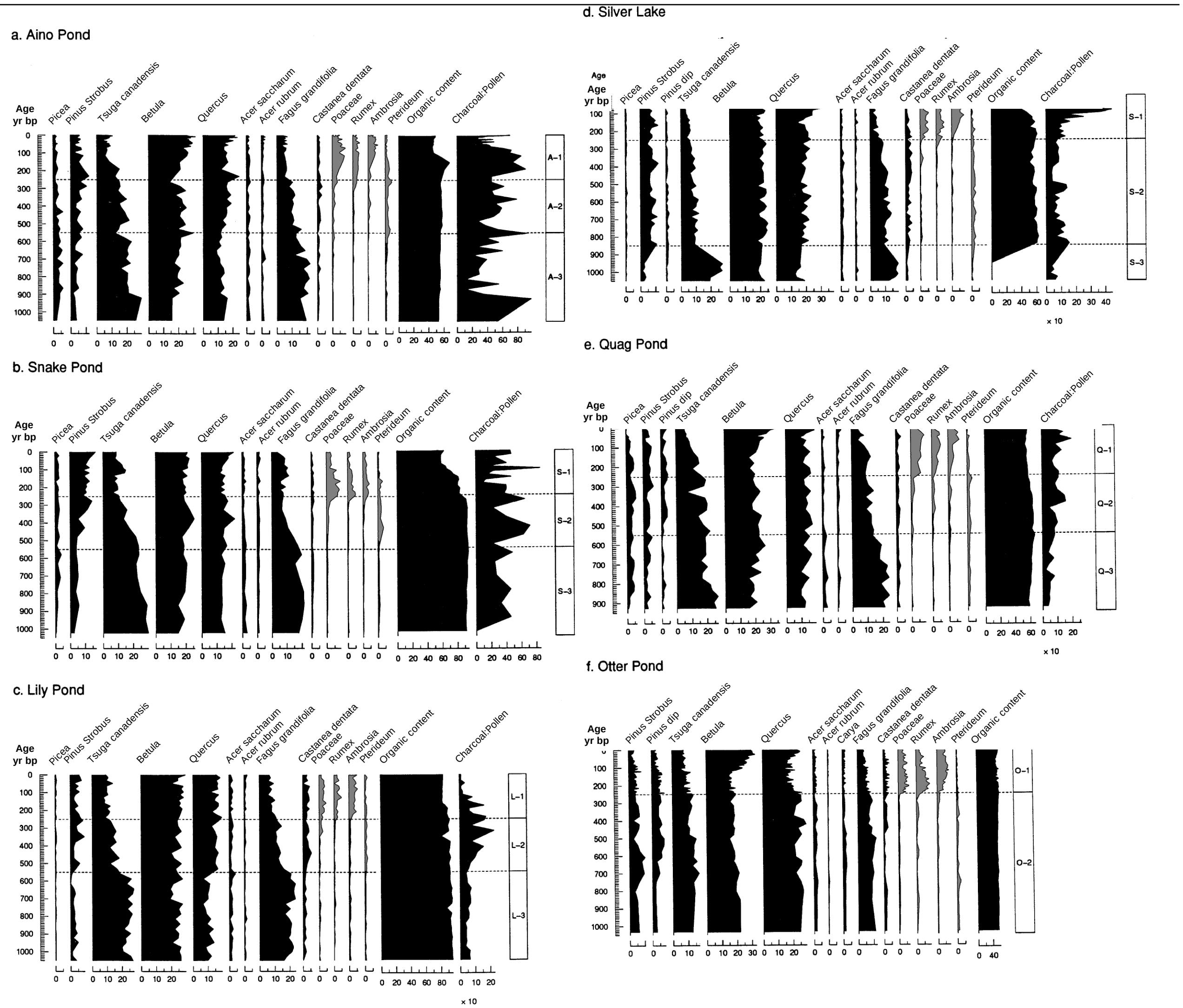

Figure 2a–k. Pollen, charcoal, and sediment data from each of the 11 lakes analyzed. Percentage pollen and spore abundance is plotted against time (years before present). Organic content of the sediments (percentage of sediment dry weight) and charcoal–pollen ratios are also shown. Dashed lines mark the boundaries of zones delimited by numerical zonation.

Zone 2 (1000–250 years bp). Before European settlement, oak was abundant in the pollen assemblages from all of the Lowland sites (20%–40%). Hickory (*Carya* spp.; 2%–4%) and chestnut (3%–5%) reached higher pollen percentages than at most of the Upland sites, which suggests the occurrence of oak–hickory–chestnut forests at this time. Hemlock, beech, and sugar maple pollen percentages were generally lower than at the Upland sites. Diploxylon pine (pitch pine) was relatively abundant (about 5%) at the sites in the Connecticut River Valley. Birch pollen percentages varied from 7% to 20%.

Beech and hemlock started to decline gradually at around 550 years bp as in the Uplands, although the change was less marked due to lower original abundances. Bracken spores were also relatively abundant, declining after 500 years bp. Zone 2 at these sites is characterized by abundant oak pollen and low herbaceous pollen percentages indicating closed forest canopy. Herbaceous pollen frequencies started to increase slowly at around 500 years bp. In general, charcoal–pollen ratios were high (100–600).

Zone 1 (250–0 years bp). At most sites, the change in the pollen record after settlement is seen most in the herbaceous taxa (increase of grasses, sorrel, and ragweed), and there was not a marked change in the relative abundances of tree pollen. Hemlock and beech pollen percentages gradually declined to low levels (2%–3%). Chestnut generally increased initially before it declined in response to the chestnut blight. Oak pollen percentages changed little in the

