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Response of small New England ponds to historic land use

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A HOLOCENE RESEARCH PAPER

Abstract: This palaeolimnological study addresses whether the timing, magnitude and nature of lake-ecosystem changes closely track changes in land-use intensity and forest cover in the watershed, and the extent to which lakes return to pre-disturbance states following the substantial long-term decline in human activity that is typical for much of the rural eastern United States. Land-use intensity in the watersheds increased rapidly with European settlement and forest clearance, peaked in the mid-nineteenth century when 60–80% of the land was cleared for agriculture, and then declined to the present as natural reforestation resulted in 65–90% forest cover. Land-use intensity in the three watersheds studied ranged from limited logging to extensive clearance for pasturing and to total clearance for pasture and tillage. In contrast to many studies in which human activity continues to increase throughout the settlement period, all three watersheds now support mature, growing forest and are in their most natural condition in the last 200 years. Dated cores from three ponds were analysed for pollen, fossil chironomids, percent organic matter and sedimentation changes to compare lake and vegetation change among sites. Increased sediment-accumulation rates and small increases in productivity occurred in all lakes during the settlement period. Both remain higher than pre-settlement levels, indicating that despite lengthy periods without disturbance and a return to completely forested conditions, the systems and sediment records have not returned to pre-disturbance states. In contrast with results from many other palaeolimnological studies, the magnitude of lake response was slight, probably due to the low intensity of nineteenth-century agriculture and the small watershed sizes.

Key words: Palaeolimnology, land-use change, disturbance, human impact, forest clearance, high resolution, Chironomidae, New England.

Introduction

Studies in central New England indicate that historical land use has had profound effects on stand-level and regional vegetation and is a major factor controlling modern forest structure, composition and pattern (Foster, 1992; Motzkin *et al.*, 1996; Foster *et al.*, 1998; Fuller *et al.*, 1998). Beginning with European settlement in the eighteenth century, the mostly forested landscape was transformed by forest clearing and agriculture. By AD 1830, more than 80% of the land was open pasture or tilled fields, and forest areas were small and frequently cut (Foster, 1992). Abandonment of agriculture and natural reforestation began about 1850 and gradually increased into the twentieth century due to relocation of US agriculture to mid-western states and rural populations to urban and suburban areas (Figure 1; O'Keefe and Foster, 1998). Currently the landscape of central New England is 65–90% reforested. In ecological terms, these landscape changes represent a history of increasing and then decreasing long-term broad-scale disturbance (Foster *et al.*, 1998).

For terrestrial and aquatic ecosystems this history provides an opportunity to examine the nature and rates of ecosystem response to changing intensities of disturbance. The initiation of logging, deforestation and agriculture in a forested watershed can exert a profound impact on lake ecosystems. Increased erosion and leaching as watersheds are deforested result in loss of particulate and dissolved materials and increased nutrient loading and productivity of aquatic systems (Bormann *et al.*, 1974; Davis, 1976; Dearing *et al.*, 1987; Gaillard *et al.*, 1991; Cooper, 1995; Wetzel, 1983). Palaeolimnological studies have been used to document changes in lakes and watersheds resulting from changing land-use practices in several New England studies (Brugam, 1978; Engstrom *et al.*, 1985; Davis *et al.*, 1985). However, in almost all prior studies of north-temperate lakes, including those cited above, watershed disturbance has continued to increase, leading to highly deteriorated or eutrophic modern conditions. In this study the watersheds underwent the more typical pattern of rural New England in which logging, deforestation and agriculture were followed by a decrease in disturbance as forestry and agriculture declined and reforestation followed agricultural abandonment. By examining this history we sought to address a fundamental ques-

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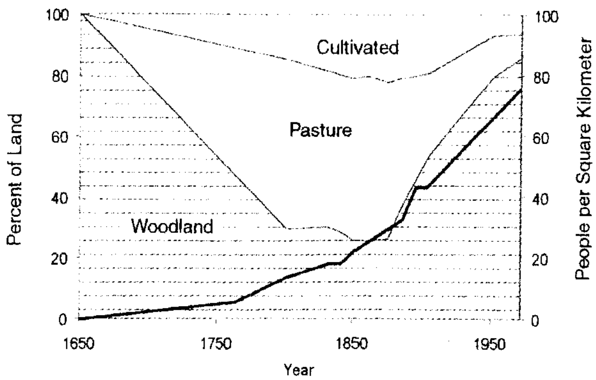

Figure 1 Land use and human population in central Massachusetts during the historical period. Land use has three phases: deforestation through 1800, intensive agriculture (1800–1875), and reforestation (1875–1985).

tion of ecological interest and relevance to conservation biology and restoration ecology: how effectively and rapidly can lake ecosystems recover from broad-scale disturbance?

Palynological and historical studies indicate that forest ecosystems have recovered incompletely through this period (Fuller *et al.*, 1998; Foster *et al.*, 1998). Before European settlement, regional vegetation patterns and tree-species distributions were related to gradients in climate, physiography and disturbance regimes. However, over the last 300 years vegetation composition has changed extensively, and regional vegetation patterns have been blurred as the distributions of trees have become essentially homogeneous at a broad scale (Fuller *et al.*, 1998). Although forest cover and structure have proven very resilient and have recovered across the region, forest composition shows no tendency to return to pre-European assemblages at stand, landscape or regional scales (Foster *et al.*, 1992; 1998; Fuller *et al.*, 1998). Thus the present study enabled us to determine whether terrestrial and aquatic systems have responded in parallel to the 300-year history of landscape change.

This study compares three small lakes whose watersheds have been subjected to a range of historical land-use activities including logging, deforestation and agriculture but are now completely forested. Questions we address include the following. How do these broad-scale, long-term disturbances in the catchment affect the physical, chemical and biotic characteristics of these small lakes? How do lakes respond or recover when the land-use disturbance ends and natural reforestation and forest maturation occurs – do they return towards pre-disturbance conditions? In what way do the responses and rates of change in lake ecosystems compare to those of terrestrial ecosystems in this area?

To address these questions, we conducted palaeolimnological studies of three small headwater lakes in central New England whose catchments represent a gradient of land-use intensity. All three watersheds are forested and have undergone a parallel history of increasing and then declining land use of varied magnitude. This design allowed us to look at responses of lakes to a range of disturbance, as well as the cessation of that disturbance. The investigation is limited to effects of agriculture and land clearance, avoiding urban and industrial influences. Our approach was to investigate changes in terrestrial vegetation using pollen records and historical data, whereas changes in aquatic systems were documented through fossil chironomid assemblages (Chironomidae: Diptera) and physical and chemical characteristics of the sediment. Chironomids were chosen as a representative of aquatic biota because they respond rapidly to changing lake conditions and have been shown to be sensitive palaeoindicators of environmental change such as eutrophication (Carter, sanen, 1985; Meriläinen and Hamina, 1993; Walker *et al.*, 1993; Walker, 1995).

