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Multiproxy Lake Sediment Records at the Northern and Southern Boundaries of the Aspen Parkland Region of Manitoba, Canada

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MULTI-PROXY LAKE SEDIMENT RECORDS AT THE NORTHERN AND SOUTHERN BOUNDARIES OF THE ASPEN PARKLAND REGION OF MANITOBA, CANADA[1]

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ABSTRACT

Aspen parkland in central Canada may change substantially with increased warming and aridity as prairies replace forests, fire return intervals decrease, and lake levels decline. We examined the relationships among vegetation, climate, fire, and lake-ecosystem properties using lake sediment cores from the current northern and southern boundaries of the aspen parkland in southwestern Manitoba. We analyzed pollen, charcoal, sediment magnetics, biogenic silica, phosphorus, grain size, and LOI, and dated the cores using 210Pb and 14C (AMS, calibrated). The Jones Lake record, from the southern edge of the parkland, began considerably earlier (~11,000 cal BP) than the Mallard Pond record at the northern edge (~8,600 cal BP). These sites were characterized as prairie communities with low fire severity and relatively low lake productivity during the warm, dry period from 9,000-6,000 cal BP. Beginning around 6,500 cal BP at Jones Lake and 3,400 cal BP at Mallard Pond, conditions appeared to get wetter as indicated by arboreal pollen percentage increases from ~30% to 40-60% concurrent with a rise in charcoal and proxies for lake productivity (biogenic silica and percent organic phosphorus). Similar to previous studies along the prairie-forest border, we found that charcoal increased during warmer, wetter periods with increased forest cover and fuel loading rather than during warmer, drier periods of prairie dominance. Our results underscore the importance of regional changes in moisture, and its effects on lake levels and forest biomass, as a dominant control of the aspen parkland dynamics.

Key words: Aspen parkland, pollen, charcoal, ecotone, prairie–forest border, Canada

INTRODUCTION

The aspen parkland vegetation zone in Canada represents a climatically sensitive region where a combination of temperature, effective moisture, and fire control the dynamics of the boreal ecotone to the north and the grassland ecotone to the south. The prairie-forest border in North America currently extends from the Gulf of Mexico north through Minnesota into Manitoba, then roughly northwest to Alberta. In the United States, this border is generally a zone of oak barrens separating tall-grass prairie from deciduous forest (Anderson, 1982; Sims and Risser, 2000). In Canada, aspen parkland runs between mixed-grass prairie and boreal

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forest (Scott, 1995). Both aspen parkland and oak barrens are woodlands, with partial tree cover and nearly complete herbaceous ground cover.

The modern limits of the aspen parkland correspond to climate moisture gradients (Hogg, 1994). This ecotone marks the eastern limit of late-summer drought (Transeau, 1935; Hogg, 1994; MacDonald and Case, 2000). The northern boundary, between aspen parkland and boreal forest, generally occurs where annual precipitation exceeds potential evapotranspiration. The southern boundary, between parkland and prairie, is generally the line along which potential evapotranspiration is 15 cm greater than annual precipitation. During the dry season, wildfires in this zone favor the spread of *Populus tremuloides*, which can reproduce vegetatively from sprouts and does so more vigorously after burning (Anderson and Bailey, 1980). Precipitation exceeds potential evaporation most of the year, allowing tall grasses and forbs to flourish, but moisture availability usually becomes negative by August, resulting in water stress for trees (Faben-Langendoen and Tester, 1993) and favorable conditions for fire (Transeau, 1935; Collins and Wallace, 1990; Grimm, 1984).

Given the sensitivity of parkland to changes in temperature and precipitation, increased warming and aridity may cause a transition from forest to prairie and a decline in fire return intervals and lake levels. Hogg (1994) predicts that aspen parkland is likely to expand northwards at the expense of boreal forest and to be replaced at its southern margin by grassland. However, along the southern and western edges of aspen parkland in Alberta and Saskatchewan, aspen and other parkland trees have been spreading into grassland over the last 100 to 150 years, according to both land surveys (Archibold and Wilson, 1980; Grant and Murphy, 2005) and pollen records (McAndrews, 1988; Campbell and Campbell, 2000; Campbell and Flannigan, 2000). Campbell *et al.* (1994) and Campbell and Campbell (2000) explain these increases as a response to near-elimination of bison populations and near-total fire suppression, both factors associated with EuroCanadian settlement, which favor aspen at the expense of prairie vegetation.

With the potential for complex interactions among climate, vegetation, and fire, there is greater need for multi-proxy records that allow assessment of these variables simultaneously. Changes in grazing, insect herbivory, and human activity, both before and after EuroCanadian settlement will complicate vegetation and fire responses even further.

The timing of shifts in the prairie-forest boundary varies geographically, as different air masses responded to changes in seasonal insolation (Webb *et al.*, 1993). In northern Illinois, Nelson *et al.* (2006) found two periods of increased aridity and prairie expansion: the first from 9,000 to 7,500 years cal BP, the second after 6,000 cal BP. There is only a single period of prairie expansion in Minnesota, from roughly 8,000 to 4,000 cal BP (Camill *et al.*, 2003; Wright *et al.*, 2004), similar to the period of maximum aridity from ~8,300 and 4,500 cal BP in the Canadian northern Great Plains (Laird *et al*., 2007). This warm, arid period, the Holocene Thermal

Maximum (HTM), began in south-central Canada between ~9000 cal BP (10,200-8,500 depending on the site) and ended about 6,000 cal BP (Anderson *et al.*, 1989; Ritchie and Harrison, 1993; Vance *et al.*, 1995; Laird *et al*., 2007). The HTM is characterized by lower lake levels regionally (Ritchie and Harrison, 1993), indicating less precipitation than present from autumn to spring (Grimm, 2001).

Studies of fossil charcoal show complex relationships between fire and vegetation. Vegetation has to be dry enough to burn in the first place but sufficiently productive and continuous to carry a fire. In the above records from the prairie/forest border in southern Minnesota (Camill *et al.*, 2003; Umbanhowar *et al.*, 2006) and in northern Illinois (Nelson *et al.*, 2006), charcoal concentrations generally increase with independent measures of aridity (based on LOI and sediment-magnetic data). However, when these aridity measures decline, indicating a wetter climate, charcoal concentrations may continue to increase, as they do at Chatsworth Bog, Illinois, between 8,500 and 6,500 cal BP and Kimble and Sharkey Lakes, Minnesota, from 5,000 to 2,500 cal BP. Some records from prairie lakes (not ecotonal) show an inverse relationship between charcoal concentrations and aridity (Clark *et al.*, 2002; Nelson *et al.*, 2004; Brown *et al.*, 2005) through the entire Holocene; presumably, these ecosystems were dry enough to burn during much of the year, and fuel load was the limit factor on wildfires.

To better understand the relative influence of climate and fire on vegetation and lake dynamics in the aspen parkland region, we collected lake sediment cores from the northern edge of the aspen-parkland ecotone (the parkland/boreal transition) and the southern edge (the prairie/parkland transition) in southwestern Manitoba, Canada—a region that has not hitherto been intensively studied. We assembled multi-proxy records of pollen, charcoal, sediment magnetic, clastic grain size, biogenic silica (bSi), total and organic fractions of sediment phosphorus. We hypothesized that the timing of vegetation, fire, and lake ecosystem changes at the southern and northern boundary of this ecotone would be driven ultimately by the timing of regional changes in moisture. Increasing moisture, which should be reflected in past changes in lake productivity proxies (bSi, total P, and organic P), should cause an increase in arboreal pollen types. We predicted higher charcoal levels as a response to greater fuel availability, less complete combustion, and the possibility of crown as well as ground fires. However, it is unclear how the northern boundary of the aspen parkland (characterized by a pollen assemblage that includes *Picea*, *Betula* and *Pinus*) and southern boundary (characterized by a pollen assemblage rich in *Quercus* and herbs) will differ in their responses to climate change.

STUDY AREAS

Prior to European settlement, the dominant vegetation of the aspen parkland included grasses (Poaceae spp.), sage (*Artemisia* spp.), and prairie taxa, particularly *Festuca scabrella* (Sims and Risser, 2000), with scattered trees, mostly *Populus tremuloides*, *Betula papyrifera* and

Pinus in the north, with some *Quercus macrocarpa* and other hardwoods in the south (Ritchie and Lichti-Federovich, 1968; Weir, 1983). According to Hanuta (2006), a roughly equal mix of prairie and forest was present in south-central Manitoba just prior to Euroamerican settlement.

