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A CHRONOLOGICAL FRAMEWORK FOR THE HOLOCENE VEGETATIONAL HISTORY OF CENTRAL MINNESOTA: THE STEEL LAKE POLLEN RECORD

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Abstract. Paleorecords from Minnesota and adjacent areas have often been used to evaluate large-scale climatic processes in the mid-continent of North America. However, most of these records are compromised by chronological flaws, making problematic any comparisons with climatic interpretations based on other records (e.g., GISP2 in Greenland). We report here a high-resolution pollen record with a secure chronology constrained by 26 ^{14}C dates on terrestrial macrofossils from Steel Lake, central Minnesota. About 11,200 years ago (calibrated yr BP) the late-glacial *Picea* forest near Steel Lake was succeeded abruptly by *Pinus banksiana* and/or *resinosa.* The *Pinus* forest began to open 9.4 ka cal BP with the expansion of prairie taxa, and a pine parkland or savanna prevailed until about 8 ka cal BP, when *Quercus* replaced *Pinus* to become the dominant tree in the prairie areas for 4500 years. The close chronological control permits the correlation of key vegetational changes with those at other reliably dated sites in the eastern Dakotas and in Minnesota, suggesting that the abrupt decline of the spruce forest was time-transgressive from southwest to northeast during 2000 years, and that the development of prairie was time-transgressive in the same direction over 2600 years. Correlation of key pollen horizons at Steel Lake with those in the high-resolution pollen profiles of Elk Lake, ca. 50 km northwest of Steel Lake, suggests that the well-known Elk Lake varve chronology for the early Holocene is about 1000 years too young.

Key words: Vegetation history, climatic changes, late-glacial transition, Holocene chronology, central Minnesota

1. Introduction

The sequence of vegetational formations in northwestern Minnesota was established by McAndrews (1966) on the basis of four pollen diagrams in an east-to-west transect from modern conifer forest to deciduous forest to prairie. This pioneer study revealed that the late-glacial forest of *Picea* (spruce) was replaced in the Holocene in turn by forest of *Pinus* (pine), deciduous forest, and prairie and then reversed to the modern *Pinus* forest. Because the clear geographic zonation of the modern vegetational formations is a manifestation of the increasing aridity westward in this region, the pollen sequences at these sites demonstrated that the mid-Holocene prairie period was an interval of dry climatic conditions.

Most of the pollen diagrams that have since been produced for Minnesota and adjacent areas have relatively low stratigraphic and taxonomic resolution. The chronology for many of them suffers because the radiocarbon dates are based on organic lake sediment in regions where the terrain includes calcareous glacial deposits, so the dates are subject to the "hard-water error", which can amount to many hundred years. In the case of late-glacial sediments with low content of organic matter, the occasional presence of pre-Quaternary pollen and spores also suggests the chance of incorporation of old carbon. The modern technique of radiocarbon dating of terrestrial macrofossils by accelerator mass spectrometry (AMS) reduces that problem, but few pollen sites in the area have enough such dates to detect anomalies and to establish the convincing temporal vegetational and climatic gradients. Varved sediments can provide an alternative approach to dating, but the uncertainties caused by variations in varve quality may result in a substantial cumulative error when attempts are made to count a series from the very top of the sediment to the base (Sprowl, 1993; Aardsma, 1996).

These problems have made it questionable to use lake-sediment records from this region to test hypotheses about abrupt large-scale climatic dynamics (Dean et al., 2002), such as the 8.2 ka cal BP event recorded in the Greenland ice cores and European lake sediments. Thus despite the abundance of published pollen records from Minnesota and adjacent areas, new well-dated pollen sequences are necessary in order to establish a chronological framework for postglacial environmental changes in that region.

In this paper we describe vegetational changes during the past 12,000 years around Steel Lake, central Minnesota, the chronology of which is securely constrained by 26 ^{14}C ages on terrestrial plant macrofossils. Our general objectives are to use the reliable chronology and high resolution pollen sequence for Steel Lake to detail the vegetational history and then to combine the resulting picture with that for other macrofossil-dated sites to provide a firmer basis for regional reconstructions of the vegetational and climatic history. We emphasize the nature and chronology of the late-glacial transition of the extensive spruce forest to pine forest and then the early-Holocene transition to prairie. These transitions are of particular interest because they occur during changes in the large-scale climatic forcing related to cycles of insolation and to the retreat of the Laurentide Ice Sheet (e.g., Baker et al.; 1992; Laird et al.; 1996; Hu et al.; 1999; Dean et al.; 2002; Shuman et al., 2002).

2. Study area

Steel Lake (46^{o} 58' N, 94^{o} 41' W, elevation 440 m a.s.l.) is in the chain of lakes (Crystal, Williams, Doe, Mary, Island, Steel, Shingobee) in the Shingobee River watershed, an area that has been intensively studied hydrologically in a long-range project of the U.S. Geological Survey (Winter, 1997). Multi-proxy analyses of the varved sediments of Steel Lake are in progress to reconstruct the climatic history at annual to decadal resolution. The Shingobee River Headwaters Area in Hubbard County lies between the Crow Wing and Mississippi rivers (Fig. 1). The hummocky terrain is characterized by lakes and wetlands that originated as a result of melting of stagnant ice masses left by the retreat of the Wadena and Rainy lobes of the Laurentide ice sheet. Sandy glacial deposits locally exceed 120 m in thickness. The modern climate is characterized by a large temperature range. At Park Rapids, 30 km west of Steel Lake, mean January temperature is –15^{o}C, mean July 20^{o}C, and mean annual 4^{o}C. Mean annual precipitation and lake evaporation are both about 66 cm. Lake level tends to be low in early summer.

The regional upland vegetation is second-growth mixed conifer-hardwood forest. Vegetation prior to timber cutting and settlement included stands of *Pinus strobus* (white pine) and *P. resinosa* (red pine) to the east and north and a mosaic of *P. banksiana* (jack pine), *Populus tremuloides* (aspen), and *Betula papyrifera* (paper birch) to the west (Marschner, 1930). The prairie-forest border at that time was located 80 km to the west. According to the current classification of Minnesota vegetation (J.A. Almendinger, personal communication), the area is located today in the central dry-mesic pine-hardwood forest, which is dominated by *Pinus resinosa* and *P. strobus*, with smaller amounts of *Betula papyrifera, Populus tremuloides, Acer rubrum (*red maple), *Pinus banksiana, Quercus borealis (*northern red oak), and *Q. macrocarpa (*bur oak), or in some areas by *Quercus borealis, Populus tremuloides, Betula papyrifera, Acer rubrum, Quercus macrocarpa, Populus* *grandidentata* (big-toothed aspen), and *Tilia americana* (basswood) with understory of *Acer rubrum, Corylus cornuta* (hazel), *Diervilla lonicera* (homeysuckle), *Prunus virginiana* (chokecherry), and *Amelanchier* spp.

3. Methods

3.1. Coring

Three sediment cores were taken with a square-rod piston sampler of 5-cm diameter (Wright, 1991) in the deepest part of Steel Lake (21 m) during the winter of 2000 (Fig. 1). These overlapping cores were easily matched on the basis of stratigraphic features (e.g. varves, turbidites), so no stratigraphic gaps existed.

3.2. Radiocarbon dating

The cores were cut in half lengthwise, and contiguous 2-cm segments of one half were washed through a 250-m-mesh sieve to concentrate terrestrial plant macrofossils. Macrofossils selected were all well preserved, and it is unlikely that they had had long residence times in the watershed. The samples were pre-treated with an acid-base-acid protocol at the University of Illinois and sent to Lawrence Livermore National Laboratory for ^{14}C analysis. ^{14}C dates were converted to calibrated years referenced to year AD 1950 with CALIB 4.2 (http://depts.washington.edu/qil/dloadcalib/). The Intcal98 atmospheric decadal dataset (Stuiver et al., 1998) was used to calibrate the ages, based on 50% median probability and 2-sigma range. Preliminary varve counts of the early and late Holocene sections (the mid-Holocene varves are ambiguous) show that the similarities of the varve and ^{14}C chronologies in these sections are statistically significant. In this paper we rely solely on the calibrated radiocarbon chronology, which is adequate for the purposes of this study.

3.3. Pollen analysis

Sediment samples of 1 cm^3 were taken for pollen analysis at 10 cm interval in general and at every 0.5 to 3 cm from 2800 cm to 2940 cm because of the interesting nature of the varved sediments. The pollen samples were prepared according to the standard methods of Faegri and Iversen (1975). *Lycopodium clavatum* tablets were added to each sample to determine pollen concentration (Stockmarr, 1971). The pollen percentages are based on the pollen sum of arboreal (AP) and non-arboreal pollen (NAP). Cyperaceae is included in the sum, whereas spores and the pollen of aquatic plants are excluded. At least 350 arboreal pollen grains were counted per sample.

For calculation and construction of the pollen diagrams the Tilia and Tilia*graph programs were used (Grimm, 1992). Pollen percentages and pollen accumulation rates (PAR) for selected taxa are plotted against depth. The subdivision of pollen diagrams into zones (LPAZ, local pollen assemblage zones) was made by CONISS (Grimm, 1987) and also by optimal partitioning (Birks and Gordon, 1985) followed by comparison with the broken-stick model (Bennett, 1996). In the pollen diagrams zone borders determined by the latter method are represented by long dashed lines, whereas zones based on CONISS are indicated by short dashed lines. The zones are numbered from the base upward and prefixed by the site designation ST.

4. Results

4.1. Lithology

The basal sediments (PAZ ST-1, 3300-3050 cm, Fig. 2) consist of mixed sand, clay, arboreal macrofossils, and clasts containing organic varves. This assemblage is interpreted as forest-floor detritus and glacial materials deposited together in a superglacial pool formed during wastage of stagnant glacial ice (Florin and Wright, 1969). The broken fragments of varved organic sediment indicate that a lake deep enough and productive enough for formation of organic varves already existed near the coring site to provide a source for the eroded and transported varved fragments. The upper few centimeters of the basal sediments contain glacial varves, which are overlain by organic varves precisely at the sharp change (3047 cm) from spruce pollen dominance (PAZ ST-1) to pine dominance (ST-2).