Hypotheses driving the study included: (1) increased erosion of mineral soil and input of nutrients to lake systems resulting from land-use activity would enhance sedimentation rates and aquatic productivity, which would be reflected by changes in organic material, C and N accumulation, C:N ratios, and chironomid assemblages; (2) the timing of lake response would parallel the history of changing land use, and the magnitude would be proportional to land-use intensity, with North Round Pond, whose watershed had the least amount of human disturbance, expected to exhibit minimal change, whereas Pecker Pond, the site with greatest agricultural activity in the watershed, was expected to exhibit the greatest response; (3) with declining land use and reforestation, conditions in the lake ecosystem should return to their pre-disturbance states as runoff and nutrient input from the landscape are ameliorated; and (4) rates of ecosystem response would be more rapid in aquatic systems than terrestrial systems, due to the fact that aquatic organisms have much shorter generation and dispersal times.

Site descriptions

Study sites were selected to obtain a range of historical land-use intensities, but were similar in other lake and watershed variables. The sites are headwater lakes of similar size and watershed:lake area ratio, elevation, and absence of large fringing wetlands (Table 1). All three lakes are currently oligotrophic to mesotrophic on the basis of summer chlorophyll *a* levels (Wetzel 1983) (Table 1). The bedrock is mainly metamorphosed Palaeozoic gneiss and schist with some granitic intrusions, overlain by Wisconsin till (Hunt, 1967; Denny, 1982; Griffith *et al.*, 1994). Aquatic systems in the area tend to be acidic and have very low alkalinity (Griffith *et al.*, 1994).

Native American settlements in central New England were concentrated in lowland areas such as the Connecticut River valley and coastal plains (Patterson and Sassaman, 1988), so prehistorical activity and impact on upland interior areas around our lakes was probably small and seasonal (Mulholland, personal communication). The lakes are located within 42 km of each other (Figure 2), and thus the timing and general history of European land use was similar (Rindge History Committee, 1989; Fuller *et al.*, 1998; Foster *et al.*, 1998). Settlement occurred between 1740 and 1770; populations, farm stock and cleared land peaked around 1840–1860 and then declined into the twentieth century. However, local factors have resulted in strikingly different intensities of land-use history at the three sites.

North Round Pond, located in Pisgah State Park, Winchester, New Hampshire (42° 50.8′ N, 72° 27.2′ W), was selected as a reference site because it has experienced the least amount of

Table 1 Summary of site characteristics

	North Round Pond	Wickett Pond	Pecker Pond
Elevation (m)	317	330	370
Lake surface area (ha)	4.3	11.5	16.5
Watershed area (ha)	21.3	95.2	78.6
Watershed:lake area ratio	5:1	8:1	5:1
Maximum depth (m)	3.4	2.25	4.8
Volume ($\times 10^6$ m^3)	0.07	0.11	0.16
Chlorophyll a ($\mu g/L$)	3.93	0.65	4.05
pH	5.6	5.6	6.2
Alkalinity (meq/L)	0.05	0.02	0.05

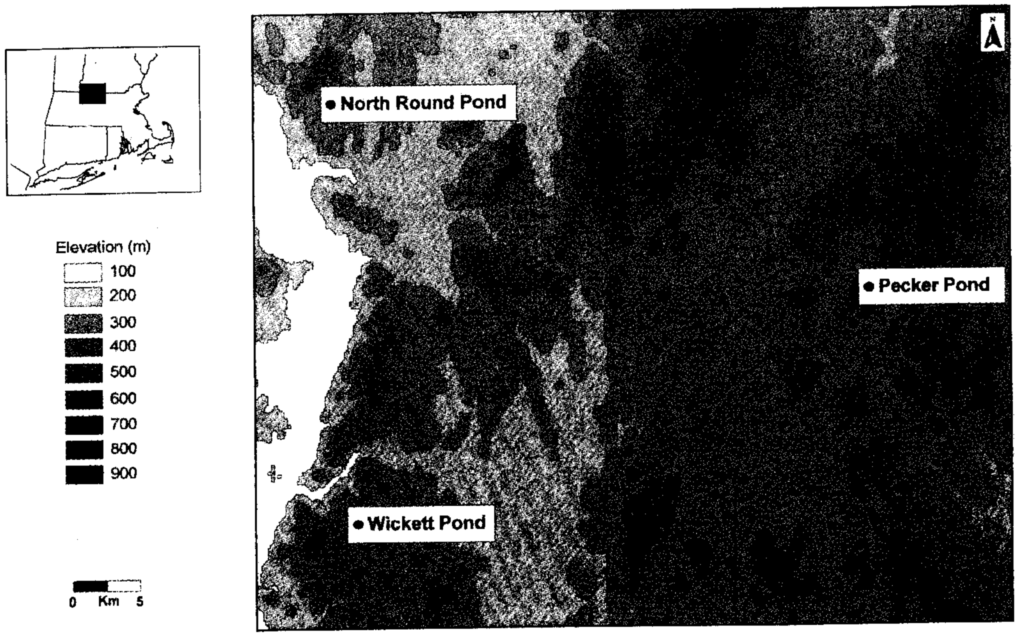

Figure 2 Map of central New England, showing pond sites and topography.

human disturbance in the watershed. The town of Winchester was settled in 1751, and most of the town land was cleared by the 1880s. However, the Pisgah area, a 13000-acre tract of steep, rocky terrain, was never settled or cleared for agriculture but experienced episodic logging activity (Branch *et al.*, 1930). Several notable old-growth forest stands exist within the North Round Pond watershed (Henry and Swan, 1974; Foster, 1988), which has been periodically affected by natural fires, hurricanes and pathogens such as the chestnut blight (Foster, 1988), but very little human disturbance. Foster (1988) documented that some cutting occurred on the southeast side of the pond in 1929–30, and cut stumps and multiple-stem trees on the northwest side indicate some cutting. However, the area was never heavily logged because of its inaccessibility (Cline and Spurr, 1942). The forest was moderately to severely damaged in the 1938 hurricane (Foster, 1988). Pisgah State Park was established in the 1960s, restricting activities to recreational uses.