The two lakes we studied were located in southwestern Manitoba, Canada (Fig. 1). Jones Lake (49°26’47”N, 99°17’28”W) is about 13 km south of Glenboro, located on the southern margin of the aspen parkland near the border with the tall-grass prairie (Fig. 1). This site was about 20 km south of Lake Agassiz during the Lockhart high stand until some time before 10,800 ^{14}C BP (12,800 cal BP; Boyd, 2007). Mallard Pond (51°17’8”N, 101°19’29”W) is about 8 km north of Roblin, Manitoba, along the western border of the province and at the edge of the boreal forest. Water depths at the coring sites were 4.4 m for Jones Lake and 10.2 m for Mallard Pond. Jones Lake has a surface area of 56 ha while the surface area for Mallard Pond is 8.0 ha. We compared the vegetation changes in these lakes to previously published pollen records from this region, from the Glenboro site and E Lake (Fig. 1, Ritchie and Lichti-Federovich, 1968; Ritchie, 1969).

Our sample sites are both located in glacial tills but extensive areas of glacio-fluvial material occur less than 2 km around Jones Lake and large colluvial deposits are found less than 2.5 km east of Mallard Pond (Matile and Keller, 2006).

METHODS

Sediment retrieval and dating

We obtained multiple overlapping cores from the deepest parts of Jones Lake in August, 2002 and March, 2003 and Mallard Pond in January and April of 2003. The top 1 meter of flocculent sediment from both lakes was collected using a clear polycarbonate piston corer and vertically extruded in 2-cm sections. The remainder of each core was collected using a modified Livingston corer (Wright *et al.*, 1984), extruded in the field, and wrapped in polyurethane and aluminum foil for transport, and split in the lab. The sediment was stored at 4°C. Sediment recovery at Mallard Pond was incomplete in a few parts of the core, leading to gaps in the analyses.

Age chronologies for the lake cores were established using a combination of calibrated AMS ^{14}C dating of macrofossils and ^{210}Pb dating. Procedures for ^{210}Pb follow a modification of the ^{210}Pb dating method of Eakins and Morrison (1978), and both cores were analyzed at the ^{210}Pb dating facilities at the Science Museum of Minnesota’s St. Croix Watershed Research Station. Age profiles are determined using a Constant Rate of Supply (CRS) model according to the method of Binford (1990). All AMS ^{14}C samples (charcoal and/or terrestrial macrophytes) were cleaned (hand-selection and acid-base-acid rinse) and submitted to Lawrence Livermore National Laboratory for analysis. All dates were calibrated using CALIB 4.2 (Stuiver *et al.*, 1998 and 1999) and are reported here in calendar years before present (cal BP) (Table 1). The sediments at each lake appear to have been almost continuously deposited in Jones Lake, starting approximately 12,000 cal BP and Mallard Pond starting about 8,500 cal BP (Fig. 2).

Sediment and lake ecosystem properties

Sampling intensity varied with analysis. For magnetic analyses, samples were taken every ~2 cm down each core. For other analyses, samples 0.5 cm thick were taken approximately every 10 cm down the core (representing one sample per average of 105 years of deposition at Jones Lake and an average of 164 years at Mallard Pond), except for grain size, which we sampled at 20 cm intervals.

We measured isothermal remanent magnetization (IRM), and anhysteretic remanent magnetization (ARM) at the Institute for Rock Magnetism at the University of Minnesota. IRM was acquired in a magnetic field of 1500 mT and reflects the concentration of ferromagnetic minerals. ARM was acquired in a peak alternating field of 100 mT and a bias field of 50 µT. All remanence parameters were measured with a cryogenic magnetometer (2G-model 760-R). ARM is strongly influenced by the presence of small single-domain (SD) and small pseudo-single-domain (PSD) particles (Hunt *et al.*, 1995). Changes in the ratio of ARM/IRM are used to characterize the relative importance of fine SD particles vs. larger particles.

Loss-on-ignition was used to estimate the relative amounts of combustible components in the sediment (Dean, 1974). The sediment was ignited in a muffle furnace at 550°C to determine the organic fraction and at 1000°C to determine the carbonate fraction.

Percent biogenic silica from diatoms was measured to further describe the residual inorganic sediment fraction. Silica was extracted from 30-mg samples of freeze-dried sediment using a 1% solution of Na_3O_2 (Conley and Schelske 1993), and the concentrations were measured colorimetrically (McKnight 2000) using a Lachat QC 8000 FIA (Method 10-114-27-1-A). Where appropriate, estimates of percentage of silica were based on the intercept of a line fit through 3, 4 and 5-hour measurements (Conley 1998).

Samples for phosphorus analysis were freeze-dried and lightly ground, and extracted using procedures described by Engstrom and Wright (1984). Total phosphorus (TP) extraction was based on digests of ~0.1-g in 30% H_2O_2 for ~1 hour at 90°C and subsequent acidification with 2.5-N HCl. Inorganic P was extracted by shaking sediment samples (0.1 g) in 10 ml of 0.5 N HCl for 16 hrs. Extracted-P was analyzed colorimetrically using a Lachat Method 10-115-01-1-B. Organic-P was calculated as TP – Inorganic P and is shown as a percentage of TP.

To analyze grain size of siliceous particles, we prepared samples by heating ~ 3.0 g of sediment in 10% HCl for 15 min. Sediments were then digested in 30% H_2O_2 for 30 min (or until reaction ceased), and two mL of 11-M HNO_3 were added for 10 min. The samples were rinsed into centrifuge tubes with deionized water and methanol, and centrifuged at 4,500 rpm for 15 minutes. In order to minimize loss of sediment after rinsing, the supernatant was removed from the tubes using a sipper apparatus instead of being decanted (modified from Triplett, 2002). Processed sediment was frozen until analysis, and grain size was measured using a Horiba LA-920 particle analyzer.

Pollen analysis

Pollen preparation and identification were done according to the methods of Faegri *et al.* (1989) and identifications were confirmed using a reference collection derived from that of Dr. E.J. Cushing (University of Minnesota). A minimum of 300 terrestrial pollen grains or spores was counted for each level (with one exception: a total of 274 grains). Levels with very low pollen concentrations were excluded from the dataset.

The sediment record was divided into zones of similar assemblages of terrestrial pollen types that are at least 5% of the total sum of terrestrial pollen and spore types for at least one level by psimpoll (Bennett, 1994), which uses algorithms from Birks and Gordon (1985). Visible changes in the pollen diagram matched the zone boundaries determined by psimpoll through optimal (non-binary) splitting of the information content of the pollen percentages. Zone boundaries were chosen that reduced the total variance (in common pollen types) by a statistically significant amount, indicating major changes in vegetation.

Pollen assemblages within a given zone are considered to have been deposited by the same vegetation type. Ecosystems are identified statistically in this analysis, through simultaneous changes in common types in assemblages, rather than by the presence or absence of a single marker. *Populus* pollen in particular seemed to be a poor choice for a marker, because it tends to be underrepresented relative to the basal area of the parent tree compared to pollen of other wind-pollinated tree types (Lee *et al.*, 1996). At Jones Lake, *Populus* is a rare pollen type, generally <1%, even in assemblages from the surface sediments, although the lake is surrounded by modern aspen parkland (Fig. 3 and 5).

Although both sites are in areas that have been cleared and are intensively farmed, the pollen assemblages in the surface sediments strongly resemble those that have been deposited over at least the past thousand years. The residual parkland vegetation still contributes far more of the regional pollen rain than the insect-pollinated crops and weeds associated with modern Great Plains agriculture. Therefore, the assemblages of the top zone are interpreted as aspen parkland (somewhat different types at the northern and southern edge), with vegetation similar to the aspen parkland known to flourished in each place hundreds of years ago (Weir, 1983; Scott, 1995).

Charcoal analysis

Charcoal was sieved from 1.0-cm^3 sediment samples using a 180-µm screen, and the area of each particle was measured at 20x magnification using image-analysis software (Clark and Hussey, 1996). Charcoal influx was calculated by multiplying the charcoal concentration by the sediment accumulation rate derived from the age model (Fig. 2). The analysis methods for magnetic properties, pollen, charcoal, and biogenic silica are also described in Camill *et al.* (2003).

