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Abstract Whitefish Lake is a large (11-km-long), shallow, basin in Northwestern Ontario, Canada. The presence of extensive stands of wild rice (*Zizania* sp.) in combination with high archaeological site density suggests that this lake was ecologically important to regional precontact populations. Collection and analysis of sediment from Whitefish Lake was initiated in 2008 in order to reconstruct changes in lake depth, climate, and vegetation throughout the Holocene. In general, the upper 4.5 m of basinal sediment is composed of ~1.5+ m of varves, which is overlain by a 1.5-m-thick unit with ped-like structures, and ~1.5 m of lacustrine sediment. This sequence documents an early proglacial lake phase, followed by a dry interval before 4,300 (4,900 cal) BP when the lake was significantly shallower, and the establishment of the modern lake during the late Holocene. Plant microfossil (phytolith) evidence indicates that wild rice had colonized the basin ~5,300 (6,100 cal) BP as the lake level rose in response to climate change. Beginning ~4,000 (4,500 cal) BP, changes in elemental data suggest a sharp increase in lake productivity and a switch to anaerobic depositional conditions as the rate of organic sedimentation increased. Recent archaeological research confirms that wild rice was locally processed and consumed during the Middle and Late Woodland periods (~300 BC–AD 1700) although it was evidently growing in the lake well before this time.

Keywords Wild rice (*Zizania*) · Paleoecology · Plant microfossils (Pollen, Phytoliths) · Boreal Forest · Holocene

Introduction

Northern wild rice (*Zizania palustris* L.) was an important source of food for precontact and historic Indigenous peoples living along the southern margin of the Boreal Forest of North America (Vennum 1988). This annual emergent grass, which is distributed from the Lower Great Lakes to central Alberta (Terrell et al. 1997), provided an abundant, protein-rich, lightweight, and storable food for use throughout the winter months when other foods were scarce. In lakes and rivers where it is established, wild rice also plays an important role as a source of food and habitat for waterfowl and many other organisms. Due to the cultural and ecological significance of this plant, several attempts have been made over the years to reconstruct the history of the species, principally through analysis of pollen preserved in Holocene lake sediment. However, because pollen from wild rice is

M. Boyd (✉) · C. Surette · J. Surette · S. Hamilton
Department of Anthropology, Lakehead University,
955 Oliver Rd., Thunder Bay, ON P7B 5E1, Canada
e-mail: matthew.boyd@lakeheadu.ca

I. Therriault
School of Applied Sciences, Bournemouth University,
Fern Barrow, Poole, Dorset BH12 5BB, UK

virtually indistinguishable from other native grasses (Lee et al. 2004), both the timing and cause of *Zizania* dispersal across the Boreal Forest remain equivocal.

Between February 2008 and June 2009, four sediment cores (ranging from 1.0 to 4.5 m long) were collected from a large wild rice-populated lake in northwestern Ontario, Canada. These sediments were analyzed for pollen, phytolith, and elemental content in order to track changes in late Holocene paleovegetation and lake evolution near several large Woodland (~300 BC–AD 1700) archaeological sites. Because many of these archaeological sites have yielded *Zizania* sp. plant remains in carbonized food residue (Boyd and Surette 2010), it is clear that the histories of wild rice and human society in this region are closely entwined. In our study, we use phytolith analysis to track the first colonization of the Whitefish Lake basin by wild rice. Surette (2008) and Yost and Blinnikov (2011) have recently identified several phytolith morphotypes that are only found in *Zizania* spp., enabling unequivocal recognition of this plant in sediment, soil, and archaeological food residue. Furthermore, because phytoliths are inorganic and tend to be deposited in place, they provide a sensitive and persistent record of local-scale plant dynamics through time. When combined with pollen analysis and other conventional paleoecological techniques, this approach promises to yield insight into the long-term development of wild rice ecosystems in the Boreal Forest.

Study area: environmental and archaeological setting

Whitefish Lake is located 50 km southwest of Thunder Bay, Ontario, in the Boreal Shield Ecozone of Canada (Fig. 1). This large (~11-km-wide) and elongate body of water drains eastward into Lake Superior and has an average water depth of 2.0 m. Due to the shallow and flat-bottomed shape of its basin, Whitefish Lake supports very large communities of aquatic macrophytes. The largest of these wetlands, located at the western end of the lake (Fig. 1), is 120 hectares in size and is dominated by *Z. palustris* (Lee and McNaughton 2004). Other common macrophytes associated with wild rice in the lake include *Nymphaea odorata* Aiton, *Nuphar variegata* Durand, *Sagittaria latifolia* Wild., and *Potamogeton gramineus* L. The vegetation surrounding Whitefish Lake is dominated by conifer and deciduous tree species typical of the Boreal and Great Lakes-St. Lawrence Forests. Today, the region falls within the subarctic climate zone (Köeppen classification: Dfc).

Deglaciation of the Whitefish Lake began before ~12,300 cal BP as the Laurentide Ice Sheet (LIS) retreated northward from the Steep Rock Moraine (Lowell et al. 2009). Until ~11,000 cal BP, when the LIS re-advanced to the Marks Moraine during the Marquette advance (Fig. 1), the basin was covered by the deep water of proglacial Lake O'Connor (Loope 2006). Varved sediments exposed near the town of Harstone (~27 km northeast of Whitefish Lake) indicate that sedimentation continued uninterrupted in Lake O'Connor for at least 300 years before it was overridden by the Superior Lobe (Loope 2006). Drainage of this proglacial lake and others in the region would have occurred with glacial retreat, as lower elevation outlets were opened along the northwestern shore of Lake Superior (Loope 2006; Phillips and Hill 2004; Zoltai 1963).