Pecker Pond (42°42.8′N, 71°57.9′ W) is located near the Massachusetts border in the town of Rindge, New Hampshire. The town was incorporated in 1768, but settlement had started several decades earlier. The watershed had the greatest amount of agriculture, as documented by the density of stone walls and open-grown white pines. Most of the acreage was probably pastureland. The 1858 map of Cheshire County, New Hampshire, shows three farmsteads near Pecker Pond, whereas a 1938 aerial photograph of the region shows the watershed completely reforested except for one 3-ha open area (a Boy Scout camp) and a 1.8-ha area in early successional vegetation (unpublished data, Harvard Forest archives). Today land use in the watershed is limited to hiking and recreational use, and one small (*c.* 1 ha) sheep pasture on the northeast side.

The watershed of Wickett Pond, located in Wendell State Forest, Wendell, Massachusetts (42°34.2′ N, 72°25.9′ W), had an intermediate level of agriculture. Local histories indicate that a settlement occurred near the pond shortly after 1754 (*History of the Connecticut River Valley*, 1879), and a map of 1830 shows the watershed as open land with only one small forest area without dwellings. An 1887 topographic map shows four dwellings along Wickett Pond Road on the east side of the pond. Stone walls occur only on the southeast section of the watershed, and the presence of a plough layer (Ap) in soil cores from this area indicates that some ploughing had occurred in these fields. Other portions of the watershed were probably used for pasturing and woodlots, as indicated by the presence of open-grown trees and multiple-stem oaks, respectively. Wendell State Forest was established in the 1920s, and during the 1930s the Civilian Conservation Corps built roads and fire lanes, planted white pines and built a small concrete spillway at the outlet of Wickett Pond (Lescard, 1997). A 1937 map shows the watershed in hardwood forest (Works Project Administration, unpublished; Harvard Forest archives).

Methods

Sediment cores were collected with a modified Livingstone piston corer (Livingstone, 1955; Wright, 1967). A clear Lexan coring tube fitted with a rubber piston was used for the uppermost unconsolidated sediments. Surface cores were sectioned at 1 cm intervals, whereas Livingstone core sections were wrapped in the field in plastic and aluminum foil. Both were stored at 4°C. North Round and Pecker Pond cores were collected in winter 1997, and Wickett Pond core was collected in September 1994. Cores were taken from the deepest point in each pond (Table 1).

Chronologies for each site were determined by ^{14}C and ^{210}Pb radiometric techniques. Bulk sediment samples (4–5 g) were analysed at Beta Analytic, Miami, Florida, for ^{14}C dates. The resulting determinations were converted to calendar years with the program Calib version 3.0 based on a combination of marine coral and bidecadal tree-ring data sets (Stuiver and Reimer, 1993a; 1993b). Calibrated radiocarbon ages are reported in Table 2.

Activity of ^{210}Pb in sediment samples was determined by the alpha activity of its daughter product ^{210}Po after samples were prepared using the method of D.R. Engstrom (personal communication). Samples were spiked with the manmade isotope ^{209}Po to act as an internal yield tracer, and activities were counted on an EG&G Ortec alpha spectrometer. Ages and sediment-accumulation rates were calculated with a CRS point transformation model (Binford, 1990). Linear interpolations were made between ^{14}C dates. An age of 250 years was chosen for the settlement horizons based on historical information. Settlement horizons in each core were based on ^{210}Pb chronologies and the rise of agricultural indicator pollen such as *Ambrosia* and *Rumex*.

Table 2 Calibrated radiocarbon age determinations

	Depth (cm)	Years	±
North Round Pond	44–48	560	120
	65–69	920	240
	91–95	1490	210
	116–120	1530	200
Pecker Pond	46–50	610	70
	65–69	725	75
	82–86	1400	120
Wickett Pond	42–46	600	75
	56–60	900	170
	72–76	1300	120
	87–91	2080	130

Techniques for chironomid analysis followed those of Walker (1987). One ml samples of wet sediment were treated with 10% HCl and warm 5% KOH and rinsed through a 100 μm sieve. The residues were sorted under a stereomicroscope at 50 × with a Bogorov counting chamber (Gannon, 1971). All chironomid head capsules were removed from each sample, transferred to microscope slides, and permanently mounted in Euparal. Chironomid remains were identified to the generic level with reference to Oliver and Roussel (1983), Wiederholm (1983), Coffman and Ferrington (1984), Kowalyk (1985) and Epler (1992).

Pollen and charcoal were analysed by Natalie Drake using standard methods of preparation (Berglund and Ralska-Jasiewiczowa, 1986; Faegri *et al.*, 1989). At least 500 arboreal pollen grains were counted for each level. Pollen percentages were 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.

The percentage of organic matter was estimated by loss-on-ignition at 550°C (Dean, 1974). Total carbon and nitrogen were determined for 5–6 mg dry subsamples with a Fisons 1500 N\C CHN Analyser. Average recovery of a known standard (atropine) was 99% for both nitrogen and carbon. Particle size was analysed on 1 g subsamples previously treated with 30% H_2O_2 to remove organic material. Analysis was done with a Coulter LS 200 laser-diffraction particle-size analyser employing fluid module software and a Fraunhofer optical model.

Plotting and numerical zonation of pollen and chironomid data were accomplished with the program psimpoll version 2.30 (Bennett, 1997). Zones were determined by optimal splitting based on information content, and the number of statistically meaningful zones determined by a Broken Stick model in psimpoll. Correspondence analysis was performed on pollen and chironomid data using the program TILIA version 1.12 (Grimm, 1992). Only taxa with an occurrence of 3% or greater in any sample were used for ordinations, and the data were square-root transformed.

Results

Age-depth curves for each core (Figure 3) show a sharp inflection at approximately the settlement horizon as identified by pollen analysis. Settlement horizons, indicated by the increase of agricultural indicators *Ambrosia*, *Rumex* and Poaceae, occurred at 40 cm in North Round Pond, 39 cm in Wickett Pond and 50 cm in Pecker Pond, and were given an age of 250 years BP (Figure 4). ^{210}Pb results generally agree with these dates. To show better resolution of the European settlement period on the diagrams, we plotted data against depth rather than age.

Sediment-accumulation rates, calculated with the chronologies as outlined above, show a sharp increase in all three cores corresponding to the onset of European settlement (Figure 5). In the Pecker Pond core, the greatest increase occurs later in the settlement period. Particle-size analysis indicates a slight increase in the amount of sand-sized particles in North Round and Wickett Pond cores but not in the Pecker Pond core.

The percentage of organic matter in North Round sediments increases in the upper 30 cm (Figure 5). There are also increases over the background level of 40% from about 85 to 35 cm. The Wickett Pond core also has an increase in organic matter in the upper levels. In the Pecker Pond core, however, a continuous decline in organic matter starts at 50 cm and continues to the top of the core. Trends in the percent of carbon in samples parallels the amount of organic matter by loss-on-ignition (Figure 5). Both North Round and Wickett Pond profiles show a decrease in the C:N ratio towards the top, particularly near the surface. In the Pecker Pond core, the C:N ratio remains constant at about 10.