RESULTS

Using the palynological zonation, we compared changes in vegetation in each of the zones to changes in sediment, lake-ecosystem, and fire proxies (magnetics, bSi, total and organic P, LOI, and grain size and charcoal). Below, we present a chronological analysis of each zone for both lakes.

Jones Lake

J1 (11,150 - 10,400 cal BP): The basal assemblages of J1 contain high percentages of *Picea* pollen (~80%), indicating a closed-canopy forest, with a little *Betula*, Poaceae, Cyperaceae, and *Artemisia* (~5%) and traces of other prairie types (Fig. 3). *Picea* pollen percentages decline as those of *Pinus* pollen increase (to ~10%) at the top of the zone. Traces of *Populus* pollen are visible throughout the record, but often as a single grain, which may have been carried to the lake from far away by wind.

Sediment proxies indicate recent glacial retreat from the area and the erosional deposition of glacial silts (Fig. 4). IRM and ARM/IRM reach maxima of 0.71 A $m^{-1}$and 0.12 (with the exception of a single ARM/IRM peak at the top of the core) indicating abundant, fine-grained magnetic material consistent with glacial silts. Alternatively, deeper water (~15 m, 5m deeper than present) (Fig. 2), combined with trees to block winds, may have resulted in anoxic conditions that favored magnetotactic bacteria that produce single-domain magnetic grains (Geiss *et al*., 2004). However, anoxia in the sediments also speeds dissolution of those magnetic minerals.

The sediment is relatively rich in organic matter (~25%) and bSi is at its highest (~10%) in this zone. Sedimentation rates were low (Fig. 2), and mean grain size of clastics (~18 µm) is similar to other zones. TP concentrations (~0.75 mg gm-1) are relatively high, but low OP (~20%) suggests generally low lake productivities. Charcoal concentration (~1 mm^2 cm^{-3}) and influx (~0.05 mm^2 cm^{-2} yr^{-1}) were uniformly low during this period.

J2 (10,400 – 9,100 cal BP): *Picea* pollen percentages decline to less than 5% early in the zone as *Pinus* pollen rapidly increases to 20-40% of the total pollen assemblage. *Quercus*, *Betula*, *Ulmus*, and other hardwood pollen types are continuously present (mostly in small amounts) from this point upwards, suggesting that these thermophilous taxa were now present in the regional vegetation, and that the climate was warming. It was getting drier as well; as indicated by the increase in pollen from Poaceae (up to 38%, the maximum for the Jones Lake record) and other herbs (Fig. 3).

IRM (~0.15 A m^{-1}) and ARM/IRM (~0.05) are both lower than in zone J1, indicating reduced concentrations and overall relatively larger magnetic particles, perhaps as the result of reduced erosion of glacial silts (Fig. 4). Mean grain size of clastics drops slightly at the base of the zone, suggesting reduced surface erosion rates in the area around the lake or a shift to more windborne material. Carbonates are at their most abundant in this zone (~35%), perhaps due to a shift to greater deposition of fine wind-borne material or increased water temperatures causing greater in-lake precipitation. BSi decreases to ~8%, TP levels remain virtually unchanged, and OP increases slightly to 30%, suggesting that the lake remained largely unproductive. There is no charcoal present in this zone, although there may have been fires; they simply left nothing behind.

J3 (9,100-6,300 cal BP): Poaceae pollen and pollen from other prairie taxa dominate this zone, especially *Ambrosia* (15-20%), *Artemisia* (15-20%), and Chenopodiineae (5-12%), suggesting a shift to warmer, drier grassland conditions (Fig. 3). There are substantial amounts of *Pinus* pollen (20-40%) as well, but this may have been derived from small stands, especially near lakes, streams, or other fire breaks, and some of it may have blown in from distant forests. *Picea* pollen is still present, but in small amounts (~2%) for the rest of the record, but it too may have come from distant forests or small, isolated stands of trees.

IRM (0.1 A m^{-1}) remains relatively constant until it declines by nearly half at ~ 6,400 cal BP (Fig. 4). Because ARM/IRM does not decline markedly, indicating fewer magnetic particles but of the same size. The siliceous fraction of the inorganic matter is dominated by fine silt-sized particles (15 µm), likely from wind-borne material. BSi (~10%) increases (~7,800 cal BP) during this period but organic matter, TP, and OP remain relatively unchanged, suggesting continued low lake productivity. Charcoal concentration (~0.5 mm^2 cm^{-3}) and influx (~0.05 mm^2 cm^{-2} yr^{-1}) remain low.

Craine and McLauchlan (2004) interpret *Ambrosia* pollen increases accompanied by decreases in Poaceae and charcoal as a response to intensive grazing rather than to aridity. But, they also predict patches of bare ground in grazed areas, which would lead to an increase in coarse siliceous particles deposited in Jones Lake, the opposite of what we observed. Therefore, we interpret the dominance of prairie taxa at Jones Lake as a response to HTM aridity. *Ambrosia* is favored by hot, wet summers, but these can be interspersed with dry ones (Grimm, 2001), which will permit grass fires and discourage the spread of trees.

J4 (6,300 – 2,450 cal BP): Poaceae pollen percentages increase (20-25%) as those of *Ambrosia* (15%-5%) decline early in the zone. Chenopodiineae and *Pinus* pollen percentages decrease gradually. *Quercus* and *Betula* pollen percentages increase early in this zone to ~7% and ~3% respectively, indicating that trees started to invade the prairie, possibly as conditions became more humid (Fig.3).

Sediment and fire proxies indicate that terrestrial and aquatic landscapes were becoming more productive (Fig. 4). Average IRM and ARM/IRM levels remain constant. Percent organic matter nearly doubles (~15%), which, in combination with higher bSi (~10%), peaking at 5,500 cal BP, increased TP (~0.75 mg gm^{-1}) and OP (~40%), suggests major increases in lake productivity, perhaps associated with warmer temperatures or higher lake levels. Grain size of terriginous materials increases and is more variable (~10-45 µm), reflecting inputs of fine sands, perhaps as a result of rising lake levels but more likely associated with extended dry periods that resulted in extensive movements of dunes in SW Manitoba at roughly the same period (Wolfe *et al.*, 2000; Running *et al.*, 2002). The combination of increased terriginous inputs and increased productivity was responsible for doubling the sedimentation rate for the lake beginning ~5,500 cal BP. Macroscopic charcoal concentration (~2 mm^2 cm^{-3}) and influx (~0.35 mm^2 cm^{-2} yr^{-1}) increased throughout the zone, especially after ~4,000 cal BP, indicating greater biomass and fuel loading.

J5 (2,450 cal BP – present): *Quercus* pollen percentages increase from ~15% to ~30% of all terrestrial pollen as the vegetation of the area changed from prairie to woodland (Fig. 3). Although *Populus* pollen percentages are very low in these assemblages, their resemblance to the surface assemblage indicates that the woodland in question is aspen parkland similar in composition to that growing in the area today. Since *Populus* pollen is a rare type at Jones Lake, its percentages were not used to define zones for that record. There is no sign of an *Ambrosia* or *Salsola* peak in J5 of the sort found in the Midwestern US at the start of intensive agriculture (Brugam, 1978; Jacobson and Engstrom, 1989), although the area around the lake is currently intensively grazed.

Sediment and fire proxies indicate a shift towards less arid conditions (Fig. 4). IRM decreases to ~0.04 A m^{-1}, and ARM/IRM changes little from zone J4, except for the top level, where the value is by far greatest in the core (it is not shown on the diagram: 0.87). The decrease in IRM may be partly due to dilution by increasing amounts of organic matter (~20%). BSi decreases slightly during this period to an average of 4%, but TP remains relatively high (~0.9 mg gm^{-1}), and OP increases to ~50%, suggesting continued high lake productivity. The decrease in bSi may also be due to dilution effects or to a shift in the composition of the primary producers (blue-green algae for example) not captured by our proxies. The decrease in the size of terriginous material (~20 µm) and reduced sedimentation rate (Fig. 2a) likely reflect a decrease in sediment input resulting from eolian activity (Wolfe *et al.*, 2000; Running *et al.*, 2002) as dunes and other open areas became vegetated.

Charcoal concentrations (~7.5 mm^2 cm^{-3}) and influx (~1.0 mm^2 cm^{-2} yr^{-1}) increase after 2,000 cal BP, coinciding with increasing arboreal pollen percentages (mainly *Quercus*) and decreasing herbaceous percentages (Fig. 3). As for results found previously (Camill *et al*., 2003), these data suggest that fire was likely responding to vegetation productivity, fuel loading, and decreasingly arid conditions. Fires had more fuel to burn and, if that fuel were wetter, it would combust less completely, leaving more charcoal behind.

