

Vegetation history of Elk Lake

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ABSTRACT

A pollen record from Elk Lake reveals the character and timing of major vegetation changes in northwestern Minnesota for the past 11.6 ka, the past 10.4 ka of which are recorded by varves. Fossil pollen spectra are compared with modern pollen data to identify the closest analogues and thereby to infer past climatic changes. The late glacial *Picea* assemblage (ca. 11,638–10,000 varve yr) lacks an exact analogue in the modern vegetation; initially it compares most closely with modern samples from Manitoba and Saskatchewan and later it is most similar to samples from northeastern Canada. The *Picea* decline at Elk Lake occurs between 10,234 and 9984 varve yr. Within this interval, percentages of *Larix*, *Juniperus*, *Betula*, *Quercus*, *Ulmus*, and *Fraxinus* increase, but the pollen-accumulation rates of these and other taxa decline. The *Pinus banksiana-resinosa* assemblage (10,000–8500 varve yr) has its closest modern analogues in northern Wisconsin and implies warmer slightly drier conditions than before. The prairie period, with high percentages of *Quercus*, Gramineae, and *Artemisia* (8500–4400 varve yr), is first matched by surface samples from central and southern Minnesota, then from southern Saskatchewan, and later from southern and central Wisconsin and Minnesota. The change in the location of the analogues suggests gradually wetter conditions after 5723 varve yr. A *Quercus-Ostrya* assemblage (4400–3000 varve yr) has its modern counterparts in the conifer-hardwood forest of the southern Great Lakes region, where the climate is wetter than that of the prairie period. The *Pinus strobus* assemblage (3000 varve yr to present) marks the development of cooler moister conditions in the late Holocene.

The Elk Lake chronology was converted to radiocarbon years to compare it with other pollen records from the midwestern United States. The *Picea* decline is registered as a time-transgressive event, although it occurred 1000 years earlier in the west than in the east. The late glacial *Ulmus maxima* and the middle Holocene prairie period appear to be synchronous across the region. Discrepancies in the timing of these events are attributed to radiocarbon dating errors, which are particularly severe in the western part of the region.

INTRODUCTION

Minnesota has been the setting for some of the most important advances in Quaternary paleoecology of recent decades, in terms of understanding the postglacial development of vegetation and the response of plant communities to specific changes in environment. Detailed pollen studies from the state have revealed a vegetational history sensitive to a wide spectrum of distur-

bances, ranging from deglaciation and its attendant modification of the late glacial landscape (Wright, 1968; Birks, 1976, 1981), to Holocene climatic fluctuations (Cushing, 1967; McAndrews, 1966; Watts and Winter, 1966; Birks, 1981; Webb and others, 1983; Grimm, 1983; Keen and Shane, 1990), changes in fire frequency (Amundson and Wright, 1979; Clark, 1988a, 1988b), and human disturbances of the environment (Grimm, 1984).

The northwestern part of the state and in particular the

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Itasca Park region have played a central role in paleoecologic investigations. A transect of sites, including Bog D from within the park, first disclosed the eastward movement of the prairie-forest boundary during a period of middle Holocene warmth and aridity (McAndrews, 1966). Pollen and phytosociological studies at the northern edge of the park delineated the relative contribution of local versus regional pollen rain in a small basin, Stevens Pond (Janssen, 1967). A comparison of several microfossil groups in a transect of cores across Elk Lake revealed the timing and extent of lake shallowing during the middle Holocene (Stark, 1976). Archeologic and paleoecologic studies near the shores of Elk Lake led to an understanding of prehistoric utilization of the prairie region during times of vegetational change (Shay, 1971). Detailed studies of fossil charcoal and pollen within the park have led to refinements in the use of paleoecologic data to reconstruct fire history (Clark, 1988a, 1988b, this volume).

In this chapter we describe a ca. 11.6 ka pollen record from Elk Lake in Itasca Park that builds upon this body of literature in three respects. First, a varve chronology for the past 10.4 ka at Elk Lake provides a time scale by which paleoenvironmental events in the region are dated in calendar years. The timing of major vegetational changes are addressed, including (1) the late glacial transition from *Picea*-dominated forest to one largely composed of *Pinus*; (2) the eastward expansion of prairie in the middle Holocene; and (3) the late Holocene spread of pine and hardwood species. Second, modern analogues are selected quantitatively from the large data base of surface samples that now exists from eastern North America; these analogues are used to reconstruct the past vegetation and environment at Elk Lake. Third, the Elk Lake varve chronology is converted to radiocarbon years and compared with other pollen records from the midwestern United States (Midwest). An analysis of important pollen events along north-south and east-west transects helps clarify the regional patterns of vegetational change and assess the variability of radiometric age determinations.

MODERN SETTING AND GLACIAL HISTORY

Elk Lake is located within the pine-hardwood forest, about 80 km east of the eastern limit of prairie (Fig. 1). A belt of deciduous forest dominated by *Quercus macrocarpa* (bur oak) and *Populus tremuloides* (quaking aspen) lies between conifer forest and prairie in the Itasca region. The pine-hardwood forest includes elements from both the boreal forest and the eastern hardwood forest. On droughty, nutrient-poor soils are extensive stands of *Pinus banksiana* (jack pine), *P. resinosa* (red pine), *Q. macrocarpa* (bur oak), *Q. ellipsoidalis* (northern pine oak), *Q. borealis* (red oak), and *Q. alba* (white oak). On widespread till soils, *P. strobus* (white pine) is common on fine-textured soil, whereas *P. resinosa* grows on coarse-textured soil. *Abies balsamifera* (balsam fir), *Picea glauca* (white spruce), *P. mariana* (black spruce), and *Larix laricina* (tamarack) are widespread but are not common in either pine or hardwood forest (McAndrews, 1966). Important hardwood elements from the boreal forest, particularly

in burned areas, are *Betula papyrifera* (white birch), *Populus balsamifera* (balsam poplar), and *P. tremuloides* (quaking aspen). Hardwoods typical of the eastern hardwood forest grow on fine-textured soils and include *Acer rubrum* (red maple), *A. saccharum* (sugar maple), *Betula lutea* (yellow birch), *Ulmus* spp. (elm), *Fraxinus* spp. (ash), *Tilia americana* (American basswood), *Ostrya virginiana* (eastern hophornbeam), and *Alnus rugosa* (speckled alder). Common upland shrubs include *Corylus* (hazel), *Cornus* (dogwood), *Amelanchier* (serviceberry), *Prunus* (cherry), *Viburnum*, and *Ribes*. Less common shrubs are *Alnus crispa* (green alder), *Taxus canadensis* (American yew), *Juniperus communis* (common juniper), and *Carpinus* (hornbeam). Many of the slopes around the site were extensively logged from A.D. 1901 to 1921 (Dobie, 1959), and today the vegetation at the lake margin is balsam fir and red pine, while aspen and birch are more abundant upslope.

Itasca Park lies in the middle-latitudinal belt of prevailing westerly winds. Air masses originate from three source areas: from the south comes warm moist subtropical air, from the north comes cold dry continental polar air, and from the west comes dry continental air (Bryson, 1966). The character of the weather and climate reflects the frequency of cyclonic storms associated with different air-mass systems. Mean temperatures are 20 °C in July and -7.8 °C in January. About 670 mm of precipitation is received yearly, most between April and September (U.S. Department of Commerce Weather Bureau, 1960).

Two lobes of the Laurentide ice sheet covered the Elk Lake region in late Wisconsin time (Wright, 1972, and Chapter 2). The Wadena lobe formed the Itasca moraine at ca. 20 ka. The Elk Lake depression is part of a subglacial tunnel-valley system that formed beneath the Wadena lobe. Later the Wadena till and stagnant ice were buried by outwash from the St. Louis sublobe of the Des Moines lobe, which reached its maximum ca. 13 ka. The oldest sediments at Elk Lake date to ca. 11.6 ka, suggesting that the basin formed from the melting of a buried ice complex ca. 1500 yr after retreat of the Des Moines lobe.

METHODS

Only the palynological procedures are discussed here, inasmuch as the field methods and the varve chronology are presented in Anderson and others (Chapter 4). The varve chronology is discussed as varve years ago (varve yr); radiocarbon years are listed as ka (1000 yr before present).

Pollen samples were extracted from the core with a 0.5 cm³ rectangular metal sampler at intervals of 50 yr; 90 samples were analyzed. The 50th yr lamina was in the middle of each sample and the number of varve years per sample was recorded. Samples processed for pollen analysis were subjected to standard treatments with HCl, KOH, HF, acetolysis, and alcohol washes outlined by Faegri and Iversen (1975), and stored in silicon oil.

Pollen was examined under magnifications of 400 \times and 1000 \times . Identifications were based on the reference collection at the Limnological Research Center, University of Minnesota, and

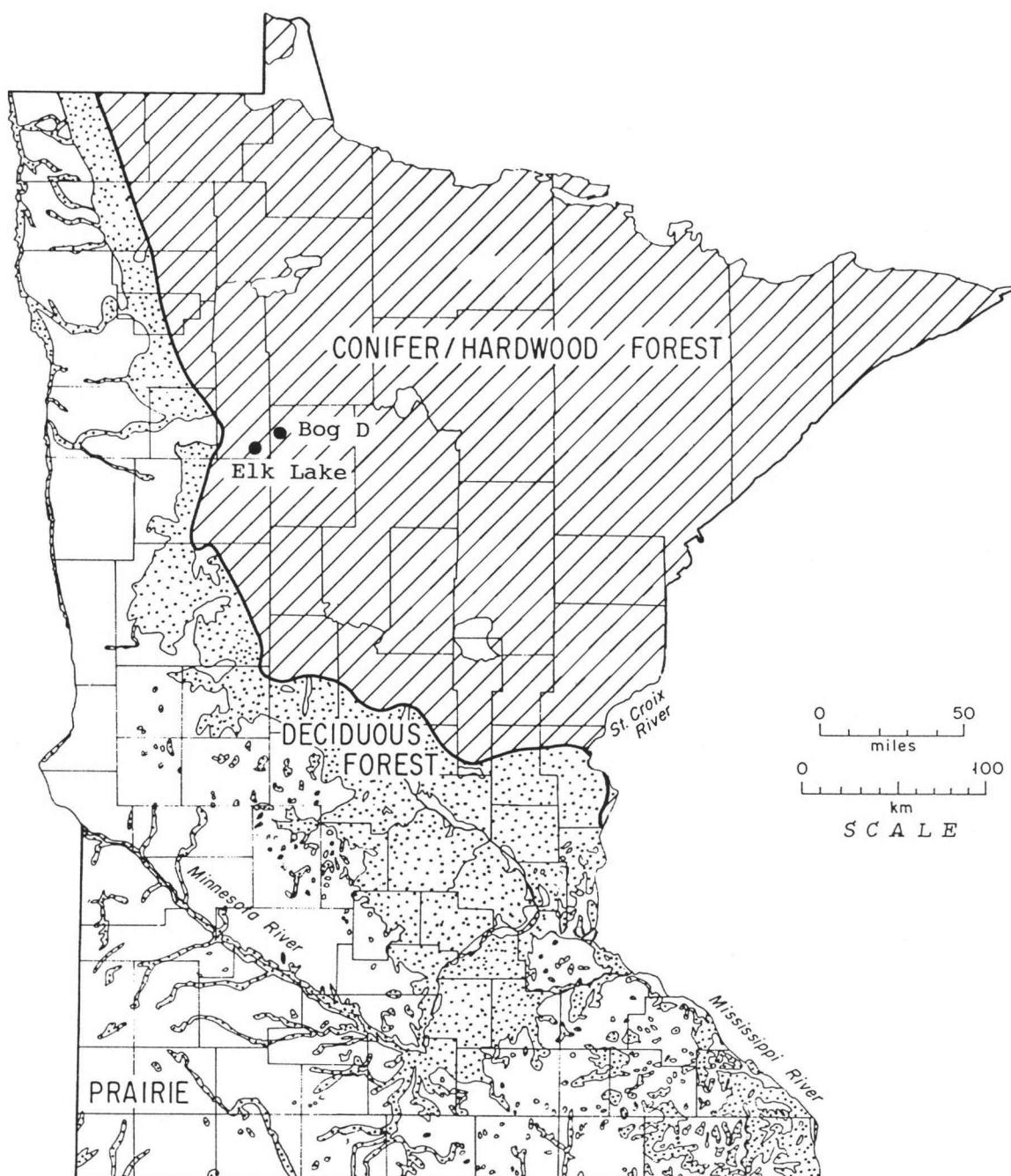


Figure 1. Vegetation map of Minnesota showing location of Elk Lake and Bog D Pond (McAndrews, 1966).

published atlases (Faegri and Iversen, 1975; McAndrews and others, 1973; Moore and Webb, 1978). Grains that could not be identified were tallied as "unknown"; grains that were deteriorated, corroded, hidden, or broken beyond recognition were considered "indeterminate." Diploxylon-haploxyton determinations were made on *Pinus* pollen with intact distal membranes; other *Pinus* were tallied as undifferentiated.

