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ORIGINAL PAPER

An 1800-year record of environmental change from the southern Adirondack Mountains, New York (USA)

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Abstract We analyzed a sediment core from Piseco Lake, New York (USA), to infer late Holocene environmental conditions and look for evidence of prehistoric human activity in the region. We analyzed fossil pollen, charcoal, and geochemistry in sediments deposited over the last ~ 1800 years. The pollen record indicates the area was dominated primarily by *Betula* (birch), *Pinus* (pine), and *Tsuga* (hemlock). *Picea* (spruce) increased after ~ 1560 cal yr BP and eventually became a major component of the forest. A transition in the fire regime around Piseco Lake occurred after ~ 900 cal yr BP, perhaps associated with drier conditions during the Medieval Climate Anomaly, ca. 1000–600 BP. A fire ca. 580 cal yr BP, along with decline of *Tsuga* after ~ 520 cal yr BP, may reflect generally dry conditions of the Little Ice Age (600–150 BP). Climate change may have swamped any evidence for low-intensity, prehistoric human activity around Piseco Lake. The rise in Poaceae (grass) and *Ambrosia* (ragweed) pollen ~ 130 cal yr BP indicates European settlement in the area, and is followed by rapid decline of *Tsuga* and *Pinus*, most likely a consequence of logging. Since about 145 cal yr BP, increases in macroscopic charcoal concentrations and changes in sediment geochemistry indicate increased erosion and nutrient influx to Piseco Lake, likely related to anthropogenic activities.

Keywords Lake sediments · Pollen · Charcoal · Stable isotopes

Introduction

Few studies have had the necessary temporal resolution to provide detailed records of decade-to-century-scale climate variability and its effects on eastern North American ecosystems (Gajewski et al. 1985, 1987; McAndrews and Boyko-Diakonow 1989; Fuller 1997; Booth et al. 2012; Houle et al. 2012; Paquette and Gajewski 2013; Lafontaine-Boyer and Gajewski 2014). Recent changes in eastern North American conifer hardwood forests began centuries before European settlement and were most likely associated with late Holocene climate events such as the Little Ice Age (LIA) and Medieval Climate Anomaly (MCA) (Gajewski et al. 1987; Finkelstein et al. 2005; Houle et al. 2012; Paquette and Gajewski 2013). There is, however, a scarcity of vegetation records from the Adirondack region with sub-

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millennial sampling resolution (LeBoeuf 2014), which limits knowledge of the extent of these paleoclimate events.

Pollen was used to identify vegetation shifts associated with Holocene climate change in the Adirondacks (Overpeck 1985; Gajewski et al. 1987; Jackson and Whitehead 1991). Deglaciation in northeastern New York led to a northward migration of plant communities, which transitioned from shrub and herb-dominated assemblages before 11,000 BP, to spruce woodland and forest until around 10,000 BP, *Pinus*-dominated forest until around 8000 BP, *Tsuga*-rich forest until around 4800 BP, and mixed northern hardwood forest until present (Overpeck 1985). *Abies* was concentrated at higher elevations, while *Pinus strobus* (white pine), *Tsuga*, and *Betula lutea* (yellow birch) were abundant at lower elevations, and *Picea* increased in abundance at mid-elevation sites within the past 3000 years (Jackson and Whitehead 1991).

A pronounced increase in *Picea* occurred in northern New York between 1500 and 1000 cal yr BP (Overpeck 1985; Gajewski et al. 1987), and around 500 cal yr BP shade-tolerant *Tsuga* and *Fagus* decreased (Gajewski et al. 1987), as they did in other parts of the northeastern United States (Fuller et al. 1998). A pollen record from Bloomingdale Bog in the Adirondacks revealed two large vegetation changes associated with charcoal peaks around ~ 5000 and 500 cal yr BP, and a large charcoal peak ca. ~ 550 cal yr BP indicating upland fires (LeBoeuf 2014) that might reflect moisture balance, or prehistoric human activity.

Human–environment interactions, both historic and prehistoric, including deforestation and agriculture, can be detected in lake sediments through multi-proxy analyses of fossil pollen (McAndrews and Boyko-Diakonow 1989; McAndrews and Turton 2007), charcoal (Clark and Royal 1995, 1996; Burney 1987; Burney and Burney 1994, 2003), and geochemistry (Lane et al. 2004, 2008). Microscopic charcoal ($\leq$ 50 μm) preserved in sediment records is thought to represent primarily regional fire events, whereas macroscopic charcoal is assumed to originate from fire events within several hundred meters of a lake (Clark 1988; Millspaugh and Whitlock 1995; Whitlock and Larsen 2001; Peters and Higuera 2007).

Several studies have used fossil pollen data as evidence of Native American modifications of northeastern North American forest composition (McAndrews and Boyko-Diakonow 1989; Bunting et al. 1998; Munoz and Gajewski 2010; Paquette and Gajewski 2013). There are, however, few such data from the Adirondack uplands because of a shortage of paleoenvironmental archives and a widespread misconception that indigenous peoples were absent and/or could not have had significant impacts on local ecology (Ekdahl et al. 2004). Prehistoric human influences on forest ecology are therefore easily overlooked (Delcourt 1987; Butzer 1992; Fuller et al. 1998; Kay 2002; Munoz and Gajewski 2010). There is, in fact, abundant archaeological evidence of Native American presence in the Adirondacks (Stager 2017), but little is known about their environmental impacts on the region.

Lane et al. (2004) documented the sensitivity of sediment $\delta^{13}C$ values in C_3-plant-dominated systems (such as temperate rain forest) to *Zea mays* cultivation and to increased dominance of agricultural weeds that use the C_4 photosynthetic pathway, which can serve as an additional proxy for forest clearance and agriculture. Forests are dominated by C_3 plants, which discriminate against the heavier carbon isotope (^{13}C) during photosynthesis and possess $\delta^{13}C$ values between − 35 and − 20‰. In contrast, C_4 plants such as maize and disturbance-related grasses produce $\delta^{13}C$ values between − 14 and − 10‰ (Meyers and Teranes 2001; Lane et al. 2004).

Carbon to nitrogen (C:N) ratios also help determine whether sediment organic matter in lakes is dominated by material of terrestrial or aquatic origin. Many terrestrial plants have a higher C:N ratio than aquatic plants (Meyers and Teranes 2001), and an increase in the ratio may correspond with erosion caused by land clearance and agriculture. Stable nitrogen isotope values can reflect aquatic productivity (Talbot 2001) and inputs of terrestrial nitrogen.