Previous paleoecological research in Northwestern Ontario indicates that late glacial vegetation ~10,000 (11,500 cal) BP was dominated by white spruce [*Picea glauca* (Moench) Voss], which may have grown alongside deciduous trees such as oak (*Quercus*), elm (*Ulmus*) and poplar (*Populus*), and heliophytic herbs and shrubs (Liu 1990). This early vegetation assemblage has no modern analogue and likely reflects the unique edaphic and climatic conditions of the region at this time (Liu 1990). An earlier, herb-dominated (e.g., *Artemisia*, Cyperaceae, Poaceae) pollen assemblage, recorded at a few sites in Northern Ontario, suggests that sparse tundra-like vegetation may have briefly covered the region prior to colonization by white spruce and other boreal species (Bjorck 1985; Craig 1972; Julig et al. 1990; McAndrews 1982). With soil development and climate change in the early Holocene, the non-analogous white spruce-dominated forest was quickly invaded by jack pine (*Pinus banksiana* Lamb.), black spruce [*Picea mariana* (Mill.) Britton, Sterns & Poggenb.], tamarack [*Larix laricina* (Du Roi) K. Koch] and other species characteristic of the modern Boreal Forest (Liu 1990). Plant macroremains recovered from an 8,900-year-old buried *Abies-Picea-Larix* forest in the Thunder Bay area supports the idea that essentially modern boreal vegetation communities were established in the

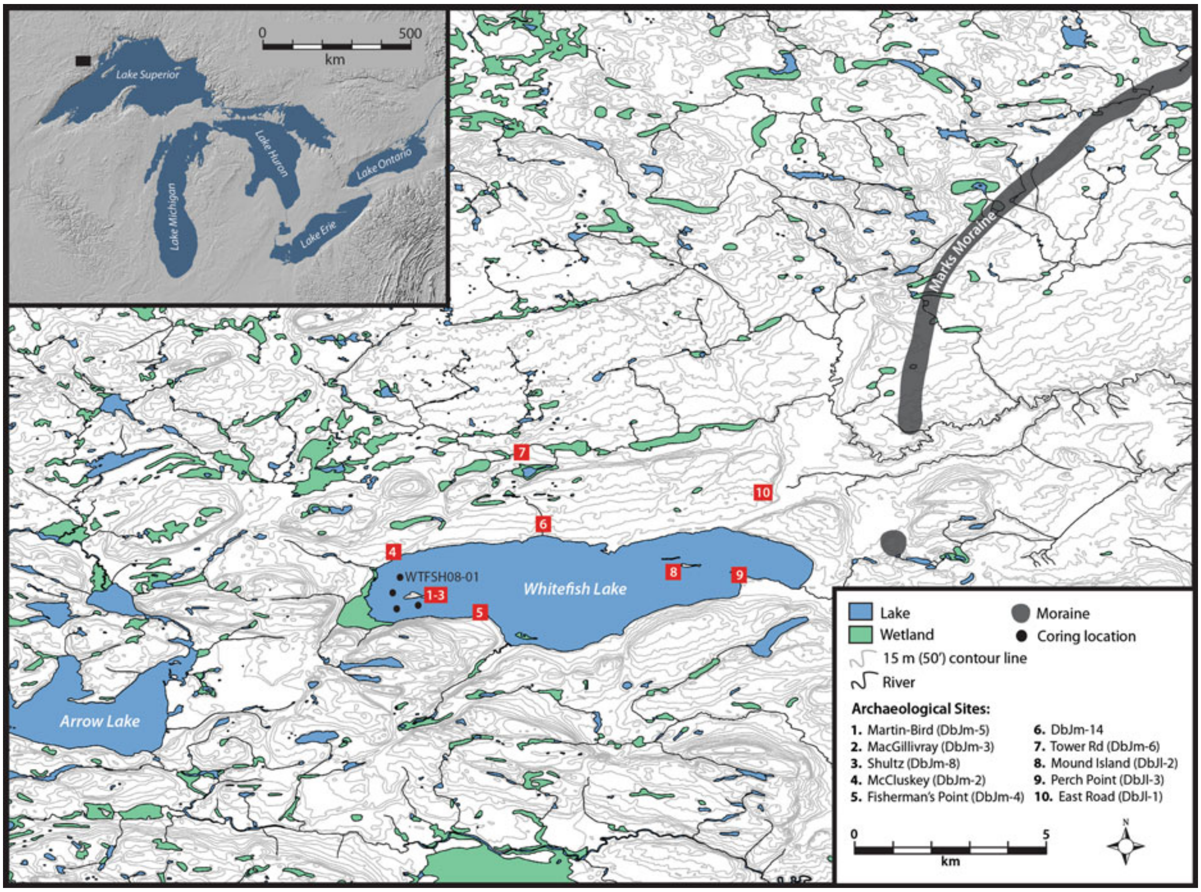

Fig. 1 Map of Whitefish Lake, Northwestern Ontario, showing location of sediment cores, archaeological sites, and physiographic features

region by the end of the early Holocene (Boyd et al. 2012). These boreal communities may have been relatively stable until ~7,000 (7,800 cal) BP, when the southern part of Northwestern Ontario was colonized by white pine (*Pinus strobus* L.), cedar (*Thuja*), hemlock (*Tsuga*), and other Great Lakes-St. Lawrence forest species (Liu 1990; Teller et al. 2008). The gradual spread northwards and westwards of the Great Lakes-St. Lawrence ecotone was probably caused by overall warmer and drier climate during the middle Holocene (Liu 1990; Wright 1976). Beginning ~4,000 (4,500 cal) BP, however, the onset of cooler climate caused a contraction in the range of *Pinus strobus* and other thermophilous tree species and a corresponding increase in pollen from *Abies*, *Picea*, *Betula*, and *P. banksiana* (Liu 1990). No information exists on the timing of *Zizania* colonization of the Canadian Shield, although estimates for its first appearance in central Minnesota range from 10,600 (12,600 cal) BP (Birks 1976) to 2,000 (1,960 cal) BP (McAndrews 1969).