Percentage data were the major tools for reconstructing past vegetation and climate. The sum of the terrestrial pollen and spores was the denominator in calculating the percentages of trees, shrubs, herbs, and terrestrial pteridophytes. The sum of all palynomorphs was used to calculate the percentages of aquatic and wetland taxa. A *Eucalyptus* tracer was added to each sample to permit calculation of pollen concentration (grains/cm³).

When divided by the deposition time (varve yr/cm), the concentration values were converted to pollen-accumulation rates (grains/cm²/varve yr). The deposition time in varved sequences can be calculated with greater accuracy than that achieved from radiocarbon-dated nonlaminated sediments, and therefore some of the imprecision inherent in calculations of pollen-accumulation rates is mitigated at Elk Lake.

The interpretation of the fossil percentage data was facilitated by identifying quantitatively the closest modern analogues for each fossil spectrum. This analysis involved selecting a set of modern pollen data from eastern North America and calculating a dissimilarity value between a fossil spectrum and the surface samples. These dissimilarity values were mapped to identify the locations of the modern spectra that are similar to each fossil spectrum.

The data set consisted of 1200 modern spectra, including some selected from the set of modern pollen data at Brown University (e.g., Overpeck and others, 1985; Bartlein and others, 1984), supplemented by additional samples from Lichti-Federovich and Ritchie (1965, 1968) and MacDonald and Ritchie (1986) for the central and western interior of Canada. The pollen sum consists of the 44 most abundant pollen types, including herb taxa with the notable exception of *Ambrosia* and *Iva*, which are generally overrepresented in modern samples as a result of agriculture and other anthropogenic disturbances. Some of the types in the sum never appear at Elk Lake (e.g., *Magnolia*) but are included to avoid fortuitous analogues. For example, the *Pinus* and *Quercus* percentages are such that, if southeastern hardwood taxa were omitted from the sum, some modern spectra from the southeastern United States would be similar to some of the fossil values at Elk Lake, even though they are clearly from a nonanalogous vegetation.

Following Overpeck and others (1985), the squared chord distance was used as the dissimilarity measure, or

$$d_{ij} = \sum_k (p_{ik}^{1/2} - p_{jk}^{1/2})^2,$$

where d_{ij} is the squared chord distance between two pollen spectra i and j , and p_{ik} is the proportion (between 0.0 and 1.0) of pollen type k in pollen spectrum i .

Anderson and others (1989) listed the desirable properties of the squared chord distance for identifying modern analogues, including (1) the ability of this measure to differentiate vegetation types at the scale of the formation and even the forest type; (2) the values of this measure that indicate that "good analogues" are robust with respect to the choice of the pollen sum; and (3) at the large geographic scale considered here, this measure emphasizes the large-scale patterns in the data and suppresses the local variability, or noise, in the modern pollen samples. Interpretation of the squared chord was facilitated by determining its value for each unique pairing of the 1200 modern samples (yielding 119,400 values). The first, fifth, and tenth percentile (0.092, 0.205, and 0.305, respectively) of these values are provisionally selected as indicators of very good, good, and fair analogues (see

Anderson and others, 1989). The modern spectra that are similar to the fossil spectra at Elk Lake lie within a limited region in eastern North America (i.e., no spectra from the southeastern United States are similar to any of the fossil spectra at Elk Lake).

POLLEN RECORD

It is not surprising that the pollen record from Elk Lake compares closely with that from nearby Bog D. McAndrews (1966) identified five assemblages that provide a useful basis for discussion: *Picea* assemblage; *Pinus banksiana-P. resinosa-Pteridium* assemblage; *Quercus-Gramineae-Artemisia* assemblage; and *Pinus strobus* assemblage, with a *P. banksiana-resinosa* subassemblage. Pollen percentages for the entire record are presented in Figure 2; the late glacial and early Holocene portions are plotted on a larger scale in Figure 3. The pollen-accumulation rates are in Figure 4.

Pollen values of the best modern analogue for each spectrum are plotted stratigraphically and compared to a fossil-pollen diagram that uses the same pollen sum (Fig. 5). Maps display the location of the modern pollen data with variably shaded symbols to reflect the degree of similarity between a particular fossil spectrum and each modern spectrum (Fig. 6). These maps identify the location of modern counterparts and illustrate the strength of the analogue. Throughout the record, the most similar modern spectrum for each fossil spectrum has a squared chord distance less than the tenth percentile of the squared chord distances among the modern samples. However, some variations exist in the strength of the similarities through time. Four episodes can be identified: (1) the interval during which the *Picea* assemblage prevailed, when the squared chord distances are relatively large, indicating relatively poor modern analogues for these spectra; (2) the interval spanning the time when *Pinus banksiana-P. resinosa-Pteridium* and *Quercus-Gramineae-Artemisia* assemblages occurred, when the squared chord distances are relatively small; (3) the interval when the *Quercus-Ostrya* assemblage prevailed, when the dissimilarities are again large; and (4) the interval from 3000 varve years to present (the *Pinus strobus* assemblage), when the squared chord distances are small, indicating good modern analogues for the fossil spectra.

Picea assemblage (11,638–10,000 varve yr)

This assemblage is characterized by high pollen percentages of *Picea* (8%–52%) and significant amounts of *Pinus*, *Larix*, *Gramineae*, *Cyperaceae*, and *Artemisia*. Low combined percentages (<8%) of *Quercus*, *Ulmus*, and *Fraxinus* are also present. Indeterminate pollen is abundant and includes degraded Cretaceous taxa derived secondarily from the bedrock. Rates of pollen accumulation of *Picea*, *Larix*, *Juniperus*, and *Betula* are variable, and the overall pollen-accumulation rates in the varved sediments are less than 8000 grains/cm²/yr, typical of modern forest tundra and boreal forest (Ritchie and Lichti-Federovich, 1967; M. B. Davis and others, 1973; R. B. Davis and others, 1975).

The six bottommost pollen samples are from the unvarved part of the core—the interval from 10,400 varve yr and extrapolated to 11.638 ka. The period probably records the initial formation of Elk Lake during ice melting. The sediments contain lots of woody plant debris derived from forest that may have grown on a buried ice block prior to the formation of the lake. Pollen-accumulation rates are lowest (<18,900 grains/cm²/yr) above and below two sand layers estimated to be 11.20 and 11.4 ka. Ostracodes from these sand units suggest a lake at least a few meters deep with irregular deposition patterns (Smith, 1991). This hypothesis is consistent with the evidence for variable deposition times implied by pollen-accumulation rates.

The pollen data suggest that before 10,000 varve yr the vegetation was a spruce forest with local hardwoods, as well as openings that supported *Artemisia*, Gramineae, and other herbs. The landscape during the spruce period was probably characterized by meltwater sand plains, unstable slopes, and shallow soils. On well-drained soil, mixtures of white spruce, paper birch, grass, and *Artemisia* may have occurred. Tamarack may also have grown on the uplands, as it does today in Canada. Poorly drained substrates would have also sustained tamarack, black spruce, and sedges. Ash and elm would have grown on seasonally moist soils.

In comparison to the Bog D record, the spruce period at Elk Lake features more *Juniperus* and less *Populus* pollen. Juniper favors open areas with high snow accumulation, and it is possible that the slopes around Elk Lake were more suited to its growth than at Bog D. *Populus* (probably both *P. tremuloides* and *P. balsamifera* types) pollen at Bog D was abundant enough for McAndrews (1966) to designate a *Picea-Populus* assemblage. Its poor representation at Elk Lake suggests either that the sedimentary matrix was less suitable for the preservation of this delicate grain or that the tree was less abundant in the pollen-recruitment area.

Modern analogues for the spruce assemblage are not exact and change midway. The analogue map for 11,638 yr shows the best match in modern samples from Manitoba and Saskatchewan, where *Picea* and herb percentages are high and *Pinus* values are relatively low (Fig. 6). Even the best modern analogues tend to overrepresent *Pinus* and *Betula* and underrepresent *Picea* and *Juniperus* in comparison with the late glacial spectra. The reconstructed climate for this period was cold and relatively dry (see Bartlein and Whitlock, Chapter 18, for specific climatic estimates).

The end of the spruce period occurs between 10,234 and 9984 varve yr, when *Picea* pollen declines from 51% to 10%. During this interval *Pinus banksiana-resinosa* pollen rises from 6% to 28%. A decline in nonarboreal percentages at Elk Lake begins at 10,334 varve yr. Prior to the rise in *Pinus* percentages, there is a brief interval in which percentages of *Abies*, *Larix*, *Juniperus*, *Betula*, *Quercus*, *Ulmus*, and *Fraxinus* are higher than before or after. This increase is not matched by a change in pollen-accumulation rates at Elk Lake. The intervening interval is more conspicuous farther south in Minnesota (Amundson and Wright, 1979) and has been interpreted as a time when various conifer and hardwood taxa grew on a landscape in which spruce

populations were declining, but before the expansion of pine. The low accumulation rates of Elk Lake, however, imply that these taxa were only minor elements of an open spruce forest in the Itasca region, if present at all. It seems likely that the climatic conditions that limited spruce suppressed all species and the period between 10,200 and 10,000 varve yr was sparsely vegetated.

Modern analogues for the 10,084 varve yr spectra can be found west of Elk Lake, where *Picea* accounts for >35% and *Pinus* percentages are high (Fig. 6). Warming and possibly drier conditions may have characterized the Elk Lake climate at that time. The analogues, however, do not contain significant percentages of *Quercus*, *Ulmus*, and *Fraxinus*.

Pinus banksiana-resinosa-Pteridium assemblage (10,000–8500 varve yr)

An increase in *P. banksiana-resinosa* percentages and *Betula* (10%–23%) occurs between 10,034 and 9050 varve yr. *Pteridium* is represented by low values (<4%). *Ulmus* (4%–8%), Gramineae (4%–8%), Cyperaceae (<5%), and *Artemisia* are also present in small percentages. *Picea*, *Larix*, *Juniperus*, and *Abies* values are insignificant. Percentages of *Artemisia* and Gramineae increase about 8450 varve yr at the end of this assemblage. The total pollen-accumulation rates during this interval range from 5740 to 20,090 grains/cm²/yr, typical of those from modern boreal forest (Ritchie and Lichti-Federovich, 1967; M. B. Davis and others, 1973; R. B. Davis and others, 1975).

The pollen record suggests development of an upland forest composed largely of *Pinus banksiana*, *Betula papyrifera*, and possibly *P. resinosa*. *Picea* and *Larix* were probably restricted to boggy sites. McAndrews (1966) suggested that *Ulmus* was an important tree on fine-textured and moist soils. High levels of charcoal at other sites, along with an abundance of *Pteridium*-type spores, suggest that frequent fires allowed bracken fern to become an important understory species in a forest dominated by jack pine. The pine period is registered at Bog D between 11 and 8.56 ka, although Webb and others (1983) decreased these dates by 1000 yr, which matches more closely the Elk Lake record. The anomalously old dates at Bog D are on calcareous gyttja and are attributed to a carbonate error. Radiocarbon dates on the Elk Lake record (Anderson and others, Chapter 4) also imply a carbonate error of about 1000 yr in this interval. Dates of 9.36 and 9.69 ka on *Larix* wood within the spruce zone from the nearby Nicollet Valley are younger and considered more reasonable (Shay, 1971; Webb and others, 1983).