The upper part of PAZ ST-2 (2968-2994 cm) contains alternating light-colored bands of carbonate varves and dark bands of very thin organic varves. Pollen samples in this section were analyzed at 0.5-cm intervals (Fig.5). The remainder of the core consists mostly of carbonate varves of variable quality. A pair of turbidites at 2804-2873 cm is reflected in the loss-on-ignition profiles (Fig. 2) and also in the depth/age curve (Fig. 3).

4.2. Chronology

We obtained a total of 35 ^{14}C ages on terrestrial plant macrofossils (Table 1). A LOWESS depth/age curve (locally-weighted polynomial regression, Cleaveland, 1979; Cleaveland and Devlin, 1988) was constructed for the Holocene sediment (Fig. 3). Not used were the two dates at 2858 and 2866 cm, which came from a turbidite that apparently contained older sediment, as implied by the dates -- an interpretation supported by pollen counts from the turbidites (not shown on the pollen diagrams) that contain an assemblage resembling that of older stratigraphic levels ca. 50 cm deeper n the core, e.g. 45% *Pinus* rather than 10%.. Also not used in the construction of the curve were the oldest seven dates, which came from the basal layer of plant trash in the spruce pollen zone. They are not in chronological order and include some very old dates plus a cluster of three dates at about 11.2-11.4 ka cal BP. Age assignments for pollen percentages and pollen-accumulation rates (Figs. 4-6) are based on the LOWESS curve for the remaining 26 dates.

4.3. Pollen stratigraphy

LPAZ ST-1 *Picea* (>12500-11200 cal yr BP)

Arboreal pollen (AP) is 83-95% (Fig. 4). *Picea* is the most abundant arboreal pollen type, with values up to 80%. *Larix, Betula,* and *Ulmus* have values up to 2% each. *Pinus, Abies, Quercus, Fraxinus nigra,* *Corylus*, and *Ostrya-Carpinus* reach 1% each. Among herbaceous taxa (NAP 5-17%) *Artemisia* (4-12%) dominates. Cyperaceae and Poaceae have values under 2%. PAR was not calculated in this zone because of the varied ^{14}C dates. The upper boundary of the zone is characterized by a strong decrease of *Picea* and increase of *Pinus banksiana/resinosa*, *Betula,* and *Ulmus*.

LPAZ ST-2 *Pinus banksiana/resinosa* (11200-9000 cal yr BP)

Arboreal pollen increases to 97%. *Pinus banksiana/resinosa* (to 77 %), *Betula* (to 21%), and *Ulmus* (to 9%) reach maximal values. *Picea* drops to 0.5%. Among NAP *Artemisia*, Poaceae, and Cyperaceae are most common, with 1-7% each. Total PAR averages 8097 grains cm^{-2} yr^{-1} (range 3700-25800) with AP/NAP ratio 10:1. The upper boundary of the zone is marked by increasing values of *Artemisia*, *Ambrosia*-type*,* and Poaceae.

LPAZ ST-3 *Pinus banksiana/resinosa* - Poaceae (9000-7900 cal yr BP)

Arboreal pollen decreases from 74% to 39%. *Pinus banksiana/resinosa* percentages change from 42% to 12%. Herb taxa reach a maximum of 61%. *Artemisia* increases to 29%, *Ambrosia*-type 11%, Poaceae 13%, and Chenopodiineae 6%. Cyperaceae is 1-4%. An increase in total PAR to 9730 grains cm^{-2} yr^{-1} (range 4240-15500) occurs in this zone, with reduction of the AP/NAP ratio to 2:1. The upper boundary of the zone is characterized by increasing values of *Quercus.*

LPAZ ST-4 *Quercus-Artemisia-Ambrosia*-type (7900-3400 cal yr BP)

Among the arboreal taxa (AP 60-89%) *Quercus* reaches maximal values of 40% as *Pinus banksiana/resinosa* decreases. Non-arboreal pollen dominates, especially Poaceae, *Artemisia*, *Ambrosia*-type*,* Chenopodiineae, and Cyperaceae. Total PAR averages 9000 grains cm^{-2} yr^{-1} (range 3715-17810), almost as high as in the pine zone below (ST-2). The AP/NAP ratio is 2.3:1. The upper boundary of the zone is characterized by decreases of *Artemisia*, *Ambrosia*-type, and Chenopodiineae and increases of *Betula* and *Ostrya/Carpinus*.

LPAZ ST-5 -*Betula-Ostrya/Carpinus,* (3400-2700 cal yr BP)

Quercus values decrease from 29% to 16%. The zone is characterized in particular by slight increases in *Populus* and then maxima of *Betula* (42%), *Ostrya/Carpinus* (6%), and *Corylus*. Non-arboreal pollen is less than 12%. Average total PAR is 8135 grains cm^{-2} yr^{-1} (range 6800-10100), with AP/NAP ratio 6.5:1. The upper boundary of the zone is characterized by a strong increase of *Pinus strobus*.

LPAZ-ST-6 *Pinus strobus* (2700-1900 cal BP)

Characteristic is a maximum of *Pinus strobus* (47%), but *Pinus banksiana/resinosa* rises gradually up to 54%. Non-arboreal pollen is reduced to a few percent. Total PAR increases to an average of 8640 grains cm^{-2} yr^{-1} (range 7275-10453) with AP/NAP ratio of 13:1. The upper boundary of the zone is characterized by decrease of *Pinus strobus* and increase of *Pinus banksiana/resinosa*.

LPAZ ST-7 *Pinus banksiana/resinosa-P. strobus* (1900-500 cal yr BP)

Pinus strobus averages 15%, and *Pinus banksiana/resinosa* increases irregularly up to 63%. Non-arboreal types show little change. Total PAR is high, with an average of 15265 grains cm^{-2} yr^{-1} (range 9710-2510), with AP/NAP ratio of 15:1. The upper boundary shows a decrease of *P. strobus* to a very low percentage.

LPAZ ST-8 *Pinus banksiana/resinosa-Ambrosia* type (500 cal yr BP to present).

Pinus strobus decreases abruptly to 1-2%, and *Pinus banksiana/resinosa* dominates. *Ambrosia*-type reaches 10% in the upper pollen spectra, where regular presence of anthropophytes is characteristic, such as *Triticum* and *Zea*. Total PAR averages 17900 grains $cm^{-2}yr^{-1}$ (range 15590-23355)

5. Discussion

5.1 Vegetational history around Steel Lake

>12,500 to 11,200 cal BP.

The late-glacial vegetation was dominated by *Picea* (LPAZ ST-1), with small amounts of pollen of *Larix*, *Abies*, *Betula*, and *Fraxinus nigra*, which today occur in the boreal forest. Pollen of temperate taxa such as *Quercus*, *Ulmus*, *Ostrya*/*Carpinus*, and *Corylus* also occur. Openings in the forest are indicated by the occurrence of *Artemisia* and Poaceae and especially *Ambrosia*-type, which today is confined to temperate regions. No macrofossils of temperate taxa have been found at this and other Minnesota sites to support the interpretation of local occurrence of these temperate tree and herb taxa, a requirement urged by Birks (2003), who favors distant transport of pollen as an explanation. But an abundant source for these pollen types for this time is not apparent, for the contemporaneous spruce forest extended south at least 800 km to Kansas, and the nearest prairie, still farther south in Texas, was dominated by grasses rather than *Ambrosia.* Pollen traps in the boreal forest of Canada collect only trace amounts of these pollen types, despite the abundant source of *Ambrosia*-type pollen in the agricultural regions to the south. A case has been made for the existence of a late-glacial climate that favored the admixture of boreal and temperate taxa (Yu and Wright, 2001).

11,200 to 9400 cal BP

Closed forests of *Pinus banksiana* and/or *resinosa* dominated the Steel Lake area for most of LPAZ ST-2 after the spruce decline until about 9.4 ka cal BP (Fig. 4). The AP to NAP ratio of 10:1 can be attributed to the dominance of *Pinus*, a big pollen producer (Fig. 6). *Betula* and *Ulmus* were important components. The conspicuous presence of *Ulmus* in the early-Holocene pine zone is apparent at many Minnesota sites, producing a pollen assemblage not found today. For example, *Ulmus* was a major component of the early-Holocene pine forest at Kirchner Marsh and other sites in southeastern Minnesota before the prairie period compared to the dominance of oak after the prairie period (Wright, 1992). Inasmuch as *Ulmus* is better adapted to moist climatic conditions than oak, its prominence in the early Holocene compared to the late Holocene may be attributed to greater monsoonal precipitation from air masses originating over the Gulf of Mexico and the Caribbean Sea as a result of greater summer insolation at this time. The *Ulmus* maximum can be seen as far inland as Moon Lake in eastern North Dakota west of the range of *Pinus* and of the enhanced monsoonal precipitation. Here *Ulmus* must have been a major occupant of moist depressions of the prairie parkland (Laird et al., 1996) at the same time as upland areas were covered by prairie and oak savanna as a result of the increased summer insolation, which resulted in higher temperatures, increased evaporation, and increased moisture stress on upland species.

9400 to 3400 cal yr BP

The prairie period started in the upper part of LPAZ ST-2 and included all of ST-3 and 4. It is dominated throughout by non-arboreal pollen. Total PAR did not change much at the beginning despite the decrease in pine, but the AP/NAP ratio decreased from 10:1 to 2:1 in LPAZ ST-3, implying that pollen production from prairie plants made up for the decrease in pine pollen. At first pine and birch were still in the area, producing a pine parkland or savanna (9.4 to 7.9 ka cal BP). As the climate became drier and warmer *Pinus* was replaced by *Quercus,* and the prairie taxa attained their maximal PAR (LPAZ ST-4). At this time the PAR of both oak and prairie plants was high, implying that the prairie was productive and that oak trees were common. After about 6 ka cal BP the percentages and PAR of *Artemisia, Ambrosia* type*,* and Chenopodiineae decreased relative to Poaceae, suggesting that in the latter part of the prairie period the climate was moister than before.