Pollen profiles (Figure 4) show changes in abundance of tree taxa similar to those found at other upland sites in central New England (Fuller *et al.*, 1998). A decline in the relative abundance of hemlock (*Tsuga*) and beech (*Fagus*) starts before the onset of European settlement and is often accompanied by an increase in chestnut (*Castanea*), pine or birch (*Betula*). All three sites have high levels of chestnut pollen early in the early European settlement period, which decline with the arrival of chestnut blight around 1920. The greatest change associated with the settlement period is the increase in weedy herbaceous taxa associated with cleared land and agricultural practices: ragweed (*Ambrosia*), grasses (Poaceae) and sorrel (*Rumex*). These taxa decline in the most recent sediments due to farm abandonment and reforestation. In contrast to other central Massachusetts sites, there is little change in the abundance of *Pteridium* spores (bracken fern) (Fuller *et al.*, 1998). Pollen of the rooted aquatic macrophytes *Brasenia* and *Nymphaea* and *Isoetes* spores increase in the upper levels of the North Round and Wickett Pond cores, but not in Pecker Pond. Charcoal:pollen ratios generally increase upcore at all sites and reach the highest values during the settlement period.

Chironomid profiles (Figure 6) indicate more variation among sites than do pollen profiles. For example, *Dicrotendipes* is much more abundant in Wickett Pond than in the other two ponds, while *Microtendipes* is more abundant in North Round Pond. *Chaoborus* mandibles were relatively rare in Wickett Pond sediments. Numerical zonation produced two significant zones in the North Round and Wickett Pond diagrams but no statistically significant zones in the Pecker Pond data.

Ordination by correspondence analysis illustrates some shifts in forest vegetation over time (Figure 7). Pre- and post-settlement samples sort out along the first axis, particularly in North Round and Pecker Ponds. These trends are similar to those found by Fuller *et al.* (1998) for other upland sites. The Wickett Pond ordination shows some tendency for the most recent samples to become similar to pre-settlement samples, an effect not seen by Fuller *et al.* (1998). In ordinations of the chironomid taxa (Figure 7), some sorting of pre- and post-settlement samples is evident along axis 1 for North Round and Wickett Ponds, but not for Pecker Pond. The Pecker Pond ordination shows very little clustering of samples along either axis.

Discussion

Overall, the effects of the broad-scale disturbance of logging, forest clearance and agriculture on the small ponds in this study were

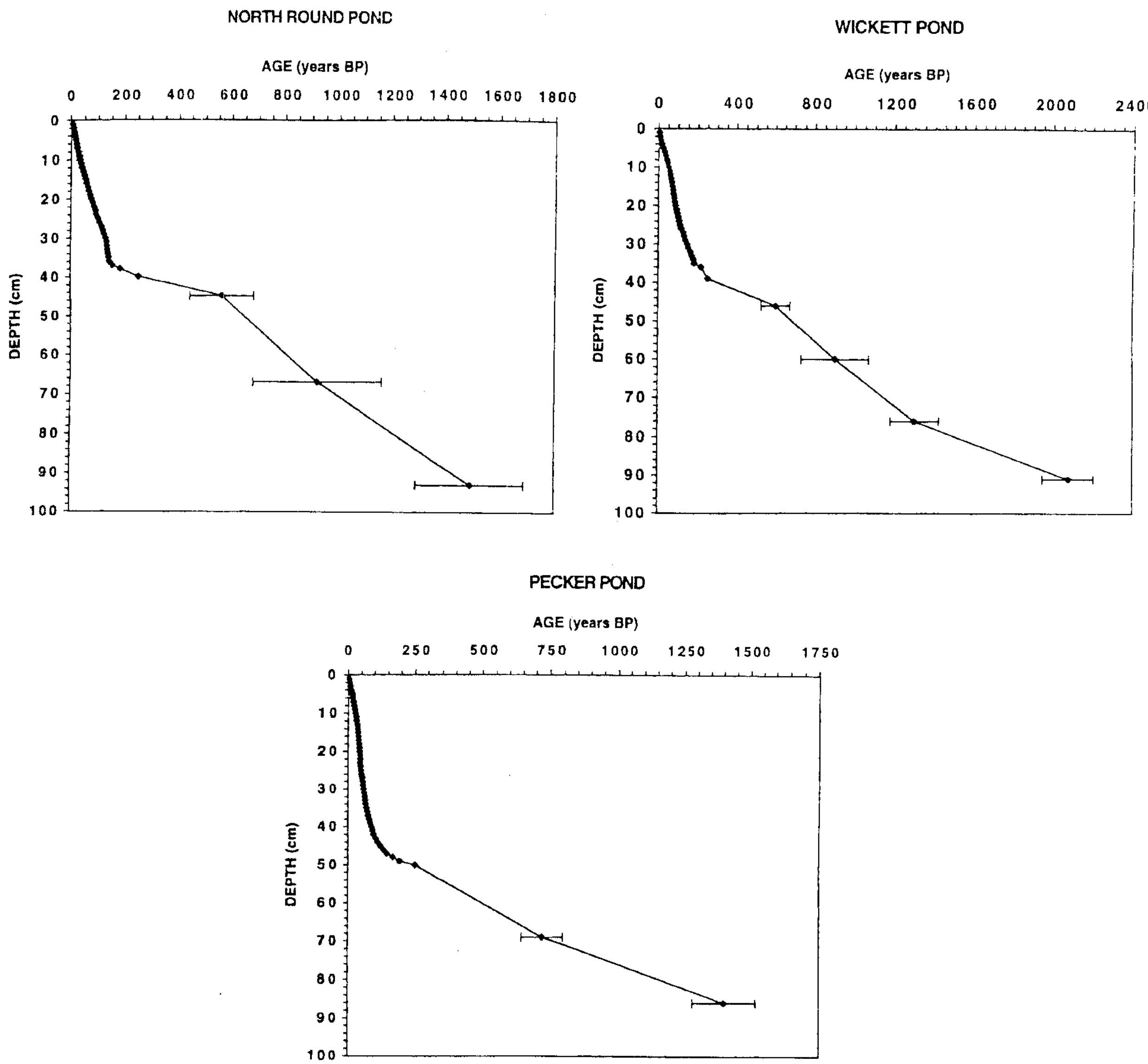

Figure 3 Age-depth curves for each site. ^{14}C ages are shown with errors of ± 2 sd. A total of 40–50 years was added to radiocarbon dates to make them comparable to ^{210}Pb dates so that 'present' is 1990 for Wickett Pond and 2000 for North Round and Pecker (rounded to nearest 10 years). Settlement was determined from the *Ambrosia* rise in pollen diagrams.

small, particularly when compared to the changes induced by development and eutrophication documented in many other palaeolimnological studies. As expected, some increase of erosion and sedimentation rates occurred, as well as some indicators of elevated aquatic productivity. However, the response of each lake was complex. North Round Pond, the site with least human disturbance, exhibited greater changes than expected during the European settlement period. The other two ponds showed less response than expected. Although the initial disturbance has ceased, and the sites have reforested, the parameters investigated have not completely returned to pre-disturbance states, a phenomenon that is similar to changes in forest composition noted throughout the study region.

