



## Synchronization of late-glacial vegetation changes at Crystal Lake, Illinois, USA with the North Atlantic Event Stratigraphy

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### ABSTRACT

Late-glacial (17–11 cal ka BP) pollen records from midwestern North America show similar vegetation trends; however, poor dating resolution, wide-interval pollen counts, and variable sedimentation rates have prevented the direct correlation with the North Atlantic Event Stratigraphy as represented in the Greenland ice-core records, thus preventing the understanding of the teleconnections and mechanisms of late-Quaternary events in the Northern Hemisphere. The widespread occurrence of late-glacial vegetation and climates with no modern analogs also hinders late-glacial climate reconstructions. A high-resolution pollen record with a well-controlled age model from Crystal Lake in northeastern Illinois reveals vegetation and climate conditions during the late-glacial and early Holocene intervals. Late-glacial Crystal Lake pollen assemblages, dominated by *Picea mariana* and *Fraxinus nigra* with lesser amounts of *Abies* and *Larix*, suggest relatively wet climate despite fluctuations between colder and warmer temperatures. Vegetation changes at Crystal Lake are coeval with millennial-scale trends in the NGRIP ice-core record, but major shifts in vegetation at Crystal Lake lag the NGRIP record by 300–400 yr. This lag may be due to the proximity of the Laurentide ice sheet, the ice sheet's inherent slowness in response to rapid climate changes, and its effect on frontal boundary conditions and lake-effect temperatures.

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### Introduction

Several factors obscure a clear understanding of environmental conditions in the midwestern United States during the late-glacial interval (17–11 cal ka BP), namely vegetation assemblages with no modern analogs, corresponding climate conditions unlike any modern conditions, and a seemingly poor correlation between changes in Midwest vegetation and North Atlantic climate changes as recorded in the Greenland ice cores that also prevent the understanding of the connections and mechanisms of late-Quaternary events in the Northern Hemisphere. Nevertheless, four recognizable phases occur in pollen records from across the Midwest from the time of deglaciation through the early Holocene (Wright, 1964; Cushing, 1967; Schweger, 1969; King, 1981; Webb et al., 1983, 1993; Shane and Anderson, 1993; Grimm and Maher, 2002; Grimm and Jacobson, 2004). These phases follow a tundra phase recorded mainly in macrofossil assemblages dating to earlier than 18,000 cal yr BP (Curry and Yansa, 2004).

In the early parts of the pollen records, *Picea* is the dominant taxon with corresponding low percentages of *Larix* and *Abies*. Deciduous taxa (mainly *Fraxinus nigra*-type, *Quercus*, and *Ostrya/Carpinus*) and lesser amounts of upland herbaceous taxa (i.e., *Artemisia*, *Ambrosia*,

and *Poaceae*) and sedges (*Cyperaceae*) also occur during this phase. The next phase is marked by a decrease in *Picea* and an expansion of deciduous taxa, especially *F. nigra*-type, but also *Ostrya/Carpinus* and *Quercus*. During this phase, other deciduous taxa such as *Carya*, *Ulmus*, *Salix*, *Fagus*, *Juglans*, and *Populus* appear in many pollen records from the Midwest. The third phase, not clearly evident at all sites, is characterized by an increase in *Picea* and a concurrent decline in deciduous taxa. *Abies* and *Larix* also expand, and sharp peaks in *Alnus*, *Betula*, and sometimes *Pinus* mark the end of this phase. This phase is loosely correlated with the Younger Dryas Chronozone (Shane and Anderson, 1993), but age control is typically poor (Grimm and Jacobson, 2004). At the onset of the Holocene, the final phase, *Picea* declines precipitously. In northern Minnesota and Wisconsin, *Pinus* increases, and in the southern Midwest deciduous taxa, especially *Ulmus* and *Quercus*, increase.