In this study, we analyzed multiple variables in a sediment core from Piseco Lake to infer paleoecological conditions and investigate the possibility of prehistoric human impacts on the local environment. We used pollen, charcoal, and sediment geochemistry (loss on ignition; $\delta^{13}C$, $\delta^{15}N$, and C:N) to investigate past climate and vegetation, and also sought evidence of agricultural activity, soil erosion, fire frequency, and changes in nutrient dynamics in and around the lake.

Study site

Piseco Lake (43°25′09.25″N, 74°32′00.18″) is an 1163-hectare lake in Arietta, New York (Fig. 1), within the 2.4-million-hectare Adirondack State Park. The region has an annual average temperature of 5.4 °C and average annual precipitation of 118 cm (ESRL 2014; LeBoeuf 2014). Anorthosite dominates the bedrock geology (McLelland 1991) and soils around the area are characterized as very deep, somewhat poorly drained, loamy soils, overlying dense till (USDA 2013).

The Adirondacks have several forest communities, based primarily on their elevational range (Adirondack Ecological Center https://www.esf.edu/aec/adks/forestcomm.htm). Upper-slope conifer hardwoods occur on steeper slopes within the typical elevational range of up to approximately 2500 ft (~ 800 m) for the northern hardwood community, and are characterized as having an abundance of sugar maple, American beech, red spruce, eastern hemlock, yellow birch, and scattered white pine. Northern hardwoods make up approximately 50% of the Adirondack forests that occupy the lower- and middle-elevation slopes in the central Adirondack region. They predominantly consist of sugar maple, American beech, and yellow birch, with lesser amounts of red spruce, white pine, eastern hemlock, black cherry and red maple. Representing the transition between the lowland conifer and north hardwoods, the hardwood-conifer forests, also referred to as the mixedwoods, are marked by American beech replacing balsam fir, defining their upper limit.

Piseco Lake has a mean water depth of 7.6 m and a maximum depth of 40 m. A few small tributaries feed the lake and it has a surface outlet at its southern end. There are several private homes at Higgins Bay (Fig. 1) and more along much of the rest of the shoreline. Three state campgrounds located on the western shore opened in 1927, 1931, and 1953. There was said to have been prehistoric human activity around Higgins Bay, including *Zea mays* cultivation. Numerous unpublished records of Holocene-age stone artifacts indicate prehistoric human activity in the Adirondack uplands (Stager et al. 2016).

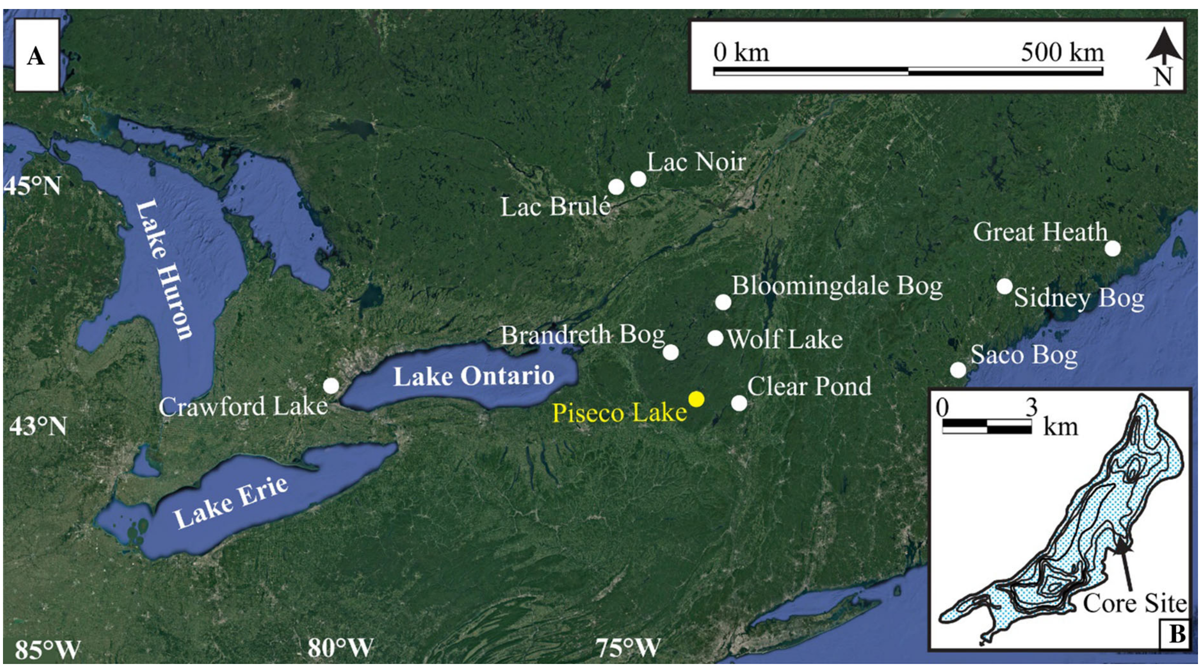


Fig. 1 **a** Location of Piseco lake in the Adirondack mountains and sites discussed in this study in northeastern North America. **b** Bathymetric map of Piseco Lake with a 20-ft contour interval. The arrow points to the core location in Higgins Bay

Materials and methods

Core collection and radiocarbon dating

The core was recovered using a gravity corer in 8.5 m of water at Higgins Bay, the deepest location of the bay mouth (Fig. 1). The 95-cm core was sub-sampled and bagged in 1-cm intervals. Seven samples of bulk sediment were submitted to NOSAMS (Woods Hole, MA) for radiocarbon dating. One pollen sample, extracted via sieving at the National Lacustrine Core Facility at the University of Minnesota (LacCore), and a terrestrial leaf sample, were also submitted (Table 1). An age model for the core was constructed using the default settings in BACON (v. 2.2), consisting of 5-cm sections, an accretion shape of 1.5, accretion mean of 20, memory strength of 4, and memory mean of 0.7 for Bayesian age modeling (Blaauw and Christen 2011).

Loss on ignition

The core was sub-sampled at 4-cm intervals for loss on ignition (LOI) analysis. Each 0.616 cm^3 sample was heated to 100 °C for 24 h, and 550 °C and 1000 °C for a minimum of 1 h to determine dry bulk density and water content, organic matter, and carbonate content, respectively (Dean 1974). The mineral influx was calculated for each sample using the calculated mass of the material remaining after combustion at 550 °C.