Sediment-accumulation rates increase at the time of European settlement in all three cores (Figure 5). North Round Pond, the least disturbed site, had a significant increase in sediment-accumulation rate, but then a decline to lower rates of about 15 mg/cm^2/yr. Pecker Pond has overall the highest sediment-accumulation rates in the post-settlement period. In Harvey's Lake, Vermont, Engstrom *et al.* (1985) obtained a similar increase in sediment-accumulation rate to about 20 mg/cm^2/yr following European settlement. Increases in sediment-accumulation rates were also recorded in Linsley Pond, Connecticut (Brugam, 1978), and Mirror Lake, New Hampshire (Davis *et al.*, 1985). However, at both Harvey's Lake and Linsley Pond, the intensity of agricultural activity continued to increase in the form of larger herds of cattle and chemical fertilization, followed by development of the landscape for housing. Increased sediment accumulation and other changes that accompanied modern house-building eclipsed the effects of the early agricultural period.

The rate of sediment accumulation declines in the three ponds in this study as the watersheds became reforested, although none has returned to the low pre-disturbance rates. This phenomenon was also noted in Douglas Lake, Michigan (Francis, 2001), which continues to have an elevated sediment-accumulation rate in spite of reforestation of the watershed following logging.

Deforestation of a watershed often results in increased nutrient inputs to surface waters, which can result in increased productivity of aquatic organisms. We expected aquatic productivity to reflect the gradient in land use, with increases at Pecker and Wickett Pond, but not necessarily at North Round Pond. Evidence of aquatic productivity in the form of organic-matter content of the

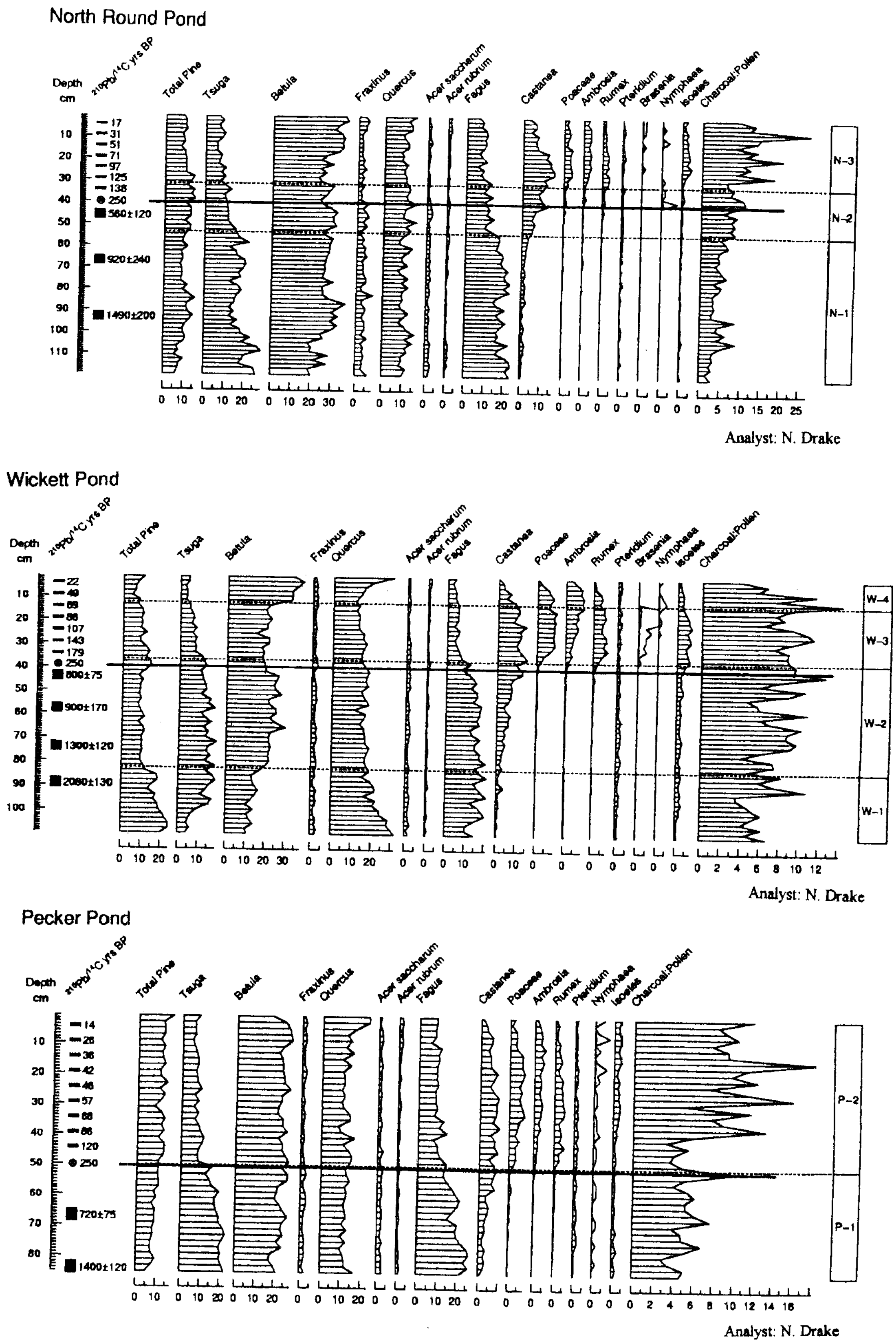

Figure 4 Pollen-percentage profiles showing the most common taxa from each site. Profiles with an open silhouette represent a 10 × exaggeration for clarity of display. Zones were calculated objectively by the program psimpoll. Settlement horizons at 250 yrs BP are marked by a ⊗ symbol and a solid line.