Mallard Pond

M1 (8,600-5,100 cal BP): The basal sediments in Mallard Pond reflect conditions similar to the warm, dry zones J2-J3 in the Jones Lake record (Fig. 5). M1 has moderate percentages of *Pinus* pollen (>20%), and little *Picea* or hardwood pollen. There are high percentages of Poaceae pollen and that of other herbs, particularly Cyperaceae and *Artemisia* (individually ~10-20%), and Chenopodiineae and Asteraceae subfam. Asteroideae (~5%). *Ambrosia* pollen percentages are much lower than in zone J-3 at Jones Lake, possibly indicating cooler summers (Grimm, 2001). These data suggest that the region around Mallard Pond was prairie, perhaps with enough scattered stands of *Pinus* to be called a woodland. Moderate levels of *Myriophyllum* pollen were present in these assemblages (~5%).

Sediment and fire proxies support the inference of warmer, drier conditions drawn from the pollen record (Fig. 6). The concentration of magnetic minerals is, on average, highest during this zone with IRM averaging 4.5 A m^{-1}, and ARM/IRM is at its lowest (~0.02), indicating the presence of relatively large magnetic grains. The magnetics, combined with abundant inorganic material (~70%) and relatively coarse terriginous material (15.5 µm), suggest that erosion of glacial silts from the surrounding uplands was prevalent until at least ~7,500 cal BP, which would require at least some patches of bare ground in certain seasons.

Relatively low percentages of organic matter (~15%), bSi (~2%), and TP (~1.0 mg gm^{-1}) values suggest low productivity, yet bSi and organic matter increased by 50% or more during this period. OP is ~35% but declines at ~5,200 cal BP. Charcoal concentration (~2.5 mm^2 cm^{-3}) and influx (~0.10 mm^2 cm^2 yr^{-1}) were moderately high and increased throughout M1.

M2 (5,100-3,400 cal BP): *Pinus* pollen (<20%) percentages decrease as those of *Betula* (~10%) increase (Fig. 5). Pollen percentages from prairie-type plants remain high, and *Quercus* and *Alnus* percentages increased (although remaining less than 5%). There is also a large increase in *Myriophyllum* percentages (equal to 20% of the total terrestrial pollen) and a peak of *Typha* pollen in mid-zone, indicating a decrease in lake level that increased the littoral area, because North American *Myriophyllum* species tend to grow sparsely in water more than 1m deep (Aiken *et al.*, 1979). Overall, the relative abundance of arboreal vs. herbaceous taxa became much more variable. The pollen record suggests that this period was characterized by increasingly variable moisture during a shift to warm, but wetter conditions.

IRM (~0.10 A m^{-1}) and ARM/IRM (~0.03) fluctuate little but remain relatively low (Fig. 6). Mean grain size is lower than in M1 (~7.5 µm) and declines slightly at the top of M2. Carbonates are at their highest (~27%), perhaps in response to warming conditions. BSi (~2.5%) is low during this zone but increases by about 50% at ~4,500 cal BP, approximately the same time that the sedimentation rate increased, suggesting higher productivity. Charcoal concentration (~0.5 mm^2 cm^{-3}) and influx (~0.03 mm^2 cm^{-2} yr^{-1}) are low, because, as the pollen data suggest, there was little fuel for fires (Fig. 5).

M3 (3,400-1,550 cal BP): Percentages of all tree and shrub pollen types increase at the base of M3, but fluctuate, as they did during M2: *Picea* pollen increases to almost 5%, *Pinus* to ~20%, and *Betula* to 20-40% (Fig. 5). Other arboreal pollen types continuously present include *Populus*, *Quercus*, *Salix*, and *Alnus*. Herbaceous pollen percentages decrease but only down to 40-50%. These data suggest that Mallard Pond was surrounded by woodland. The high percentages of *Populus* indicate that this woodland was aspen parkland, although of a different composition from that in zone J4, with higher percentages of tree pollen types, especially *Populus, Picea, and Betula*, but lower percentages of *Quercus*. *Myriophyllum* pollen percentages also decline, suggesting increasing water levels.

Sediment and fire proxies suggest that, like zone J4 in Jones Lake, this zone was characterized by warm, but wetter, conditions (Fig. 6). IRM increases slightly (~0.15 A m^{-1}) from the previous zone, and ARM/IRM (~0.045) almost doubles at the base of the zone and fluctuates considerably throughout, indicating a shift toward finer magnetic particles, possibly produced by magnetotactic bacteria or the episodic addition of fine-grained minerals as also suggested by fluctuations evident in the percent of organic matter (~18%). Terriginous grain size (~7 µm) increases gradually through the period but varies relatively little. Biogenic silica (~4%) again nearly doubles, and both TP (~1.16 mg gm^{-1}) and OP (~35%) increase substantially, reflecting more productive lakes and possibly higher water tables. Charcoal concentration (~2 mm^2 cm^{-3}) and influx (~0.3 mm^2 cm^{-2} yr^{-1}) increased gradually and became more variable in response to the available fuel load (Fig. 5).

M4 (1,550 cal BP – present): *Picea* and *Populus* pollen percentages increase in M4 (Fig. 5). *Myriophyllum* and *Betula* pollen percentages decrease while Poaceae, Cyperaceae, and Chenopodiineae pollen percentages increase near the base of the zone. Mallard Pond is at the border between the modern boreal forest and the aspen parkland, but little spruce grows right near the lake. Again, the similarity of the assemblages that define this zone to the modern assemblage at the top of the core imply that they were all produced by aspen vegetation much like that of the area today.

Myriophyllum pollen percentages are variable in this zone, with peaks over 60%, possibly indicating changes in lake level. One of these peaks is in an assemblage deposited about 800 cal BP, so the pollen must have come from *M. exalbescens* or *M. verticillatum*, one of the native milfoils. Neither of these has been observed undergoing large and abrupt population increases that characterize the Eurasian invader *M. spicatum* in historic times, but the three types are closely related (Aiken *et al.*, 1979). Presumably, uncolonized shallow-water habitat became available when lake levels rose, and a native milfoil was able grow densely and to flower abundantly. These populations declined sharply at times when lake levels fell.

Sediment and fire proxies were consistent with cooler, wetter conditions at this time (Fig. 6). IRM (~0.3 A m^{-1}) doubles at ~1,000 cal BP. At the same time, the increased ratio of ARM/IRM (~0.05), combined with little change in size of terriginous particles until ~200 cal BP, suggests increasing activity of magnetotactic bacteria. LOI carbonate and organic sediment percentages remain little changed. BSi (~4%) remains relatively high in this zone. TP (~2.5 mg gm^{-1}) more than doubles, although OP does not show a similar increase. The absence of an increase in organic sediment, BSi, or OP is puzzling in light of the increase in TP, and suggests other factors may have limited productivity or increased decomposition rates.

DISCUSSION

The modern vegetation around Mallard Pond is somewhat different from that surrounding Jones Lake, although both are aspen parkland. These differences are reflected in pollen in the surface layers of each core; M4 has more *Populus* pollen, typical of the nearby boreal forest, and J-5 has more *Quercus* pollen (presumably derived from *Quercus macrocarpa* which grows more abundantly near the prairie-parkland border).

Despite differences in community composition, the southern and northern boundaries of the aspen parkland in Manitoba responded strongly to changes in moisture. Climatic changes and corresponding ecosystem shifts apparently occurred in two steps: a shift to relatively more mesic conditions beginning ~6,400 cal BP, followed by another increase in moisture after ~2,500-3,500 cal BP. It is possible that the first increase in moisture allowed more trees to grow in protected sites, whereas the second allowed tree populations to expand into less-protected areas. Changes in the seasonality of precipitation probably had more of an effect on the local environment than changes in the average annual amount of precipitation.