Pollen analysis

The sediment core was sub-sampled (0.616 cm^3) at 4-cm intervals for pollen and microscopic charcoal analysis. Standard techniques were followed for pollen processing including the addition of HCl, HF, KOH and acetolysis to dissolve and remove all non-palynomorph and non-carbonized material in the sediment (Faegri and Iversen 1964). One *Lycopodium*

Table 1 AMS dated samples at selected depths with calibrated age ranges

Depth (cm)	Sample type	Lab ID[a]	Raw age (^{14}C yr BP)	Reservoir-corrected age (^{14}C yr)	Calibrated age range[b] ± 20 (cal yr BP)	Area under probability curve	Weighted mean[c] (cal yr BP)
40–41	Bulk sediment	OS-125439	670 ± 20	570 ± 20	534–562	0.40339	584
					593–637	0.59661	
50–51	Bulk sediment	OS-127724	935 ± 20	835 ± 20	697–784	1.00000	739
60–61	Bulk sediment	OS-125440	1110 ± 15	1010 ± 15	920–957	1.00000	914
70–71	Bulk sediment	OS-127725	1320 ± 20	1220 ± 20	1067–1184	0.858327	1115
					1207–1234	0.141673	
74–76[d]	Plant/wood (leaf)	OS-126359	1190 ± 20	1190 ± 20	1063–1177	1.00000	1120
74–77	Plant/wood (pollen)	OS-131175	1330 ± 20	1330 ± 20	1187–1204	0.082817	1197
					1240–1250	0.023539	
					1255–1298	0.893644	
74–77	Bulk sediment	OS-131176	1430 ± 20	1330 ± 20	1187–1204	0.082817	1197
					1240–1250	0.023539	
					1255–1298	0.893644	
80–81	Bulk sediment	OS-127726	1490 ± 25	1390 ± 25	1282–1340	1.00000	1301
90–91	Bulk sediment	OS-122377	2040 ± 20	1940 ± 20	1826–1852	0.11291	1663
					1859–1932	0.88709	

[a]Analyses were performed by National Ocean Sciences Accelerator Mass Spectrometry at Woods Hole Oceanographic Institution in Woods Hole, MA

[b]Calibrations were calculated using Calib 7.1 (Stuiver and Reimer 1993)

[c]Weighted mean of the probability distribution of the calibrated age

[d]Dated sample was not used to construct age model

tablet from Lund University (batch number 1031, containing 20,848 ± 1546 spores) was added to each pollen sample to enable calculation of pollen concentration and influx (Stockmarr 1971). The processed samples were stained with safranin to aid pollen identification and mounted on slides in silicone oil.

A minimum of 300 pollen grains were counted per slide (total of 24 slides) at 400× magnification and identified using standard pollen guides and keys (Faegri and Iversen 1964; Richard 1970), a pollen reference collection, and referencing existing pollen records in the area. The average pollen count was 360 grains per sample. Microscopic charcoal particles > 50 µm were enumerated during pollen counts using scales on the optical lenses. Each slide was scanned at 100x magnification to search for *Zea mays* pollen (Lane et al. 2009).

Macroscopic charcoal analysis

Macroscopic charcoal was counted in continuous 1-cm-interval sub-samples. A 1.2-cm^3 sample was collected at each level and bleached with 3% hydrogen peroxide, and washed with distilled water using nested 500-µm, 250-µm, and 125-µm sieves (Whitlock and Larsen 2001; Schlachter and Horn 2009). The samples were transferred onto a gridded petri dish and the macroscopic charcoal was counted in size classes of 125–250 µm, 250–500 µm, and > 500 µm. The charcoal accumulation rate (CHAR) was calculated by multiplying the charcoal concentration by the sedimentation rate, determined from the age model. The charcoal data were statistically analyzed using CharAnalysis software with a 100-year moving average smoothing setting (Higuera et al. 2009). The signal-to-noise index (SNI) used in the software compares the variability in the signal population to the variability in the noise population to quantify the separation of charcoal peaks representing local fires from other variability in the record (Kelly et al. 2010).

$\delta^{13}C$, $\delta^{15}N$ and C:N analysis

The core was sub-sampled at 4-cm intervals and samples were lyophilized and ground to a fine powder for bulk sediment $\delta^{13}C$ and $\delta^{15}N$ analyses. Isotope ratios are expressed in delta (δ) permille (‰) notation, calculated as:

$$\delta X = 1000 * \left[\left(R_{sample}/R_{standard}\right) - 1\right]$$

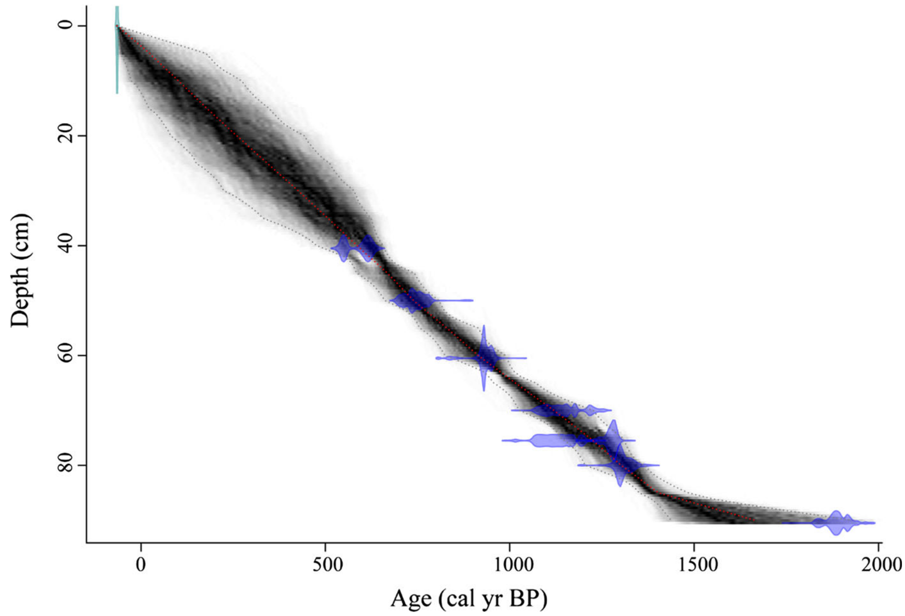
where X is ^{13}C or ^{15}N, and R is the ^{13}C:^{12}C or ^{15}N:^{14}N ratio of the sample and standard, respectively. Ground samples were decalcified with 10% HCl, washed with distilled water until neutral and dried in crucibles at 50 °C (Brodie et al. 2011). The acidified samples were then reground to a fine powder and loaded into tin capsules. A total of 96 samples (48 acidified; 48 non-acidified) were analyzed using a Thermo Delta V Plus mass spectrometer interfaced with a Costech 4010 elemental analyzer for bulk $\delta^{13}C$ and $\delta^{15}N$ analyses and C:N ratios. The $\delta^{15}N$ of non-acidified samples was measured because nitrogen isotope values can be affected by the acidification process (Brodie et al. 2011). The acidified carbon content (%) was divided by the non-acidified nitrogen content (%) of samples to calculate C:N ratios. All isotope samples were analyzed in duplicate.