3400 to 2700 cal yr BP

The suggested moister conditions late in the prairie period were continued in the transition to the late-Holocene pine forests of LPAZ ST-6 to 8. This transition (LPAZ ST-5) is marked at 3.4 ka cal BP by an increase in the ratio of AP/NAP to 6.5:1, reflecting pronounced maxima of *Betula* and *Ostrya/Carpinus*, as the percentages of *Quercus* and prairie herbs decline. A comparable transition zone is registered at nearby Williams Lake (Locke and Schwalb, 1997). In Itasca State Park, 50 km northwest of Steel Lake, *Ostrya/Carpinus* exceeds 20% at Elk Lake, and at nearby Stevens Pond (Janssen, 1967) *Tilia* and *Acer* are prominent as well. A somewhat similar transitional sequence is identified at six sites on sand plains 20-100 km west and north of Steel Lake by Almendinger (1992). The sand plains are now covered by *Pinus banksiana* forest, but the pollen profiles imply that a transitional *Populus-Quercus* brushwood preceded the late-Holocene pine occupation of prairie. The dates for the beginning of the transition at the several sites differed by as much as 2000 years, depending on the local presence of firebreaks such as wetlands, which halted prairie fires and allowed the brush to advance and make way for the forest an average of 2000 years later. The development or effectiveness of firebreaks was enhanced by the rise in the water table brought by the wetter/cooler climate following the prairie period. A similar mechanism may have operated in the Steel Lake and Itasca Park areas to explain the transitional pollen zone between prairie and pine forest, although the morainic topography around both sites makes the analogy more complicated, and the pine involved was *P. strobus* rather than *P. banksiana/resinosa.* It also might explain the different time spans for the transition at Steel Lake and Elk Lake.

2700 cal yr BP to present.

Pinus strobus entered Minnesota from the east about 8 ka cal BP in the early Holocene, but its westward expansion was stalled by the mid-Holocene warmer/drier climate of the prairie period (Jacobson, 1979). After this interval it resumed its expansion and reached Steel Lake about 2.7 ka cal BP. In PAZ ST-7 the pollen ratio of *Pinus strobus* to *P. banksiana/resinosa* gradually declines until 2.2 ka cal BP, after which in ST-8 *P. strobus* is a minor component. The dominance of the pines and the high pollen productivity especially of *P. strobus* resulted in the increased AP/NAP ratio to 13:1 in PAZ ST-6 and 15:1 in ST-7. Its decrease in ST-8 to 8:1 reflects the decrease of *P. strobus* pollen.

The "*Ambrosia* rise" near the top of the core is the hallmark of agricultural settlement in the American Midwest. At Steel Lake the abundant pollen may have blown from areas of mechanized agriculture in the Lake Agassiz plain to the west, which started in the 1880s -- the so-called bonanza farming -- for such practice provides more land disturbance for the spread of weeds and the distant transport of their pollen to the forests. The decrease in *Pinus* pollen slightly later is a result of the selective logging of both *P. strobus* and *P. resinosa* in the Steel Lake area

5.2. Regional relations

5.2.1. Abrupt spruce-pine transition

The termination of the late-glacial at Steel Lake is represented in the pollen diagram (Fig. 3) by the sharp decline in *Picea* pollen and rise of *Pinus* at about 3047 cm. This level also marks the change from glacial varves to organic varves. Two dates just above this horizon are 11207 and 11242 cal yr BP, with up to 60% pine pollen (Table 1). Below is the trash layer, almost 2 m thick, with about 80% *Picea* pollen. The trash layer is believed to have been deposited in a superglacial pool resulting from down-wasting of stagnant ice (Florin and Wright, 1969). It includes glacial sands along with plant detritus that yielded three old dates (18 ka, 35 ka, and 41 ka ^{14}C BP), suggesting that it had probably been eroded by the advancing ice sheet and redeposited in the superglacial pool as the ice melted. But the layer is also marked by dates of 11257, 11371, and 11434 cal yr BP on macrofossils that must be from forest-floor litter of contemporaneous spruce growing on the superglacial sediments. The *Picea* pollen in the trash layer is well preserved and must have been blown from the contemporaneous forest. In consideration of the three dates in the *Picea* zone (11257, 11371, and 11434 cal yr BP) and the two in the overlying *Pinus* zone (11242 and 11207 cal yr BP), it would seem that the *Picea/Pinus* boundary can be set at 11.2 ka cal BP. Within this close cluster of five ages, the age of 9860±50 ^{14}C BP on a plant macrofossil with an adequate amount of carbon for higher-precision ^{14}C analysis is not associated with an extensive ^{14}C plateau. This date has a 2-sigma (95% confidence interval) calibration range of 11172-11339 BP, which agrees with the 95% CI on the basis of our LOWESS regression analysis and is consistent with the larger calibration age ranges obtained for the other four dates in the cluster. Thus we consider this range to be the most likely time interval for the *Picea/Pinus* transition at Steel Lake, and we use the date of 9.2 ka cal BP as the center point of this range. The same *Picea/Pinus* switch occurs at 11.5 ka cal BP at Deep Lake, 100 km to the northwest, although not so well controlled by ^{14}C dating as at Steel Lake. There the dates are based on varve counts over short intervals from AMS dates on wood (9.0 ka cal BP), needle (12.6 cal BP), and seed bract (9.0 cal BP) (Hu et al., 1997; Hu, unpublished).

Pinus immigrated rapidly into eastern and northwestern Minnesota from the east, ultimately from its glacial refuges in the Appalachian Mountains (Wright, 1968). It had been held up in its westward migration by the barrier represented by Lake Michigan and by the ice lobes to the north, and its migration around the south end of Lake Michigan was impeded by a climate that was already too warm. The abruptness of the change from *Picea* forest to *Pinus* forest has been attributed to widespread catastrophic fires that reduced *Picea* forests and favored the fire-adapted *Pinus banksiana* (Critchfield, 1985), but a close-interval study of the charcoal frequency during this transition at Lake Mina in west-central Minnesota provided no evidence that fire was involved in that area, but rather that charcoal was more common in the *Pinus* pollen zone than at the boundary below (Olson, 1993). At several sites in southern Minnesota beyond the range of the earliest *Pinus* immigration from the east, when *Picea* declined it was replaced first by an assemblage of *Betula*, *Alnus*, and *Populus* before the arrival of *Pinus*. These opportunistic taxa, which had been present in the *Picea* forest, spread over the land freed from *Picea* forest. In areas farther west beyond the range of the immigrating *Pinus*, e.g. at Moon Lake in eastern North Dakotas, the *Picea* decline occurred in the absence of a charcoal maximum (Clark et al., 2001). Apparently the termination of *Picea* dominance had no relation either to catastrophic fires or to competition from immigrating pine, but instead it resulted from a change to a climate too warm and dry for spruce regeneration, which today is limited at its southern border by high summer temperatures (Heinselman, 1957) as well as by drought. And in northeasternmost Minnesota the *Pinus* expanded 2 ka before *Picea* declined.

If the beginning of the *Picea* decline in Minnesota marks a climatic change, the date might be earlier in the south than in the north if it was contemporaneous with the retreat of the ice front, which was certainly time-transgressive. On the other hand, the vegetational succession in response to climatic change may have been more rapid than the slow wastage of the huge ice mass, or independent of the rate of ice retreat. Selection among these alternatives must depend on reliable radiocarbon dates. Satisfactory dates come from terrestrial macrofossils and from high-quality varves counted only a few hundred years from the level of a macrofossil date. Wood at the top of the *Picea* pollen zone at Pickerel Lake in northeastern South Dakota was dated about 12.5 ka cal BP (Watts and Bright, 1968) and at nearby Medicine Lake 12.9 (Kennedy, 1994). At Moon Lake in eastern North Dakota the spruce decline started at about 12 ka cal BP (Clark et al., 2001). At Lake Mina in west-central Minnesota the start was also at 12 ka cal BP, on the basis of a date on a *Picea* needle combined with a count of 560 well defined varves (Olson, 1993). These dates of 12 ka cal BP or greater are significantly older than the 11.2 ka cal BP for the start of the *Picea* decline at Steel Lake. Eastward from here the most reliable dates are in northeasternmost Minnesota, where the non-calcareous nature of the glacial drift indicates that dates on organic sediment are not subject to hard-water errors. There at Kylen Lake (Birks, 1981), where the chronology before 9 ka cal BP is controlled by nine radiocarbon dates, the start of the *Picea* decline is at 10.4 ka cal BP (Fig. 7). At Lake of the Clouds just to the north at the Canadian border it occurs at 9.8 ka cal BP, according to a radiocarbon date on a varve count of 9.5 ka BP (Stuiver, 1971; Craig, 1972), and at Rattle Lake in adjacent Ontario at about 9.5 ka cal BP (Bjorck, 1985). It would seem from these dates that the start of the *Picea* decline was older in the eastern Dakotas than at Steel Lake by about 800 years, and older by at least 2000 years than in northeasternmost Minnesota. In fact at Kylen Lake in the east the *Picea* decline was so late that *Pinus* had already immigrated, and *Picea/Pinus* forest prevailed there for 2 ka (Fig. 7).

At Elk Lake the highly detailed pollen sequence is very similar to that of Steel Lake and Deep Lake, but the start of the *Picea* decline and the sharp rise of *Pinus* is plotted as 10.2 ka BP (Whitlock et al., 1993), based on the total varve count from the top of the core to the base as determined by Anderson (1993). This varve date is about 1000 years younger than the older end of the 95% confidence interval (11172-11339 cal BP) for the *Picea/Pinus* transition at Steel Lake. The uncertain interpolations between core segments, as well as the poor quality of varves in some sections, may explain the ca. 1000 yr difference from the 11.2 ka date at Steel Lake (Fig. 7). At Elk Lake, the precision of the varve counts on four different cores from the same deep hole is estimated to be 12% (Sprowl, 1993). When this error estimate is applied, the Elk Lake varve date (10.2 ± 1.2) for the *Picea/Pinus* transition would be consistent with those of the same vegetational transition from Steel Lake and Deep Lake as well as with the regional vegetational pattern.