Both lakes showed a dominance of prairie taxa during the Holocene Thermal Maximum, which occurred ~9,000-6,000 cal BP in this region (Anderson *et al.*, 1989; Ritchie and Harrison, 1993; Vance *et al.*, 1995; Laird *et al*., 2007). Beginning around 6,400 cal BP at Jones Lake, conditions likely became wetter as indicated by increases in arboreal pollen percentages concurrent with an increase in charcoal (suggesting greater terrestrial biomass and fuel loading) and proxies for lake productivity (biogenic silica and organic phosphorus), but the corresponding changes at Mallard Pond 5,100 cal BP reflect more variable moisture availability, which presumably restricted tree/shrub growth, in turn reducing the amount of charcoal left by fires (Figs 3-6). If the regional increase in precipitation at the end of the HTM was primarily in the fall, winter, and spring months, there may have been a greater effect on the vegetation at the southern edge of the aspen parkland than at the northern edge. The southern part would have received a greater proportion of its winter precipitation as rain rather than as snow compared to the northern edge, resulting in relatively greater contributions to soil moisture than to runoff.

However, parkland replaced prairie in the Mallard Pond record about 1,000 years earlier (~3,500 cal BP) than at Jones Lake (~2,500 cal BP). The more arid conditions of the HTM may have persisted longer at the southerly Jones Lake site. Alternatively, frequent grass fires may have prevented aspen parkland establishment around Jones Lake without leaving much charcoal.

Similar to previous vegetation-history studies of ecotones between prairie and forest biomes, we found that charcoal increased during wetter periods with increased tree cover and fuel loading rather than during drier periods of prairie dominance (Camill *et al.*, 2003; Nelson *et al.*, 2006; Clark *et al.*, 2002). Fire frequency is partly a function of precipitation and potential evaporation, but charcoal, the basis of our estimates of fire frequency, is also affected by the amount of fuel and how thoroughly it can be combusted (Umbanhowar and McGrath, 1998). The vegetation at Jones Lake and Mallard Pond is probably not changing as part of a direct response to climate but rather in response to changes in fire frequency and the amount of vegetation burned.

There have been several attempts to synthesize the origin and history of aspen parkland. Strong and Hills (2005) identify aspen parkland as a distinct ecosystem since 8,000 ^{14}C BP in southwestern Manitoba. They define aspen parkland as “a grassland pollen group” with a minimum *Populus* pollen percentage of 0.5%. They amalgamated pollen counts within 1000-year increments, effectively increasing pollen count size and reducing random variation in the number of grains counted for rare types. At both Jones Lake and Mallard Pond, the zones categorized as aspen parkland, (J5, M3, and M4), are described as woodland rather than grassland, because their arboreal pollen percentages are generally over 40%, and because there are scattered stands of trees growing in the remaining natural areas of the modern aspen parkland, including those around Jones Lake and Mallard Pond.

Our work supports the earlier analyses of pollen records from this area by Ritchie (1969) and Ritchie and Lichti-Federovich (1968). Their chronologies are based on radiocarbon dates from bulk sediment rather than AMS. Bulk sediment samples may include older carbon from soils and sediments in the lake’s watershed (Cohen, 2003), which may be why zone transitions in the Glenboro site and E Lake occur earlier than in the Jones Lake and Mallard Pond records, particularly the older ones.

Ritchie (1969) found evidence for mid-Holocene aspen parkland at E Lake (50°42’ N, 99°42’W) (Figs. 1, 7) in the Riding Mountain upland, which currently supports boreal forest, near the border of the modern aspen parkland. He interprets pollen assemblages from zone (c) of the E Lake record as having characteristics of aspen parkland, particularly the percentages of

Corylus, even though they lack *Populus* pollen (perhaps because of preservation issues). The arboreal pollen in this zone is from shrubs, mostly *Alnus*, *Salix*, and *Corylus*, rather than from the tree types more common in the aspen parkland zones of the Glenboro site, Jones Lake, and Mallard Pond records. The E Lake record also shows a prolonged prairie period in zone b, during the early Holocene, well to the north of the modern limit of prairie (Fig. 7). Ritchie and Lichti-Federovich (1968) observed a pollen sequence very similar to our Jones Lake record in sediment from the Glenboro site (49°24'N, 99°18'W), a few kilometers west of Jones Lake (Figs. 1 and 7).

According to our interpretation, aspen parkland became established at the northern end of its range, represented by Mallard Pond, about 3,400 cal BP and spread to the southern edge of its range around Jones Lake 2,400 cal BP, which is similar to the interpretation of Ritchie and Lichti-Federovich (1968) for the Glenboro site (Fig. 7). Before 3,400 cal BP, southwestern Manitoba was prairie with lower abundance of arboreal taxa (Figs. 3-6). This prairie was similar to the grasslands now found south of the modern aspen parkland, so during the mid-Holocene, aspen parkland, or a vegetation type with many of the same dominant species and physical features, may have flourished north of its current location or at higher elevations, and spread from there to the area around Mallard Pond as Manitoba became cooler and wetter in the late Holocene.

The interactions among climate, vegetation, fire, and grazing make interpretations of past changes challenging. Fire frequency is also affected by factors other than climate, such as human activity. Boyd (2002) proposes that fire frequency in southwestern Manitoba increased after 2,500 ^{14}C BP because Plains Woodland Native Americans intentionally burned areas to maintain prairie habitat for the local bison populations that they hunted. Just as in records from Alberta (Campbell *et al.*, 1994), *Populus* pollen percentages for the last hundred years are highest for the entire record in both the Jones Lake and Mallard Pond cores, indicating a greater abundance of aspen in the regional vegetation. The relative contributions of changes in bison populations, human fire management strategies or land use, or climate change and attendant wildfire changes to this recent increase in aspen in southwestern Manitoba are not yet understood. However, human land use changes during the latest century may overwhelm the recent effects of climate change. Aspen itself may be spreading, but most of the area of modern aspen parkland has been converted to farmland; only about 10% remains under woodland or any other type of natural habitat (World Wildlife Fund, 1999).

CONCLUSION

Identifying the interactions among climate, vegetation, fire, and lake-ecosystem dynamics is essential for understanding how the aspen parkland ecotone will change with climate warming. With the onset of the Holocene Thermal Maximum ~9,000 BP, post-glacial forests were replaced by dry prairie. Beginning around 6,400 cal BP at Jones Lake and 3,400 cal

BP at Mallard Pond, conditions appear to get wetter as indicated by arboreal pollen percentage increases from ~30% to 40-60% concurrent with an increase in charcoal and proxies for lake productivity (biogenic silica and organic phosphorus). However, lake levels at Mallard Pond appeared to fluctuate more than those of Jones Lake. Trees and shrubs became more common after 3,400 cal BP, as the vegetation developed into aspen parkland. At Jones Lake, modern aspen parkland does not develop until 2,450 cal BP. The aspen parkland continues to change: *Populus* pollen is becoming more common. Our work supports previous studies of the prairie-forest border indicating that wetter conditions increases tree biomass and fuel loading, which, in turn, increase fire severity. Charcoal was least abundant during warm, dry periods when this region was dominated by prairie taxa. We found that both the northern and southern parkland boundary is responsive to changes in moisture, and indicators of fire severity tend to be greatest in modern sediments.

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Table 1: AMS radiocarbon dates from Jones Lake and Mallard Pond, Manitoba, Canada.

CAMS #	Depth (cm)	^{14}C yr BP	+/- error	Calibrated age (cal yr BP)	Material dated
Jones Lake					
105832	428	345	30	390	Charcoal
103308	495.5	995	35	920	Charcoal
103309	557	1645	35	1540	Charc. Frags, Seeds[1], Leaf Frag.
103310	607	2065	35	2030	Charcoal
103311	797	3025	40	3230	Charcoal
105121	924	3495	35	3760	Charcoal
105122	1054	3800	40	4180	Charcoal
105123	1164	4455	50	5100	Charcoal
109284	1264.4	6230	45	7120	Charcoal
109285	1387.4	7250	60	8060	Charcoal
97116	1488.4	8320	40	9350	Charcoal
97117	1555.4	9940	70	11360	Charcoal
Mallard Pond					
105833	1082	1645	35	1550	Charcoal Fragments
105116	1145	1905	40	1850	Charcoal Fragments
103810	1189	2220	35	2230	Cone Scale
107018	1242	2535	40	2590	Charcoal Fragments
107019	1292	2980	60	3160	Charcoal Fragments
105118	1364	3700	50	4040	Charcoal and Leaf Fragments
105117	1395	4295	40	4860	Charcoal and Leaf Fragments
105119	1443	4565	40	5180	Charcoal Fragments
105120	1491	5840	60	6650	Charc. Frags & *Polygonum* Seeds
93676	1528.5	6325	40	7260	Charcoal Fragments
97115	1565.5	7960	40	8840	Charcoal Fragments & Seeds

[1]All seeds submitted for radiocarbon samples are almost certainly from terrestrial plants. Seeds of the following aquatic taxa were excluded from radiocarbon samples: *Potamogeton*, *Najas*, *Elodea*, *Ceratophyllum*, or *Vallisneria*.