Results

Age-depth model

The radiocarbon age of the pollen sub-sample from 74 to 77 cm was 1330 (± 20) yr BP, and that of the leaf from 74 to 76 cm was 1190 (± 20) yr BP (Table 1). The radiocarbon age of the bulk sediment at 74–77 cm, however, dated to 1430 (± 20) BP. The ~ 100-year offset between allochthonous pollen and bulk sediment indicates a potential reservoir effect. The leaf represents one depositional moment in time as opposed to the dated pollen, which represents a period of time averaged across the sampled interval, which likely provides a more realistic estimate of potential reservoir effects through time. In addition, using the 100-year correction yielded sedimentation rates through the 74–77 cm depth interval that were in better agreement with older and younger dates. We therefore subtracted 100 years from all bulk sediment radiocarbon dates to correct for the possible reservoir effect, before constructing the age-depth model with BACON. The leaf was not included in age-depth construction. The age model represents a time span of approximately 1730 years (Fig. 2). The basal age was extrapolated by assuming a constant sedimentation rate from the deepest radiocarbon date to the core's base at 94 cm, which extends the Piseco Lake record

Fig. 2 Age-depth model for the Piseco lake core using BACON (version 2.2). The outer dotted lines represent 95% confidence intervals and the central dotted line is the best fit model



to approximately 1865 cal yr BP. Sedimentation rates were relatively low from around 1865 to 1455 cal yr BP, at approximately 0.02 cm/yr, then increased to 0.05–0.07 cm/yr towards the surface.

Pollen

Picea pollen abundances were low relative to the rest of the record at approximately 5% around ~ 1560 cal yr BP, but increased afterwards and remained relatively high (Fig. 3). A decline in *Tsuga* (7%) and *Pinus* (4%) pollen percentages occurred, while *Betula* increased to around 36% at ~ 1300 cal yr BP. A microscopic charcoal:pollen ratio peak of approximately 0.80 occurred ~ 1300 cal yr BP, as well. *Picea* pollen percentages increased markedly and reached 27–29% from ~ 1235 to 915 cal yr BP. A decline in *Fagus* pollen percentages from ~ 6 to ~ 2.5% occurred between ~ 710 and 650 cal yr BP. *Tsuga* began to decline after ~ 520 cal yr BP, while *Pinus* appeared to peak at around 12%. Sharp increases in *Ambrosia* and Poaceae pollen percentages are evident from ~ 255 to − 65 cal yr BP. *Ambrosia* increased to 0.8% at ~ 195 cal yr BP, then to 1.3% at ~ 130 cal yr BP, accompanied by a sharp increase in Poaceae, which reached 4% at ~ 65 cal yr BP. The charcoal:pollen ratio increased rapidly to 1.6 at ~ 0 cal yr BP (1950 CE). *Betula* pollen became dominant at about 30%, while *Tsuga* declined to less than 10%. *Pinus* began to decline after a high value of 16.3% relative to the record at ~ 195 cal yr BP.

Sediment geochemistry

Carbon content of the Piseco Lake sediments was initially low at 11%, then increased to 12.7% and remained generally between 12 and 12.5% until increasing to 13% at ~ 650 cal yr BP (Fig. 4). Nitrogen content averaged around 0.97%, followed by a decrease to 0.74% by ~ 0 cal yr BP, then increased at the surface to 1.1%. Sediment $\delta^{13}C$ values were around − 26.3‰ throughout most of the record, then began to decrease slightly after ~ 195 cal yr BP, reaching − 27.1‰ at the surface. $\delta^{15}N$ values were generally around 4‰ until an increase to 4.8‰ occurred by ~ 0 cal yr BP, followed by a decrease at the surface. The C:N ratio was stable between 12.5 and 13.5, then increased after ~ 195 cal yr BP to > 17, until it displayed a sharp decline at the surface. Organic matter (OM) content was initially relatively low, around 20%, but then increased to 23.8% around 1385 cal yr BP, with the mineral influx simultaneously increasing from ~ 2.5 to ~ 6 mg/cm^2/yr. The OM decreased from 25.8% at ~ 65 cal yr BP to 19.3% at ~ 0 cal yr BP. Carbonate content averaged 3.9% until a shift occurred after ~ 710 cal yr BP, when it averaged 3.4% to the surface.