Paleoecologic data point to the Appalachian region and the Atlantic coastal plain as the glacial refugia for jack pine (Davis, 1983; Watts, 1979). The species migrated to Minnesota from the south and east, colonizing areas disturbed by fire and wind throw within a spruce forest that was declining as a result of warmer, effectively drier summers and winters (Amundson and Wright, 1979). The establishment of pine about 10,000 yr ago may be attributed to climatic warming and its effect on the disturbance regime. The closest modern analogues are found in northern Wis-

ELK LAKE, Clearwater County, Minnesota
Pollen Percentages

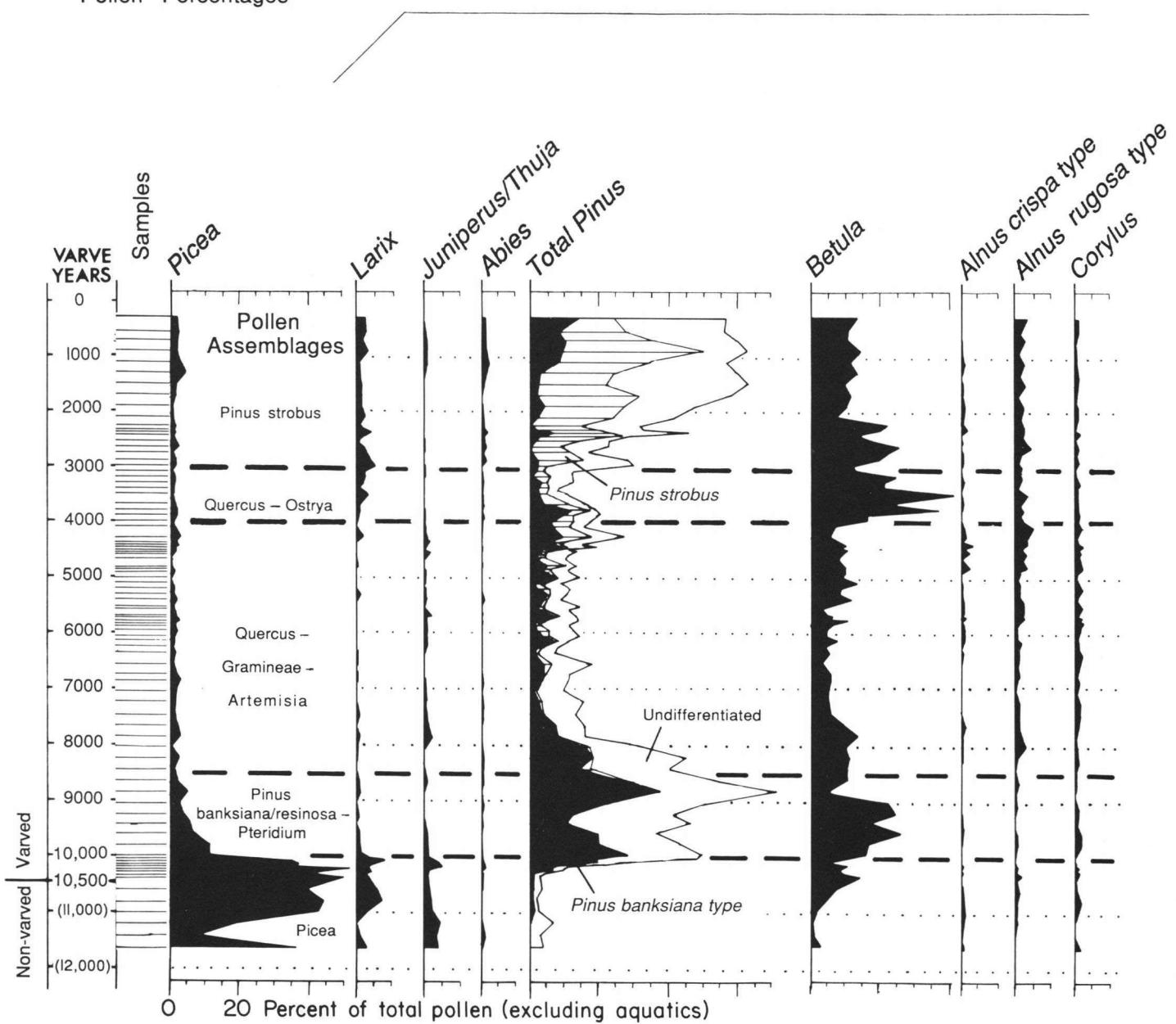


Figure 2 (on this and following three pages). Pollen percentage diagram.

consin and southern Alberta at the southern edge of the boreal forest (Fig. 6, analogue maps for 9984 and 9584 varve yr).

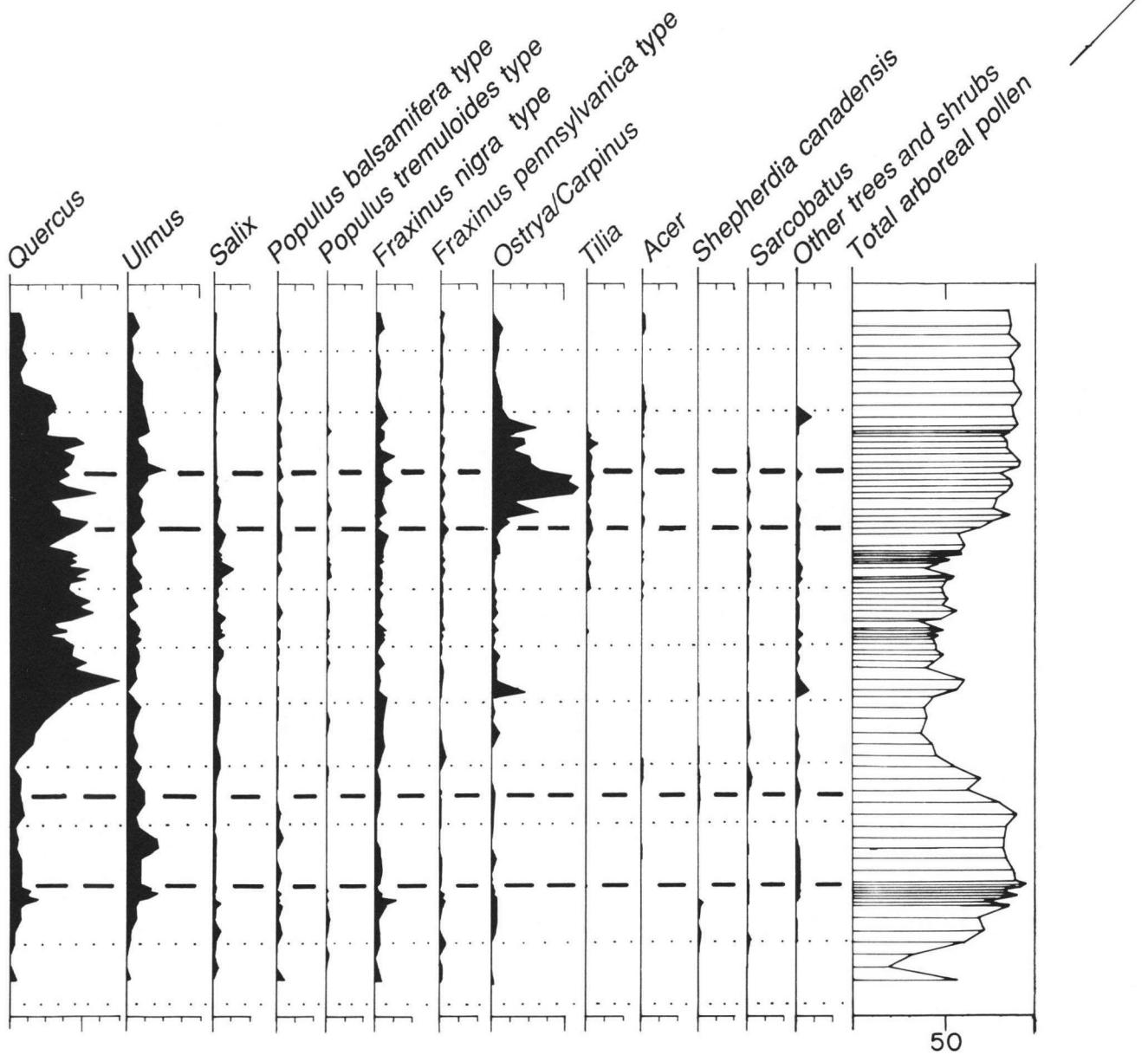
Quercus-Gramineae-Artemisia assemblage
(8500–4000 varve yr)

Percentages of *Quercus*, Gramineae, and *Artemisia* increase after 8500 varve yr. These pollen types are most abundant after 8000 varve yr, when they occur with *Ambrosia*, *Tubuliflorae*, *Iva*,

ciliata-type, *Chenopodiinae*, and other herbaceous taxa. *Salix*, *Corylus*, *Fraxinus*, and *Alnus* are represented steadily throughout the assemblage. The pollen-accumulation rates for this period fluctuate widely between 1870 and 48,050 grains/cm²/yr.

The assemblage suggests a gradual transition from jack pine forest to oak savanna and prairie in the middle Holocene. McAndrews (1966) suggested that *Quercus macrocarpa* was the dominant tree during the prairie period, but that *Q. ellipsoidalis*

— TREES AND SHRUBS —

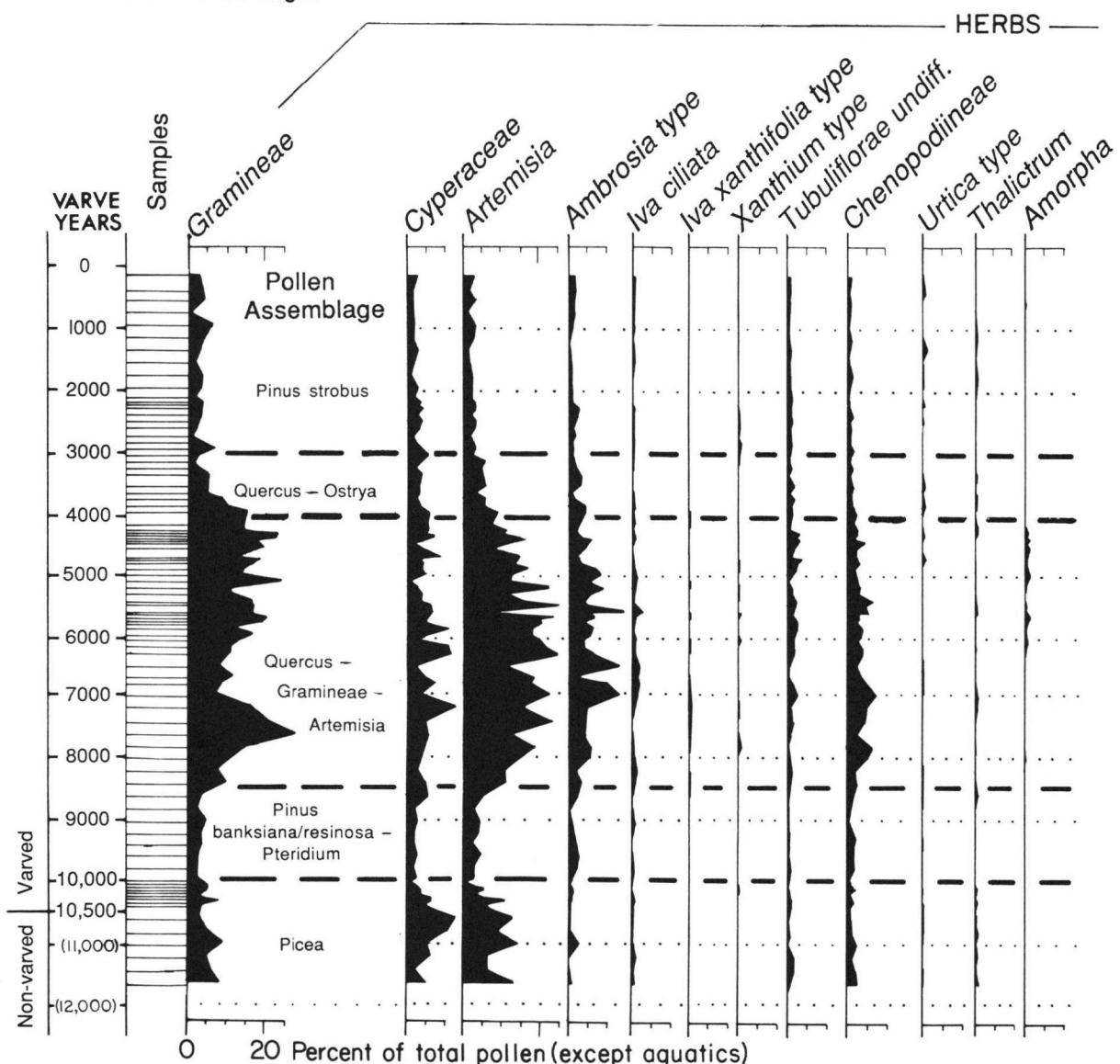


probably grew on outwash soils. *Artemisia* pollen is attributed to *A. ludoviciana*, *A. frigida*, and *A. glauca*. *Corylus*, *Salix*, *Alnus rugosa*, and *Fraxinus* may have been common on fine-textured soils.