In any case if the end of the *Picea* zone was time-transgressive across 600 km in the Minnesota area it is not everywhere the equivalent of the end of the Younger Dryas as defined in Greenland and Europe, where it is abrupt and synchronous at 11.5 ka cal BP over the entire region. The Younger Dryas is also identified in eastern North America as far west as Ohio, where it is represented by an abrupt recurrence of *Picea* and other conifers after a short absence (Shane, 1987). The time transgression in Minnesota reflects the continued cooling influence of the retreating Laurentide ice sheet in the summer, allowing *Picea* to survive longer in northeastern Minnesota than in the southwest, even though summer insolation at this time was near its maximum according to Earth/Sun orbital changes. However, for practical purposes the *Picea* zone in Minnesota is termed the late-glacial even though its termination is time-transgressive.

5.2.2. Development of the Mid-Holocene Prairie

In contrast to the abrupt change in the forest cover from *Picea* to *Pinus* at Steel Lake and other sites, the development of the prairie assemblages of Poaceae, *Artemisia*, *Ambrosia*-type, and Chenopodiineae was a gradual process. At Steel Lake it started at 9.4 ka cal BP with the decline of *Pinus.* The chronology of this sequence is the same at Deep Lake (Hu et al., 1997). If we assume that the dating error at 9.4 ka cal BP is the average of those of the two bracketing ^{14}C dates (7210 ± 60 and 8580 ± 130 ^{14}C BP; Table 1), the 2-sigma range (95% CI) of the age for the *Pinus* decline is ca. 9200-9600 cal yr BP. A LOWESS regression analysis yielded a similar 95% CI.

The early-Holocene transition from forest to prairie was time-transgressive from west to east, as had been the termination of the *Picea* forest. The *Pinus* that abruptly immigrated into eastern and northwestern Minnesota when *Picea* declined never reached as far as eastern North Dakota. There at well-dated Moon Lake the *Picea* forest was replaced at ca.12 ka cal BP by a *Betula*-*Populus*-*Ulmus*-Poaceae assemblage, which may have resembled the aspen parkland that borders the boreal forest today in southern Manitoba. Prairie components steadily increased during the next 2300 years, and prairie was fully developed with *Artemisia*, *Ambrosia*-type, and Chenopodiineae by 9.7 ka cal BP. During this time the Steel Lake area and elsewhere in central Minnesota were still dominated by *Pinus* forest. By the time that prairie began to invade the *Pinus* forest at Steel Lake (9.4 ka cal BP) the parkland trees were gone from the Moon Lake area.

.The early-Holocene pollen sequence at Steel Lake and Deep Lake is very similar to that at Elk Lake, which has a high stratigraphic resolution but a questionable chronology (Fig. 7). At Elk Lake the beginning of prairie development is set at 8.5 k varve yr BP and is followed at .8.2 k varve yr BP by sharp changes in the records of limnological conditions attributed to increase in windiness related to the waning influence of the retreating ice sheet on atmospheric circulation (Dean et al., 2002). The changes are correlated by these authors with the 8.2 ka BP cooling event recorded in the Greenland ice cores and elsewhere around the North Atlantic. In fact they postulate that the change in atmospheric circulation inferred from the Elk Lake date for the beginning of the prairie period was the cause of the 8.2 event in Greenland rather than the reverse.

A more realistic early-Holocene scenario is described by Shuman et al (2002), who emphasize the waning influence of the retreating ice sheet at the same time as summer insolation was reaching its mazimum, resulting in different climatic effects in different parts of the eastern half of North America, including the development of prairie in the mid-continent. The 8.2 event was a relatively minor feature in the changing climatic picture and was largely restricted to the region affected by North Atlantic Ocean circulation, for it is attributed to the abrupt release of meltwater from proglacial lakes when the Laurentide ice sheet collapsed.

In any case the prairie period started at ca. 9.4 ka cal BP at Steel Lake rather than 8.5 or 8.2 ka, so any correlation with the 8.2 event of Greenland is unlikely, let alone the causal relation postulated by Dean et al. (2002). This chronological discrepancy of 900-1200 years between Steel Lake and Elk Lake is similar to that indicated for the *Picea* decline (Fig. 7).

Thus the reliable AMS chronologies for Moon Lake in eastern North Dakota and Steel Lake imply that the climatic change affecting the start of the prairie/forest transition was gradual and time-transgressive over 2.6 ka (from 12 to 9.4 ka cal BP), and the full development of prairie occurred over 1.8 ka (from 9.7 to 7.9 ka), rather than abrupt and synchronous at 8.5 or 8.2 k varve yr BP, as stated by Dean et al (2002). If the 50-km distance between Steel Lake and Elk Lake had been enough to encompass a difference in the forest cover and associated pollen diagrams, the change in key pollen horizons should have been earlier at the more westerly Elk Lake than at Steel Lake rather than later, for the temporal gradient of prairie development was from west to east, just as was the *Picea* decline.

The initiation of prairie in south-central Minnesota is recorded in two new well-dated pollen diagrams by Camill et al (2003), who also place the full development of the prairie at about 8 ka cal BP, but in eastern Iowa and in Wisconsin it was about 6 ka BP (Baker et al., 1992).

6. Conclusions

Because the Steel Lake pollen diagram has high stratigraphic resolution as well as the high temporal resolution afforded by 26 radiocarbon AMS dates, it offers the possibility to re-evaluate the development and chronology of the late-glacial and Holocene vegetational and climatic sequence in central Minnesota. The rapid replacement of spruce forest by jack pine or red pine or, in the southwest, the expansion of aspen and birch before the immigration of pine all indicate that the warmer/drier Holocene climate rather than catastrophic fire or competition with pine caused the decline of spruce. Sites with reliable calibrated radiocarbon dates suggest that the spruce decline was time-transgressive over at least 2000 years from the eastern Dakotas to northeasternmost Minnesota.

The early-Holocene pine forest was converted to pine parkland or savanna at Steel Lake at about 9.4 ka cal BP, and the pine was replaced by oak about 7.9 ka cal BP as the prairie became more extensive in response to drier and warmer climatic conditions. The trends in the pollen profiles contain no indication of the 8.2 ka paleoclimate event found in the Greenland ice cores. The inception of prairie was time-transgressive over about 2600 years from eastern North Dakota to the Steel Lake area.

The long transition from the dominance of spruce forest through the pine-elm maximum to the development of prairie in the Minnesota area reflects the diminishing climatic influence of the retreating ice sheet, while at the same time summer insolation was at or near its maximum. The changing combination of these large-scale atmospheric and landform processes provided the climatic controls on vegetational history, including the development of plant assemblages not existing today.

The reforestation of the prairie in the late Holocene featured a transitional woodland marked by *Betula* and *Ostrya* or *Carpinus*, followed by *Pinus strobus* and later *Pinus resinosa / P. banksiana*, which dominated the Steel Lake area until logging and agricultural development late in the 19th century.

If the calibrated AMS radiocarbon chronology of these vegetational changes is compared with the varve chronology for Elk Lake, about 50 km to the northwest, it appears that the latter is as much as 1000 years too young.

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Table 1.

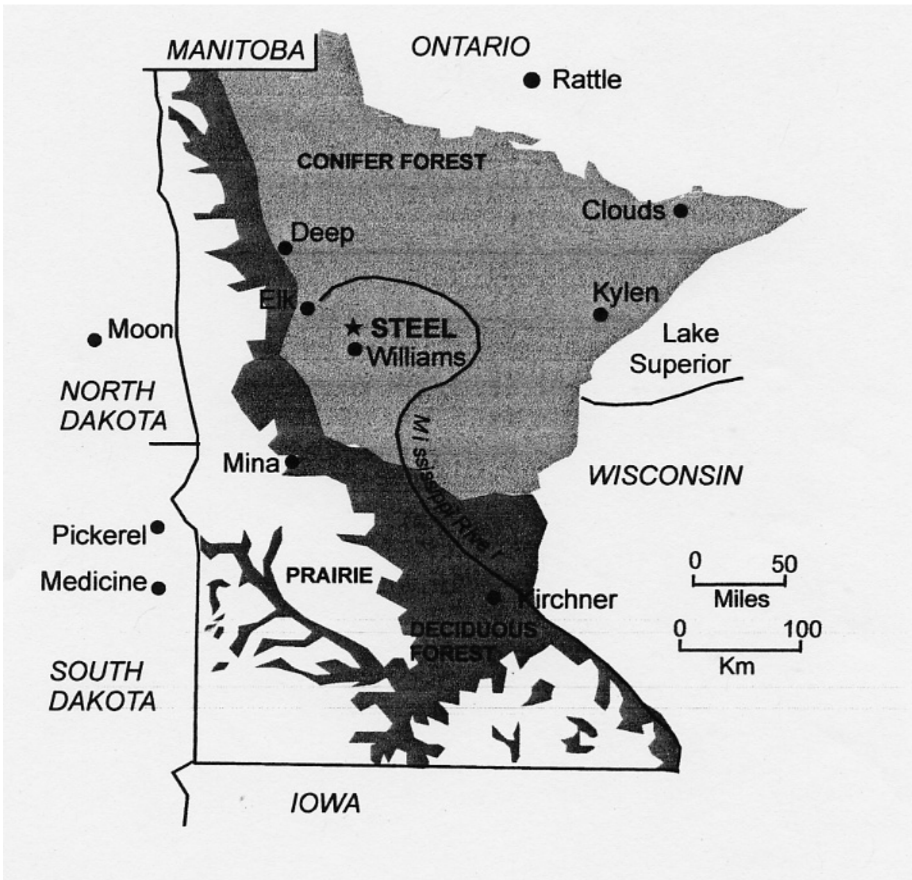
AMS radiocarbon dates. Dates marked with star (*) indicate small amounts of carbon and thus have large error bars; 2330 cm (0.05 mg C), 2411.5 cm (0.06 mg C), 2428.6 cm (0.07 mg C), 2448 cm (0.07 mg C), 2556 cm (0.07 mg C), 2586cm-B (0.06 mg C), 2632 cm (0.03 mg C), 2798 cm (0.09 mg C), 2983 cm (0.07 mg C), 3022 cm (0.04 mg C), 3033 cm (0.05 mg C), 3046 cm-B (0.05 mg C).