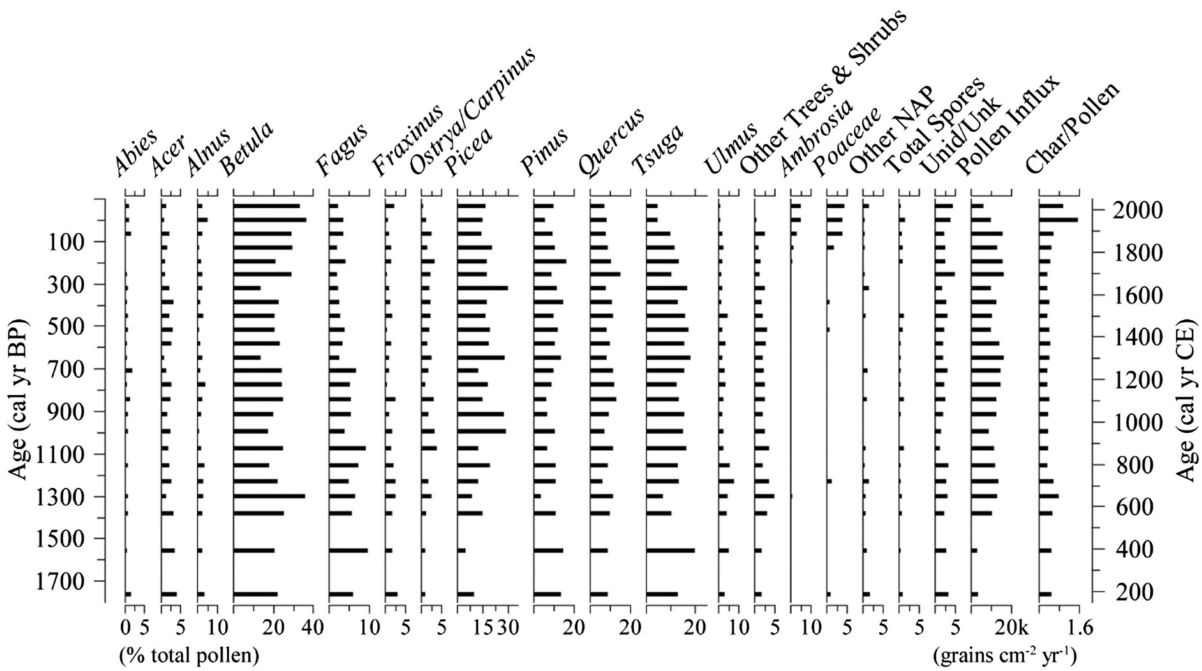
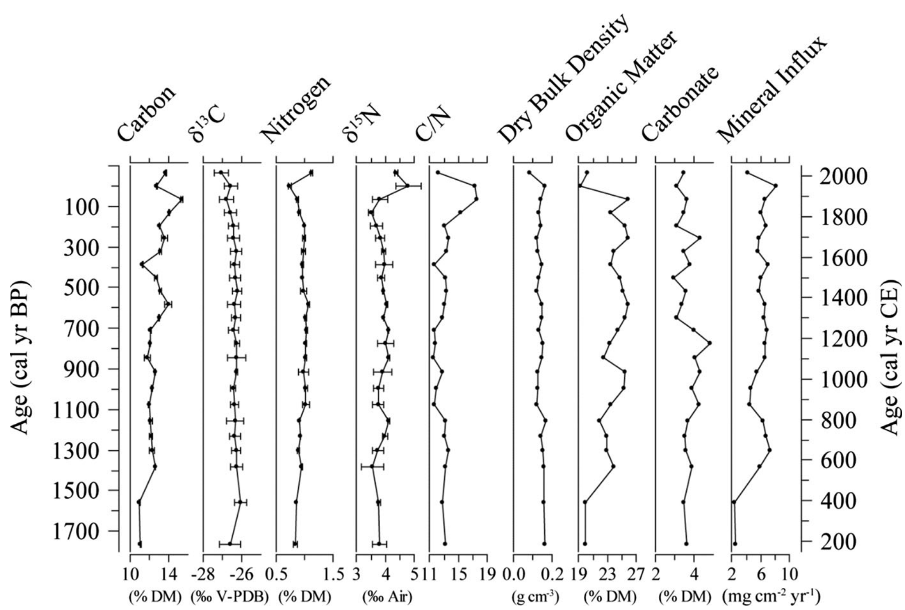


Fig. 3 Pollen percentages of arboreal and non-arboreal taxa relative to total pollen, along with spores from the Piseco Lake core

Fig. 4 Sediment geochemistry and characteristics based on dry mass for the Piseco Lake core. Acidified carbon content and non-acidified nitrogen content are presented and error bars are the standard deviation between the two averaged samples for each interval



Charcoal

Macroscopic charcoal particles were rare until ~ 895 cal yr BP, when abundances became elevated and more consistent (Fig. 5). A small peak in CHAR occurred between about 845 and 810 cal yr BP, reaching accumulations of approximately 0.23 particles/cm^2/yr. A very large macroscopic charcoal peak occurred between ~ 680 and 650 cal yr BP with total charcoal concentration of approximately 27.6 particles/cm^3 and total CHAR of approximately 1.9 particles/cm^2/yr. Another substantial increase in macroscopic charcoal occurred between ~ 585 and 550 cal yr BP with a total concentration of 12.2 particles/cm^3 at ~ 585 cal yr BP and a total CHAR of 0.73 particles/cm^2/yr at ~ 550 cal yr BP. Charcoal concentrations and CHAR increased after ~ 160 cal yr BP and remained high up to the surface relative to the rest of the record. CharAnalysis identified fire events at ~ 870, 820, 685, 580, 190 and 105 cal yr BP.

Discussion

Nutrient cycling conditions

Bulk sediment $\delta^{13}C$ values were between − 26 and − 27‰ (Fig. 4), within the range typical for C_3 plant tissues (Meyers and Teranes 2001). Sediment $\delta^{15}N$ values remained high relative to the atmosphere (0‰) and ranged between 3.5 and 4.1‰, which may have been a consequence of ammonium and nitrate being available for phytoplankton assimilation after nitrification and denitrification processes. The residual pool of dissolved ammonium and nitrate is enriched in ^{15}N relative to the atmosphere because of discrimination against the heavier isotope, which leads to relative isotopic enrichment in phytoplankton that consume nitrogen from these pools (Talbot 2001). The sediment mass C:N ratios in the core from Piseco Lake were generally around 13, slightly higher than values typical for phytoplankton, which generally fall between an atomic ratio of 4 and 10 (Meyers and Terances 2001), indicating relatively minor contributions of terrestrial organic matter to the sediment organic matter pool. Linear sedimentation rates were relatively low from ~ 1865 to 1455 cal yr BP, averaging approximately 0.02 cm/yr. Low OM, carbon content (Fig. 4) and pollen influx (Fig. 3), coinciding with the low sedimentation rates may indicate generally low aquatic and terrestrial productivity during this time. There may, however, be alternative explanations for the low sedimentation rates, including an error in radiocarbon dating, bioturbation, and/or variable deposition caused by shifting wind and water flow at that point in time.

Vegetation, fire, and climate regimes

The pollen record indicates an arboreal ecosystem ~ 1800 years ago around Piseco Lake, dominated by *Betula*, *Tsuga*, *Pinus*, *Quercus*, and to a lesser extent *Fagus*. *Picea* began to increase after ~ 1560 cal yr BP and eventually became a major component of the forest in the area over the next ~ 500 years (Fig. 3).