The archaeological record of the Whitefish Lake area is extremely sparse until the appearance of Woodland peoples ~300 BC; the importance of the lake after this time can be seen in the numerous large habitation sites located along the modern shore or on islands within the lake (Fig. 1). Here, as elsewhere in the Great Lakes region, the Woodland tradition is marked by several important changes in technology, and social relations—most notably, the advent of pottery, burial mound ceremonialism, increased long distance trade, greater site permanency and larger population sizes (Boyd and Surette 2010; Reid and Rajnovich 1985, 1991; Wright 1999). Changes in diet may have also occurred at this time. For example, Boyd and Surette (2010) have recently documented a pattern of widespread consumption of domesticated plants such as maize as early as AD 500 in the boreal subarctic. Likewise, in an effort to explain the subtle shift towards larger and more complex settlements and social systems, some archaeologists have proposed that intensive wild rice exploitation began only in the Middle Woodland period (Laurel phase, ~300 BC–AD 1100) on the Canadian Shield (Reid and Rajnovich 1985, 1991; Wright 1999). Dispersal of wild rice by Laurel peoples has also been suggested as a mechanism for its expansion west of the Great Lakes during the Holocene (Buchner 1979; Wright 1999). However, virtually no Laurel components in Canada have yielded wild rice macroremains, or processing/storage features (Boyd and Surette 2010); this, in combination with the lack of paleoecological research in the Boreal Forest, means that the extent of the relationship between subarctic human societies and wild rice is largely unknown. In summer 2009, two of us (MB and SH) initiated a multi-year archaeological project focused on the excavation of a large Woodland site on an island in Whitefish Lake (#1 in Fig. 1). The objective of this on-going project is to track the emergence of food production and the traditional wild rice economy, against the backdrop of late Holocene ecosystem change and lake evolution in the Whitefish basin.

Materials and methods

One long (4.5 m) core was collected from the western side of Whitefish Lake in February 2008 using a vibracorer (Smith 1998) (Fig. 1). In the lab, the core was split, described, and sub-sampled for plant macrofossils, pollen, phytoliths, and bulk geochemistry. Three additional short (~1.0 m) cores of the water–sediment interface and underlying sediments were collected in summer 2009 using a universal percussion core sampler (manufactured by Aquatic Research Instruments) deployed from a boat. In order to reduce the possibility of mixing during transport, sediment collected in the short cores was extruded in the field in 2-cm increments using a core extruding apparatus. The majority of paleoenvironmental analyses, however, were conducted on the sedimentary sequence from the long core (WTFSH08-01), and only these results are presented in this paper.

AMS radiocarbon dates were obtained on identifiable plant macroremains sieved from lacustrine sediment contained in both the short and long cores. These remains consisted of graminoid (cf. *Zizania*) leaves and stems. However, no plant macroremains were recovered below ~1.5 m. As a result, we opted to date the bulk C fraction of the lower part of the sequence, despite well-documented problems with 'bulk dates' on lake sediment in the region (Teller et al. 2008). Calibration of radiocarbon ages was performed using the IntCal09 terrestrial dataset (Reimer et al. 2009).

Pollen

Sub-samples of 2 cc were collected for pollen analysis using a syringe every 2 cm (vertically) from the face of the split vibracorer barrels. Generally, every second sample (4 cm) was analyzed for pollen in the case of the long core (WTFSH08-01). Although collected, the samples from the varved (proglacial lake) interval at the base of the core were not analyzed due to the high quantity of redeposited pollen typical in these sedimentary environments (Nambudiri et al. 1980), and due to our research emphasis on mid- to late-Holocene events at Whitefish Lake.

Pollen grains were concentrated following Faegri and Iversen (1989), and between 300 and 500 non-aquatic palynomorphs were counted per sample. Identification was aided by published keys (McAndrews et al. 1973; Moore et al. 1991) and comparative material from Lakehead University. Zonation of pollen data was determined using stratigraphically constrained incremental sum of squares (CONISS) cluster analysis (Grimm 1987).

Phytoliths

Sub-samples of 3 cc were collected for phytolith extraction every 2 cm down the long core to a depth of 3.41 m. Phytolith content of the long core was initially analyzed every 10 cm, followed by closer-interval (2–4-cm) analysis of key biostratigraphic zones. No phytoliths were observed below 2.14 m depth.

Phytoliths and other biogenic silica (e.g., diatoms) were extracted from the sediment through a combination of sieving, acid digestion, and heavy liquid flotation (Surette 2008). First, all samples were deflocculated using 0.5 % sodium hexametaphosphate solution. The remaining material (consisting of organic and inorganic components) was separated by gravity settling; this was done in order to recover phytoliths that may have been sequestered in organic (largely graminoid) debris within the sediment. This lighter, organic, fraction was then dissolved in 50 % nitric acid and then sieved through 250-, 118-, and 35-µm Nitex® cloth. The heavier, inorganic, fraction was sieved separately through the same mesh sizes. Phytoliths from both fractions were then extracted separately using sodium metatungstate (specific gravity = 2.3) and mounted onto slides for observation under a compound light microscope. Phytolith counts ranged from 0 (for the barren section at the base of the long core) to 730 per sample. The criteria used for identification of *Zizania* rondel phytoliths followed Surette (2008) and Yost and Blinnikov (2011). In general, rondel phytoliths with four spikes, and one to three indentations on the base, are characteristic of *Zizania* spp. (Fig. 2).

Geochemistry

Bulk samples for elemental analysis were collected every 16 cm down the entire length of the long core. Samples were first homogenized using a food processor and micronizing mill, then dried in an oven and reduced to a fine powder using a mortar and pestle. For each sample, 1 g was reserved for acid digestion and the rest was set aside for determining carbon, hydrogen, and nitrogen content using a CHN analyzer (Wachberger et al. 1971).