FIGURE 1: Map of Manitoba, showing vegetation formations (modified from Weir 1983) and location of Jones and Mallard Lakes. Locations of E and Glenboro Lakes (Ritchie and Lichti-Federov, 1968; Ritchie 1969) are discussed in text and included for reference.

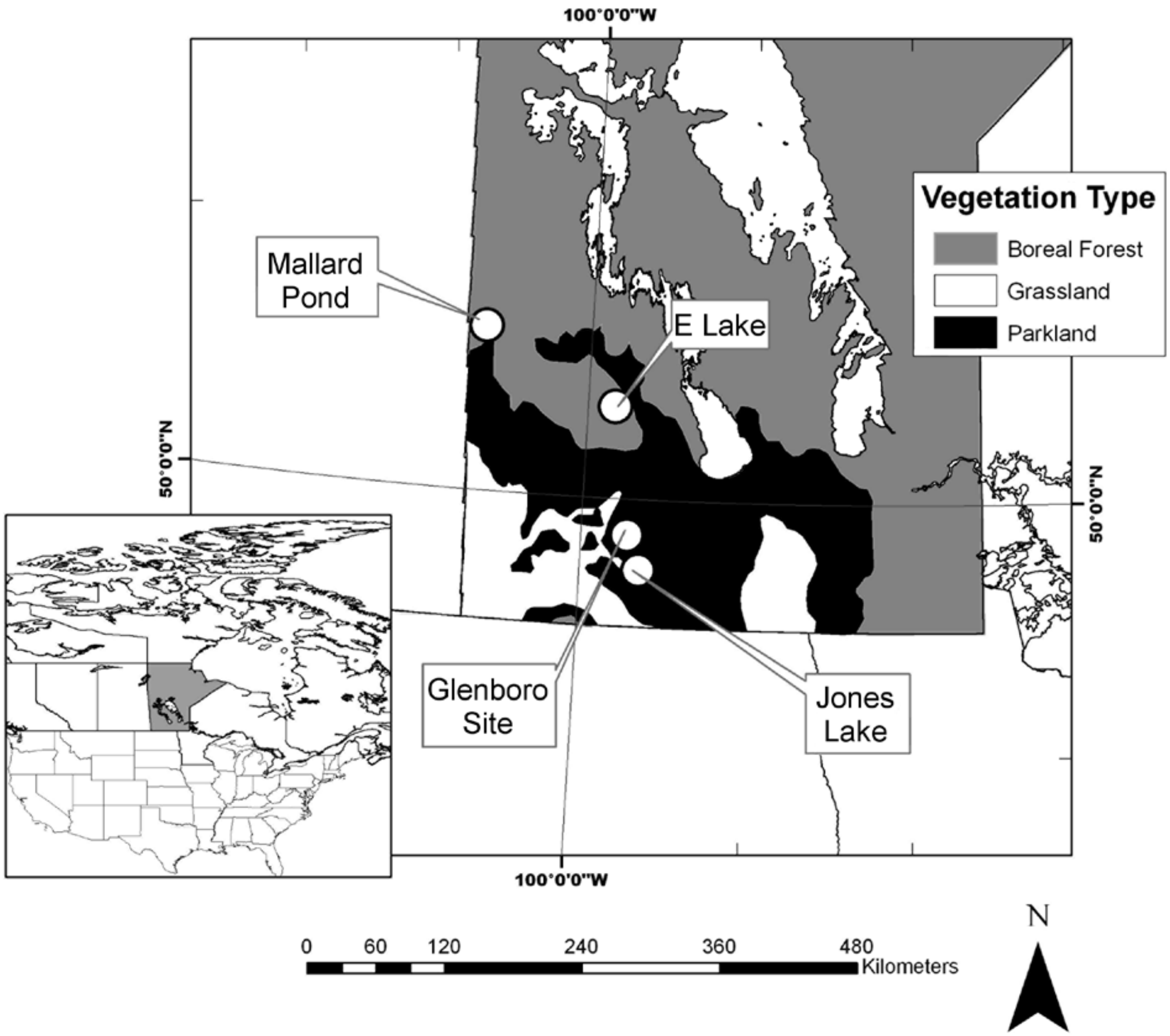


FIGURE 2: Calibrated age-depth models for (a) Jones and (b) Mallard Lakes based on 210Pb dating of surface sediments and calibrated AMS-^{14}C dating of charcoal or plant macrofossils (Table 1).

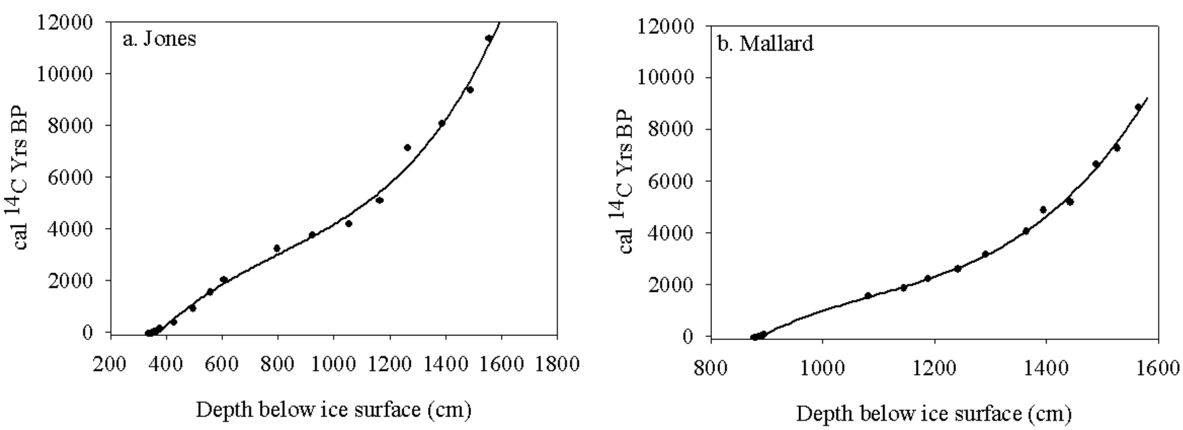
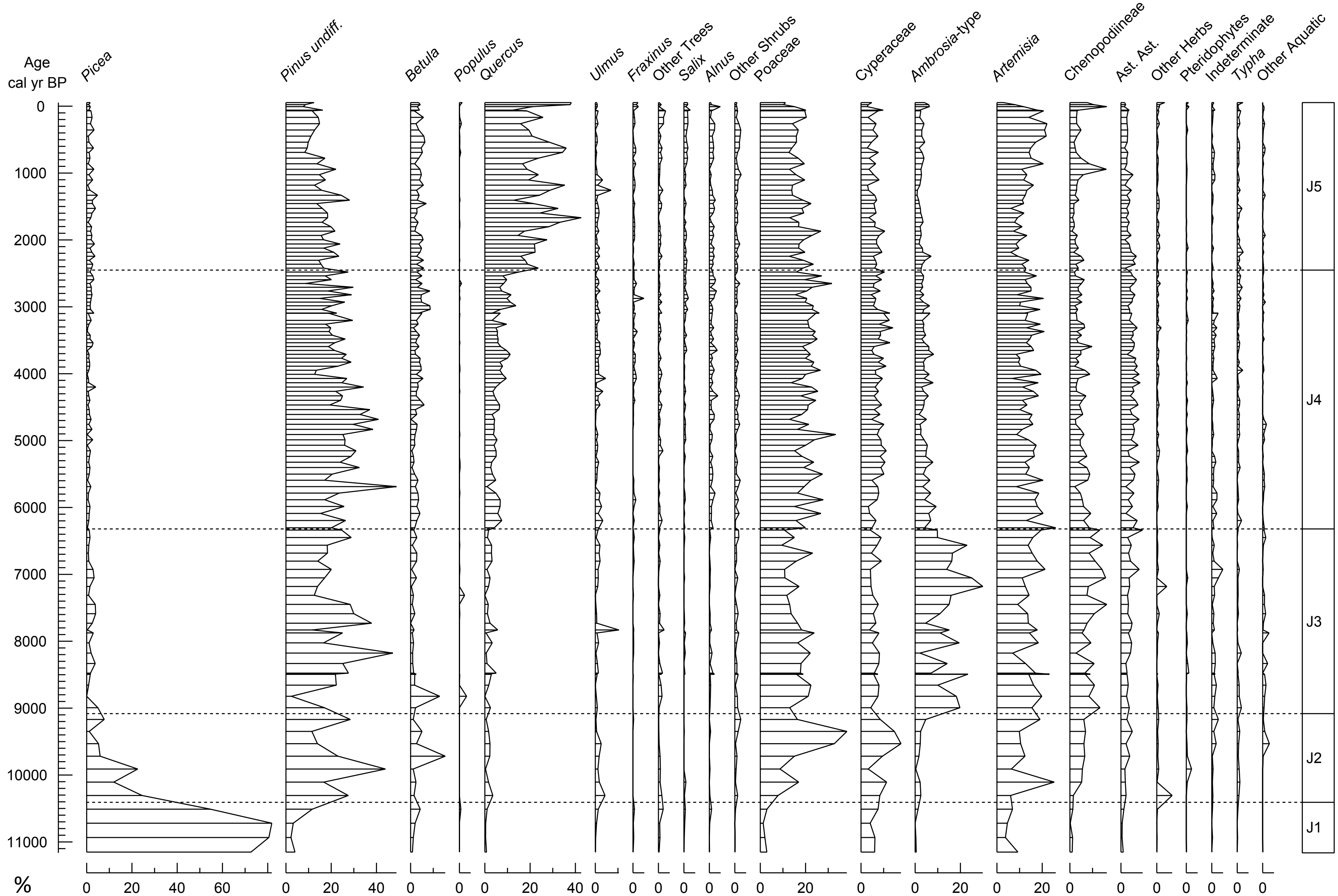