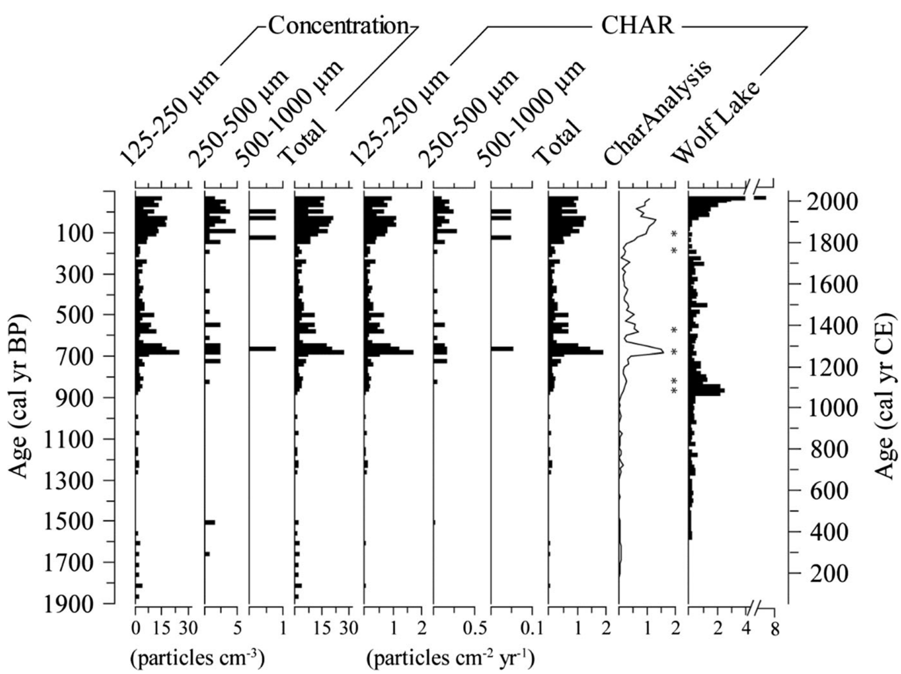


Fig. 5 Macroscopic charcoal concentrations and charcoal accumulation rates (CHAR) for 125–250 µm, 250–500 µm, and > 500 µm size classes and totals from the Piseco Lake core. CharAnalysis results with asterisks indicating significant peaks (Higuera 2009), and the Wolf Lake charcoal record (Stager et al. 2016) for comparison

This increase in *Picea* was also documented in other Adirondack (Overpeck 1985; LeBoeuf 2014) and northern New York pollen records (Gajewski et al. 1987). Although the increase in *Picea* began ~ 1560 cal yr BP, percentages were highly variable prior to that time, so it is possible that increased *Picea* dominance commenced earlier than ~ 1560 cal yr BP in the Adirondack uplands. *Picea* is a cold-tolerant species (Fuller et al. 1998), so the increase may indicate a general cooling trend. Records indicate south-central Adirondack vegetation became more boreal and the climate was cooler in the late Holocene compared to the middle Holocene (Overpeck 1985).

At ~ 1300 cal yr BP, *Tsuga* and *Pinus* pollen percentages declined sharply, while *Betula* dominated the pollen record. This change in the pollen assemblage was accompanied by an increase in charcoal: pollen ratios (Fig. 3), possibly indicating increased fire disturbance and secondary succession. It can be difficult to interpret the ecological significance of *Betula* and *Pinus* pollen because these genera are prolific pollen producers and the numerous species in the *Betula* genus have different ecological optima and tolerances (Gajewski et al. 1987). If the decline of major arboreal taxa at ~ 1300 cal yr BP represents a natural fire disturbance, it may have occurred somewhere else in the Adirondacks as well. Stager et al. (2016) reported a statistically significant charcoal peak ~ 1200 cal yr BP from nearby Wolf Lake in the central Adirondack uplands (Fig. 5). A 150-year gap between the Wolf Lake and Piseco charcoal peaks, which is similar in magnitude to the age offset we inferred from the radiocarbon ages of older plant and sediment samples and applied to the entire Piseco core, makes it difficult to ascertain if the two charcoal peaks represent synchronous events or not.

Macroscopic charcoal was scarce in Piseco Lake's record until ~ 895 cal yr BP, after which macroscopic charcoal concentrations increased. A peak in the macroscopic charcoal record was accompanied by fire events ~ 870 and 820 cal yr BP (Fig. 5). The Char-Analysis program generally detects fire events from variations in accumulation in the charcoal record. Low macroscopic charcoal concentrations in Piseco Lake's sediment record, however, complicate signal identification relative to background noise, resulting in a signal-to-noise ratio that is generally well below the theoretical CharAnalysis signal-to-noise cutoff of 3, making it difficult to identify peaks as distinct fire events (Kelly et al. 2010). Stager et al. (2016) reported a large charcoal peak in the nearby Wolf Lake record ~ 850 cal yr BP (Fig. 5), which falls almost exactly mid-way between the identified Piseco Lake fire events. It is possible the two fire events in the Piseco Lake sediment record, at ~ 870 and ~ 820 cal yr BP, represent two separate fires, but are linked to the fire event Stager et al. (2016) reported at ~ 850 cal yr BP in the Adirondacks.

When comparing the charcoal records of the Piseco and Wolf Lake cores, it is difficult to assess whether the discrepancies are a consequence of local differences or problems associated with the Piseco Lake age model, particularly when examining the largest CHAR peaks detected in each record before the historical period. The general trend in Piseco Lake's CHAR record between ~ 700 and 500 cal yr BP is quite similar to Wolf Lake's between ~ 850 and 700 cal yr BP (Fig. 5). Unless this discrepancy between the records represents local environmental changes around each lake, assumptions associated with the Piseco Lake age model may explain the age offset between the similar CHAR trends in the two records. Nevertheless, the trends in the pollen and charcoal records of Piseco Lake, when compared with other regional records, favor the current age model.

Fire occurrence is not considered to be a dominant factor that affects the conifer-hardwood forest dynamics in southeastern Canada and the northeastern United States (Clark and Royall 1996; Clark et al. 1996; Fuller 1997; Carcaillet and Richard 2000; Long et al. 2011) because of the dominance of tree species with low flammability and a relatively moist climate regime (Paquette and Gajewski 2013). The transition in the fire regime around Piseco Lake, however, may indicate the onset of generally drier conditions during the MCA (~ 1000–600 BP). The MCA has been interpreted as a period of widespread drought in southwestern North America (Cook et al. 2014; Woodhouse et al. 2010), and a period of increased aridity in areas of the northeastern United States (Pederson et al. 2005; Stager et al. 2016). Pederson et al. (2005) analyzed sediments from a tidal marsh in the Hudson River Estuary. The marsh's bi-decadal record revealed increases in charcoal and *Pinus* dominance, along with higher inputs of inorganic sediment from ~ 800 to 1300 AD (1150–650 BP). A 3% decrease in OM in the Piseco Lake sediment record ~ 845 cal yr BP may indicate increased terrestrial sediment input from land-surface erosion following fire disturbance (Fig. 4). *Pinus* pollen percentages increased after ~ 845 cal yr BP in the Piseco Lake pollen record, potentially indicating drier conditions. LeBoeuf (2014) reported a dominance of *Pinus strobus* pollen in Bloomingdale Bog in the north-central Adirondacks throughout the Holocene. In addition, Gajewski et al. (1987) reported dominance of *P. strobus* in late Holocene sediments from Clear Pond, located just east of the southern Adirondacks. *Pinus strobus* is present in every county in New York and flourishes throughout the Adirondacks (Wendel and Smith 1990). The *Pinus* pollen is most likely from *P. strobus*, which frequently germinates in canopy gaps following forest disturbance (Hibbs 1982; Gajewski et al. 1987). In addition, pollen percentages of *Picea*, a boreal, cold-tolerant genus, decreased between ~ 845 and 710 cal yr BP. Percentages of pollen from *Tsuga*, a generally mesic and fire-intolerant taxon (Fuller et al. 1998), were relatively low between ~ 845 and 775 cal yr BP.