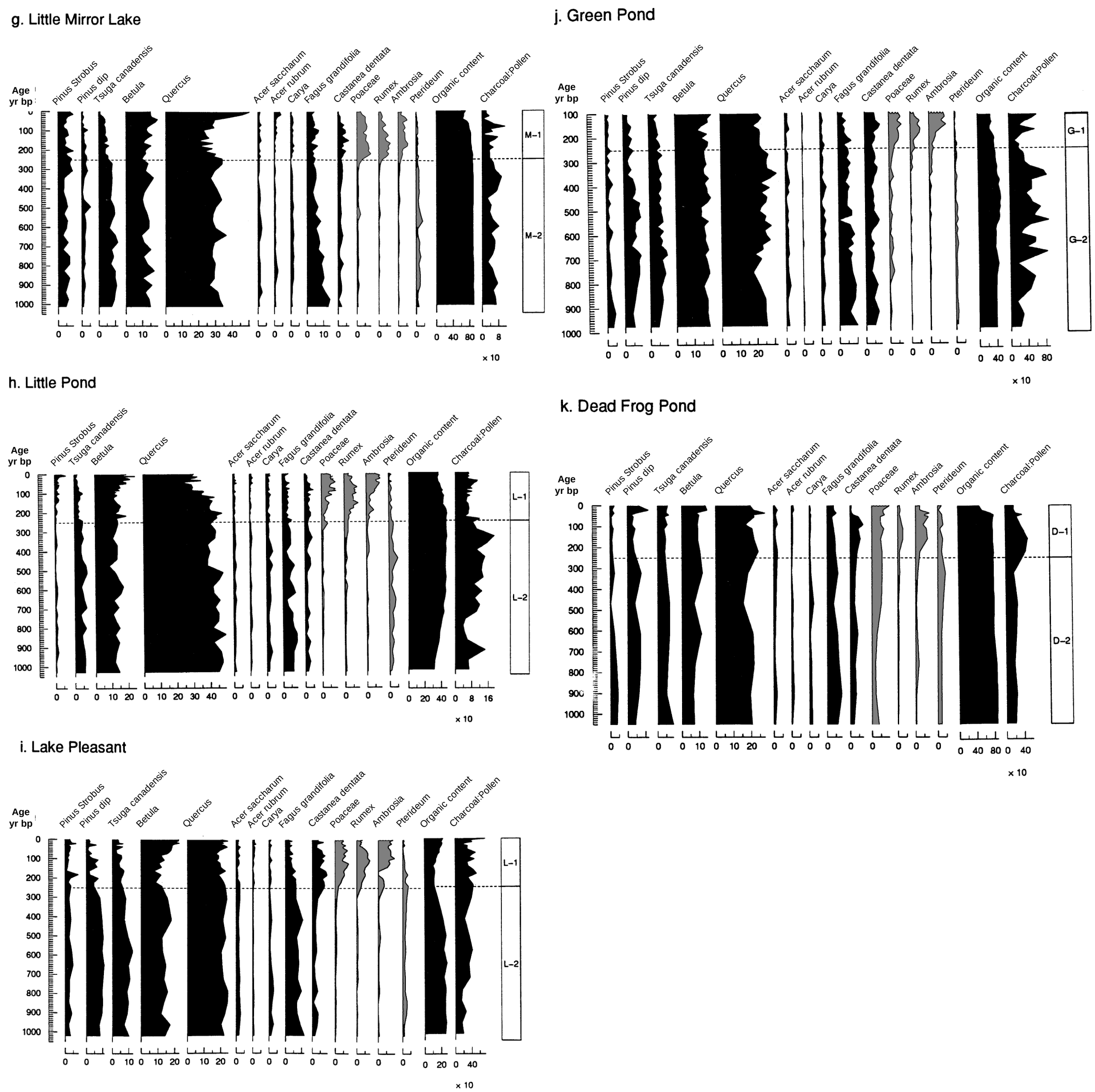

Figure 2. Continued

sites on the Montague Sand Plain (Green Pond, Lake Pleasant, and Dead Frog Pond). At the other sites, oak generally decreased initially and then increased as reforestation took place.

There are differences in the post-European settlement changes observed at the two sites in the Eastern Lowlands: Little Mirror Lake and Little Pond. Prior to settlement, oak pollen percentages were higher at Little Pond (greater than 40%) than Little Mirror Lake (around 30%). After settlement, oak percentages decreased somewhat at Little Mirror Lake but then increased sharply (greater than 45%) in the last 100 years as reforestation took place. By contrast, Little Pond oak percentages did not change immediately after settlement, but decreased slightly starting approximately 100 years ago (to less than 30%) while birch increased. More recently, white pine and oak pollen percentages have started to increase.

White pine pollen frequencies increased at the sites in the Eastern Lowlands, whereas it decreased in the Connecticut River valley. Pitch pine is now abundant on the Montague Sand Plain in the Connecticut River Valley (Motzkin and others 1996). It appears that pitch pine declined initially after settlement and then increased as reforestation took place, as seen in the pollen record from Dead Frog Pond, and from historical data (Motzkin and others 1996). Red maple increased at most sites, starting less than 100 years bp, although its pollen percentages was low. Hickory pollen percentages decreased.

There was also a decrease in the organic content of the lake sediments. Charcoal–pollen ratios increased, at least initially, in the Connecticut River Valley sites. At Dead Frog Pond, charcoal–pollen ratios increased from 200 to 400, and then declined to about 200, while, in the Eastern Lowlands, charcoal–pollen ratios generally decreased. This decrease was marked at Little Pond (from more than 140 to less than 30) and may be related to the decline of oak pollen percentages. Charcoal–pollen ratios were lower at Little Mirror Lake and did not change as markedly.

Local Vegetation Dynamics

Ordination of the pollen data from individual sites by CA shows the local patterns of vegetation change over the past 1000 years. In the Upland sites, the samples (pollen levels) generally fall into three clusters (Figure 3) that correspond with the three zones delimited independently by the stratigraphically constrained, numerical zonation. The main points to note from this analysis of Uplands sites are as follows: First, there was a change in forest composition beginning at around 550 years bp. Samples covering this period (550–250 years bp) had lower levels of hemlock, beech, and sugar maple in their pollen assemblages. Second, there was a marked change in forest composition after European settlement as the landscape was cleared, and hemlock and beech declined sharply. Third, although the landscape has reforested, there is no evidence of a return to pre-European forest composition and no trend in that direction. The most recent samples do not overlap with those from the presettlement period.

There was a sharp increase in rates of change at the Upland sites immediately after European settlement (Figure 4a). At most sites, rates of change increased after settlement to levels higher than at any time in the previous 1000 years, with the exception of Lily Pond, at which the increase in rates of change after European settlement matched the increase that occurred 550 years bp. Rates of change declined after their initial postsettlement increase, before increasing again as reforestation took place regionally. Because of abrupt changes in the pollen record prior to settlement, estimates of rates of change from Silver Pond are variable, which is potentially due to problems with the chronology. The trend at Silver Pond was different to other sites, as rates of change increased gradually and have decreased in recent decades. Rates of change also increased prior to European settlement in the Uplands, as hemlock and beech declined in abundance around 550 years bp.

In the Lowland sites ordination (Figure 3), the samples form two clusters covering the pre- and post-European settlement periods. Again there was a change in forest composition after European settlement, although it appears less marked than in the Uplands, and forest composition, as sampled by pollen rain, has not returned to pre-European conditions.