Modern analogues for the prairie period first lie in northern Wisconsin and Minnesota and after 8247 varve yr in central and southern Minnesota (Fig. 6). This shift suggests a significant drying trend (See Bartlein and Whitlock, Chapter 18). The analogues for 7862 varve yr are found along the United

States–Canada border, where modern Gramineae values are high and suggest drier conditions than before. By 7232 varve yr, the best modern analogues are from southwest of Elk Lake, where the *Artemisia* and Chenopodiinae percentages are high and conditions are even drier. The best modern analogues for 5723 varve yr come from southern and central Wisconsin and Minnesota, where *Betula* pollen is well represented today and the climate is wetter. It is noteworthy that this shift toward wetter conditions

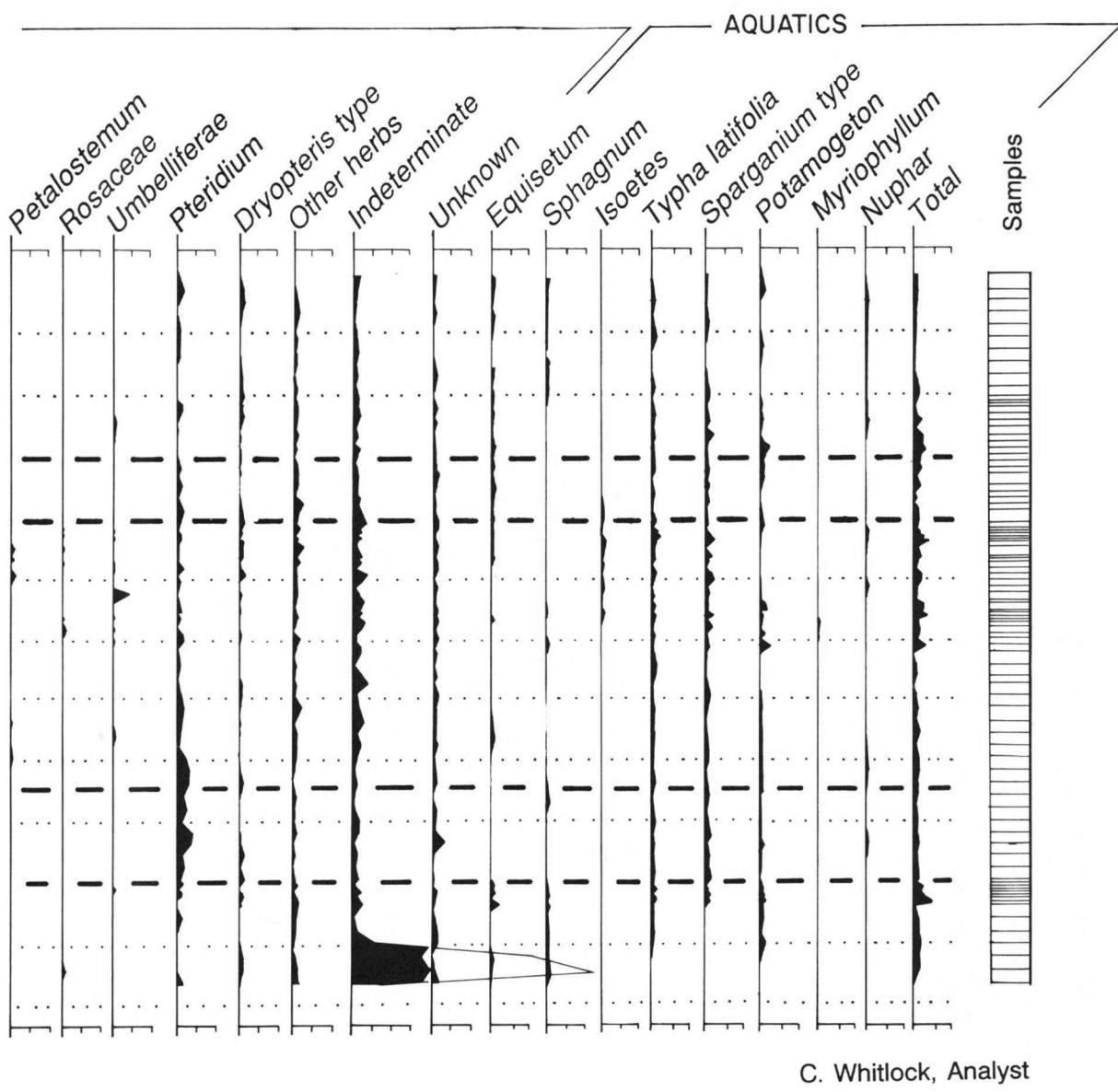
ELK LAKE, Clearwater County, Minnesota
Pollen Percentages



coincides with renewed alluviation of flood plains in southwestern Wisconsin, which is also attributed to increased precipitation at the end of the prairie period (Knox, 1983, 1985; McDowell, 1983). It also coincides with an abatement of eolian activity and evidence of higher precipitation in east-central Minnesota (Keen and Shane, 1992).

At Elk Lake the prairie period has been divided into three climatic phases on the basis of diatom, sedimentologic, and geochemical data: an early xeric phase between 8500 and 5400 varve

yr, a somewhat wetter phase from 5400 to 4800 varve yr, and a dry phase between 4800 and 4000 varve yr (Dean and others, 1984; Dean, Chapter 10; Bradbury and Dieterich-Rurup, Chapter 15). The pollen record does not show this subdivision clearly, although subtle fluctuations in pollen percentages do occur for several taxa and considered together these may reflect climatic changes (see Bartlein and Whitlock, Chapter 18). *Artemisia* percentages, for example, increase at 8447 varve yr and decline beginning at 4439 varve yr. *Quercus* percentages increase signifi-



C. Whitlock, Analyst

cantly at 7232 varve yr as *Pinus* and *Betula* decrease, and they remain high until 1600 varve yr. Some herb pollen types show minor trends during the prairie period. Gramineae pollen, an indicator of relative wetness, shows two peaks centering at 7660 and 4675 varve yr. *Ambrosia* percentages are high between 8047 and 4573 varve yr. *Chenopodiinae* is best represented between 8047 and 5534 varve yr, and values decline gradually after that. Pollen of *Petalostemum purpureum*-type and *P. candidum*-type (combined together as *Petalostemum* in pollen diagrams) and

Amorpha-type are present consistently after 6000 varve yr. Furthermore, pollen-accumulation rates are lowest for the period from 5400 to 4800 varve yr, which may represent a time when slopes were less vegetated than before or after.

The prairie period is generally attributed to unidirectional warming and drying in the middle Holocene, caused by the reduced frequency of arctic air masses and more common occurrence of warmer and drier Pacific air masses (Bartlein and others, 1984). However, Forester and others (1987) on the basis of os-

ELK LAKE, Clearwater County, Minnesota

Pollen Percentages

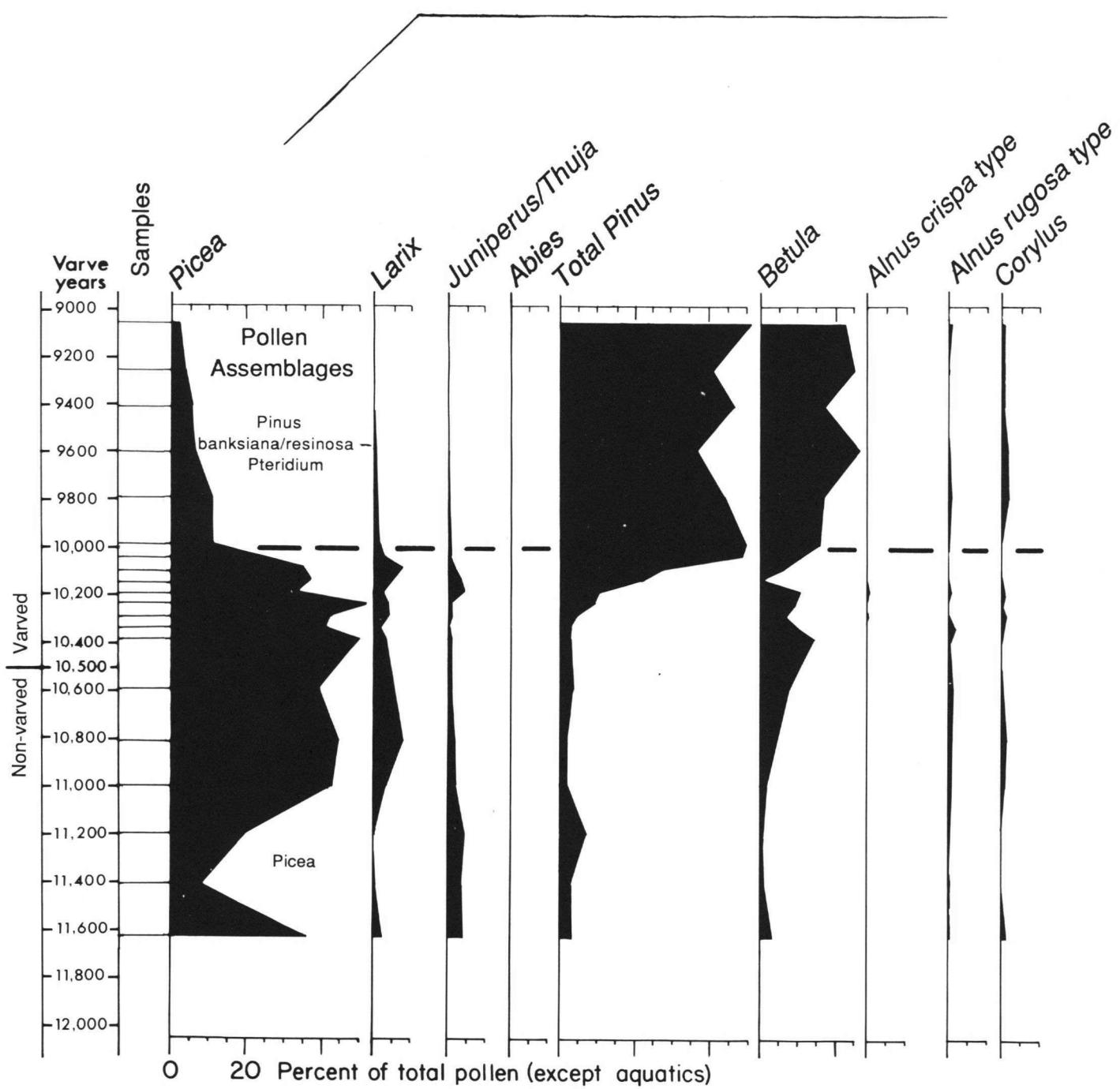
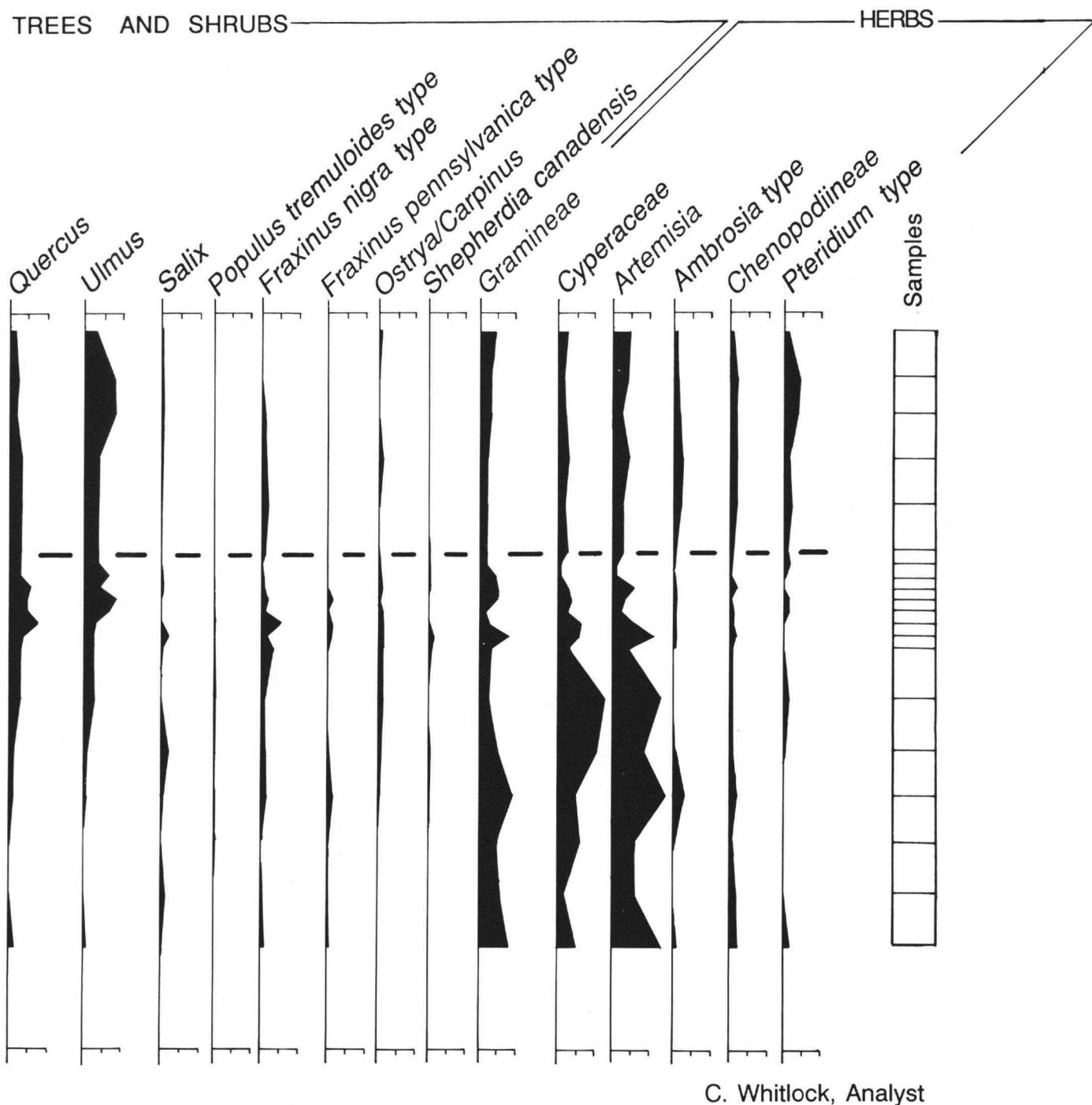


Figure 3. Expanded pollen percentage diagram showing the late glacial and early Holocene periods.