A major change in the forest composition around Piseco Lake occurred coincident with the LIA (~ 600–150 cal yr BP), initiated by the decline of *Fagus* pollen percentages sometime between ~ 710 and 650 cal yr BP, and of *Tsuga* after ~ 520 cal yr BP (Fig. 3). Both *Pinus* and *Picea* pollen were abundant in the pollen record throughout much of the LIA. The decline in *Fagus* appears earlier in Piseco Lake's pollen record than in other records in northern New York (Gajewski et al. 1987), which may indicate an earlier change in climate in the southern Adirondacks. Northeastern U.S. pollen records contain additional evidence of change in forest composition associated with cooler conditions during the LIA (Bernabo 1981; Campbell and McAndrews 1995; Fuller et al. 1998). Bernabo (1981) reconstructed temperatures using pollen data from northwestern lower Michigan and reported a cold interval between 1450 and 1150 cal yr BP, a warm period from 950 to 750 cal yr BP, and prolonged cooling after 750 cal yr BP. Campbell and McAndrews (1995) modeled the LIA with a 2 °C decrease in mean annual temperature from 750 to 100 cal yr BP and showed vegetation changes matching those in southern Ontario. The apparent change in forest composition in the Piseco Lake pollen record may mark the transition from the MCA (~ 1000–600) to the LIA (~ 600–150 cal yr BP) in the southern Adirondack uplands.

Piseco Lake's sediment record also provides evidence of drought in the region around the transition from the MCA to the LIA. Stager et al. (2016) reported that the central Adirondack uplands were likely relatively wet during the LIA (~ 600–150 yr BP) compared to the MCA (~ 1000–600 BP), based on high percentages of planktonic diatoms, rather than similar to or drier than the MCA, as indicated by a pollen record from Clear Pond in the southeastern Adirondacks (Gajewski et al. 1987). Additional hydroclimate reconstructions from the Adirondacks will be needed to determine whether these apparent discrepancies represent flaws in proxy records or their interpretation, or true climate variability within this topographically complex region.

In addition, sub-regional differences in the timing of the transition to drier and cooler conditions during the LIA may have occurred. Paquette and Gajewski (2013) reconstructed vegetation patterns over the past 1000 years from a varved sediment record from southwestern Quebec and found an abrupt decrease in pollen accumulation rates for *Tsuga*, *Fagus*, *Acer*, and other trees, while *Pinus* diploxylon (hard pines), *Picea glauca* (white spruce), *Abies balsamea* (balsam fir) and several shrubs increased slightly around 400 cal yr BP (1550 CE). The data indicate that up to ~ 390 BP the area was relatively warm, corresponding to the latter part of the MCA and the transition into the cool LIA (Paquette and Gajewski 2013). Between ~ 960 and 390 cal yr BP (990–1560 CE) *Tsuga*, *Fagus*, and *Acer* pollen percentages were relatively high in the Lac Noir sediment record, indicating relatively warm and moist conditions. Afterwards, decreases in pollen production of hardwoods such as *Acer* and *Fagus*, and *Tsuga* indicate an abrupt cooling and significant impact on vegetation at the site (Paquette and Gajewski 2013). An abrupt decline of mesic species such as *Fagus* and *Tsuga* around ~ 600–500 yr BP, however, was recorded in northern New York (Gajewski et al. 1987; LeBoeuf 2014) and in parts of New England (Fuller et al. 1998; Foster et al. 1998), potentially caused by a combination of temperature change, drought, and fire (Fuller et al. 1998; Clifford and Booth 2013).

Two of the highest CHARs in the entire Piseco Lake macroscopic charcoal record occurred between ~ 685 and 550 cal yr BP (Fig. 5). During that time interval, charcoal particles > 250 µm became particularly abundant, which indicates fires may have occurred very close to the lake. Sites in Maine (Saco Bog, Sidney Bog, and Great Heath) contain evidence of drought and widespread fire ~ 550 yr BP, based on proxy evidence for greater water table depth and charcoal peaks (Fig. 1; Clifford and Booth 2013). Lafontaine-Boyer (2014) reported a decrease in *Tsuga* and evidence of post-fire succession, along with a peak in microscopic charcoal ~ 575 cal yr BP in Lac Brulé, southwestern Quebec, indicating a fire in the region. After a fire, forests dominated by *Tsuga* generally do not return to pre-fire composition (Ziegler 2000) because *Tsuga* species experience difficulty regenerating after fire (Lafontaine-Boyer 2014).

LeBouef's (2014) record from Bloomingdale Bog in the north-central Adirondacks contains a depositional hiatus between ~ 1210 and 570 cal yr BP, complicating comparisons of late Holocene vegetation change. LeBoeuf, however, recorded a 50% decrease in *Fagus* pollen and a 50% increase in water-table depth after the hiatus ~ 570 cal yr BP, along with one of the largest fire events relative to the remainder of the record, potentially the result of drought (LeBoeuf 2014). In addition, LeBoeuf (2014) recorded a very large microscopic charcoal peak at ~ 550 BP and suggested an increased occurrence of regional upland fires. The Piseco Lake sediment record, however, does not possess a large microscopic charcoal peak around the same time as the Bloomingdale Bog sediment record, although particle counts did increase in that time interval. This may be because pollen grains and microscopic charcoal particles were counted at 4-cm intervals in the Piseco Lake record, resulting in a data gap between ~ 585 and 520 cal yr BP. Microscopic particles < 100 μm are capable of traveling great distances, and theoretical models of charcoal distribution suggest there is a "skip distance" between the base of a fire's convective column and depositional site, which can range from meters to kilometers, depending primarily on the height of the convective column (Whitlock and Larson 2001). It is possible the regional upland fires suggested by LeBoeuf (2014), indicated by the large microscopic charcoal peak ~ 550 cal yr BP, may have occurred closer to Piseco Lake than Bloomingdale Bog, explaining the lack of a microscopic charcoal peak in Piseco Lake's charcoal:pollen ratio.