The sequential acid digestion procedure used in this study is based on Engstrom and Wright (1984) and Engstrom et al. (1985). This standard technique enables separation of acid-soluble (‘authigenic’) from siliclastic mineral (‘allogenic’) fractions. The elemental composition for each fraction was determined separately through Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES). Quality control was regularly assessed by running duplicates and triplicates of samples, in addition to blanks and element standards. Raw ICP-AES data were processed by first subtracting the mean value for elements obtained on the blanks. These results were multiplied by a dilution factor and, for the major elements (Al, Ca, Fe, K, Mg, Mn, Na, P and Ti), sample ppm (parts per million) values were converted to major oxide values (%). Next, sample results for each element were compared to results obtained on the standards; only the elements that deviated by no more than ~10 % were retained for further consideration. Results on sample duplicates and triplicates were then compared to one another using graphs and statistical analysis (Spearman’s rank-order correlation coefficient). Similar results were averaged, but in the cases where reproducibility failed, only comparable values were retained. Zonation of geochemical data was determined using stratigraphically constrained incremental sum of squares (CONISS) cluster analysis.

Results

Stratigraphy and AMS radiocarbon dates

The upper 4.6 m of sediment in Whitefish Lake is divided into four lithostratigraphic units. The lowest of these (unit D), consists of >1.5 m of rhythmically laminated clay to silty clay. The individual laminae in this unit vary in thickness from ~3 to 1 cm, are generally faint, grey, and barren of any macroscopic biological remains; a total of ~265 light–dark couplets were counted in unit D. Overlying this is ~1.5 m of clay to silty clay with abundant ped-like structures throughout (unit C). Individual ped-like forms are ~1–5 mm in diameter/thickness, and change in shape from platy at the bottom to more granular near the top of the unit. The upper 40 cm of unit C appears to have higher water content, and is slightly sapropelic with occasional diatom frustules visible in smear slides; the lower ~1 m of this unit is barren of macroscopic biological remains as well as biogenic silica (e.g., phytoliths, diatoms). Unit B is differentiated from underlying sediment by the presence of abundant, well-preserved, herbaceous (graminoid) debris in a clayey matrix, and lack of sedimentary structure. Much, if not all, of this fine debris consists of *Zizania* remains (e.g., leaf and stem portions) based on examination of short cell morphology. This unit is overlain by a massive, 20-cm-thick, sapropel with occasional herbaceous (mostly graminoid [cf. *Zizania*]) debris, ostracods and other shell remains.

Three AMS radiocarbon ages were obtained on hand-picked graminoid remains from units A and B in the long core: 2,640 ± 40 ^{14}C BP (18–20 cm depth), 3,220 ± 40 ^{14}C BP (64–66 cm), and 4,330 ± 40 ^{14}C BP (146–148 cm) (Table 1; Fig. 4). Unit B in one of the short cores yielded three AMS radiocarbon ages on

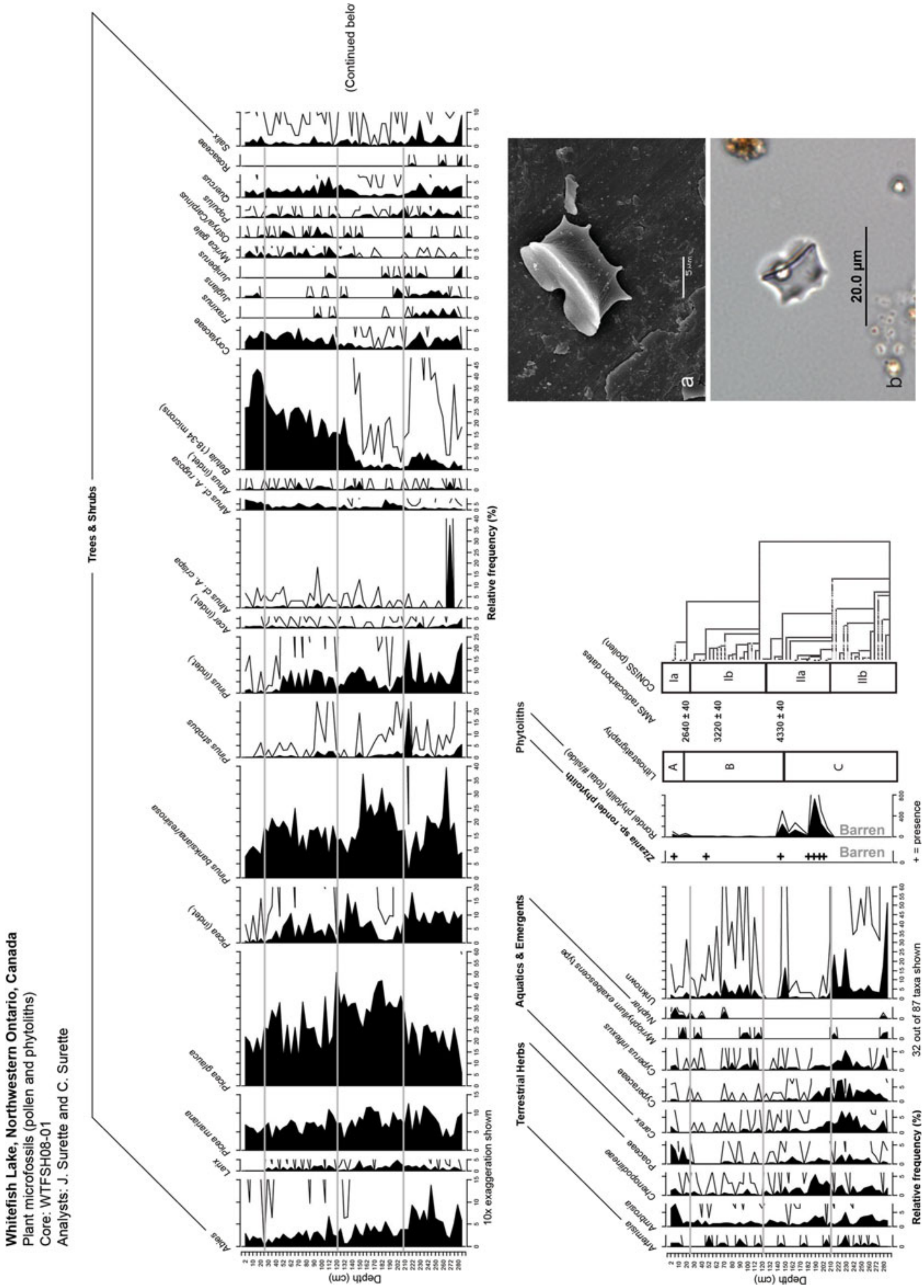

Fig. 2 Plant microfossils (pollen and phytoliths) recovered from core WTFSH08-01, Whitefish Lake, Ontario. **a** Scanning electron microscope (SEM) and **b** transmitted light micrographs of rondel phytolith morphotype produced by *Zizania* spp. (wild rice)