FIGURE 3: Summary of major pollen taxa for Jones Lake. Data are expressed as percentage of main sum. Pollen zones were determined by optimal (nonbinary) splitting of the information content of pollen percentages for taxa that were at least 5% of the total sum of terrestrial pollen and spore types for one or more levels by psimpoll (Bennett, 1994).



Data are available at https://www.neotomadb.org/

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FIGURE 4: Profiles of sediment magnetics, sediment composition, lake productivity proxies, pollen, and charcoal for Jones Lake. Isothermal remanent magnetization (IRM) and anhysteretic magnetic remanence (ARM) (a, b) are measures of the concentration of magnetic particles (increases with IRM) and particle size (decreases as ARM:IRM ratio increases). Sediment composition includes LOI (c) organic, carbonate, and residual inorganic fractions, and mean grain size of terriginous materials. Productivity proxies include percent biogenic silica (d), total phosphorus (e) and percent organic phosphorus (f). Vegetation (g) is given as percentage (as fraction of main sum) trees, shrubs, herbaceous, and fire severity is expressed in terms of charcoal area (h) and influx (i). Pollen zones were determined by optimal (nonbinary) splitting of the information content of pollen percentages for taxa that were at least 5% of the total sum of terrestrial pollen and spore types for one or more levels by psimpoll (Bennett, 1994). The ARM:IRM ratio from the uppermost sample is not shown here: 0.87.

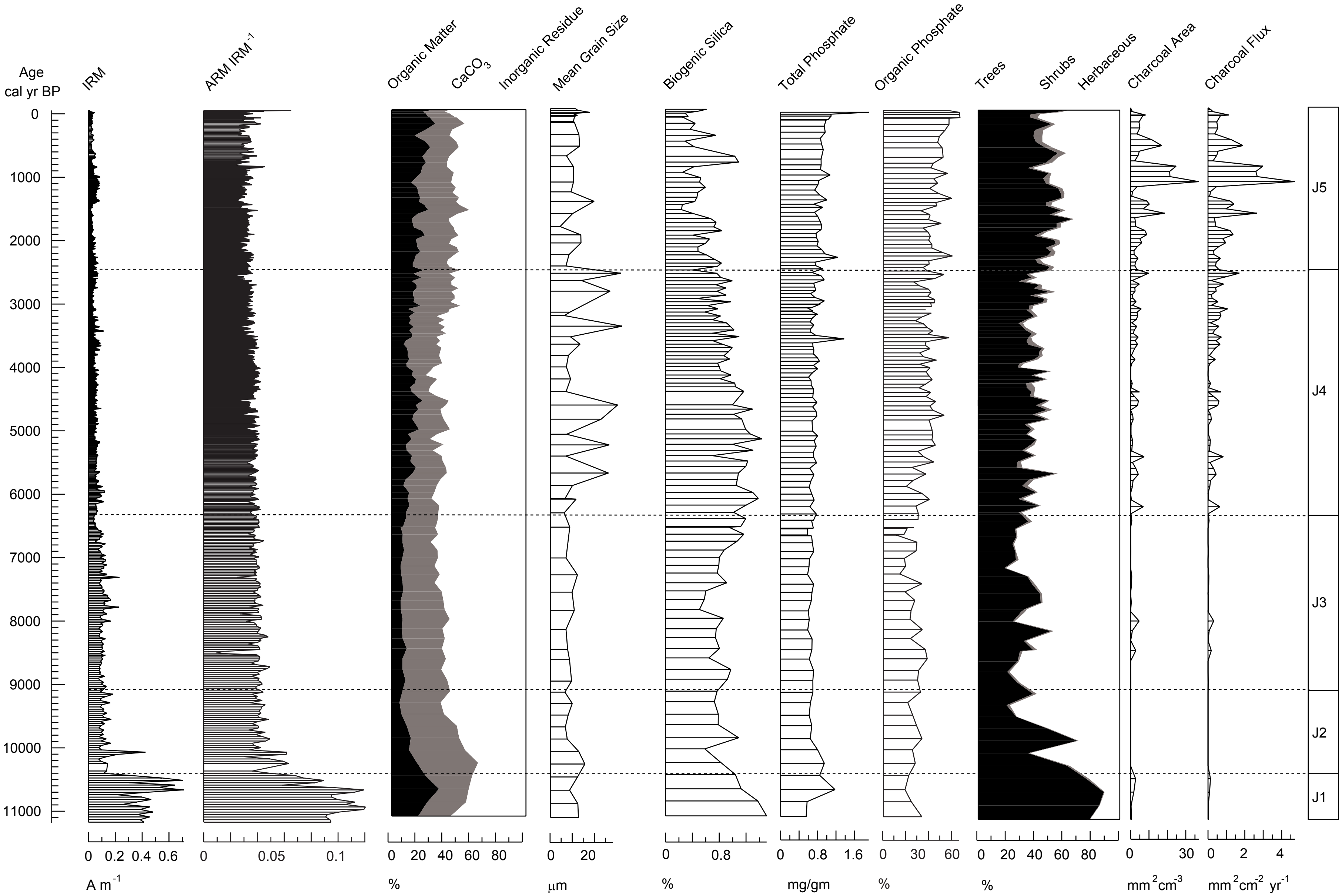

FIGURE 5: Summary of major pollen taxa for Jones Lake. Data are expressed as percentage of main sum. Pollen zones were determined by optimal (nonbinary) splitting of the information content of pollen percentages for taxa that were at least 5% of the total sum of terrestrial pollen and spore types for one or more levels by psimpoll (Bennett, 1994).