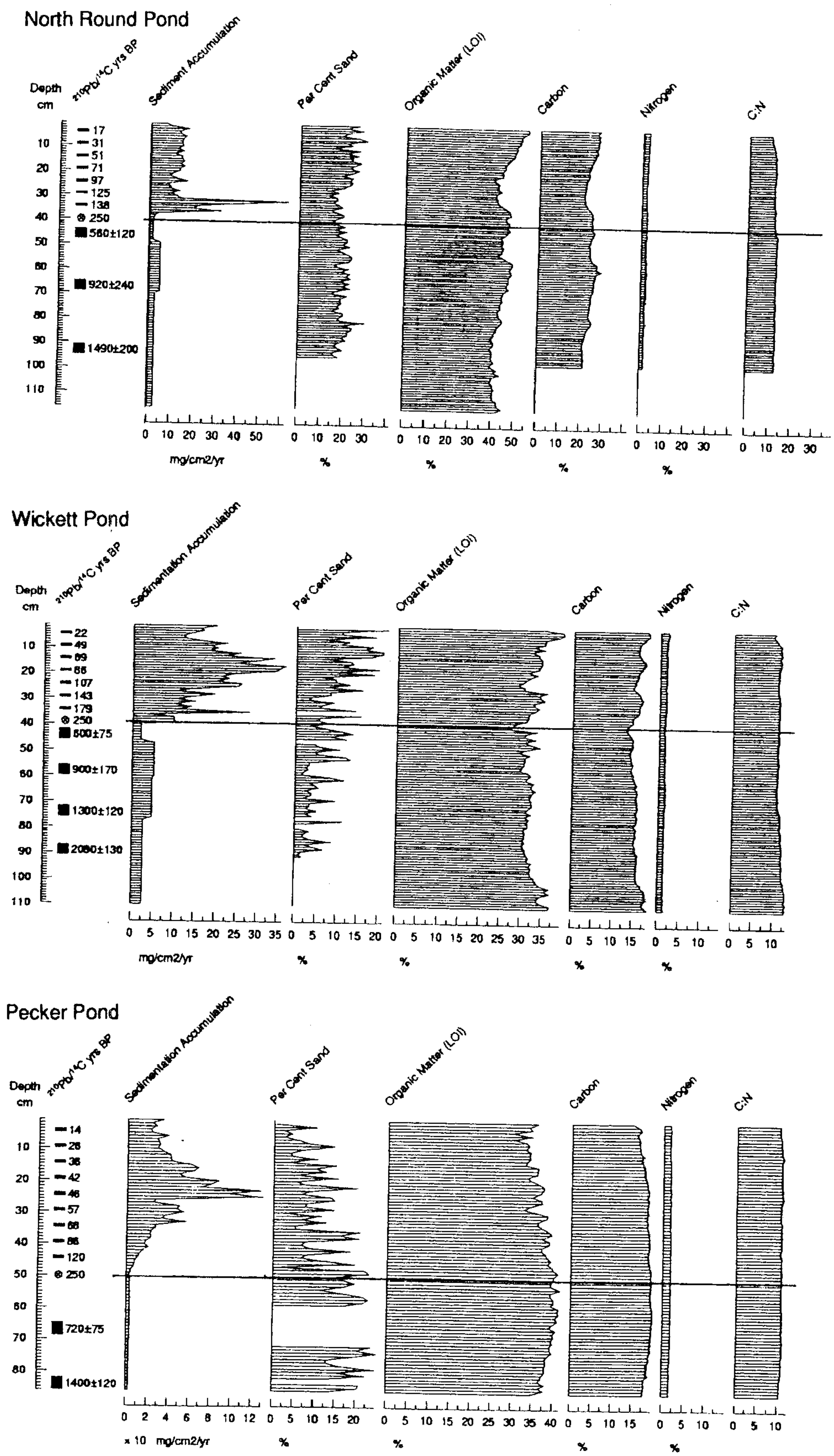

Figure 5 Sediment-accumulation rates and sediment chemistry recorded in cores from three sites. Percent sand = sand-sized particles (68.2–1000 μm diameter, or phi sizes 3 through 0). The gap in the Pecker Pond profile represents missing data. Percent carbon and nitrogen was determined by CHN analysis. Settlement horizons at 250 yrs BP are marked by a ⊗ symbol and a solid line.

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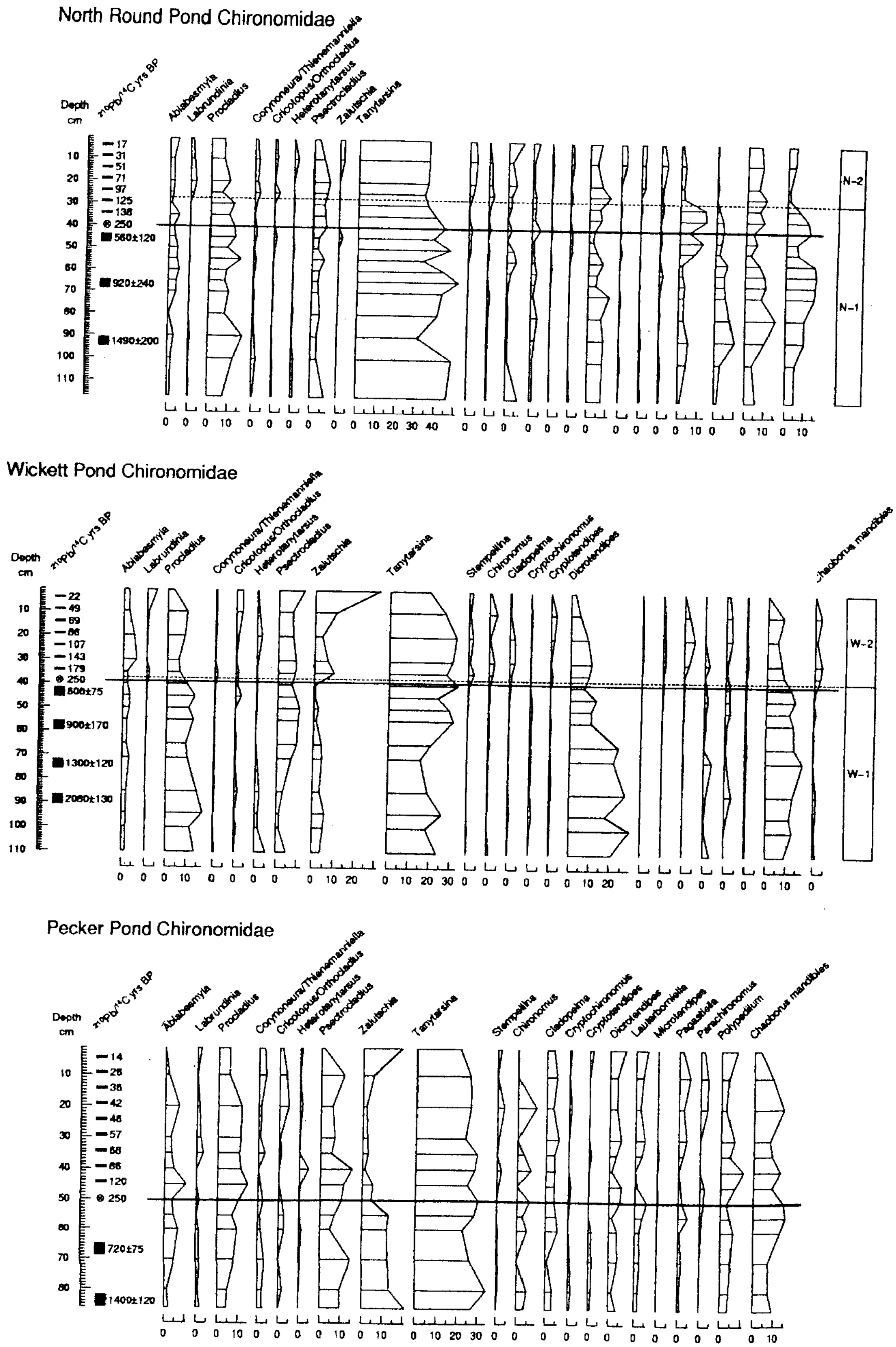