Table 1 Radiocarbon ages obtained on hand-picked plant macrofossils and bulk sediment from Whitefish Lake cores WTFSH08-01 and -02. Radiocarbon years were calibrated using the IntCal09

	Core	Depth (cm)	Unit	14C BP	cal BP (2-sigma range)	cal BP (mean)	Material dated	Lab number	Comments
1	WTFSH08-01	18–20	A	2,640 ± 40	2,790–2,730	2,760	Graminoid debris	Beta-256940	
2	WTFSH08-01	64–66	B	3,220 ± 40	3,550–3,370	3,460	Graminoid debris	Beta-256941	
3	WTFSH08-01	146–148	B	4,330 ± 40	4,970–4,840	4,905	Graminoid debris	Beta-256942	
4	WTFSH08-01	216–218	C	14,820 ± 80	18,530–17,660	18,095	Bulk sediment	Beta-256943	Rejected
5	WTFSH08-01	258–260	C	18,820 ± 100	22,560–22,160	22,360	Bulk sediment	Beta-256944	Rejected
6	WTFSH09-02	42–44	B	3,480 ± 40	3,850–3,640	3,745	Graminoid debris	Beta-271856	
7	WTFSH09-02	68–70	B	3,490 ± 40	3,870–3,640	3,755	Graminoid debris	Beta-271855	
8	WTFSH09-02	100–102	B	3,520 ± 40	3,900–3,690	3,795	Graminoid debris	Beta-271854	

herbaceous debris between 42 and 102 cm in depth: 3,480 ± 40 ^{14}C BP, 3,490 ± 40 ^{14}C BP, and 3,520 ± 40 ^{14}C BP (Table 1). Due to the lack of identifiable organic macroremains in unit C, two radiocarbon dates were obtained on bulk sediment. These dates, which range in age from ~15,000 to 19,000 BP (Table 1), are rejected as too old because they predate the retreat of the LIS by several thousands of years in this region.

Pollen and phytoliths

Pollen in the upper 3.0 m of the long core is divided into four biostratigraphic zones. The oldest of these (IIb, 300–210 cm) is dominated by *Abies*, *Picea*, and *Pinus*, with low to moderate amounts of pollen from *Quercus*, Corylaceae, *Salix*, *Ambrosia*, Chenopodiineae, grasses (Poaceae), and sedges (Cyperaceae indet., *Carex*, and *Cyperus*) (Fig. 2). The overlying zone (IIa, 210–120 cm) is associated with a decrease in the relative frequency of *Abies*, *Salix*, most other trees and shrubs, an increase in *P. glauca* and *P. banksiana/resinosa*, and a decrease in pollen from *Ambrosia*, Chenopodiineae, and Cyperaceae. Zone Ib (120–25 cm) shows a pronounced rise in *Betula*, moderate increases in Corylaceae and *Quercus*, and slightly lower levels of *Picea* and *Abies* pollen. *Betula* reaches its maximum in zone Ia (120–0 cm), alongside small peaks in *Ambrosia* and Poaceae.

Sediment below ~214 cm is barren of biogenic silica. Between 212 and 142 cm, however, rondel phytoliths (from grasses) are very abundant and rondel morphotypes produced only in *Zizania* sp. were recovered in most samples in this interval (Fig. 2). Diatom frustules, which are absent below 214 cm, and rare between 212 and 142 cm, are abundant in all samples above 134 cm. Grass phytoliths, however, become uncommon above this depth, likely as a result of dilution by diatom remains.

Geochemistry

Authigenic and allogenic elemental data, and CHN values, from the long core are divided into three zones. The lowest zone (II, 457–206 cm) is characterized by low C, H, N, and S, high but variable C/N ratios, and relatively minor variations in authigenic and allogenic elemental content through time (Fig. 3). Between 206 and 126 cm (zone Ib), however, we observe a brief increase in authigenic Al_2O_3, Ba, Cu, La, Nb, V, and Y. Towards the top of this zone, furthermore, C, H, N, S begin to increase at about the same time as the C/N ratio declines. The uppermost zone (Ia, 0–126 cm) is associated with an overall decline in elemental concentrations combined with relatively high values of C, H, N, and S, and low C/N (Fig. 3).

Discussion

The lithostratigraphic, geochemical, and biological records from Whitefish Lake document the following sequence of events: (1) a deep-water, proglacial lake phase with high sediment flux; (2) subsequent shallowing of the lake under a more arid climate; (3) establishment of wild rice (*Zizania* sp.) in the western basin by ~5,300 (6,100 cal) BP as relative humidity increased and the lake deepened; (4) gradual increase in lake productivity beginning ~4,000 (4,500 cal) BP and continuing to recent times.

The basal, rhythmically laminated, sediments recovered from Whitefish Lake (unit D) are interpreted as varves due to their uniformity, repetitiveness, and similarity to varved sediments described elsewhere in the Lake Superior basin (Boyd et al. 2012; Breckenridge 2007; Loope 2006). Based on varve counts, the upper 1.5 m of unit D represents ~265 years of uninterrupted deposition in a deep-water setting. The combination of high sediment flux (~0.60 cm $year^{-1}$), paucity of biological remains, and deep-water conditions are consistent with deposition in a proglacial lake such as glacial Lake O'Connor, which formed due to impounding of meltwater to the north and east by the Superior Lobe of the LIS (Loope 2006; Phillips and Hill 2004; Zoltai 1963). As the LIS retreated from the northwestern Superior basin, lower elevation outlets would have opened and caused proglacial lakes perched in the uplands west of Thunder Bay to quickly drain into glacial Lake Minong (Loope 2006; Phillips and Hill 2004; Zoltai 1963). Radiocarbon dates east of the Marks Moraine indicate that the LIS had retreated from the Thunder Bay lowland shortly before 9,300 (10,500 cal) BP (Boyd et al. 2012; Table 1). Thus, conservatively, the proglacial lake phase in the Whitefish basin must have ended by at least this time.