Although broad trends in late-glacial vegetation are evident across the Midwest, it has been difficult to compare regional vegetation patterns with the North Atlantic Event Stratigraphy (Björck et al., 1998; Björck et al., 2002; Southon, 2002; Lowe et al., 2008) because of poor dating, variable sedimentation rates, and low-resolution pollen records (Shane and Anderson, 1993; Grimm and Jacobson, 2004). Low-resolution late-glacial Midwestern pollen records have widely spaced pollen counts that result in coarse temporal resolution at millennial to multi-centennial scales (Shane and Anderson, 1993; Grimm and Jacobson, 2004). Most radiocarbon dates from existing

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Midwestern records are on bulk sediment. In the Midwest, where sources of old carbon (carbonate rocks, coal, and organic-rich shale) are ubiquitous, bulk sediment dates are especially susceptible to contamination from  $^{14}\text{C}$  depleted carbon (Grimm and Jacobson, 2004). As a result, temporal correlation between events in coarse-resolution late-glacial pollen records and the fine-resolution Greenland ice cores is uncertain.

Midwestern late-glacial climates were strongly influenced by increased seasonal amplification of insolation, lowered atmospheric  $\text{CO}_2$ , and the retreating Laurentide ice sheet (LIS) to the north. The melting LIS altered the atmospheric circulation over the mid-continent by splitting the jet stream between 21 and 14 cal ka BP (Bartlein and Prentice, 1989; Bartlein et al., 1998; Jackson and Williams, 2004). The dominance of *Picea* in pollen records across the Midwest during the late-glacial interval has been used to infer colder temperatures than present (Shane and Anderson, 1993); however, because most Midwestern pollen records do not differentiate between *Picea glauca* and *Picea mariana*, an essential key to determining dry/wet conditions is missing. Both taxa have similar temperature ranges; however, *P. glauca* grows on well-drained soils whereas *P. mariana* prefers poorly drained soils (Hansen and Engstrom, 1985; Nienstaedt and Zasada, 1990; Viereck and Johnston, 1990). Some studies have suggested that the air flowing off the LIS warmed adiabatically and was relatively dry, thus ameliorating extreme climate conditions in the Midwest (Bryson and Wendland, 1967; Yu and Wright, 2001). Grimm and Jacobson (2004) argued that the prevalence of *F. nigra*, which grows on poorly drained and swampy soils, indicates wet conditions during the latter part of the late-glacial interval. They propose that the cold air flowing off the LIS converged with warm, moist air from the Gulf of Mexico, producing abundant precipitation in the Midwest along the frontal boundary. Alternatively, Yansa (2006) suggested that melting ice blocks buried beneath local till soils would have provided moisture to plants during dry late-glacial climates.

Here we use a high-resolution pollen record to reconstruct the vegetation at Crystal Lake, in northeastern Illinois. The Crystal Lake record has 36 high-precision radiocarbon dates and pollen counts with an average temporal resolution of ~60 yr between samples. Thus, we are able to establish a temporal relationship of events at Crystal Lake comparable to those in the NGRIP ice-core record at the century scale (Andersen et al., 2006; Rasmussen et al., 2006). We explore the late-glacial and early Holocene climate conditions at Crystal Lake with the pollen assemblages during these intervals.

In this paper we use the familiar North European chronostratigraphy of Oldest Dryas, Bølling, Older Dryas, Allerød, but we recognize the arguments for the event stratigraphy proposed by Björck et al. (1998) and also reference their suggested Greenland stadial and interstadial terminology. Whereas Björck et al. (1998) refer to the GRIP ice core, following Lowe et al. (2008), we refer to the new NGRIP core (Andersen et al., 2006; Rasmussen et al., 2006) for the chronology of the North Atlantic Event Stratigraphy.

Botanical nomenclature follows the Flora of North America Editorial Committee (1993+) insofar as possible, and otherwise it follows Gleason and Cronquist (1991). Some pollen taxa are identified as types. Of particular concern is *F. nigra*-type, which includes *F. nigra* and *F. quadrangulata*. Today, the southern range limit of *F. nigra* overlaps with the northern range limit of *F. quadrangulata* in northern Illinois. We assume that during the late-glacial interval, *F. nigra*-type represents *F. nigra*, rather than the more southern *F. quadrangulata* (Grimm and Jacobson, 2004).