At most of the Lowlands sites, rates of change did not increase sharply after European settlement, but increased either gradually or in the past 100 years during the period of reforestation (Figure 4b). In some cases, rates of change also increased slightly prior to settlement, as beech and hemlock declined, although this decline was less significant than in the Uplands (Figure 4a).

Regional Vegetation Dynamics

CA of all the Upland sites combined (Figure 5) demonstrates the marked shift in forest composition after European settlement. The first axis, representing the highest proportion of variation, shows the trend over time (from right to left along axis 1) as the vegetation changes from a forest type dominated by late-successional species such as hemlock, beech, and sugar maple to one where oak, birch, and red maple are more abundant. The second axis reflects subregional differences in the Uplands related to elevation. For example, the highest elevation sites, Aino Pond and Quag Pond, have higher abundances of spruce than Silver Lake and Lily Pond, which are at slightly lower elevations. By contrast, CA of all the Lowland sites (Eastern Lowlands and Connecticut River Valley; Figure 6) suggests that there was a less marked shift in forest composition, as sampled by the pollen rain, after European settlement. There is considerable overlap between the pre- and postsettlement samples of pollen levels, indicating similar pollen assemblages. Several tree taxa changed in abundance, but pollen percentages did not change as notably as in the Uplands.

DCA of all the samples from the entire transect highlights the patterns in vegetation dynamics across the region. A high proportion of variation is reflected on ordination axis 1. The scores of samples along this axis are plotted against time to see the temporal trends (Figure 7). Around 1000 years bp, DCA indicates that there was regional differentiation among the sites, in terms of forest composition

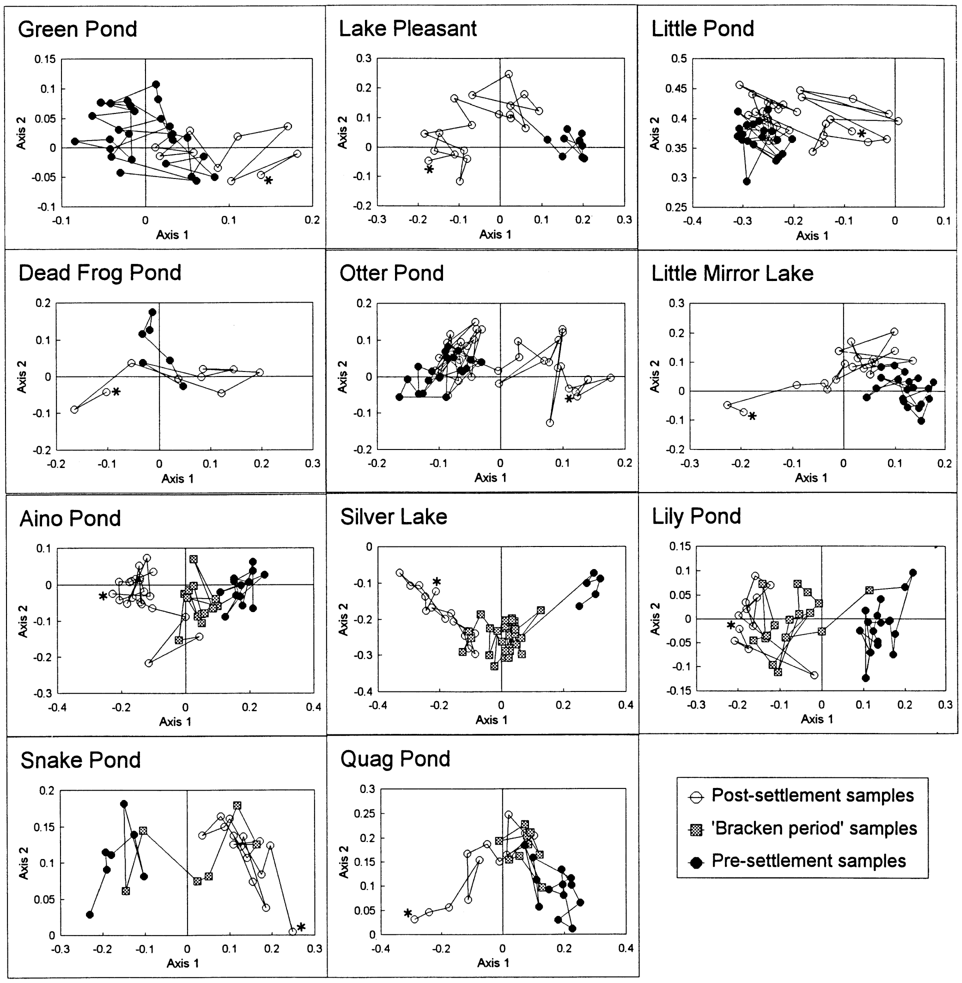

Figure 3. Correspondence analysis ordinations for each of the sites. The first two axes are plotted and samples are linked stratigraphically. Different symbols are used to highlight the pollen assemblage zones determined by numerical zonation (two zones for Lowland sites and three zones for Upland sites). Zone 2 for the Upland sites, characterized by a pre-European settlement decline in hemlock and beech, and an increase in bracken, is labeled as the *bracken period*. This change was not recorded at Lowland sites. The most recent sample is marked with an asterisk.

(as recorded by the pollen data), because the lower elevation sites are separated from the higher elevation sites along the first ordination axis (from the bottom to the top of the *y*-axis). The temporal trajectories for each site start to converge with one another, beginning around 500–600 years bp. This corresponds with the gradual decline in the abundance of beech, sugar maple, and hemlock that is recorded at all sites but appears to have been more significant in the Uplands. After European settlement, approximately 250 years bp, there was further regional homogenization of forest composition and less distinction between sites.

Linear regression of presettlement axis-1 CA scores, for samples recording vegetation 1000 years bp, onto modern GDD produces an r^2 value of 0.46* (* = $P < 0.05$). CA scores for samples just prior to settlement (around 300 bp) do not have a significant relationship with climate ($r^2 = 0.38$). Postsettlement (modern) sample scores have a poor relationship with GDD ($r^2 = 0.15$). These results suggest that, at 1000 years bp, vegetation as recorded by pollen assemblages had a strong relationship with climate. Immediately prior to settlement, this relationship had become weaker, and modern pollen rain at the study sites does not reflect climatic differences among sites.