CAMS #	Depth (cm)	AMS 14C Dates (yr BP)	Calibrated Dates (yr BP)	Probability Distribution	Dated Material
66721	2183.7	340 ± 40	391 (307, 486)	1	Bark
68535	2211	780 ± 50	720.5 (651, 790)	0.999	Leaf and bark
71309	2330*	1700 ± 120	1612 (1352, 1868)	1	1 *Betula* seed
71310	2352	1880 ± 40	1819 (1713, 1895)	0.991	1 Cyperaceae seed
71311	2356	1850 ± 60	1780 (1614, 1922)	1	1 *Betula* and 1 Cyperaceae seeds
68536	2392	2160 ± 50	2159 (2003, 2312)	1	Charcoal
68537	2411.5*	2490 ± 100	2557 (2346, 2756)	1	1 seed
68538	2428.6*	2680 ± 90	2802 (2672, 3000)	0.993	2 *Betula*/*Alnus* seeds
71312	2448*	2920 ± 90	3071 (2849, 3335)	1	1 *Alnus* seed
70220	2556*	4100 ± 90	4620 (4411, 4836)	1	Leaf fragments
70221	2586-A	4290 ± 40	4853 (4731, 4968)	0.994	Wood
69532	2586-B*	4510 ± 100	5150 (4862, 5454)	1	1 *Betula* seed
70222	2632*	4840 ± 210	5559 (4970, 5994)	0.994	Wood
66722	2672.5	5280 ± 40	6063 (5935, 6173)	1	Leaf fragments
68539	2741.8	5830 ± 40	6642 (6501, 6732)	1	1 bud
68540	2753	6170 ± 50	7076 (6909, 7227)	1	Wood
70223	2798*	6890 ± 90	7729 (7580, 7926)	1	Charcoal, leaf fragment
70224	2858	7880 ± 70	8719 (8539, 8991)	0.993	1 seed bract
71313	2866	8160 ± 50	9115 (9008, 9271)	1	2 Cyperaceae seeds
71314	2888	7210 ± 60	8016 (7876, 8164)	1	1 Cyperaceae seed
70225	2890	7240 ± 60	8060 (7949, 8169)	1	1 seed bract
70226	2983*	8580 ± 130	9607 (9272, 9924)	0.976	3 *Betula* seeds
70227	3008	8750 ± 80	9770 (9546, 10148)	1	Leaf fragments
71315	3022*	9470 ± 250	10760 (10150, 11434)	0.99	1 *Betula* seed
70228	3030	9420 ± 140	10687 (10274, 11117)	1	2 *Betula* seeds
71316	3033*	9620 ± 190	10927 (10397, 11344)	0.971	2 *Betula* seeds
70229	3046-A	9860 ± 50	11242 (11172, 11339)	0.977	1 seed
70230	3046-B*	9790 ± 210	11207 (10557, 12089)	1	1 *Betula* seed
68541	3080.4	15490 ± 70	18519 (17875, 19197)	1	Charcoal
68542	3119.6	10430 ± 40	12373 (11751, 12878)	1	Bark and bract
68543	3152.1	41190 ± 870	N/A	N/A	Charcoal
68544	3190.3	9870 ± 60	11257 (11169, 11549)	1	Bark
66723	3229.3	10010 ± 40	11434 (11258, 11685)	1	Bark and charcoal
68545	3242.4	9960 ± 50	11371 (11223, 11625)	1	Charcoal
68546	3289.5	35290 ± 910	N/A	N/A	Charcoal

Captions

1. Map of Minnesota showing major vegetational belts and location of Steel Lake and other sites mentioned in the text.
2. Lithology, loss-on ignition profiles, and pollen zones. A pair of turbidites at 2804-2838 and 2853-2873 cm are shown as sharp maxima of inorganic matter. The maximum at 2750 cm records a thin sandlayer. Sediment types: A continuous carbonate varves, B - Alternating carbonate varves, mixed layers, and turbidites, C - Alternating carbonate varves and dark varved bands, D -Continuous carbonate varves, E - Clayey silty non-varved sedmient, F- Sandy non-varved sediment.
3. Depth/age curve based on a LOWESS model. The short vertical segments at 2804-2873 cm mark the pair of turbidites shown in Figure 2. The dates below 3047 cm, also not used in the curve, are from the trash layer at the base of the core. Calibrated 14C-age error bars are indicated. The sediment surface is set at -51 BP (A.D.2001).
4. Pollen percentages. A. Arboreal pollen AP. B. Non-arboreal pollen NAP.
5. Pollen percentages for selected taxa for the section of detailed analysis at 28002940 cm. A. Arboreal pollen AP. B. Non-arboreal pollen NAP.
6. Pollen accumulation rates (PAR) for selected taxa for zones ST-2 to ST-8. The anomalous maxima between 2804 and 2873 cm result from a pair of turbidites, which increase the rate of sediment deposition and thus the pollen accumulation rate.
7. Ages (ka cal BP) for major vegetational phases from eastern North Dakota to northeastern Minnesota, as controlled by sites with reliable chronologies. The anomalous varve chronology for Elk Lake is indicated. Most of the boundaries of phases between control sites are shown diagrammatically as straight lines because of poor chronological control at intermediate sites.

Figure 1


MANITOBA
ONTARIO
Rattle
CONIFER FOREST
Clouds
Deep
Kylen
Elk
STEEL
Williams
Moon
Lake
Superior
NORTH
DAKOTA
Mississippi River
Mina
WISCONSIN
Pickerel
Medicine
PRAIRIE
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Miles
Kirchner
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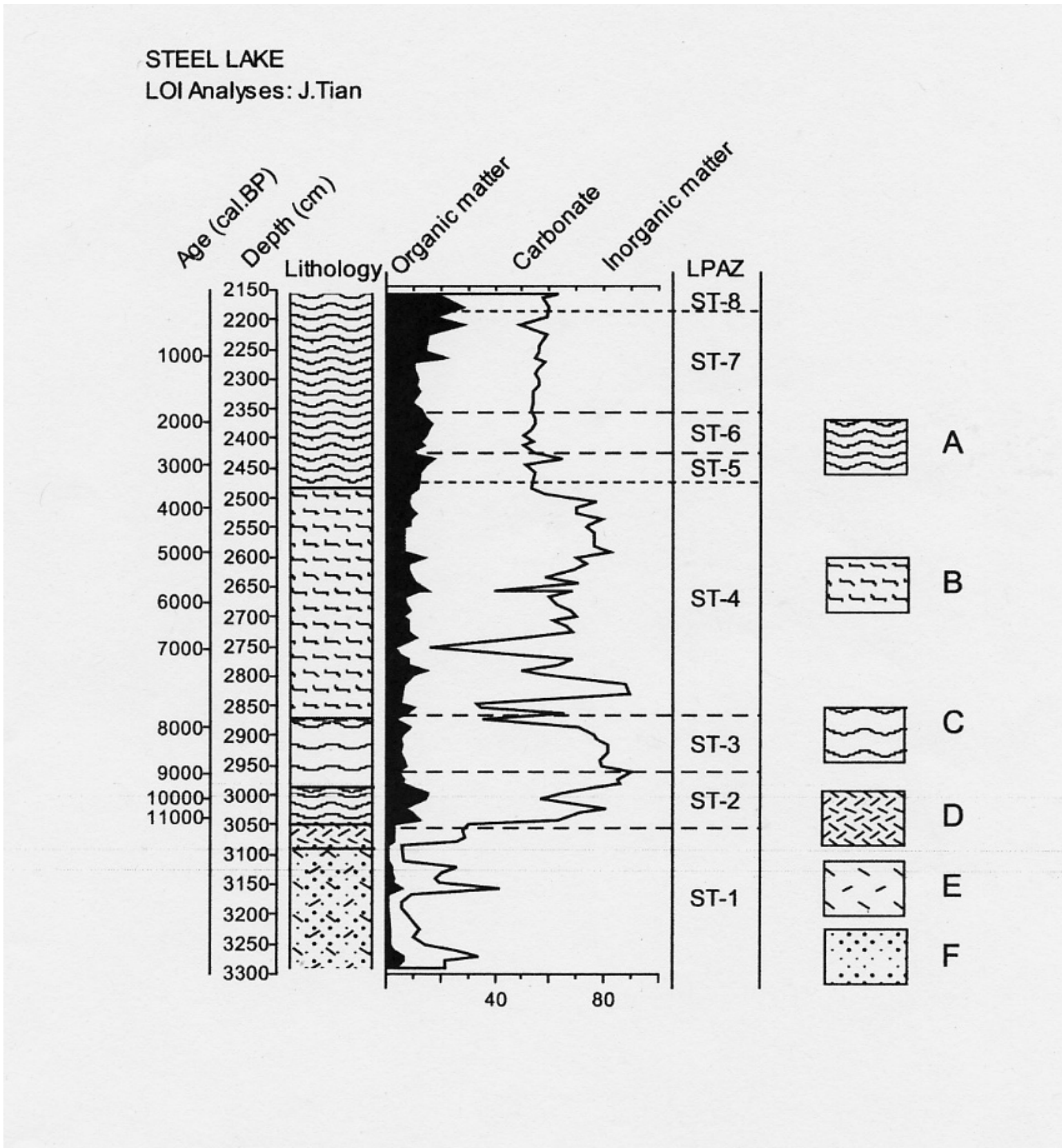
Km
DECIDUOUS
FOREST
SOUTH
DAKOTA
IOWA

Figure 2


STEEL LAKE
LOI Analyses: J.Tian
Age (cal.BP)
Depth (cm)
Lithology
Organic matter
Carbonate
Inorganic matter
LPAZ
ST-8
ST-7
ST-6
ST-5
ST-4
ST-3
ST-2
ST-1
A
B
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F
40
80