ELK LAKE, Clearwater County, Minnesota
Pollen Influx

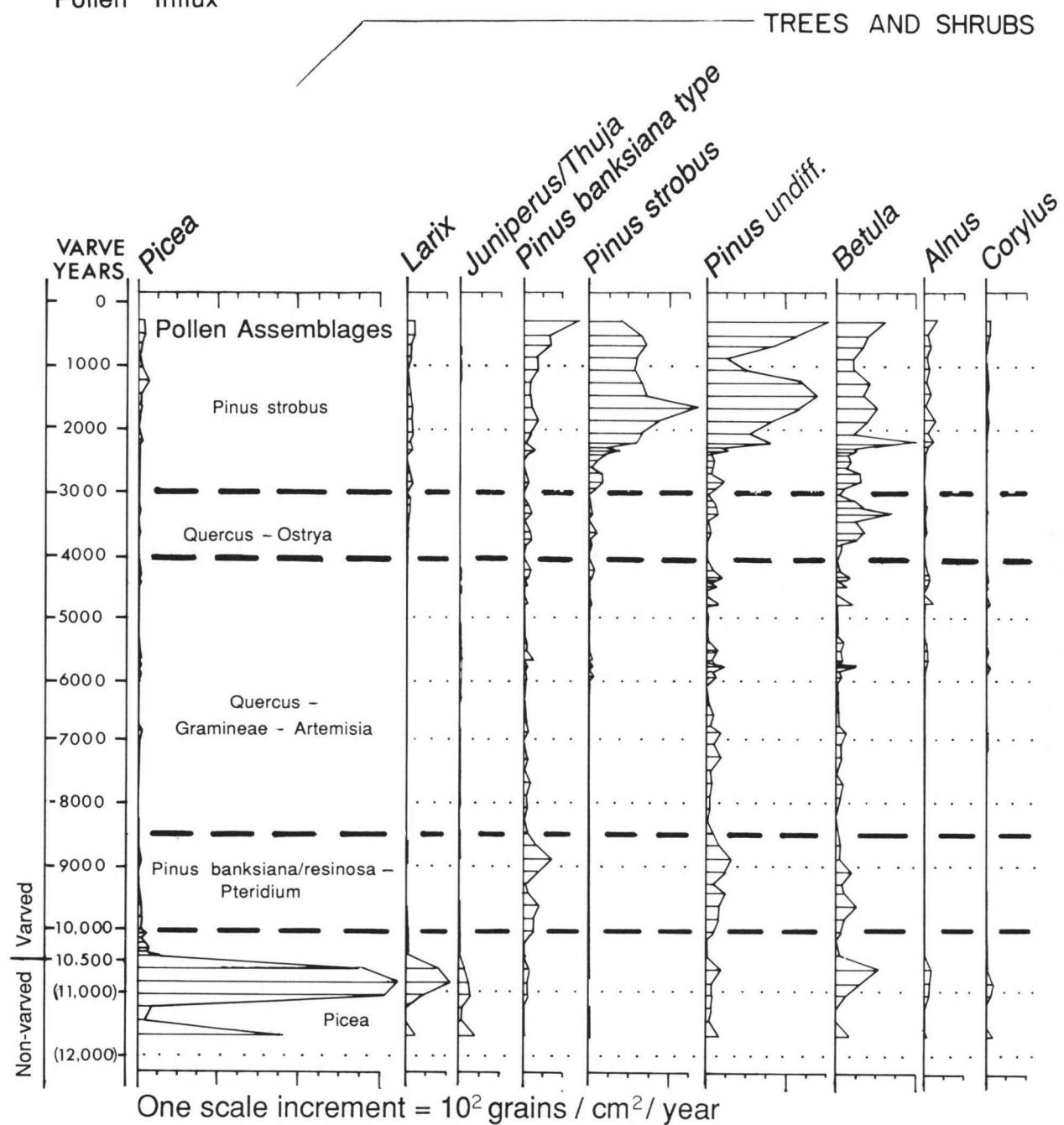
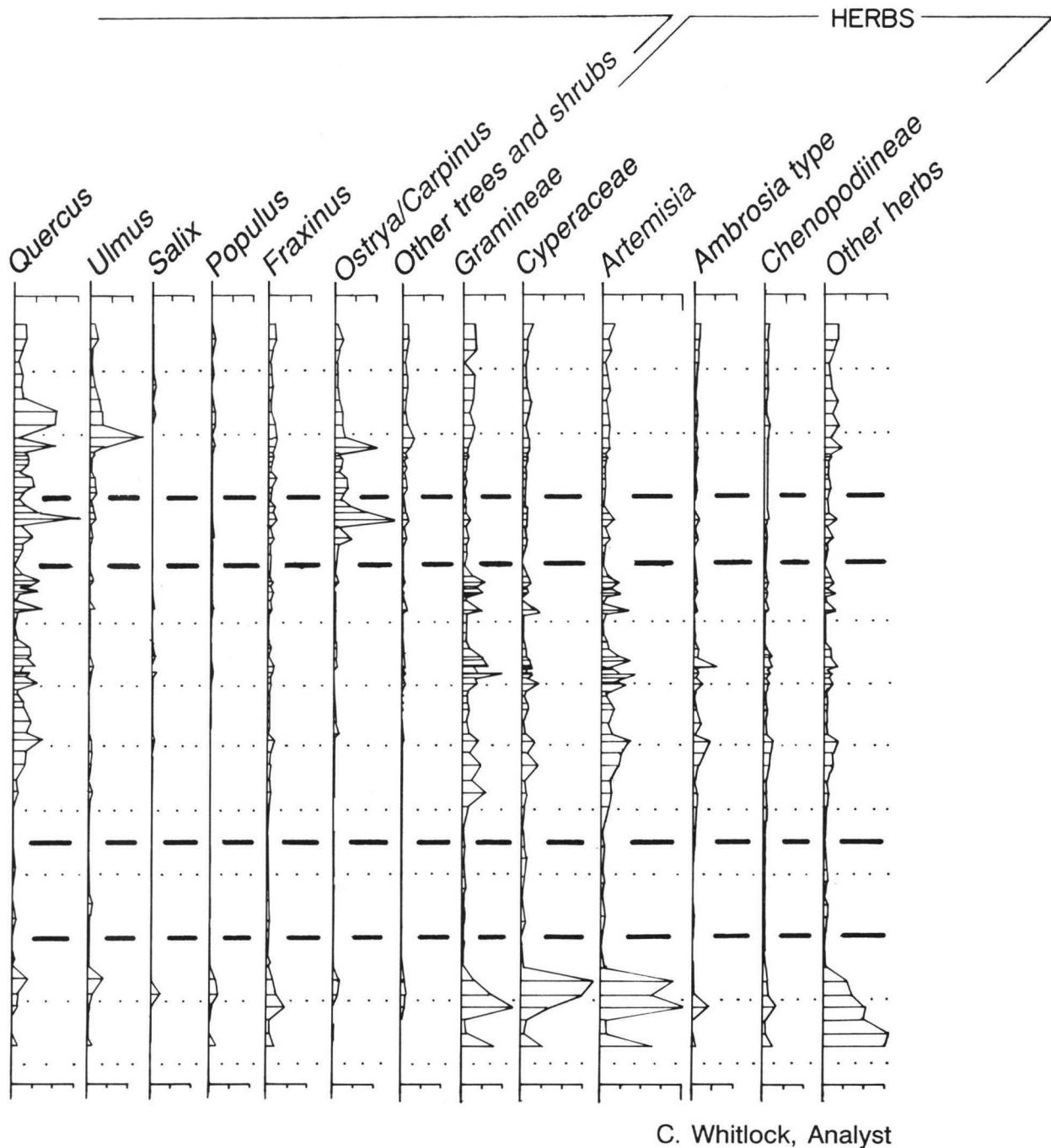
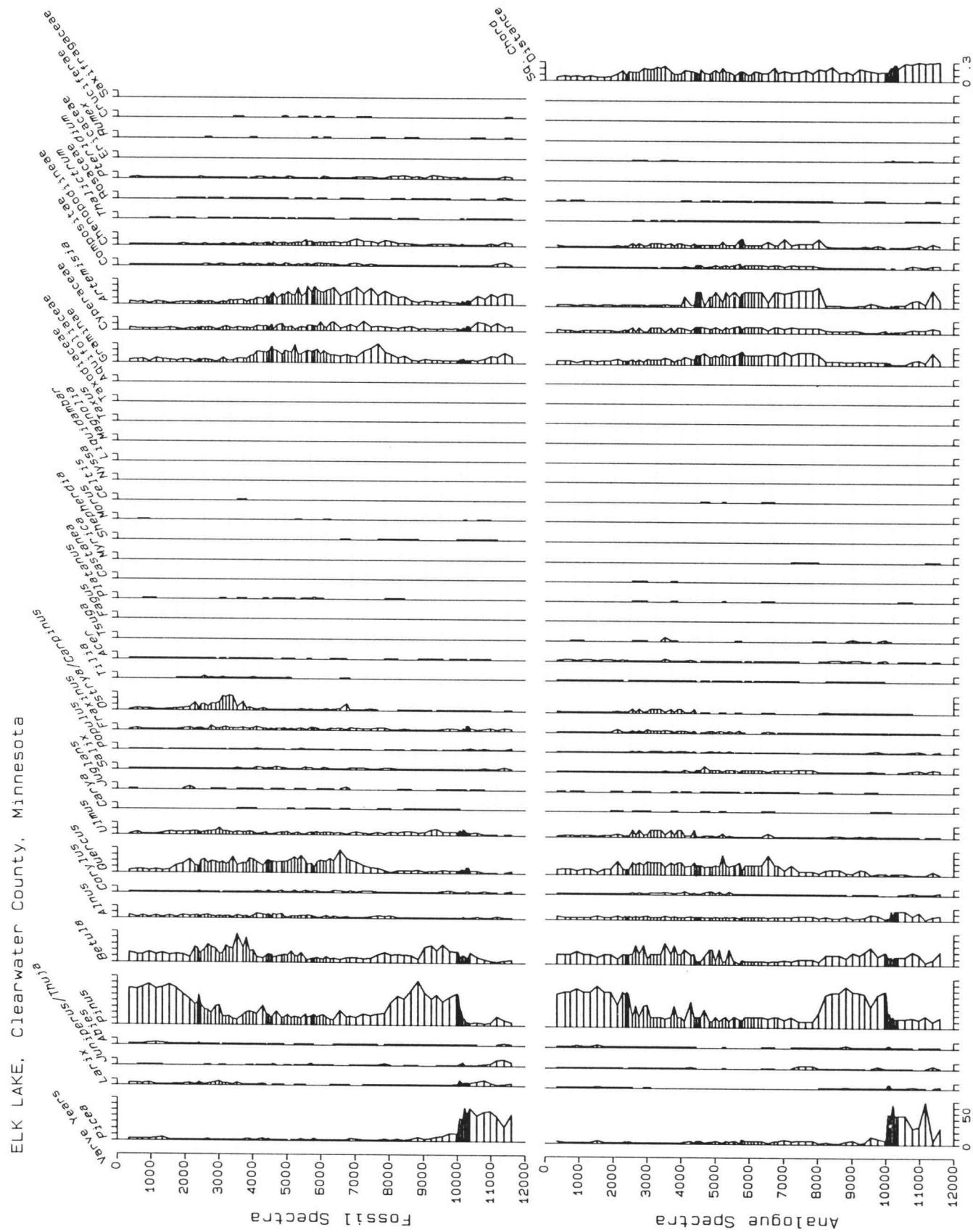


Figure 4. Pollen-accumulation rates (grains/ cm^2/yr) for selected taxa.





trancode data, suggested that winters and summers were cooler and summers were driest between 7800 and 6700 varve yr. From 6700 to 4000 varve yr, the ostracode record indicates that the climate was transitional leading to the modern climate. Summers were initially warmer than at present, and precipitation was highly variable. This reconstruction has some support in the pollen record, which has its best analogues for 7800 to 6600 varve yr in southern Saskatchewan (Fig. 6). The analogues lie west of the modern prairie forest border for the spectra between 7232 and 5723 varve yr and then shift eastward for spectra between 4848 and 4509 varve yr. The pattern is interrupted slightly at 4848 varve yr, when the analogues occur farther east in southern Wisconsin and imply greater precipitation.

Quercus-Ostrya assemblage (4000–3000 varve yr)

Nonarboreal percentages decline to <25% after 4000 varve yr, whereas percentages of *Quercus* and *Betula* increase. In addition, pollen of other hardwood taxa become significant in the record, namely *Ostrya-Carpinus*, *Ulmus*, *Tilia*, *Fraxinus*, and *Acer saccharum*. Percentage increases in *Abies*, *Picea*, *Larix*, and *Pinus strobus*-type also occur. Pollen-accumulation rates of these taxa increase, and the overall values compare with those from the modern mixed conifer-hardwood forest (M. B. Davis and others, 1973; R. B. Davis and others, 1975).