Discussion

Paleoecological data from central Massachusetts confirm that European settlement had a major impact on forest composition and dynamics. Forest cover was reduced dramatically following the arrival of Europeans, resulting in soil erosion recorded in lake sediments. There was a shift in forest composition soon after settlement, most notably in Upland elevations. After agricultural abandonment, the landscape reforested, resulting in further compositional changes. Local and regional patterns of forest composition and dynamics have not reestablished despite a decline in the intensity of disturbance following agricultural abandonment at the end of the 19th century.

Regional patterns of forest composition, associated with a climatic and disturbance gradient, have

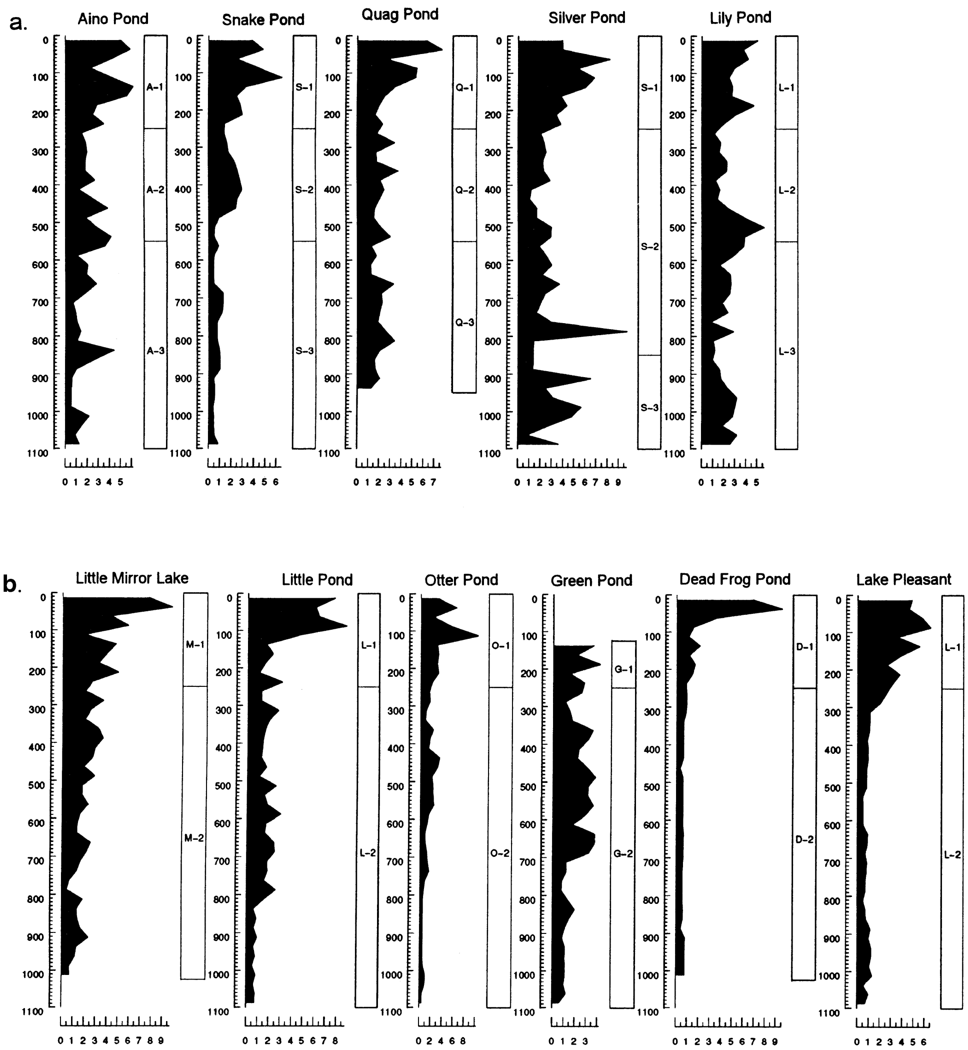

Figure 4. Rates of palynological change, as measured by chord distances, for each of the pollen records from the Uplands (a) and the Lowland sites (b) in the Connecticut River Valley and Eastern Lowlands. Zone boundaries for each site are also shown.

become obscured over the past 1000 years. Prior to European settlement, low- and high-elevation sites were distinct in terms of vegetation composition. There was a shift in forest composition in the Uplands, starting at approximately 550 years bp, characterized by a decline in long-lived, shade-tolerant tree taxa. Widespread disturbance associated with European settlement appears to have accelerated and accentuated this change.

The following discussion describes pre-European settlement forest history and then compares it with postsettlement dynamics. Due to differences in the pre- and postsettlement patterns between Upland and Lowland sites, in terms of forest composition, disturbance history, and response to European settlement, they are discussed separately.

Pre-European Settlement Forest Dynamics

Uplands. Shade-tolerant, mature-forest species, including hemlock, sugar maple, yellow birch, and beech (Nichols 1935), dominated the presettlement forests in the Uplands. A subtle but distinct change in forest composition apparently occurred at all of the Upland sites prior to European settlement (starting around 600–500 years bp), characterized by a gradual decline in the abundance of beech, hemlock, and sugar maple, an increase in rates of change, and higher values of bracken fern spores. Because hemlock and beech cast dense shade (Godman and Lancaster 1990; Tubbs and Houston 1990), and bracken fern produces more spores in higher light conditions, changes in bracken may reflect an increase in spore production and/or bracken abundance as a result of the decline in hemlock and beech. What factors were driving this change in forest composition?

The composition timing corresponds with the beginning of the Little Ice Age (around AD 1450), an apparently global climatic phenomenon (Grove 1988; Bradley and Jones 1993) characterized by greater variability in climate rather than uniformly