Although late Holocene climate change may have been the primary cause of increased fire frequency and changing vegetation composition in the Adirondacks, prehistoric human activities may have also contributed to changes in the landscape that are not represented clearly in Piseco Lake's sediment record. Fuller et al. (1998) recorded slight increases in microscopic charcoal:pollen ratios in central Massachusetts upland sites starting ~ 600–500 cal yr BP, and suspected possible increases in fire frequency caused by prehistoric human activities. Distinguishing natural from anthropogenic fire events, based only on sediment charcoal records, is impossible without another proxy indicator of anthropogenic activity (Fuller et al. 1998). Stager et al. (2016) identified a significant decrease in OM at Wolf Lake during the late 17th and early 18th centuries, possibly related to Native American land clearance.

Piseco Lake's relatively high macroscopic charcoal concentrations and CHAR ~ 680–650 and ~ 585–550 cal yr BP, occurred during the same time period when enhanced Iroquoian activity was documented in the sediment record of Crawford Lake, Ontario (Fig. 1). Iroquoian settlement and agriculture around Crawford Lake occurred between ~ 682 and 430 cal yr BP (1268–1520 CE; McAndrews and Turton 2007), and the pollen and charcoal records of that time period align fairly well with those of the Piseco Lake record. Additional evidence of prehistoric human disturbance in lake sediment records, as seen in the Crawford Lake record, are needed to identify and separate natural environmental change from prehistoric human disturbance in the region.

Impacts of Euro–American settlement

Perhaps the greatest influence on forest composition in the Adirondacks (LeBoeuf 2014) and other areas in the northeast (Fuller et al. 1998) has been Euro-American settlement and associated deforestation. A rise in *Ambrosia* and Poaceae at Piseco Lake from ~ 195 to 130 cal yr BP (Fig. 3) represents a well-established chronomarker indicating Euro–American land clearance and deforestation, which were well under way by ~ 150 cal yr BP in the Adirondacks (LeBoeuf 2014). *Pinus* pollen decreased steadily after ~ 130 cal yr BP, while *Betula* pollen increased. *Tsuga* was already declining prior to European arrival, but declined more rapidly after settlement. In the early 1800s, and perhaps earlier, *P. strobus* was selectively harvested for lumber and *Tsuga* for tannins (NYS Adirondack

Park Agency 2016), leading to an expansion in the region of *Betula* populations, which are more tolerant of disturbance (Fuller et al. 1998). Widespread deforestation led to the creation of the Adirondack Park in 1892, a consequence of concerns for water and timber resources in the region (NYS Adirondack Park Agency 2016).

The C:N ratio in the Piseco Lake sediment record increased sharply ~ 130 cal yr BP (Fig. 4), which may indicate increased land clearance and allochthonous sediment inputs to the lake. Slightly increased sediment $\delta^{15}N$ values may be related to increased eutrophication, which resulted from increased nutrient loading related to modern land use practices such as deforestation, application of fertilizers, and/or increased atmospheric nitrogen deposition (Talbot 2001). The declining sediment nitrogen content after ~ 195 cal yr BP, and slight increases in $\delta^{15}N$ values might also indicate a change in nitrogen cycling in the watershed. Covariance of sediment $\delta^{15}N$ values with *Betula* and *Alnus* pollen percentages (Figs. 3 and 4) in the record may represent an increase in nitrogen fixation by *Alnus* species (Hu et al. 2001) and/or a symbiotic relationship with mycorrhizal fungi commonly associated with *Alnus* and *Betula* species (Nadelhoffer et al. 1996), which can elevate $\delta^{15}N$ values of the host plant and the resulting $\delta^{15}N$ composition of allochthonous organic matter in the lake sediment (Hobbie et al. 1999; Kohzu et al. 2000; Hyodo and Wardle 2009). The covariance, however, may be overrepresented because of a high error at ~ 0 cal yr BP.

Sediment $\delta^{13}C$ values began to decrease ~ 130 cal yr BP (Fig. 4), possibly because of the Suess effect, from increased input of soot particles or declining $\delta^{13}C$ of dissolved inorganic carbon from fossil fuel combustion (Keeling 1979), but the apparent negative trend may not be significant because of the error range on $\delta^{13}C$ values. Macroscopic charcoal concentrations and CHAR increased after ~ 145 cal yr BP (1805 cal yr CE; Fig. 5) as did the abundance of charcoal particles > 250 µm in diameter, indicating increased occurrence of local fires around Piseco Lake. Microscopic charcoal concentrations increased rapidly after ~ 65 cal yr BP (1885 cal yr CE), indicating increased regional fires as well (Whitlock and Larson 2001). Contribution of dry fuel after logging activities made fires more common (Latty et al. 2004; LeBoeuf 2014), and the opening of the state campgrounds along Piseco Lake's western shore (two in the late 1920s and early 1930s, and one in the early 1950s) likely contributed to increased charcoal concentrations in the sediment record. A sharp decline in OM content occurred after ~ 65 cal yr BP, likely because of erosion from land clearance and settlement within the watershed. Recent recreational activities at Piseco Lake were probably responsible for near-surface sediment mixing, especially in the bay.

Conclusions

The sediment record from Piseco Lake presents evidence of climate change in the Adirondacks over the past 1800 years, including during the MCA and LIA. Increasing *Picea* pollen percentages after ~ 1500 cal yr BP and declines in *Tsuga* and *Fagus* pollen are in good agreement with other pollen records from northern New York State. An abrupt change in forest composition at ~ 1300 cal yr BP appears to represent an ecological disturbance that has not been documented previously in the region, and a changing fire regime around ~ 900 cal yr BP may have been caused by an increase in forest fires around Piseco Lake. The relative influences of climate and prehistoric human activity on changes detected in the Piseco Lake sediment record remain unclear, but the Adirondack region experienced its most rapid changes in forest composition following European settlement and activities. Piseco Lake's record of change in forest composition, fire regime and sediment characteristics also provides a point of reference for projections of how climate change and human activity may impact northeastern North American environments in the foreseeable future.

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