Figure 3

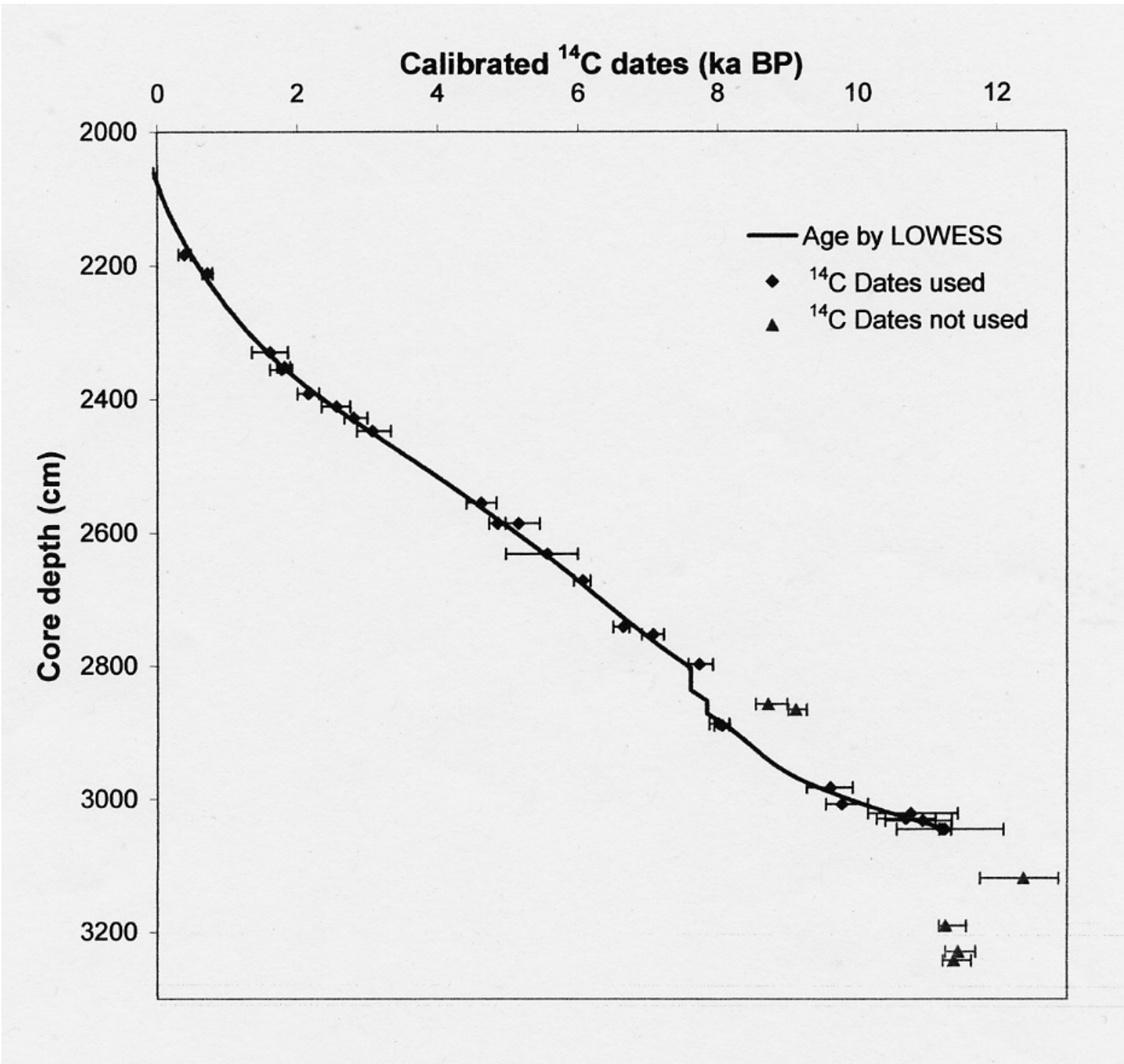

Calibrated ^{14}C dates (ka BP)
0
2
4
6
8
10
12
2000
2200
2400
2600
2800
3000
3200
Core depth (cm)
Age by LOWESS
^{14}C Dates used
^{14}C Dates not used

Figure 4A

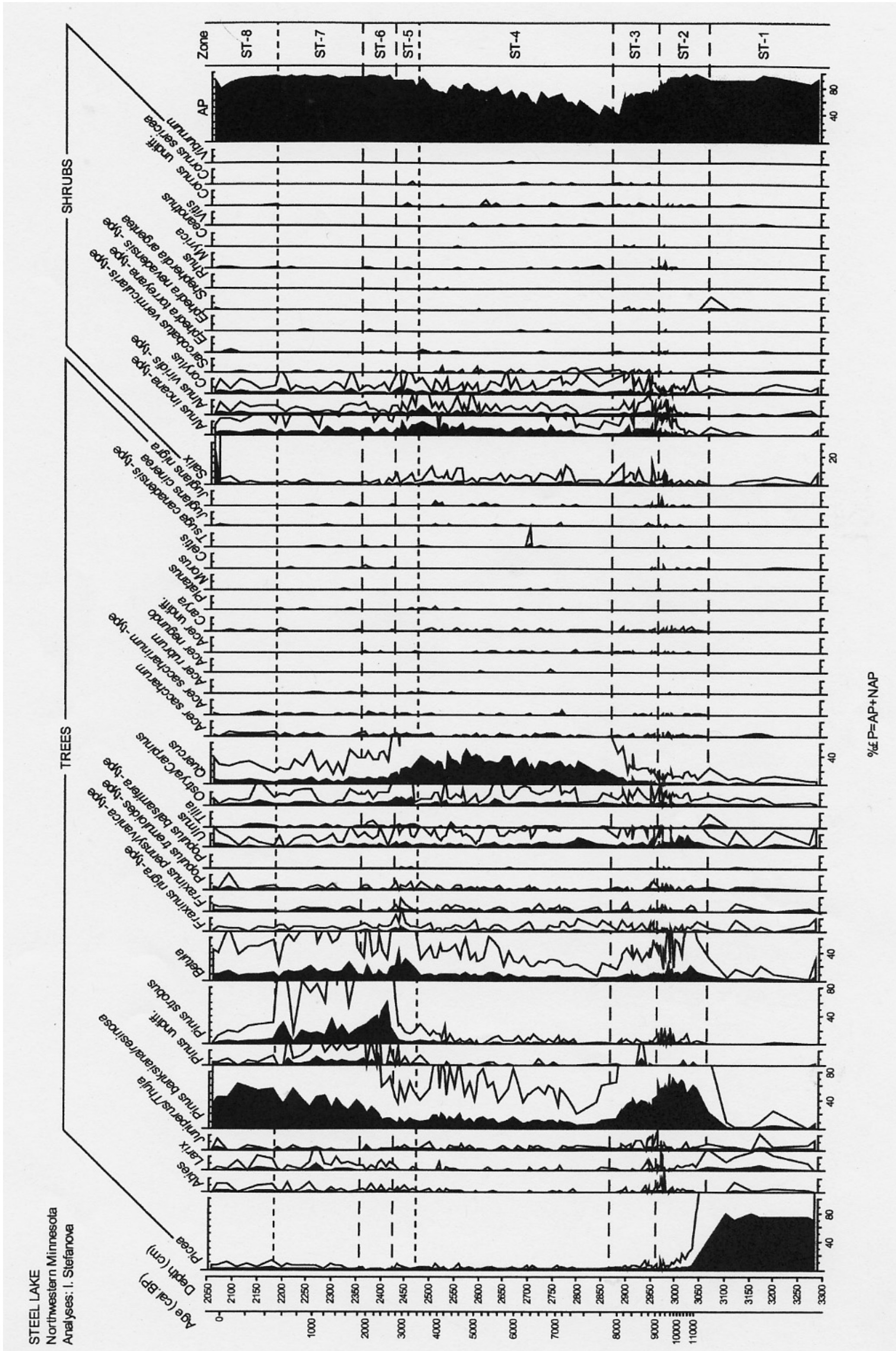

STEEL LAKE
Northwestern Minnesota
Analyses: I. Stefanova
Age (cal BP)
Depth (cm)
TREES
SHRUBS
Picea
Abies
Larix
Juniperus/Thuja
Pinus banksiana/resinosa
Pinus undiff.
Pinus strobus
Betula
Quercus
Ostrya/Carpinus
Salix
Corylus
Alnus viridis -type
Alnus incana-type
AP
Zone
ST-1
ST-2
ST-3
ST-4
ST-5
ST-6
ST-7
ST-8
%Σ P=AP+NAP