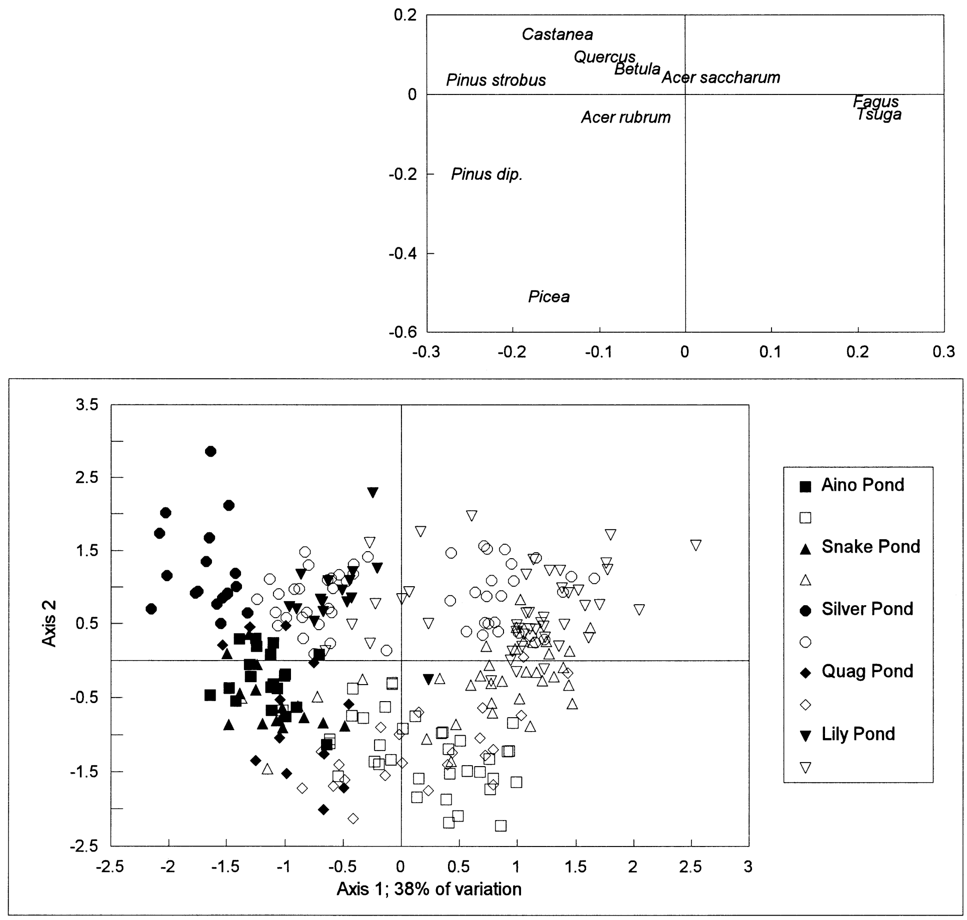

Figure 5. Correspondence analysis ordination (plot of taxa above and samples plot below) of the data from sites in the Uplands, covering the past 1000 years. Open symbols represent the presettlement samples (of forest composition as measured by the pollen record) and closed symbols represent postsettlement samples.

colder conditions (Bradley and Jones 1993; Baron and Smith 1996). Historical evidence suggests that the Little Ice Age in New England was characterized by higher frequencies of extreme winters and cool summers (Baron 1992; Baron and Smith 1996). In pollen records from central Massachusetts, however, as beech, sugar maple, and hemlock declined, there was no corresponding increase in pollen percentages of cold-tolerant species (such as spruce or fir), and in some cases there was an increase in oak pollen percentages and/or white pine. Therefore, these pollen data do not suggest cooler conditions, but perhaps indicate a shift in moisture balance (J. Fuller and others unpublished). Some authors suggest that this period was drier [for example, see Payette and Filion (1993), Fritz and others (1994), and Laird and others (1996)], whereas results from other studies suggest moister conditions (Clark 1990). However, most of these data are from areas considerably further west or north of New England. Changes observed in pollen data from Michigan, along an east–west transect from Maine to Minnesota, and from southern Ontario, are suggested to reflect a response in forest composition to cooler conditions during the Little Ice Age (Bernabo 1981; Gajewski 1987; Campbell and McAndrews 1993). Additional independent data are required to determine the nature of any climate change at this time.

An increase in disturbance by Native American populations is another potential factor that could have been responsible for the shift in forest composition and structure in central Massachusetts. Similar changes in vegetation are recorded in pollen data from sites throughout eastern North America (Gajewski 1987; Campbell and McAndrews 1993; Russell and others 1993; J. Fuller and others unpublished). However, it seems unlikely that human activity could have produced such a widespread change in forest composition at this time without the extensive use of fire for which there is some evidence from central Massachusetts (discussed below). Estimates of human population densities in the late Woodland period for southern New England indicate they were low (Mulholland 1984; unpublished data). In Massachusetts, Native American settlements were concentrated at lower elevations, such as coastal areas and the Connecticut River Valley (Patterson and Sassaman 1988), whereas the change in forest composition was most pronounced in the Central Uplands, where hemlock and beech were formerly abundant.

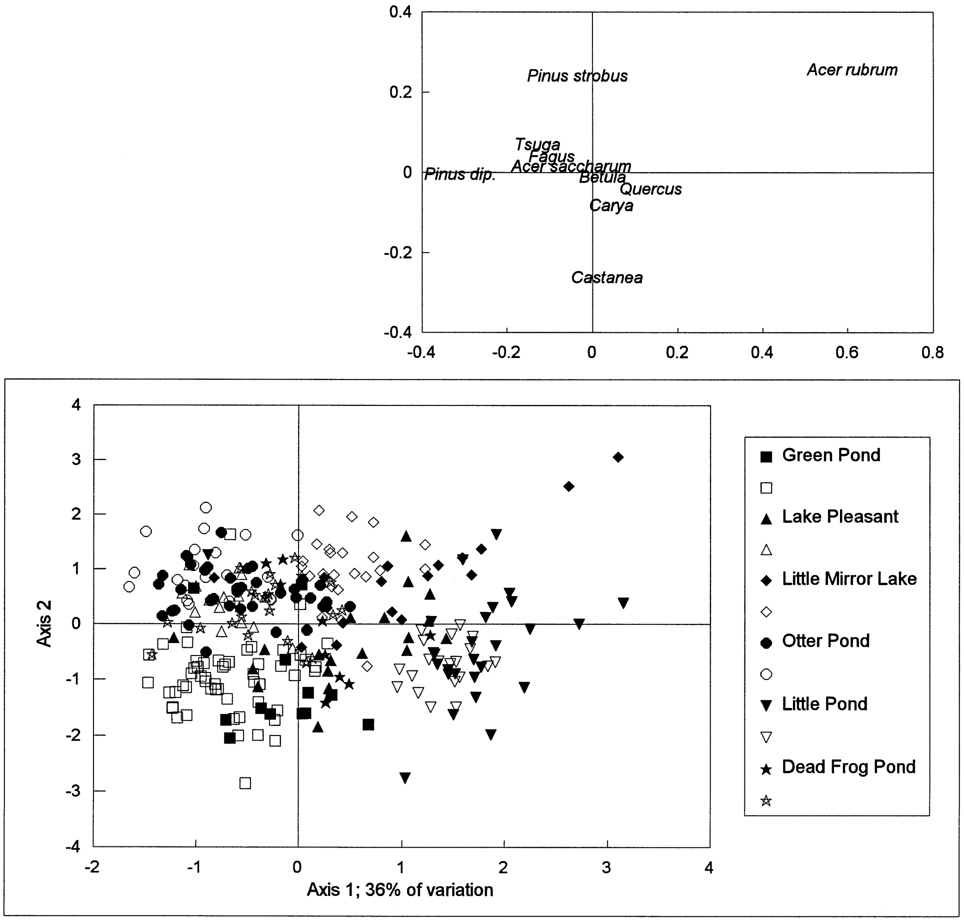

Figure 6. Correspondence analysis ordination (plot of taxa above and samples plot below) of the data from all the Lowland sites (Eastern Lowlands and Connecticut River Valley), covering the past 1000 years. The open symbols represent the presettlement samples (of forest composition as measured by the pollen record) and the solid symbols represent postsettlement samples.