This assemblage indicates decline of prairie vegetation and oak savannah around Elk Lake and the spread of mesic deciduous forest, dominated by oak and birch. Oak, both *Q. macrocarpa* and *Q. rubra*, according to McAndrews (1966), continued to grow on the dry upland slopes and outwash gravels, but the mesic lowlands were invaded by birch, hophornbeam, elm, basswood, and maple. Tamarack, spruce, and fir probably occupied peatlands, which were developing at this time (Webb and others, 1983). The increase in *Pinus strobus*-type pollen ca. 3000 varve yr records the westward migration of white pine into the region.

The pollen assemblage at 3880 varve yr typifies the first part of the assemblage. The best modern analogues lie in the mixed conifer-hardwood forest boundary of the southern Great Lakes region (Fig. 6), which implies a wetter warmer climate than before. The *Ostrya-Carpinus* maximum at 3390 varve yr has fewer analogues, but the inferred climate is similar to or slightly warmer than before.

Pinus strobus assemblage (3000 varve yr to A.D. 1890)

During the past 3000 varve yr pine is once again the dominant pollen type at Elk Lake, but its source is *P. strobus* as well as *P. banksiana* and *P. resinosa*. Jacobson (1979) described the Holo-

cene migration of white pine in the Great Lakes region from glacial refugia in the Appalachian highlands. White pine reached northeastern Minnesota by 7.2 ka but was unable to expand farther west during the prairie period. Its appearance at Elk Lake coincides with the introduction of cooler, moister conditions in the late Holocene. A second rise in the pollen-accumulation rates of white pine probably indicates its local prominence ca. 2320 varve yr. Pollen percentages and accumulation rates of *Pinus banksiana* and *P. resinosa* increase in the past millennium. Jack pine would have occupied the sandy substrates of drift deposits, and both pines would have been favored by frequent fires (Almendinger, 1992).

At 2990 varve yr the climate reconstruction suggests cooler and slightly drier conditions. Modern spectra from central Minnesota and northern Wisconsin match the assemblage at 2651 varve yr, suggesting the type of vegetation that was present just before pollen percentages of white pine increase. After the immigration of white pine, the best analogues center on northern Wisconsin and northern Minnesota (Fig. 6). At the white pine maximum, ca. 1319 varve yr, the analogues imply that winters became warmer than before. Thus the exclusion of *Pinus strobus* from Minnesota during the preceding prairie period could have been effected by cold winters as well as by dry conditions. In the past 4000 yr, the climate has become drier, as evidenced by the fact that the best analogues lie progressively westward, and from 1319 to 320 varve yr they occur in the Itasca region.

The varved record does not include a rise in the percentages of *Ambrosia*-type and other weedy taxa at the top of the core that is conspicuous in latest Holocene records from Minnesota. This increase marks the beginning of extensive agriculture in the region after 1890. Frozen cores taken from Elk Lake, however, register the *Ambrosia* rise (Bradbury and Dieterich-Rurup, Chapter 15; Anderson and others, Chapter 4).

REGIONAL CONTEXT OF THE ELK LAKE POLLEN STRATIGRAPHY

The vegetation history in the vicinity of Elk Lake is a reflection of larger changes occurring throughout the Midwest. Cushing (1967) examined these regional patterns along a north-south transect of pollen records in eastern Minnesota. In our study three major pollen events are compared: the *Picea* decline–*Pinus* rise, the late glacial *Ulmus* maximum, and the maximum of prairie forbs in the prairie period. The comparison is made for pollen records along three transects: south to north from western Iowa to Manitoba, south to north from eastern Iowa to northeastern Minnesota, and west to east from northeastern South Dakota to northeastern Minnesota (Figs. 7 and 8). The time scale for all the pollen profiles is in radiocarbon years, and accordingly the varved records at Elk Lake and Lake of the Clouds were converted with the calibration equations of Stuiver and others (1986).

To interpret pollen profiles in terms of regional vegetational changes required mapping at close time intervals and an assessment of the magnitude of dating errors. Variation in the timing of

Figure 5. Observed and analogue pollen spectra for Elk Lake. The upper pollen diagram shows the observed fossil-pollen spectra. The bottom diagram was constructed by plotting the most similar modern pollen spectrum for each fossil spectrum; the right column shows the squared chord distance between each fossil spectrum and the closest modern spectrum.