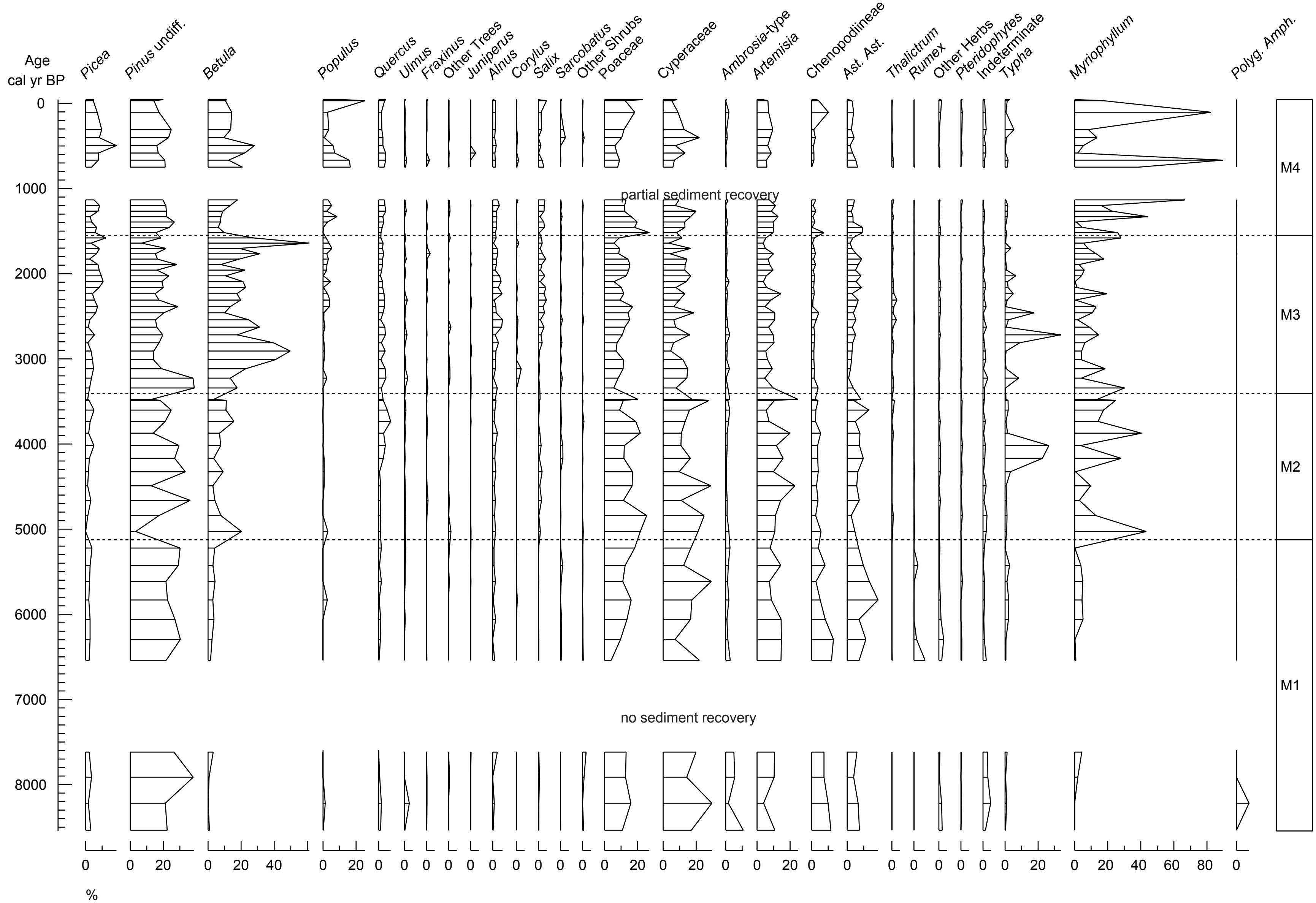

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FIGURE 6: Profiles of sediment magnetics, sediment composition, lake productivity proxies, pollen, and charcoal for Mallard Lake. Isothermal remanent magnetization (IRM) and anhysteretic magnetic remanence (ARM) (a, b) are measures of the concentration of magnetic particles (increases with IRM) and particle size (decreases as ARM:IRM ratio increases). Sediment composition includes LOI (c) organic, carbonate, and residual inorganic fractions, and mean grain size of terriginous materials. Productivity proxies include percent biogenic silica (d), total phosphorus (e) and percent organic phosphorus (f). Vegetation (g) is given as percentage (as fraction of main sum) trees, shrubs, herbaceous, and fire severity is expressed in terms of charcoal area (h) and influx (i). Pollen zones were determined by optimal (nonbinary) splitting of the information content of pollen percentages for taxa that were at least 5% of the total sum of terrestrial pollen and spore types for one or more levels by psimpoll (Bennett, 1994).

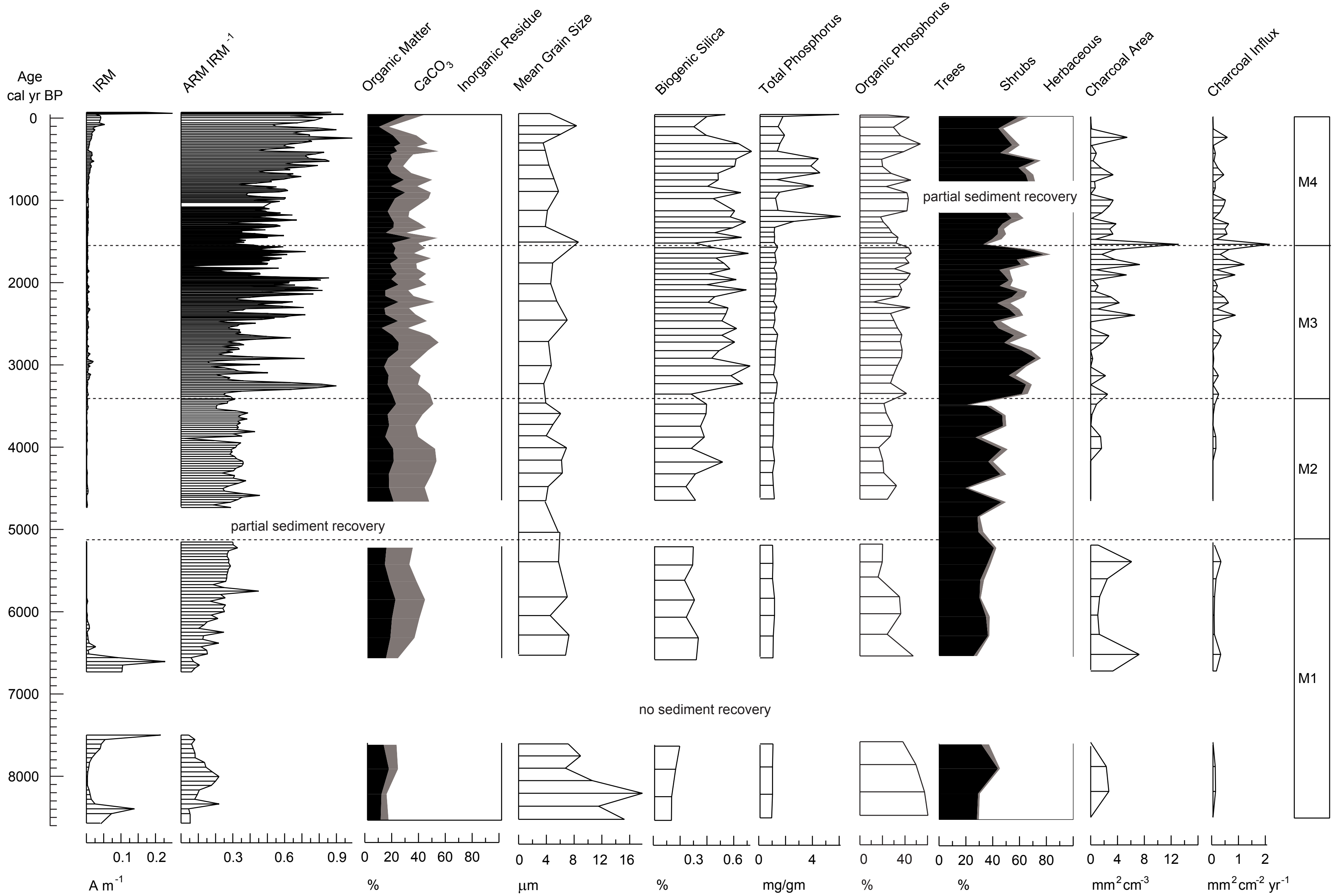

FIGURE 7: Comparison of pollen zones at Jones Lake and Mallard Pond (this study) with vegetation records from the Glenboro site (Ritchie and Lichti-Federovich, 1968) and E Lake (Ritchie, 1969). The zone labels are those defined by the authors, but zones are not necessarily the same as the general vegetation types being discussed in the text. Note that dates for the Glenboro site and E Lake are based on a linear interpolation (Grimm, 1999) between radiocarbon dates from bulk sediments and dates from correlation with other sites. These were calibrated using CALIB 5.0.2 (Stuiver et al., 2005). The E Lake dates were partially adjusted for bias caused by the inclusion of older carbon by Ritchie (1969) in the text of his paper. However, radiocarbon dates from these bulk sediment samples may be considerably older than AMS radiocarbon dates from terrestrial macrofossils if there has been inclusion of older carbon from watershed soils or sediments into the lake sediments (Cohen, 2003).