### Site description

Crystal Lake (42°14.07'N, 88°21.48'W, 273 m a.s.l., 93 ha) is an oblong kettle lake (500×2110 m) that formed during the last deglaciation on an outwash fan associated with the Woodstock

Moraine and the older, eroded Barlina Moraine (Curry, 2005). Crystal Lake has a shallow eastern basin that slopes into the deeper western basin, and it is primarily groundwater-fed (Sasman, 1957). Its maximum depth is 13 m (Fig. 1). The watershed of Crystal Lake is covered by silty loess, lacustrine silt and clay, clayey glacial diamicton, sand and gravel, and peat. These surficial sediments are 60–70 m thick, overlying Paleozoic dolomite bedrock (Curry, 2005).

Today, Crystal Lake is located within the town of Crystal Lake, McHenry County, Illinois (Fig. 1). Prior to Euro-American settlement, the region was covered by a mosaic of prairie and oak groves (Anderson, 1970) as evidenced by the *Quercus*-dominated pollen assemblages during this interval (Pan and Brugam, 1997). During the 1830's, the development of Euro-American farmlands coincided with an abrupt rise in *Ambrosia* pollen and subsequent decline of *Quercus* (Pan and Brugam, 1997). In the mid-1940's, the area was heavily urbanized (Pan and Brugam, 1997), and today the lake is surrounded by a residential neighborhood.

### Methods

#### Core acquisition

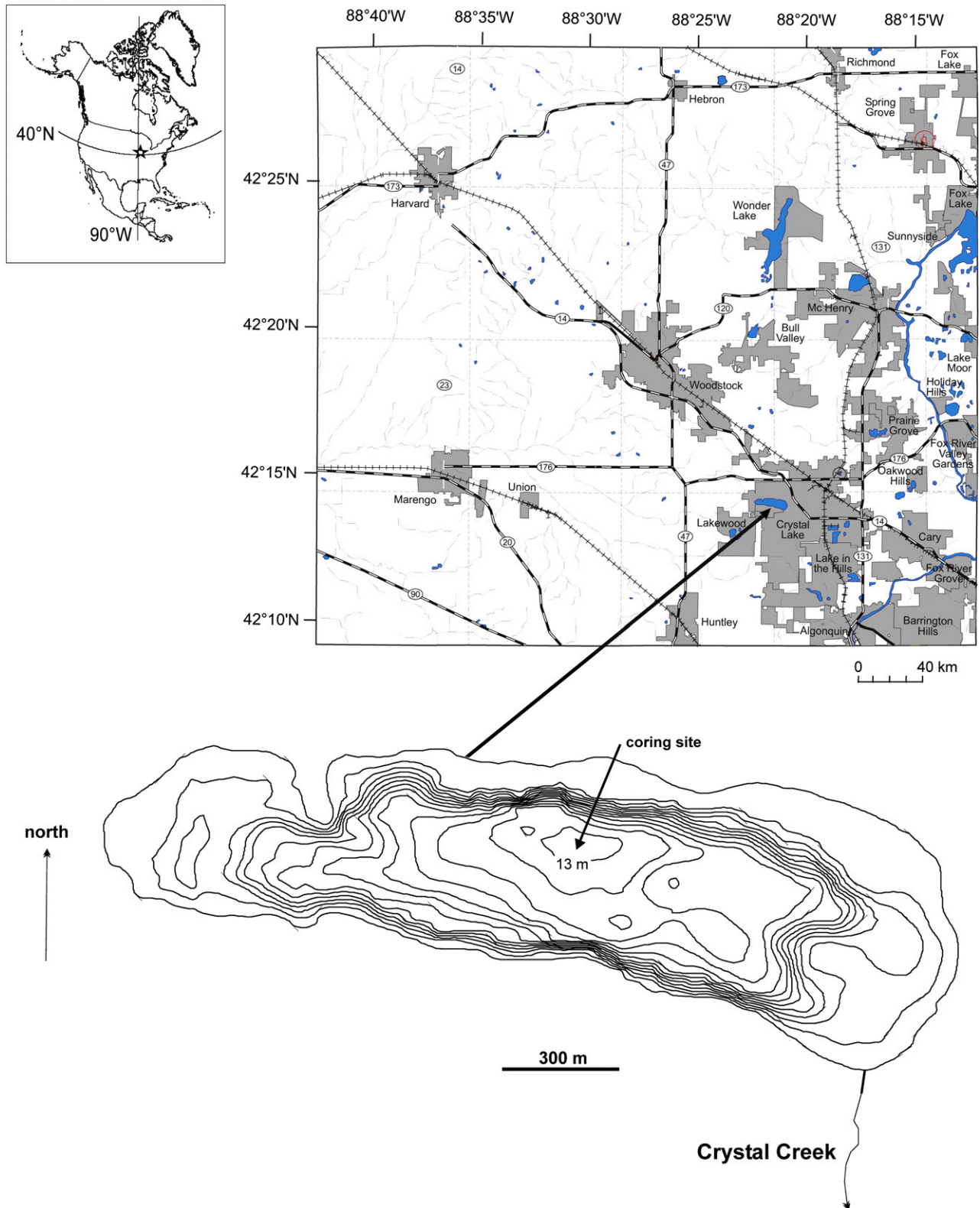
On January 30–31, 1999, two overlapping cores were taken from the ice at the deepest part of Crystal Lake with a 5-cm-diameter Wright square-rod piston corer (Wright et al., 1984). The mud-water interface for both cores was 12.89 m. Recovery of both cores was nearly 100% for all but the basal drives, which ended in coarse sand. Cores were wrapped in plastic film and aluminum foil in the field and were then transported to the Illinois State Museum Research and Collections Palynology Lab, where they were split, wrapped, and placed in cold storage. The initial core was used for pollen analysis. Macrofossils used for radiocarbon dates were obtained by sieving from both cores.