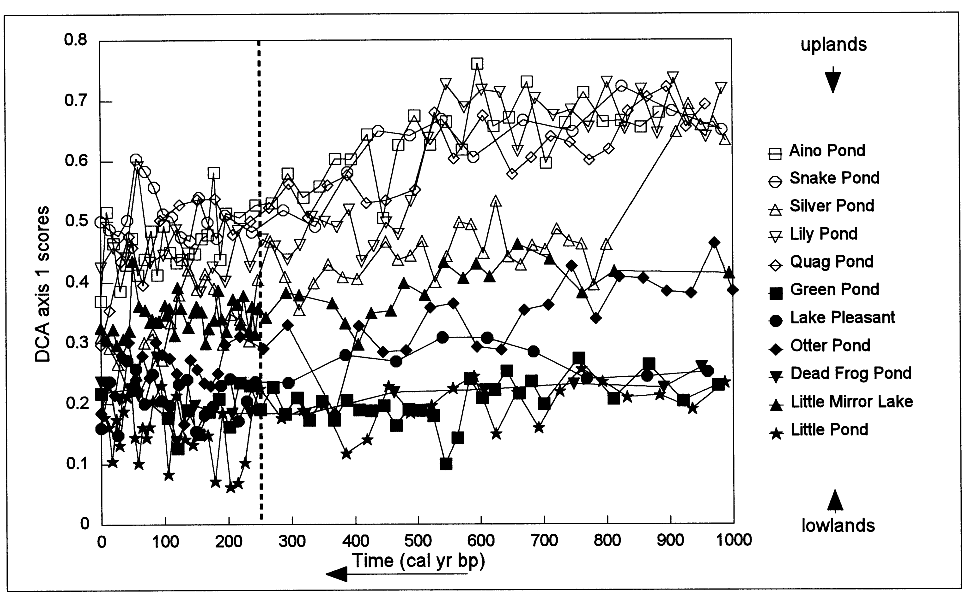

Figure 7. Detrended correspondence analysis (DCA) axis-1 scores, for all the sites, plotted against time (years before present). Axis 1 represents 32% of the variation within the dataset. Upland sites are represented by the open symbols, Eastern Lowland sites by black and Connecticut River Valley sites by gray.

Charcoal–pollen ratios for most of the central Massachusetts Upland sites were low but in some cases increased slightly during this period. If this does reflect an increase in fire frequency, it is not possible to distinguish from the charcoal record whether fires were caused naturally or resulted from human activity. Beech, sugar maple, and hemlock are our fire-sensitive species (Godman and Lancaster 1990; Tubbs and Houston 1990) and even low levels of fire may exclude them in favor of oak, white pine, and birch (Winer 1955). A slight increase in fire frequency, therefore, may have contributed to the decline in these taxa as observed during this period. Clark and Royall (1995) suggest that a decrease in the abundance of beech and sugar maple in southern Ontario, followed by an increase in oak and pine, was due to the use of fire by Iroquois populations. Additional data from other lines of evidence are required to determine whether the observed change was due primarily to climatic change (temperature and/or moisture balance), fire, and/or Native American activity (J. Fuller and others unpublished). Clearly, however, forest composition was in a state of flux prior to European settlement.

Lowlands. The Eastern Lowland and Connecticut River Valley sites are discussed together because of similarities in vegetation composition and temporal trends. Prior to European settlement, all of the lower-elevation sites were dominated by oak, chestnut, and hickory, with some pine (white pine and pitch pine) and low abundances of hemlock, beech, and sugar maple. On average, higher levels of charcoal were recorded at the low-elevation sites, suggesting a different fire regime from the Central Uplands. These data fit with the general notion that disturbance (such as fire) is thought necessary to maintain oak dominance in this part of eastern North America (Abrams 1992), although climate regime and substrate are also important. The pattern of charcoal abundance from north-central Massachusetts supports the conclusions of Patterson and Sassaman (1988), who suggest that there was a presettlement gradient of fire intensity and frequency from coastal and southern Lowlands in New England, where charcoal abundance was highest in a number of sedimentary records, decreasing northward and westward. Patterson and Sassaman (1988) also infer higher fire frequency in the Connecticut River Valley, decreasing northward. This gradient reflects the patterns of Native American settlements, as well as differences in climate and substrate.

The highest levels of charcoal in this study were recorded at sites on the Montague Sand Plain (Green Pond, Dead Frog Pond and Lake Pleasant). The sandy, drought-prone substrate on the plain and slightly warmer climate in the Connecticut River Valley may make this area more conducive to natural fire (Motzkin and others 1996). This area is also near a documented Woodland Period Native American settlement (Mulholland 1984). The fire-dependent species, pitch pine, was more abundant at sites on the plain, thus differentiating these sites from those in the Eastern Lowlands.

Charcoal values in the Eastern Lowlands were generally higher than those in the Central Uplands prior to settlement, but lower than those from sites in the Connecticut River Valley. Oak pollen percentages were highest at sites in the Eastern Lowlands. The two Lowland areas have similar climates, but differences in substrate and fire regimes may have resulted in the small differences in forest composition (pitch pine appears to have been always more abundant in the Connecticut River Valley). Although the two sites in the Eastern Lowlands are not far apart (Figure 1), Little Pond had greater presettlement percentages of oak pollen (more than 40%) and higher charcoal–pollen ratios (more than 120) than Little Mirror Lake (oak, less than 35%; and charcoal–pollen, less than 80). Fire may therefore have been controlling the abundance of oak locally. The difference in pre-European settlement vegetation between the Uplands and the Lowlands was probably influenced by the interaction between climate, fire, and Native American populations.