The overlying ped-like structure between ~3.0 and 1.5 m indicates significantly lower water levels in Whitefish Lake. Similar structures have been observed in postglacial pond sediments in Alaska (Anderson et al. 1988; Edwards and Brubaker 1986) and elsewhere, and may be attributed either to pedogenic processes (Teller and Last 1982) or to the effect of freeze–thaw cycles on lake sediment (Anderson et al. 1988; Edwards and Brubaker 1986). In either case, they indicate a switch to shallow-water conditions in the Whitefish basin during all or some of the time represented by unit C. As summarized above, lake levels would have dropped with drainage of glacial Lake O'Connor >9,300 (10,500 cal) BP. However, pollen evidence from unit C also indicates a period of prolonged aridity which would have further contributed to lake-level decline; this can be seen in the elevated levels of *Ambrosia* and Chenopodiineae in zone IIb, and higher proportions of *Salix* and Cyperaceae due likely to expansion of shallow wetland shrubs and forbs inside the basin. Higher levels of 'unknown' pollen in this unit may reflect poorer preservation of common types due to periodic dying of the substrate, and anomalously high levels of *Abies* and *Alnus* pollen may be explained by incursion of these taxa into the basin as the lake level dropped.

The, often significant, impact of mid-Holocene climate change on lake levels has been observed elsewhere in North America. Lewis et al. (2007, 2008), for example, argue that the Michigan, Huron, and Georgian Bay basins were hydrologically closed between ~7,900 and 7,500 (8,770–8,300 cal) BP due to a combination of climate change and meltwater diversion into Hudson Bay. Similarly, based on stratigraphic evidence from the lower Kaministiquia River Valley (Ontario), Boyd et al. (2012) infer that the level of Lake Superior had fallen below its outlet between at least 9,100 and 8,900 cal BP. Thus, lower-than-modern lake levels were widespread in the early mid-Holocene across the Upper Great Lakes, and the record from Whitefish Lake appears to reflect wider climate-driven hydrological trends during this time.

Our plant microfossil results indicate that wild rice had colonized the western Whitefish Lake basin beginning by at least ~5,300 (6,100 cal) BP (based on linear extrapolation from a date of 4,330 ± 40 ^{14}C BP obtained 64 cm above the lowest occurrence of wild rice phytoliths [212 cm]) (Figs. 2, 4). Importantly, the interval between ~212 and 120 cm is also associated with changes in pollen content, bulk geochemistry, and lithostratigraphy which, when