Figure 6 Chironomidae percentages showing the most common taxa for each site. Zones were calculated objectively by the program psimpoll. There were no statistically significant zones in the Pecker Pond data. Settlement horizons at 250 yrs BP are marked by a ⊗ symbol and a solid line.

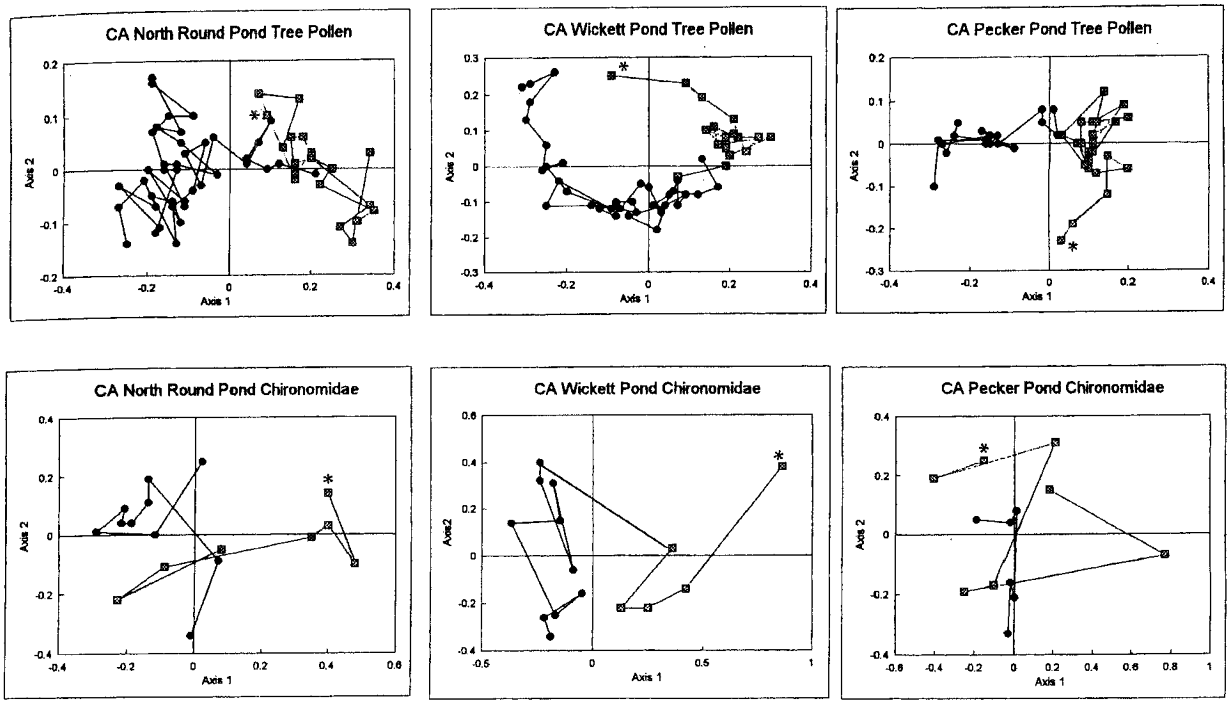

Figure 7 Correspondence-analysis ordination axes 1 and 2 for arboreal pollen and Chironomidae for each site. Samples are linked stratigraphically. Circles represent pre-settlement samples, squares represent post-settlement samples. The most recent sample is marked with an asterisk.

sediments, the carbon and nitrogen ratio of sediment samples, and chironomid assemblages yields a more complex story. At North Round and Wickett Ponds, the percentage of organic matter generally increases over pre-settlement levels, and the C:N ratio decreases, indicating an increase in the productivity of aquatic organisms. Aquatic plants tend to have less structural carbon than terrestrial plants, and therefore lower C:N ratios (Hassan *et al.*, 1997). In Pecker Pond, however, the C:N ratio is stable over the length of the core, and the amount of organic matter actually decreases during the settlement period. This decrease in percentage of organic matter, which also occurs in North Round Pond during the settlement period, probably reflects the increased runoff from the watersheds and subsequent dilution of the organic matter by mineral sediments, as well as decreased allochthonous inputs of litter from the watershed.

Chironomid results agree with other sediment analyses. In North Round and Wickett Ponds, zonation indicates a change in assemblages during the settlement period (Figure 6). This is also reflected in the clusters in the ordination diagrams for these two ponds (Figure 7). Some species that increase in the post-settlement period include *Chironomus, Endochironomus* and *Glyptotendipes*, which are all indicators of productive aquatic environments (Saether, 1979). In Pecker Pond, however, the percentages of species such as *Chironomus* were relatively stable over time, and there were no significant zones. In addition, CA ordination did not produce distinctive clusters, evidence that chironomid assemblages were stable through time. Increased *Zalutschia* in the most recent sediments of all three cores may indicate increasing acidification of these ponds, as *Zalutschia* is more common in acidic environments (Walker, 1995).

Aquatic-productivity changes accompanying settlement are also recorded in other New England lakes. At those lakes, however, disturbance has continued and intensified, and productivity has also increased to eutrophic levels. As with sedimentation changes, by far the most dramatic changes in those lake basins occurred in the recent past. At Harvey's Lake in Vermont, the greatest impact on the lake in the early settlement period was due to the discharge of sawdust from a mill situated on the inflow stream. Much greater increases in lake trophy have occurred since 1945, when several dairy farms expanded and began using phosphorus fertilizers, and a large number of houses with septic systems was built in the watershed (Engstrom *et al.*, 1985). Brugam (1978) found that Linsley Pond, Connecticut, responded to initial deforestation with a slight increase in organic matter in the sediments but few changes in diatom assemblages. Massive changes in lake trophy did not occur until the 1960s, when more than 100 houses and a golf course were built in the watershed. Finally, in Mirror Lake, New Hampshire, the sediment record shows only a slight increase in productivity during the settlement period (Davis *et al.*, 1985), although sediment-accumulation rate increased, as in the present study.