At the Lowland sites, hemlock, beech, and sugar maple were present at low abundances (probably restricted by higher fire frequency). Although these taxa declined somewhat prior to European settlement, the change was much less marked than that recorded in the Uplands. This may be due to the higher abundance of disturbance-tolerant tree taxa at the time, or it may indicate that temperature was not the main driving factor of the change, as a response in vegetation composition would also be expected in the Lowlands.

Post-European Settlement Forest Dynamics

Uplands. Forest composition in the Uplands was changing prior to European settlement, although it is unclear what the driving factors were. Rates of vegetation change increased again after settlement, reaching levels greater than those estimated for the previous 1000 years. This change appears to have occurred rapidly. Similar increases in rates of vegetation change, associated with European activity and based on palynological data, were estimated for several sites in eastern North America (Jacobson and others 1987). Intensive disturbance of the central Massachusetts landscape following European settlement appears to have had a greater impact on vegetation dynamics than other disturbances, such as wind, fire, and activity by Native American populations, which were previously the dominant disturbance factors.

The sharp increase in herbaceous pollen types at the time of European settlement and increase of inorganic content of the lake sediment (reflecting erosion into the basins) indicate the rapid opening of the landscape as land was cleared for agriculture. Long-lived, slow-growing, and shade-tolerant species, such as hemlock, beech, sugar maple, and yellow birch, declined sharply in abundance. These species were replaced by those more tolerant of disturbance, such as white pine and chestnut initially, followed by oak, red maple, and birch as the region reforested.

Pre-European settlement forest dynamics may have influenced how forests responded to widespread disturbance after European arrival. Hemlock and beech were declining prior to settlement, and the disturbance associated with European settlement resulted in a further, rapid decline of these late-successional species.

Intense agricultural activity lasted for almost 100 years, but declined at the end of the 19th century. As natural reforestation began, rates of change increased again due to the increase in abundance of white pine, oak, birch, and red maple, all taxa more tolerant of disturbance than hemlock and beech. Historical data show that red maple, in particular, increased in abundance significantly throughout Massachusetts since settlement (Foster and others 1998). Rates of vegetation change have generally remained high in this century. The Massachusetts landscape is still experiencing continuous disturbance through small-scale logging and development (Foster and others 1998), as well as natural disturbances such as hurricanes (Boose and others 1994), maintaining the abundance of disturbance-tolerant species and high rates of vegetation change. In most cases, the organic content of the sediments is still lower than it was prior to European settlement, indicating that erosion or sediment redistribution is still occurring in the lake basins. This suggests that the aquatic systems and watersheds have not stabilized following reforestation.

Lowlands. At the Lowland sites, the increase of herbaceous pollen types at the time of European settlement indicates the removal of forest cover. Organic content of lake sediments decreased, reflecting erosion on the landscape. Ordination of pollen data from all the Lowland sites, however, suggests that overall forest composition did not change markedly, even though cover was greatly reduced. In addition, rates of vegetation change did not increase initially after European settlement. Presettlement forests in the Lowlands were dominated by oak, chestnut, and hickory, charcoal–pollen ratios were high, and late-successional species such as hemlock and beech were present at low abundances. The taxa that dominated the Lowlands at this time are tolerant of disturbance and may have been maintained by greater fire frequencies. After European settlement, therefore, forest composition may not have changed dramatically in the Lowlands because of the higher abundance of disturbance-tolerant taxa due to a different disturbance regime (fire and/or people had a greater impact) from that in the Uplands.

Rates of vegetation change increased at the end of the last century, as the landscape reforested and oak, birch, and red maple became more abundant, and still remain high. Historical data document a sharp increase in red maple and birch in the historical period (Foster and others 1998). Forest composition, therefore, has changed in the Lowlands, but the timing and nature of the change was different from that which occurred in the Uplands. The main shift in forest composition has been since agricultural abandonment and through reforestation.

Regional differences between the Eastern Lowlands and the Connecticut River Valley sites are mainly based on higher oak pollen percentages in the eastern Lowlands and pitch pine in the Connecticut River Valley. Vegetation around two sites in the eastern Lowlands, which are relatively close together, Little Mirror Lake and Little Pond, responded differently to European disturbance. At Little Mirror Pond, oak decreased in abundance initially and increased markedly during the period of reforestation to dominate the modern vegetation along with white pine. Oak was abundant in the presettlement forests around Little Pond and did not change significantly after European settlement, but declined somewhat at the end of the last century as birch increased.

Regional Patterns of Abundance

Prior to European settlement, forest composition at low elevations in central Massachusetts was distinct from that in the Uplands. Oak, chestnut, and hickory were abundant in the Lowlands, whereas hemlock, beech, sugar maple, and yellow birch were common in the Uplands. This regional variation started to become less distinct at around 500–600 bp, as hemlock, beech, and sugar maple declined in abundance at higher elevations. Widespread and intensive disturbance associated with European activity appears to have accelerated this change in forest composition, leading to vegetation homogenization across central Massachusetts. Oak, red maple, and birch increased in the Uplands as late-successional species declined. In the Lowlands, oak decreased overall, while red maple and birch increased during recent reforestation, resulting in greater similarity between high- and low-elevation sites in terms of forest composition. As a result, the climatic gradient reflected in forest composition prior to European settlement (and related to fire and Native American settlement) has become obscured.

Other historical and ecological studies suggest regional vegetation homogenization occurred after widespread disturbance associated with European settlement (Whitney 1990; White and Mladenoff 1994; Palik and Pregitzer 1992; Abrams and Ruffner 1995; Foster and others 1998). For instance, Palik and Pregitzer (1992) suggest that presettlement forest composition in northern Lower Michigan at two sites was related to fire frequency, physiography, or climate. Compositional convergence between these sites is attributed to similarities in the post-European settlement disturbance history on each landscape. Abrams and Ruffner (1995) find landform and physiography were important in determining presettlement forest composition in north-central Pennsylvania and suggest disturbance following European settlement has diminished this relationship. White and Mladenhoff (1994) suggest that vegetation on the northern Great Lakes landscape is more homogeneous since European settlement. Finally, detailed historical and ecological data from central Massachusetts (covering the same study area as this report) indicate that disturbance during the Colonial period has obscured the climatic gradient determining regional patterns in forest composition, leading to vegetation homogenization across the landscape (Foster and others 1998).