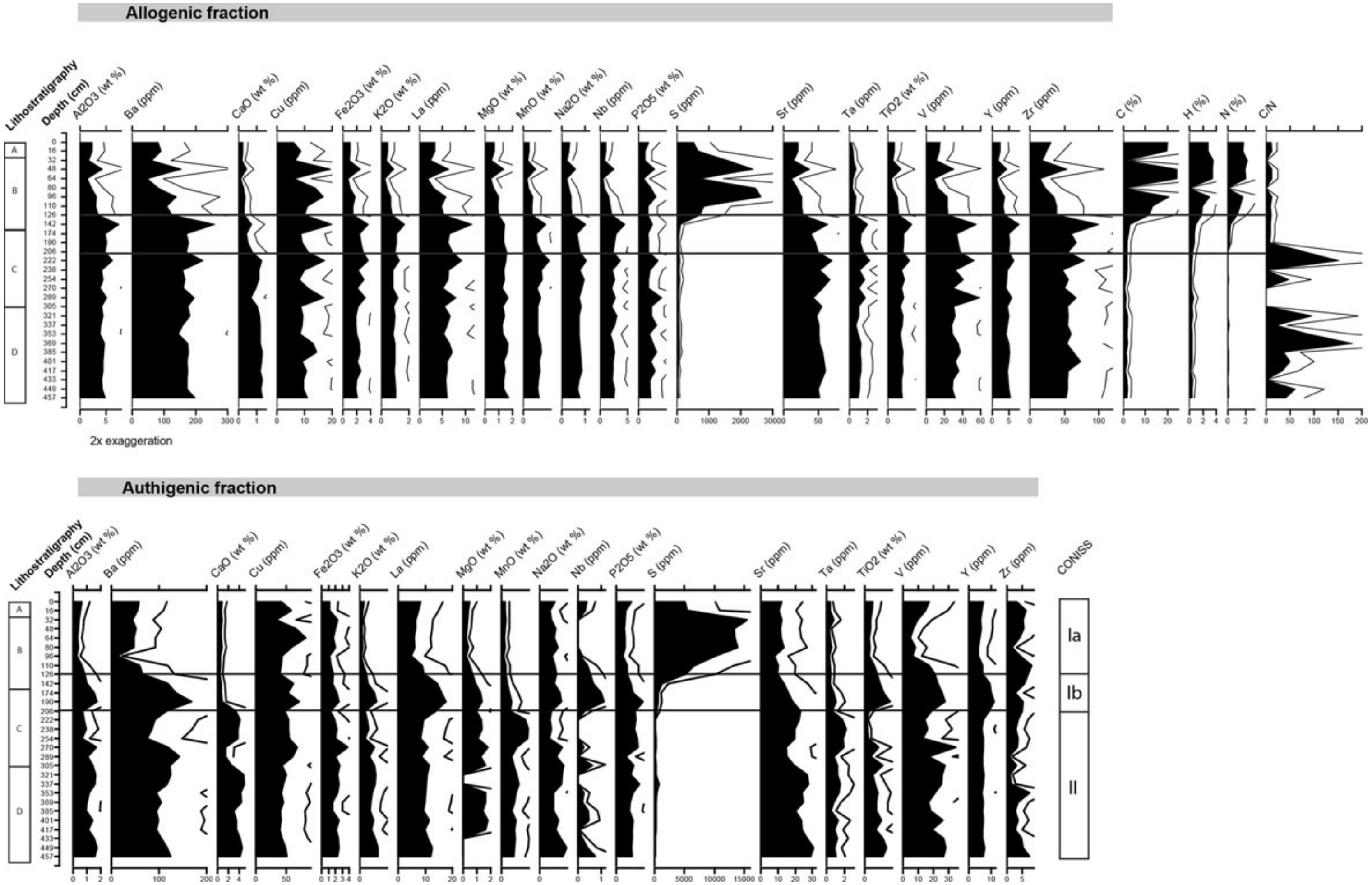

Fig. 3 Allogenic and authigenic elemental content of core WTFSH08-01, Whitefish Lake (Ontario)

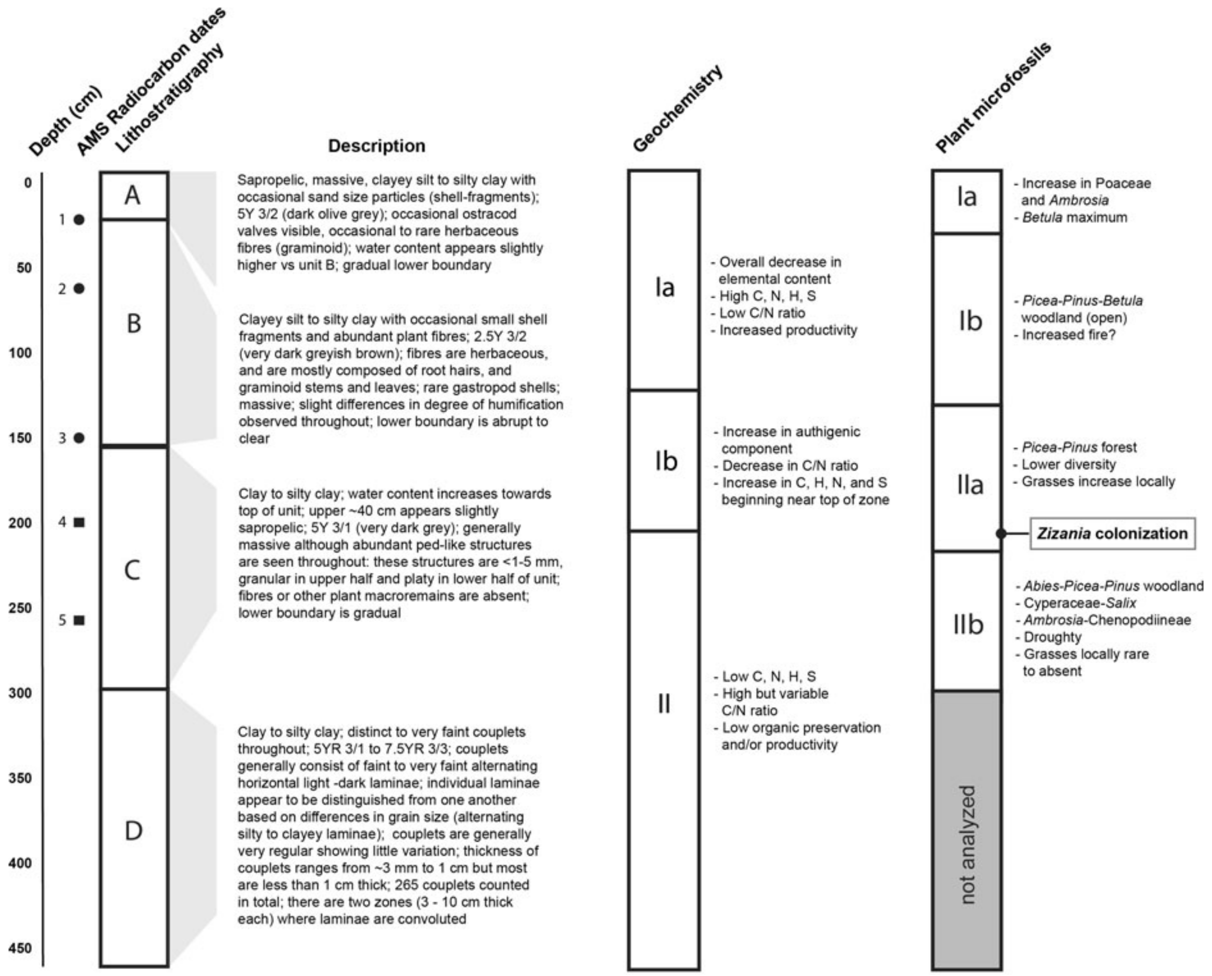

Fig. 4 Summary diagram showing major changes in lithostratigraphy, elemental and plant microfossil content of the upper ~4.5 m of sediment in Whitefish Lake. Numbers adjacent to radiocarbon age locations as listed in Table 1

combined, suggest increased relative humidity/decreased aridity, overall higher water levels, and increased lake productivity towards the top of this zone. Specifically, we observe the following trends during this time: (1) a decline in drought indicators (*Ambrosia* and Chenopodiineae) near the bottom of pollen zone IIa (210–120 cm) in addition to decreased evidence of shallow-water wetland shrubs and forbs such as sedge and *Salix*; (2) decreased pollen from terrestrial herbs and deciduous trees/shrubs, suggesting a more closed coniferous forest in the region; (2) increased carbon, hydrogen, nitrogen, and sulphur beginning at the top of this interval; (3) sharp decrease in C/N ratio, and increasing diatom content, indicating a rise in autochthonous organic matter (phytoplankton) in the lake (Dean 1999); (4) an increase in the authigenic elemental fraction at the bottom of this interval (peak at ~190 cm); and (5) transition from lithological units C to B, marked by an increase in water content, organic preservation, and disappearance of ped-like structures indicative of shallow-water depositional conditions. Based on these lines of evidence, we suggest that the timing of colonization of wild rice in Whitefish Lake was largely controlled by climate and associated changes in local hydrology; prior to ~5,300 (6,100 cal) BP, the lake may simply have been too shallow to sustain permanent stands of wild rice. Importantly, because Whitefish Lake is flat-bottomed, with little variation in depth from one place to the next, changes in lake level and other environmental parameters recorded at the coring site probably represent the whole basin.