Figure 4B

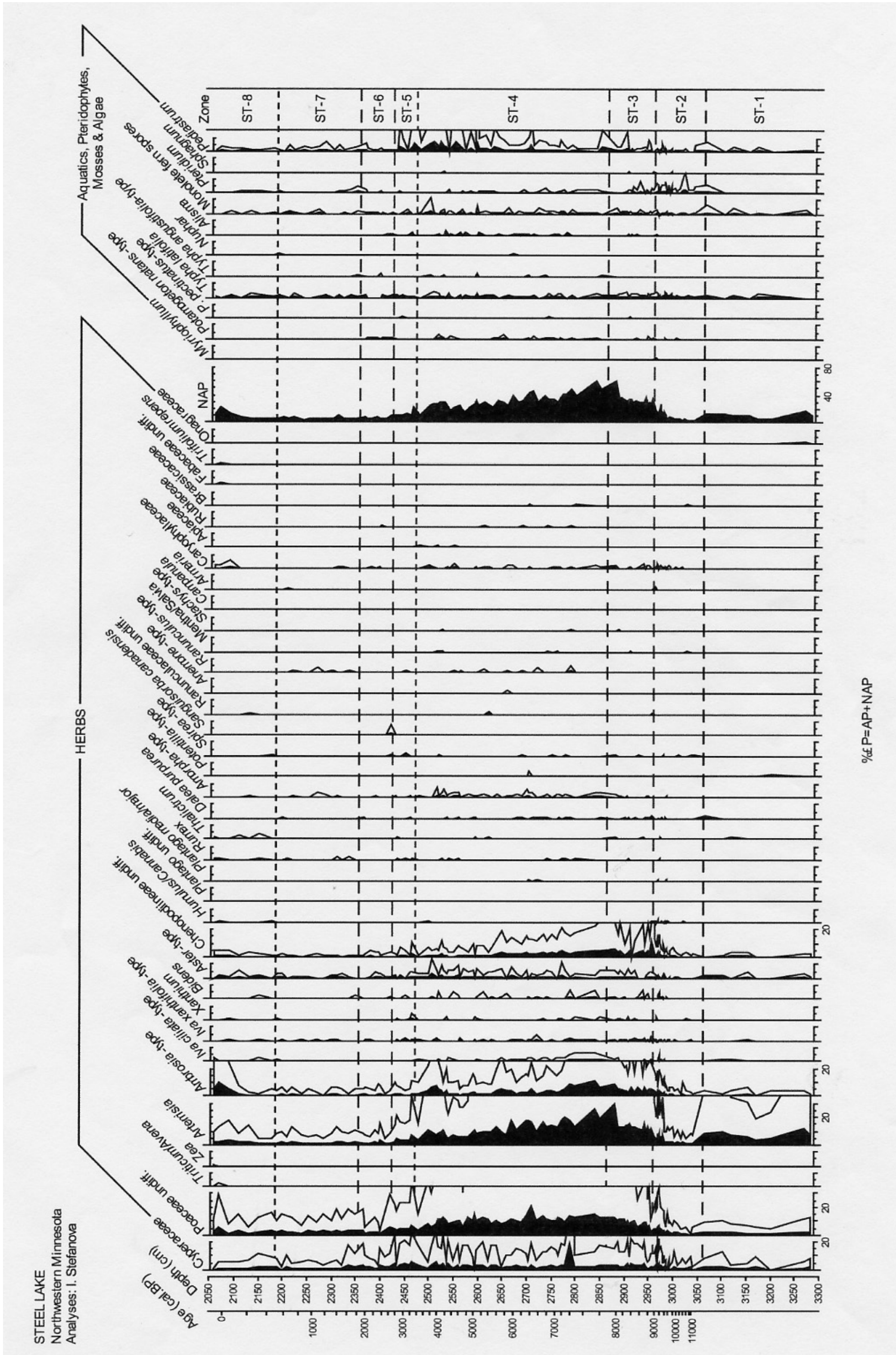

STEEL LAKE
Northwestern Minnesota
Analyses: I. Stefanova
Age (cal BP)
Depth (cm)
Cyperaceae
Poaceae undiff.
Triticum/Avena
Zea
Artemisia
Ambrosia-type
Iva ciliata-type
Iva xanthifolia-type
Xanthium
Bidens
Aster-type
Chenopodiineae undiff.
Humulus/Cannabis
Plantago undiff.
Plantago media/major
Rumex
Thalictrum
Dalea purpurea
Amorpha-type
Potentilla-type
Spirea-type
Sanguisorba canadensis
Ranunculaceae undiff.
Anemone-type
Ranunculus-type
Mentha/Salvia
Stachys-type
Campanula
Armeria
Caryophyllaceae
Apiaceae
Rubiaceae
Brassicaceae
Fabaceae undiff.
Trifolium repens
Onagraceae
NAP
Myriophyllum
Potamogeton natans-type
P. pectinatus-type
Typha latifolia
Typha angustifolia-type
Nuphar
Alisma
Monolete fern spores
Pteridium
Sphagnum
Pediastrum
Zone
HERBS
Aquatics, Pteridophytes, Mosses & Algae
ST-8
ST-7
ST-6
ST-5
ST-4
ST-3
ST-2
ST-1
%£P=AP+NAP

Figure 5A

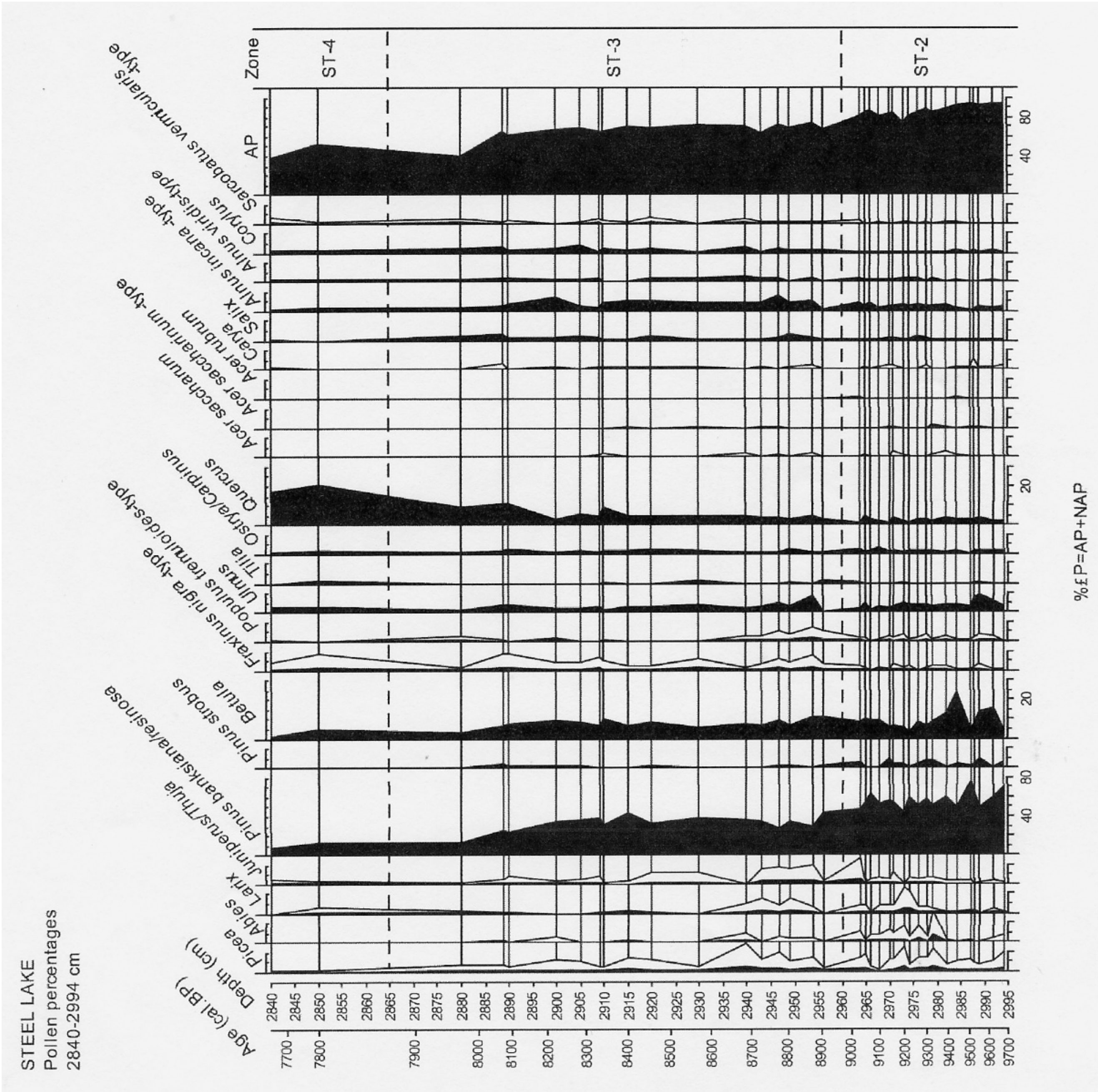

STEEL LAKE
Pollen percentages
2840-2994 cm
Age (cal.BP)
Depth (cm)
Picea
Abies
Larix
Juniperus/Thuja
Pinus banksiana/resinosa
Pinus strobus
Betula
Fraxinus nigra-type
Populus tremuloides-type
Ulmus
Tilia
Ostrya/Carpinus
Quercus
Acer saccharum
Acer saccharinum
Acer rubrum
Carya
Salix
Alnus incana -type
Alnus viridis-type
Corylus
Sarcobatus vermicularis -type
AP
Zone
ST-4
ST-3
ST-2
%£P=AP+NAP