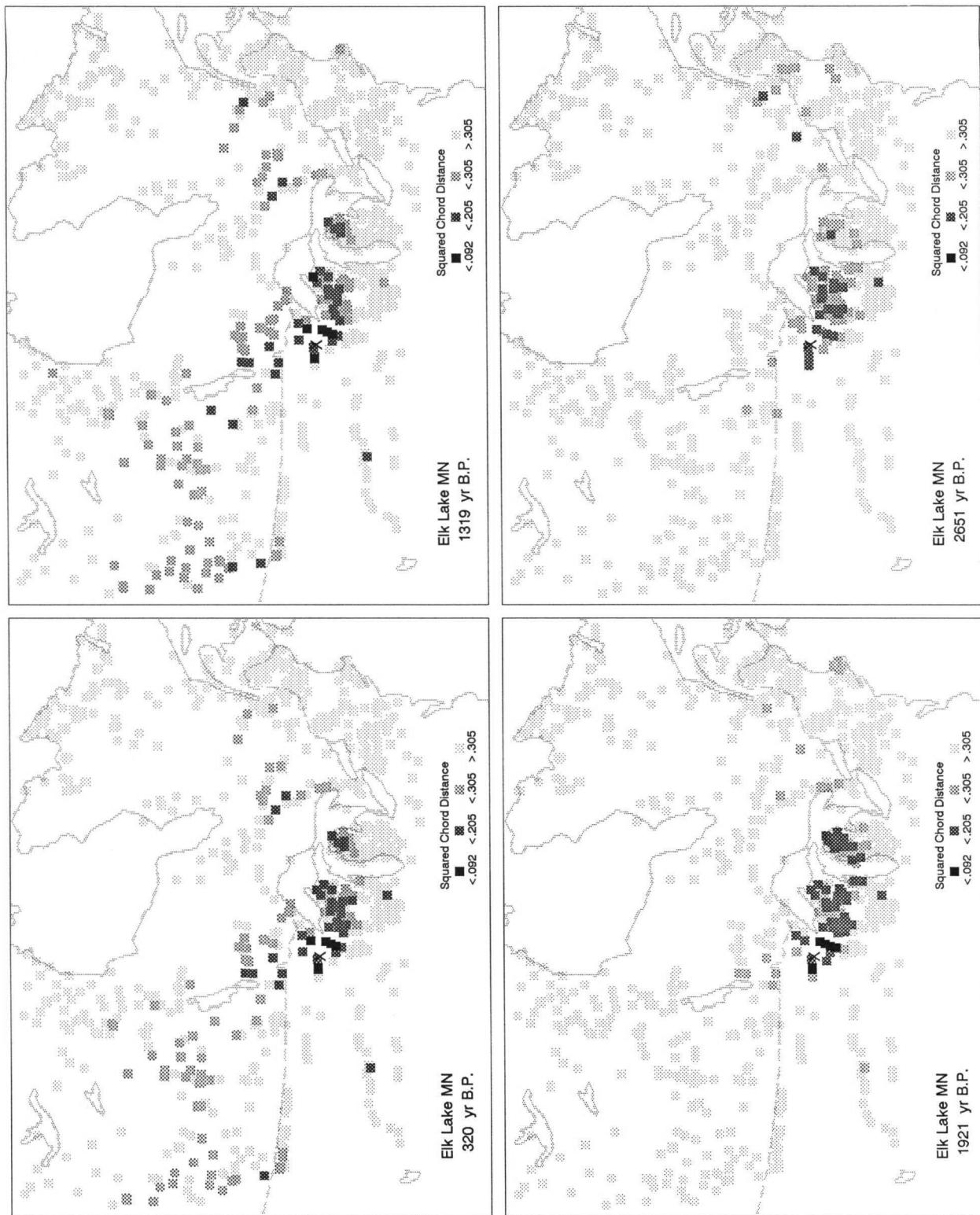
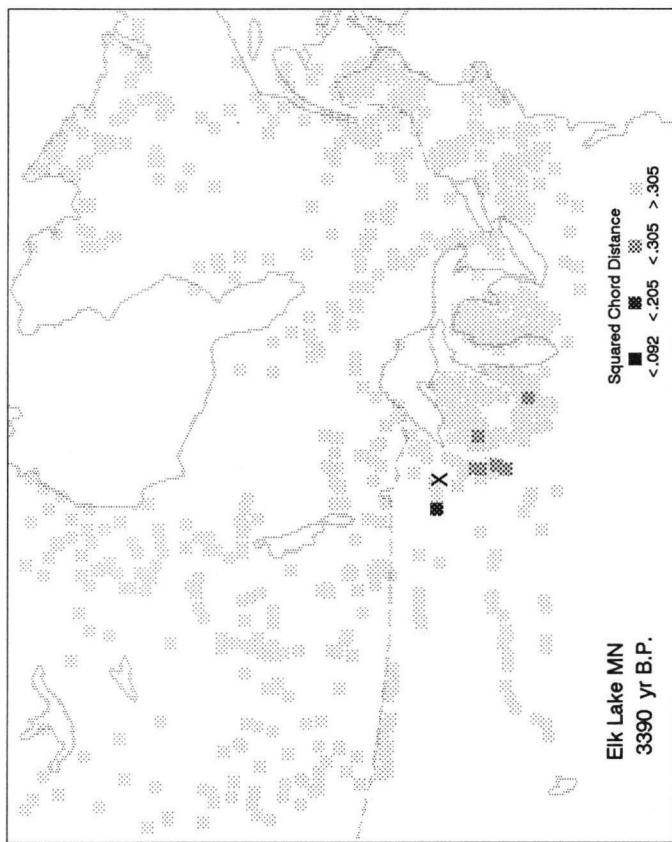
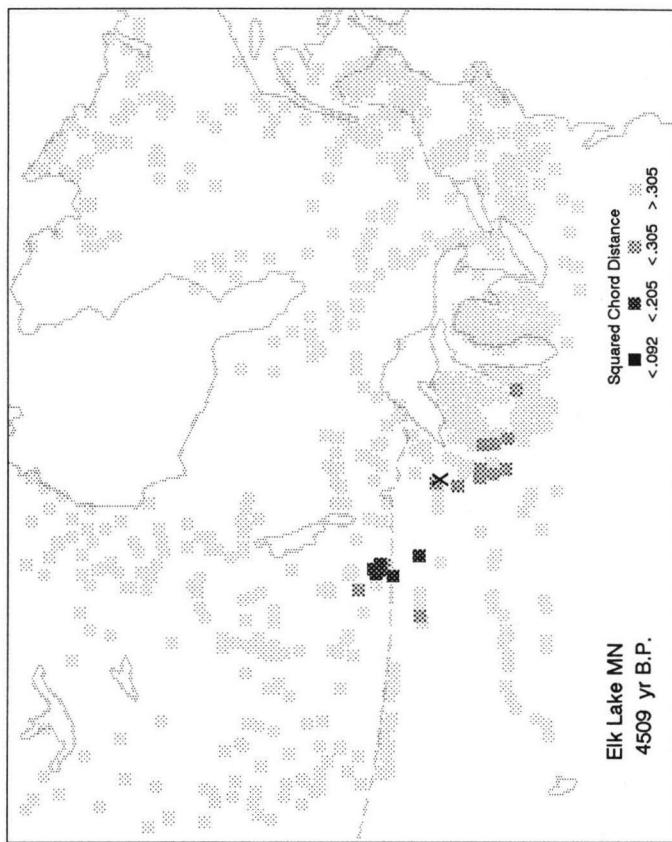
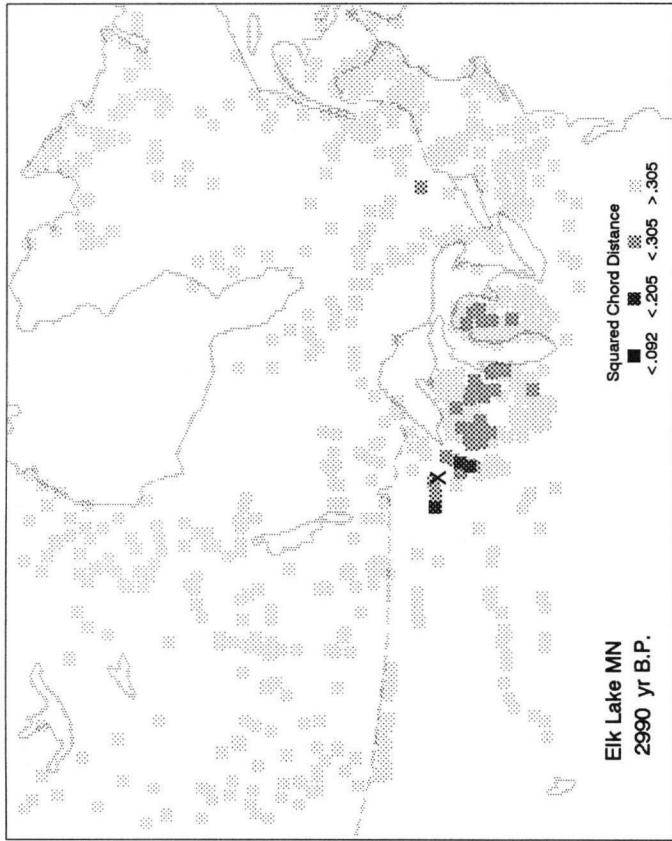
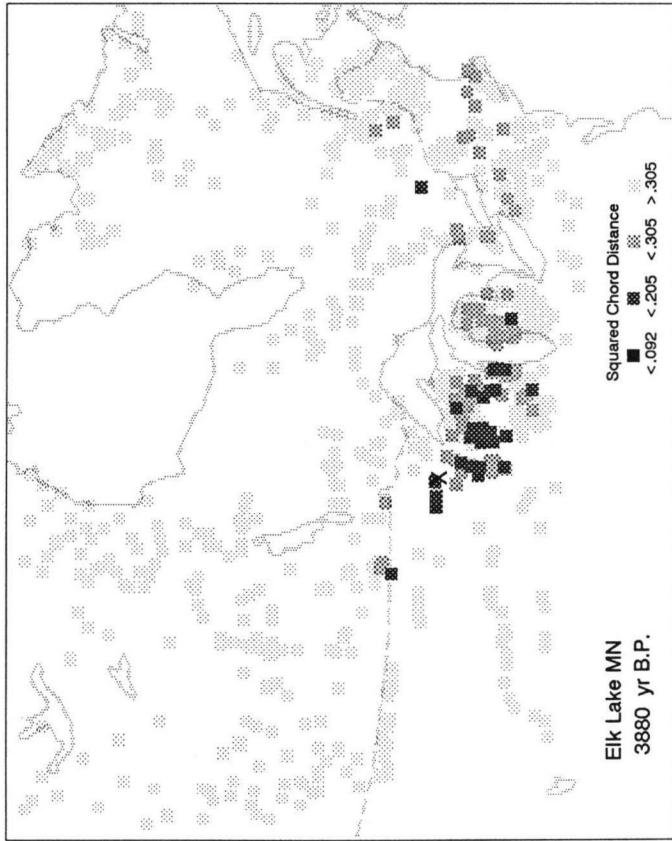
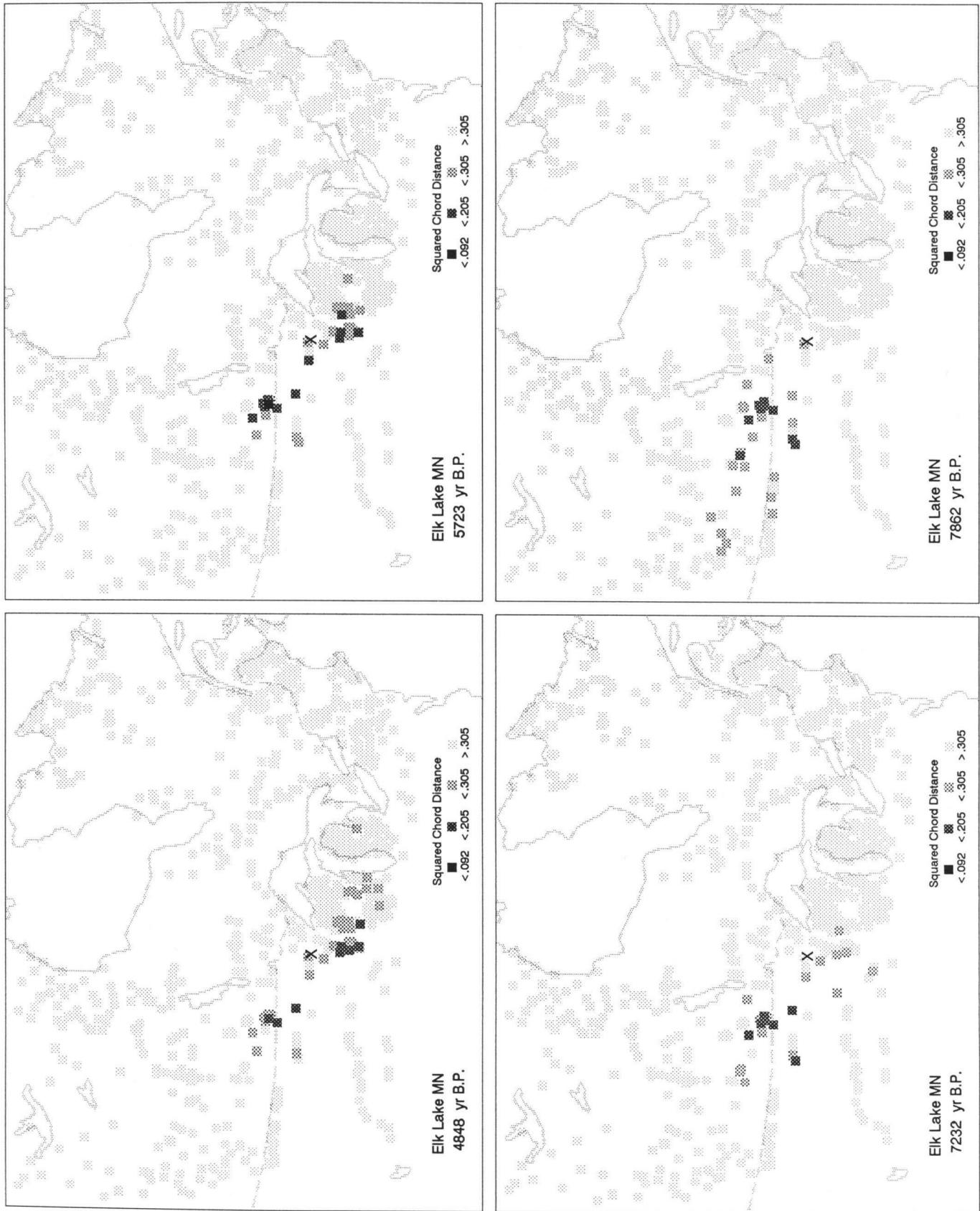
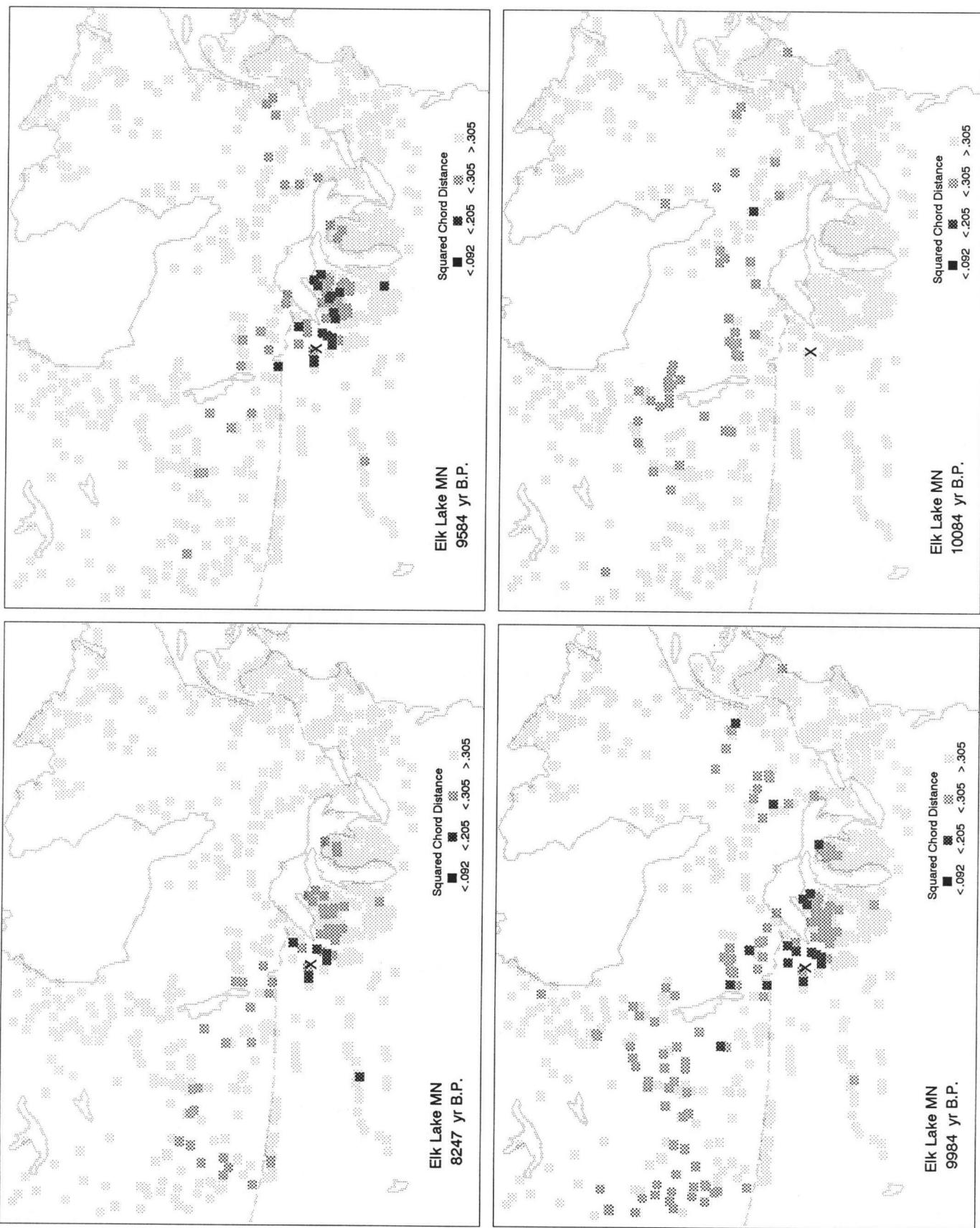
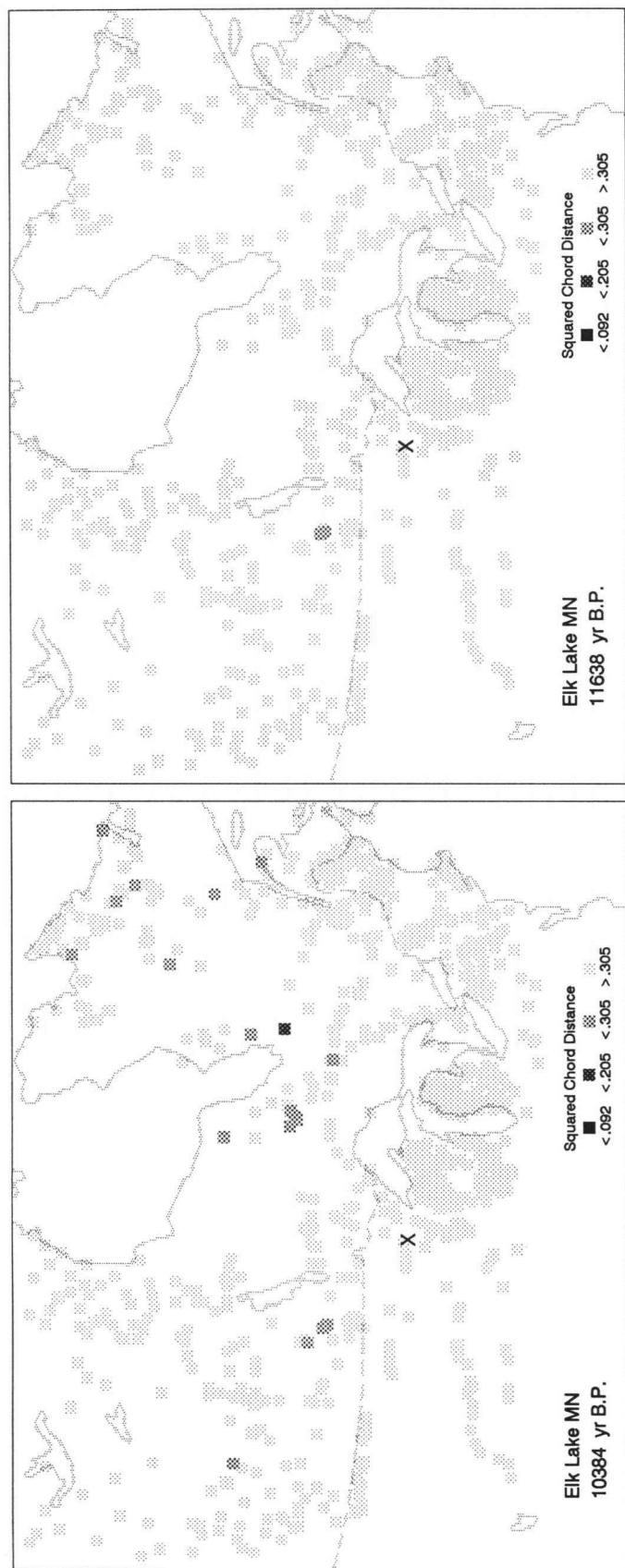


Figure 6 (on this and following four pages). Analogue maps showing the pattern of modern analogues for a particular fossil spectrum. The location of each modern pollen spectrum is shown by a shaded square, and the degree of similarity to the particular fossil spectrum indicated by the intensity of the shading. The location of Elk Lake is indicated by an X.