Previous paleoecological research in the Upper Great Lakes has produced widely varying estimates for the first appearance of wild rice in this region. Based on size measurements of grass pollen from Rice Lake (central Minnesota), McAndrews (1969) provides an estimate of 1,935 ± 100 BP for the spread of *Zizania* across this lake—an event which he attributes to climate change and/or water shallowing due to sedimentation. Huber (2000), in contrast, argues that wild rice was part of the regional flora of Minnesota by the early Holocene. Direct support for the early postglacial origin of wild rice in Minnesota comes from Wolf Creek Bog, where *Zizania* seeds were recovered from lake sediment dating to ~10,600 (12,600 cal) BP (Birks 1976). Ultimately, however, the vast majority of paleoecological sites in this region record the presence of wild rice only after 3,000 (3,200 cal) BP (Huber 2000) indicating, perhaps, that significant expansion in the range of *Zizania* west of Lake Superior only occurred during the late Holocene (McAndrews 1969). This observation has led some archaeologists (Buchner 1979; Rajnovich 1984; Wright 1999) to conclude that the expansion of wild rice across the southern Boreal Forest was accompanied, and perhaps caused, by the northward and westward movement of Middle Woodland (Laurel) peoples into the same region.

The occasional recovery of wild rice processing areas and *Zizania* macrofossils in Laurel sites (Valppu 2000), as well as proximity of many of these sites to extant wild rice fields (Rajnovich 1984), supports the idea that Woodland peoples routinely exploited this food source in the Great Lakes region. At Whitefish Lake, *Zizania* phytoliths were recovered from carbonized food residue preserved on Laurel and Late Woodland pottery at the Martin-Bird, McCluskey, and MacGillivray sites (Fig. 1) (Boyd and Surette 2010), confirming that wild rice was harvested from the lake by precontact human societies over the last two millennia. However, it is clear from paleoecological evidence that wild rice had colonized the basin at least 3,000 years earlier. Woodland peoples could therefore not have been responsible for the introduction of wild rice into the study area, and the paucity of earlier (Archaic) sites reported in the region likewise lends little support for anthropogenic dispersal. Instead, as argued above, this event was probably the result of climate-driven lake-level rise and the gradual establishment by the end of the middle Holocene of wild rice habitat.

Beginning ~4,000 (4,500 cal) BP (120 cm), carbon, nitrogen, hydrogen, and sulphur values increase significantly (Fig. 3). Due to the high degree of organic preservation in unit B, this probably reflects the onset of reducing/anaerobic conditions in the basin as the rate of organic deposition and preservation increased. The high organic sedimentation rate during this time can be seen in core WTFSH09-02, where radiocarbon ages obtained on wild rice macrofossils between 42 and 102 cm range from 3,480 ± 40 to 3,520 ± 40 BP (Table 1). In general, organic influx may have increased after 4,000 (4,500 cal) BP due to higher densities of aquatic macrophytes (including *Zizania*), which would have contributed more organic litter to the lake, and/or increased eutrophication and associated phytoplankton growth (indicated by abundant diatoms above 134 cm). Eutrophication could have been caused by increased run-off due to higher fire frequencies, suggested in the pollen record (zones Ia and Ib) by a rise in fire-tolerant species (e.g., *Betula*, *Quercus*, *P. banksiana/resinosa*) and a decline in *Picea* and *Abies* (Fig. 2). However, the allogenic elemental fraction does not show a corresponding increase during this time (Fig. 3). Instead, concentrations of most inorganic elements generally decline in the upper 1.2 m of the sequence, likely due to dilution of siliclastic minerals as the autochthonous organic sedimentation rate increased. Alternatively, eutrophication of Whitefish Lake may have occurred as a direct result of wild rice colonization. One potential mechanism involves nutrient loading by waterfowl. Wild rice is a major source of food for geese and ducks in the southern Boreal Forest, and Whitefish Lake attracts and sustains very large populations of waterfowl today for this reason. Aquatic birds, furthermore, have been shown to change water quality in modern lakes (Kerekes 1994) and in the paleoecological record (McAndrews and Turton 2007) through nutrient importing, and perhaps by increasing the transfer of nutrients into the water through partial digestion of forage, among other effects (Bazely and Jefferies 1985).

Conclusions

Wild rice (*Zizania* spp.) was a mainstay of Aboriginal diet for at least the last two millennia across the Great Lakes and, today, forms an important component of aquatic ecosystems in many regional lakes. Despite its ecological and cultural importance, the history of this plant is poorly understood, and both the timing and cause of its spread during the Holocene are largely unknown. By tracing the evolution of a large wild rice lake near Thunder Bay, Ontario, this study provides the first paleoecological evidence of *Zizania* in the Canadian Boreal Forest. Our results indicate that wild rice began to colonize the Whitefish Lake basin by ~5,300 (6,100 cal) BP, in response to climate-driven lake level rise. Prior to this time, perhaps for much of the middle Holocene, the Whitefish basin was shallower than today due to a drier climate and it therefore may have failed to provide suitable habitat for wild rice. Once established, productivity was low in the lake until ~4,000 (4,500 cal) BP, when the rate of organic sedimentation increased and anaerobic depositional conditions were produced in the basin. We suggest that increased organic inputs at this time may have been the result of larger, more productive, populations of aquatic macrophytes over time, perhaps in combination with eutrophication.

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