Figure 5B

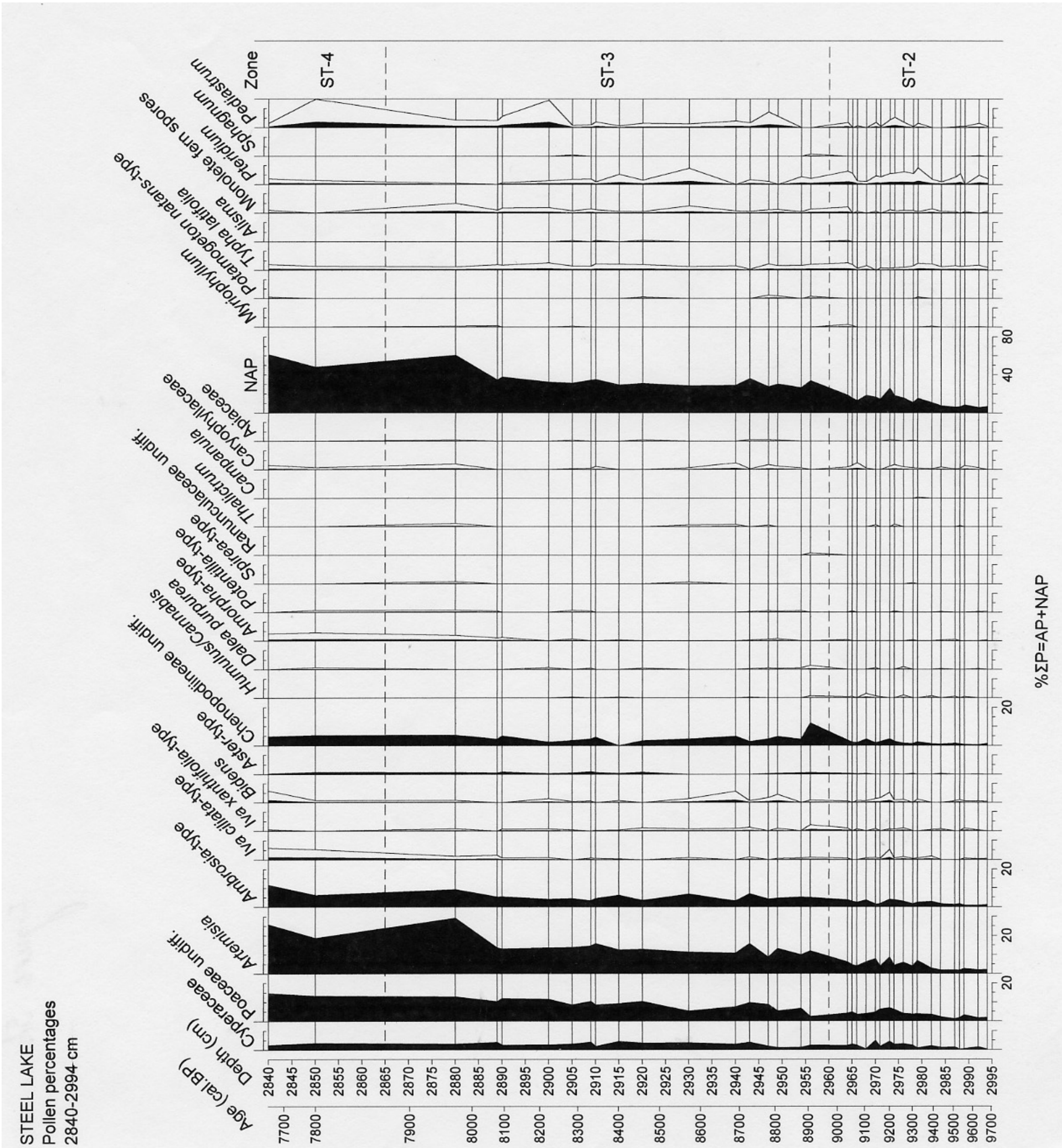

STEEL LAKE
Pollen percentages
2840-2994 cm
Age (cal.BP)
Depth (cm)
Cyperaceae
Poaceae undiff.
Artemisia
Ambrosia-type
Iva ciliata-type
Iva xanthifolia-type
Bidens
Aster-type
Chenopodiineae undiff.
Humulus/Cannabis
Dalea purpurea
Amorpha-type
Potentilla-type
Spirea-type
Ranunculaceae undiff.
Thalictrum
Campanula
Caryophyllaceae
Apiaceae
NAP
Myriophyllum
Potamogeton natans-type
Typha latifolia
Alisma
Monolete fern spores
Pteridium
Sphagnum
Pediastrum
Zone
ST-4
ST-3
ST-2
%ΣP=AP+NAP

Figure 6

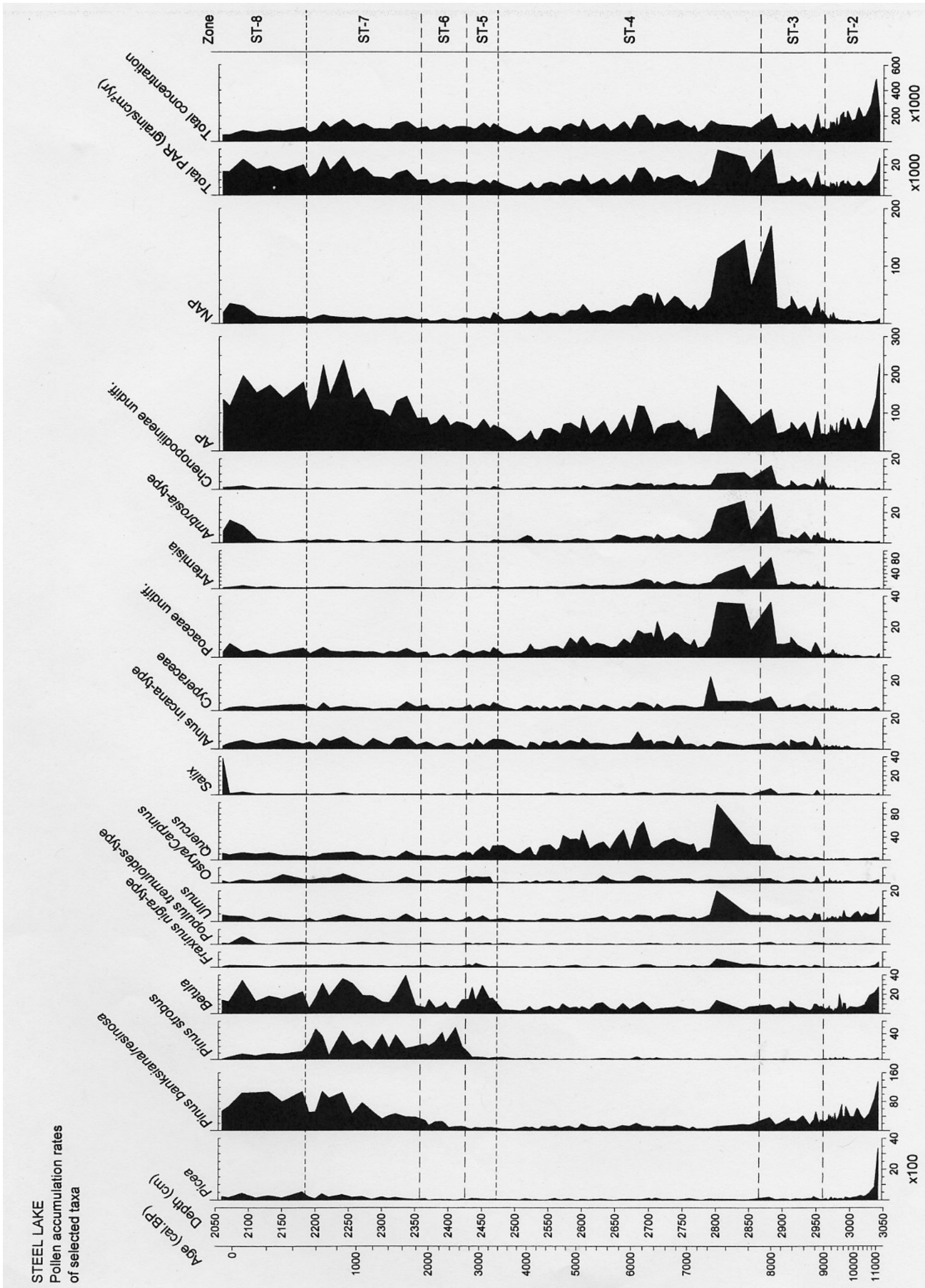
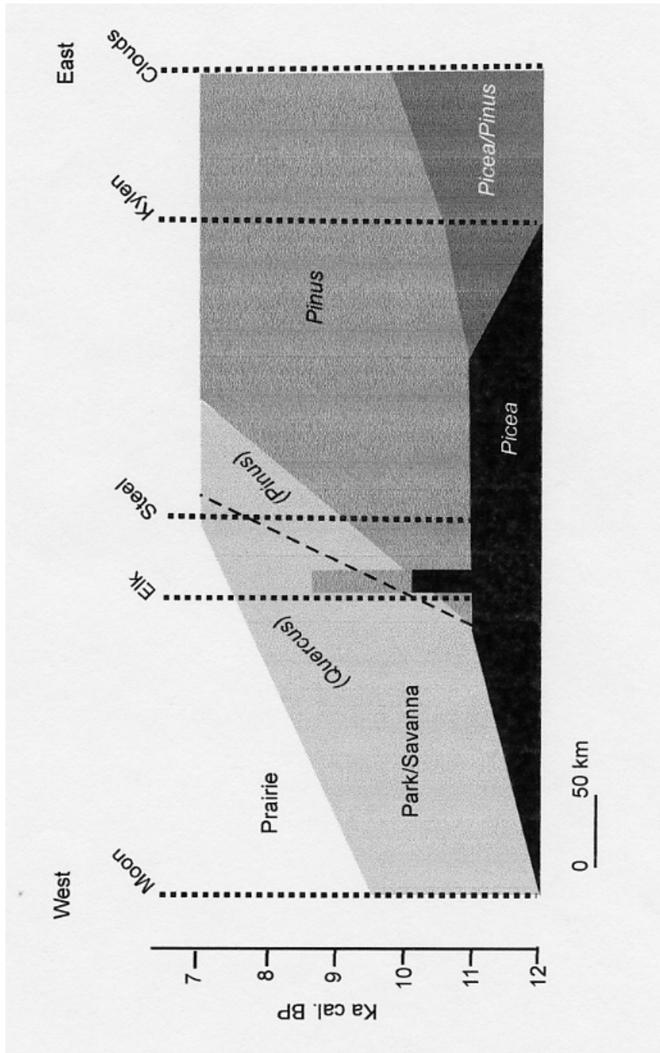

STEEL LAKE
Pollen accumulation rates
of selected taxa
Age (cal BP)
Depth (cm)
Picea
Pinus banksiana/resinosa
Pinus strobus
Betula
Fraxinus nigra-type
Populus tremuloides-type
Ulmus
Ostrya/Carpinus
Quercus
Salix
Alnus incana-type
Cyperaceae
Poaceae undiff.
Artemisia
Ambrosia-type
Chenopodiineae undiff.
AP
NAP
Total PAR (grains/cm²/yr)
Total concentration
Zone
ST-8
ST-7
ST-6
ST-5
ST-4
ST-3
ST-2
x100
x1000
x1000

Figure 7


Ka cal. BP
7
8
9
10
11
12
West
East
Moon
Elk
Steel
Kylen
Clouds
Prairie
Park/Savanna
(Quercus)
(Pinus)
Pinus
Picea
Picea/Pinus
0
50 km