Elk Lake MN
3390 yr B.P.Elk Lake MN
4509 yr B.P.Elk Lake MN
2990 yr B.P.Elk Lake MN
3880 yr B.P.







important pollen stratigraphic events may have several explanations. First, the event or episode may be a response to a time-transgressive change in climate or to a migration lag. It is difficult, perhaps impossible, to separate these two possibilities (Prentice, 1983). Second, local habitat variability creates landscape heterogeneity that may result in differences in the timing of pollen events from one site to another. Third, local geology, including the composition of the surficial deposits, may lead to variability in dating. Sites along the western transect, for example, are more likely to have sediments containing old carbon from limestone- and shale-rich tills than sites from the eastern transect; thus the western pollen records may register a synchronous event earlier than those from farther east. Finally, the type of material being dated creates variability in radiocarbon ages, and unfortunately Midwest pollen chronologies have been developed from a combination of radiocarbon dates on wood, peat, and lake sediments.

Picea fall-Pinus rise

The abrupt decline of *Picea* and subsequent spread of *Pinus* is perhaps the most striking feature in the late glacial pollen record of eastern North America. This transition is commonly perceived as a time-transgressive decline in spruce forest from south to north followed by the spread of pine (Ritchie and MacDonald, 1986). In the Midwest spruce spread from Illinois, Missouri, and northeast Kansas into the Great Lakes region after 15 ka. Spruce formed an open woodland at Wolf Creek Lake at 13 ka (Birks, 1976), but it took another 1500 yr before it reached Kylen Lake, 350 km to the northeast (Birks, 1981).

The south to north transect in eastern Minnesota shows the time transgression of the *Picea* decline (Figs. 7 and 8). *Picea* percentages decrease between 10.2 and 9 ka from south to north; *Pinus* percentages increase between 10.8 and 9 ka with no obvious spatial trend. A south to north transect of western sites shows the *Picea* decline before 10.0 ka at Lake West Okoboji, Medicine Lake, Pickeral Lake, Glenboro, and Bog D, and after 10.0 ka at Elk Lake and Lake E (Riding Mountain). That Elk Lake and Bog D differ from each other by 1200 yr points to the likelihood of a dating problem in the western sites, where the radiocarbon ages for the *Picea* decline are about 1000 yr older than the age determined by the Elk Lake varve chronology.

A west to east transect of sites from Pickerel Lake to Weber Lake shows considerable spatial variability in the timing of the *Picea* decline and in the *Pinus* rise, but the transition occurred between 10.8 and 9.2 ka.

The overall pattern is consistent with the hypothesis that spruce declined in response to environmental changes accompanying deglaciation, when the frontal position of arctic air shifted northward. The subsequent spread of pine was more variable. Superimposed on this general pattern are west-east variations related to radiocarbon dating errors.

Late glacial Ulmus maximum

The profiles for *Ulmus* place its greatest abundance in western Minnesota between 10.8 and 9 ka and in eastern Minnesota

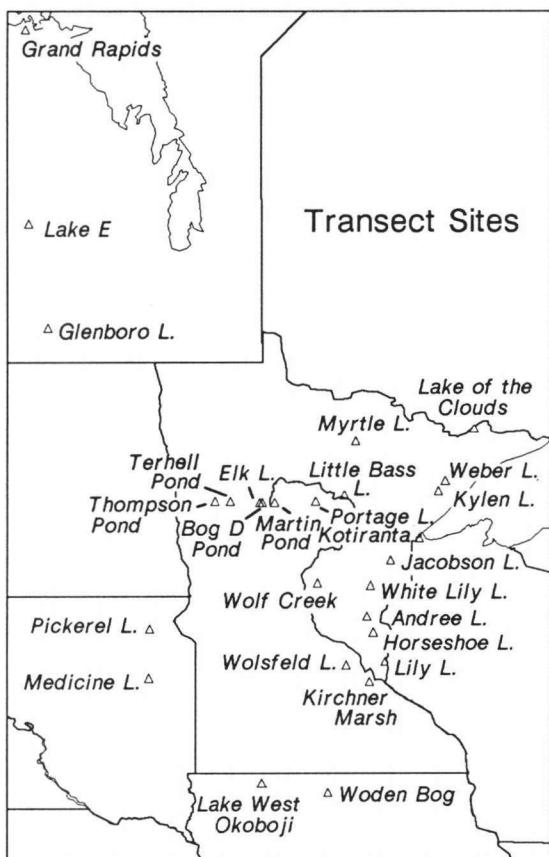


Figure 7. Location of sites used in regional transects (L is lake).

between 10 and 8.6 ka. The west to east transect has the *Ulmus* maximum at ca. 10 ka. Allowing for the uncertainty in dating, the apparent synchronicity in the timing suggests that the event was not time transgressive or related to deglaciation. It may be a region-wide environmental change related to the amplification of the seasonal cycle of radiation, which was a hemispheric-scale climatic control (Kutzbach and Guetter, 1986; Wright, 1992).

Prairie period

A comparison of prairie forb percentages along the west to east transect shows some of the patterns presented as isopoll maps in Webb and others (1983). The prairie moved eastward in the Great Lakes region from 9 to 7 ka and then retreated westward to its present position. Between 8 and 7 ka the prairie reached its easternmost limit in Minnesota and Wisconsin, although farther south in Illinois the border began to shift westward. By 3 ka the prairie border shifted westward in Minnesota; in Illinois it moved eastward again (Webb and others, 1983).

The sites in the western north to south transect, again with the exception of Elk Lake, record a rise in forbs at 9 ka that reaches maximum values before 8 ka. The eastern sites from Martin Pond to Weber Lake, and Elk Lake, show a forb rise later, ca. 8 ka. This same conclusion is reached when the south to

north transects are compared for eastern and western Minnesota. The prairie period begins about 1000 radiocarbon yr earlier in the west than in the east, which might be used as evidence that the vegetational changes were time transgressive from west to east. Alternatively, if radiocarbon dates in the west were too old because of a carbonate error, they would create a false impression of time transgression. The radiocarbon conversion of the Elk Lake record places the beginning of the prairie period at the same time as in the east, which suggests that the transition was a synchronous event across Minnesota.

CONCLUSIONS

Pollen diagrams from varved sediments offer an opportunity to define important stratigraphical boundaries in terms of calendar years. At Elk Lake, the spruce decline occurred during a 250 yr interval from 10,234 to 9984 varve yr ago. Although higher percentages of hardwoods (*Betula*, *Quercus*, *Ulmus*, and *Fraxinus*) and other conifers (*Abies*, *Larix*, *Juniperus*) occurred during the spruce decline, they are not matched by a decrease in pollen-accumulation rates, and the ecological significance of their percentage rise is suspect. The increase in *Pinus* pollen began at 10,000 varve yr. The prairie period, defined by high percentages of *Quercus*, *Artemisia*, and *Gramineae*, occurred between 8500 and 4000 varve yr. Fluctuations within this interval suggest that the climate was variable. The period began with a drying trend, which culminated about 5723 varve yr, followed by increased precipitation and warmer January and continued warm July temperatures. The analogues during this interval shift from southern Saskatchewan southeastward to southern Wisconsin. During the *Quercus-Ostrya* assemblage, from 4400 to 3000 varve yr, the best analogues are from the southern Great Lakes region. The *Pinus strobus* assemblage after 3000 varve yr occurs with the onset of cooler and slightly drier conditions. The expansion of white pine across the Great Lakes region may be related to cooler winters and wetter conditions than those of the prairie period.

Our ability to reconstruct patterns of vegetational change through time depends upon the accuracy of the chronology at each of the sites considered. The radiocarbon chronology of Midwest pollen sites and the varve chronology at Elk Lake, converted to radiocarbon years, suggest that the decline of *Picea* pollen and the increase of *Pinus* pollen in the latest Pleistocene was a time-transgressive event from south to north. The likely explanation for the spatial pattern is the environmental changes that occurred with the progressive retreat of Laurentide ice northward. The late glacial increase in *Ulmus* occurred across the region synchronously and may have been a response to environmental changes that affected the entire region (such as the seasonal cycle of radiation). The prairie period at Elk Lake is dated 1000 yr later than at adjacent sites, suggesting that the dates at other sites are erroneously old. The period at Elk Lake, however, occurs concurrently with sites farther east, where the possibility of a dating error is less. Thus the onset of the prairie period may appear to be time transgressive, when in fact it was a regionally synchronous event.

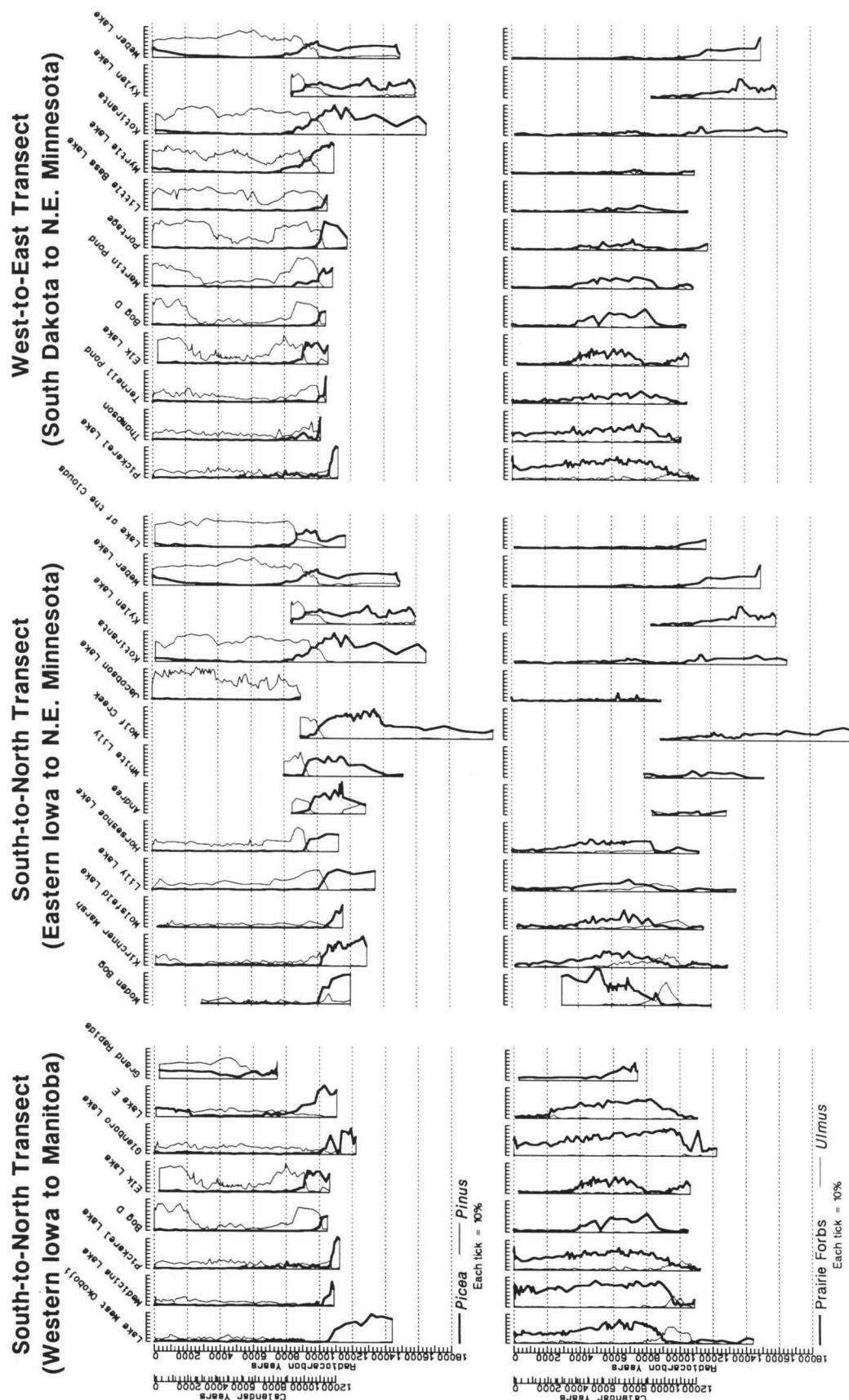


Figure 8. Three transects of pollen sites, comparing the timing of three pollen stratigraphical events in the Midwest: the *Pinus* fall–*Pinus* rise, the late glacial *Ulmus* maximum, and the “prairie period.” The chronology at all sites is in terms of radiocarbon years and varve years. Data are from Webb and others (1983), who used the set of fossil pollen data at Brown University.

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