Paleoecological records from central Massachusetts, however, suggest that convergence in vegetation composition among sites was also occurring prior to European settlement (Figure 7). Forest composition at higher elevations was changing gradually with a decline in shade-tolerant species. These taxa were less abundant in the Lowlands and, as a result, vegetation composition between the Uplands and Lowlands became more similar. Widespread disturbance after European settlement accelerated the decline of hemlock and beech in the Uplands, to be replaced by oak, birch, and red maple. In the Lowlands, forest composition did not change immediately after European arrival, despite a significant reduction in forest cover, due to the dominance of disturbance-tolerant taxa. However, lowland forest composition did change following agricultural abandonment, with the increase of red maple and birch. Chestnut had declined because of the blight (Beattie 1954), and oak decreased slightly at most sites. Without a paleoecological approach, these changes in regional patterns of forest composition after European settlement cannot be placed in a longer-term context. Presettlement forest dynamics and disturbance regimes undoubtedly influenced the response of vegetation to disturbance after European settlement.

Analyses of pollen data from individual sites do not indicate a return to pre-European forest composition since reforestation (Figure 3). Several factors may contribute to this observation. Widespread agricultural abandonment began at the end of the 19th century. A hundred years of reforestation may be insufficient for late-successional species such as hemlock, sugar maple, and beech to reestablish themselves as dominant taxa. Disease eliminated chestnut populations in the early 1900s (Beattie 1954), and beech-bark disease is currently affecting and limiting the expansion of beech. In addition, widespread ongoing disturbance by selective logging and development is helping to maintain early-successional species, such as oak, birch, and red maple. And, finally, the natural fire regime has changed, as fire suppression has probably reduced the frequency of fire at low elevations, which may affect oak dominance in the long term (Abrams 1992).

Regional patterns have not been reestablished on the landscape despite approximately 100 years of natural reforestation. Modern patterns of abundance in central Massachusetts are, therefore, to a large extent the result of intensive land use and do not strongly reflect the underlying climatic gradient. Fire frequency has decreased regionally, as seen in most of the charcoal records, because of fire suppression, and this will undoubtedly influence the long-term development of forests in central Massachusetts (Abrams 1992). In addition, human activity on the modern landscape is more prevalent in the lower elevations near urban centers, which will also affect long-term forest dynamics.

Conclusions

Pre-European forests in central Massachusetts were highly dynamic, responding to climate change (potentially climatic variability associated with Little Ice Age), natural disturbances, and/or Native American activity, although it is difficult to separate the different driving factors involved. Differences in climate, as well as disturbance regime (fire and human activity), resulted in regional differences in forest composition prior to settlement, across the subtle elevational gradient examined. Lower-elevation sites, with variation in substrate and fire regime, but with similar climate, had high abundances of oak, chestnut, and hickory, with pitch pine common in the Connecticut River Valley. Higher elevations had greater abundances of late-successional species such as hemlock, beech, sugar maple, and yellow birch. Convergence in forest composition across the region started at around 500–600 years bp as beech, hemlock, and sugar maple declined in the Uplands. After European settlement, widespread disturbance across the entire study region produced similar disturbance regimes in the Lowlands and Uplands, resulting in further regional vegetation homogenization.

A paleoecological perspective demonstrates the importance of preEuropean settlement forest composition, dynamics, and disturbance regimes in determining the response to European arrival. Regional patterns of modern forest composition appear to be still strongly determined by past land use which has obscured the influence of the climatic gradient across the study region. These results have important implications for ecological studies of modern patterns of forest composition in this and similar landscapes.

Forest composition changed markedly, and rates of vegetation increased after European settlement (immediately in the Uplands and at the end of the 19th century, during reforestation, in the Lowlands). The nature of the disturbance since European settlement resulted in far higher rates of vegetation change than estimated for the presettlement period, when fire, wind, and Native American populations were the predominant disturbance factors.

To date, there has been no return to pre-European regional patterns of forest composition and dynamics, and no trend in that direction, because of continuing low levels of disturbance and perhaps insufficient time.

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Appendix Radiocarbon and Lead-210 Age Determinations for Each Site

Site	Depth (cm)	Age	Error	
Aino Pond	2	2.2		*
	4	6.3		*
	6	8.7		*
	8	11.4		*
	10	15.4		*
	12	18.8		*
	14	23.5		*
	16	30.3		*
	18	37.6		*
	20	45.1		*
	22	50.1		*
	24	55.3		*
	26	63.6		*
	28	74.2		*
	30	85.3		*
	32	100.5		*
	34	120.3		*
	78	670	80	**
	90	840	80	**
	110	1120	60	**
	118.5	1340	100	**
Lily Pond	51	490	70	**
	75	830	110	**
	93	1064	110	**
	123	1225	102	**
Silver Lake	55	686	54	**
	90	792	122	**
Snake Pond	2	7.7		*
	4	25.1		*
	6	37.6		*
	8	83.2		*
	10	89.5		*
	45	591	80	**
	60	1181	120	**
	79	1830	120	**
	100	2513	200	**
Little Mirror Pond	80	990	80	**
Otter Pond	136	615	70	**
	156	1112	160	**
Quag Pond	1	4		*
	2	11.4		*
	3	20.3		*
	4	28.9		*
	5	36.2		*
	6	43.6		*
	7	46.5		*

Appendix. (Continued)

Site	Depth (cm)	Age	Error	
Quag Pond (Continued)				
	8	49		*
	9	52.2		*
	10	63.8		*
	11	74.7		*
	12	89.2		*
	13	107		*
	45	590	30	**
	68.5	950	30	**
Green Pond	19	496	70	**
	65	696	70	**
	94	1483	130	**
	130	2531	185	**
Little Pond	1	5		*
	2	8.1		*
	3	11.3		*
	4	14.9		*
	5	21.9		*
	6	28		*
	7	35.6		*
	8	44.6		*
	9	48.4		*
	10	55.8		*
	11	73.5		*
	12	78.8		*
	13	85.6		*
	14	88.5		*
	15	93.2		*
	16	95.7		*
	17	100.5		*
	18	105.1		*
	19	109.6		*
	20	115.3		*
	21	121.7		*
	23	126		*
	24	131.2		*
	76	820	110	**
	90	1180	110	**
Lake Pleasant	2	1.7		*
	4	7.6		*
	6	15.1		*
	8	20.5		*
	10	22.2		*
	12	29.9		*
	14	38.9		*
	16	59.1		*
	18	76.8		*
	20	82		*
	24	107.1		*

Appendix. (Continued)

Site	Depth (cm)	Age	Error	
Lake Pleasant (Continued)				
	42	430	130	**
	50	720	90	**
	66	1180	125	**
Dead Frog Pond	2	11.3		*
	4	27.1		*
	6	43		*
	8	50.1		*
	10	60.7		*
	45	2170	170	**

**Lead-210 date; **calibrated radiocarbon date.*