There are several possible reasons for the minimal impact of the agricultural period on our sites. First, the relative watershed size of these sites is small, with watershed to lake area ratios of 5:1 to 8:1 (Table 1). In a study of the influence of catchment size on eutrophication following the hemlock decline, Hall and Smol (1993) found that the only lake exhibiting a marked productivity response to the forest succession was the one with the largest watershed:lake area ratio (55:1). The two smallest lakes *in the* Hall and Smol study had ratios of 4.5:1 and 5.5:1, comparable to the ones in the current study, and these two lakes exhibited the weakest response, based on diatom and chrysophyte assemblages. In a small lake in the Pocono Mountains of Pennsylvania, Lott *et al.* (1994) observed significant changes in assemblages of scaled chrysophytes and an increase in inferred specific conductivity associated with logging in the watershed; the watershed:lake area ratio was 26:1. Thus, although clearing and farming did occur at Pecker and Wickett Ponds, the relatively small size of the catchments may be part of the reason for minimal responses in the aquatic systems. In northwestern Ontario, six lakes whose watersheds were 90% deforested by clearcutting or burning showed only minor changes in composition of scaled chrysophytes (Paterson *et al.*, 1998). These lakes had watershed:lake area ratios of 1:1 to 9:1.

Another factor may be the type of agricultural practices and technology used in the nineteenth century. Early New England farmers had little technology at their disposal, and the earliest settlers cleared small patches of land by hand (Whitney, 1994). However, the cost of removing stumps was prohibitive, and they were often left to decay in place. Clearing was also accomplished by girdling trees and burning (Whitney, 1994). In addition, most of the agricultural lands during this period consisted of pastureland, extensive areas of open grassland and some wooded pasture, both created with minimal soil disturbance. The percentage of land in tilled fields (16%) and pasture (70%) in the mid-1800s on one tract in central Massachusetts reflects trends for the whole region (Foster, 1992). Patric and Helvey (1986) review the effects of livestock grazing on erosion and conclude that erosion and nutrient losses in pastureland are low. Erosion requires overland flow, which is generally very low in pastureland, because infiltration usually exceeds precipitation (Patric and Helvey, 1986). In Yellowstone National Park, Engstrom *et al.* (1991) found no sedimentary record of increased erosion associated with grazing by large ungulates.

The increase in aquatic productivity recorded in sediments of North Round and Wickett ponds may be due not only to increased nutrient inputs from the watershed but also to the increased bulk sedimentation rate and gradual filling in of the basins. As ponds become more shallow, nutrients become more concentrated, and aquatic productivity can increase (Wetzel, 1983). In the North Round Pond core, the amount of organic matter and percentage of carbon begin to increase even before the time of European settlement (Figure 5). Some indications of basin infilling can be seen in the increase in aquatic macrophyte pollen and spores (Figure 4). *Brasenia* and *Nymphaea* are rooted aquatic plants with floating leaves, and both increase after settlement. *Isoetes* also becomes more abundant. An increase in *Isoetes* spores was also recorded in a core from Berry Pond, Massachusetts, reflecting the time at which the lake became shallow enough for its growth (Whitehead *et al.*, 1973). The decline in the abundance of *Chaoborus* mandibles (Figure 6) may also be a result of basin shallowing. Larvae of this insect group (Chaoboridae: Diptera) are free-swimming and tend to be more abundant in deeper, stratified lakes (Lehmkuhl, 1979; Crisman, 1988). There is also a decline in the chironomid species *Pagastiella* in the North Round core. *Pagastiella ostansa*, the only North American species in the genus, feeds exclusively on large benthic diatoms (Edlund and Francis, 1999), and these benthic diatoms may be shaded out by increased numbers of phytoplankton cells as productivity increases.

Pecker Pond, on the other hand, is the deepest of the three ponds and has the greatest volume. There is little evidence of productivity changes in this lake, despite the greatest intensity of land use in the watershed. As stated earlier, the impact of early agriculture on these small ponds was small, and the larger volume of Pecker Pond may have prevented the increased nutrient and sediment inputs from affecting aquatic productivity.

Another possible explanation for the observed increased productivity is that the ponds are responding to post-'Little Ice Age' climatic warming. European settlement began during the 'Little Ice Age', a cool period lasting from approximately the sixteenth to the mid-nineteenth centuries (Bradley and Jones, 1993). The post-settlement and reforestation period coincide with the recent climatic warming and this climatic signal may be confounding the response of the ponds to settlement disturbance.

Because sediment-accumulation rates and productivity levels remain somewhat elevated over pre-settlement conditions in the three ponds, and, because of changes in chironomid species assemblages, it is clear that, despite forest recovery and the minimal responses to disturbance, the lake systems have not returned to pre-settlement states. Although aquatic organisms may respond more quickly to disturbance and cessation of disturbance due to their short generation times and dispersal capabilities, in our study chironomid assemblages may be responding to other confounding factors, including basin shallowing, acidification or climate warming. These processes continue, regardless of the fact that the watersheds are now completely reforested. In the central Massachusetts vegetation studies Fuller *et al.* (1998) found that, although forest composition had changed during the settlement period, no tendency to return to the pre-disturbance state was apparent. This is also seen in the pollen diagrams from these three sites and also in the midge assemblages of North Round and Wickett Ponds. It was proposed that the forests have not returned to pre-disturbance states due to the short time period, and continuation of other disturbances such as logging, forest diseases, hurricanes and fire suppression (Fuller *et al.*, 1998). Forest composition can influence watershed inputs to lakes. For example, in a study of the hemlock decline of 4800 BP and replacement by hardwoods in a small lake in western Massachusetts, Whitehead *et al.* (1973) suggested a higher lake productivity may have resulted from erosion as well as the input of deciduous litter to the lake. Broadleaf trees potentially contribute more allochthonous input to the lake than do conifers. Coniferous forests also intercept more water and result in lower water yields than hardwood forests (Swank *et al.*, 1988).

In both the terrestrial and aquatic systems, species composition changed during broad-scale disturbance and does not 'return' to pre-disturbance composition. The trajectory of community composition seems to have been altered, and perhaps a new steady state is being established. This phenomenon is also being observed in lakes that have been affected by acid rain (Keller *et al.*, 1999) and other types of disturbances (Power, 1999). This may have implications for managers involved in conservation and restoration of ecosystems. It may not always be a realistic to attempt to restore the same communities exactly.

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