#### Pollen and loss-on-ignition analyses

Volumetric samples for pollen analysis (0.5 ml) were taken at 4-cm intervals with a sampler consisting of a metal tube and calibrated plunger. Samples were prepared with standard methods (Fægri and Iversen, 1989), with successive treatments of 10% HCl, 10% KOH (hot), HF for 1 h, and acetolysis solution for 1 min. A 0.5-ml suspension of polystyrene microspheres was added to each sample prior to processing in order to determine pollen concentration. Processed samples were mounted in silicone oil for counting and storage.

An average of 300 pollen grains of upland types were counted per level with a 40× apochromat objective (n.a.=0.95) on a Zeiss Axioskop, with occasional critical examinations at 100× with an oil immersion objective (n.a.=1.30). *Picea* pollen was differentiated into *P. glauca* and *P. mariana* based on protocols developed by B.C.S. Hansen (Hansen and Engstrom, 1985; Lindbladh et al., 2002). *Pinus* pollen was also differentiated into *P. subg. Strobus* and *P. subg. Pinus*. Pollen percentages were calculated based on the sum of upland pollen types. Macrofossils were obtained by sieving with 250- and 500- $\mu\text{m}$  screens as well as through routine processing for pollen.

Samples of 0.5 ml for loss-on-ignition analysis (Dean, 1974) were taken at 1-cm intervals with the same sampler used for pollen. Samples were dried at 100°C for 8 h, cooled for 1 h in a vacuum dessicator and weighed. Samples were then ignited at 500°C for 1 h, cooled for 1 h in a vacuum dessicator, and weighed. Samples were finally ignited at 900°C for 1 h, cooled for 1 h in a vacuum dessicator and weighed. Ashless filter paper and laboratory grade  $\text{CaCO}_3$  were used as controls in all steps of the process to ensure complete incineration of organic matter at 500°C and decomposition of  $\text{CaCO}_3$  at 900°C.



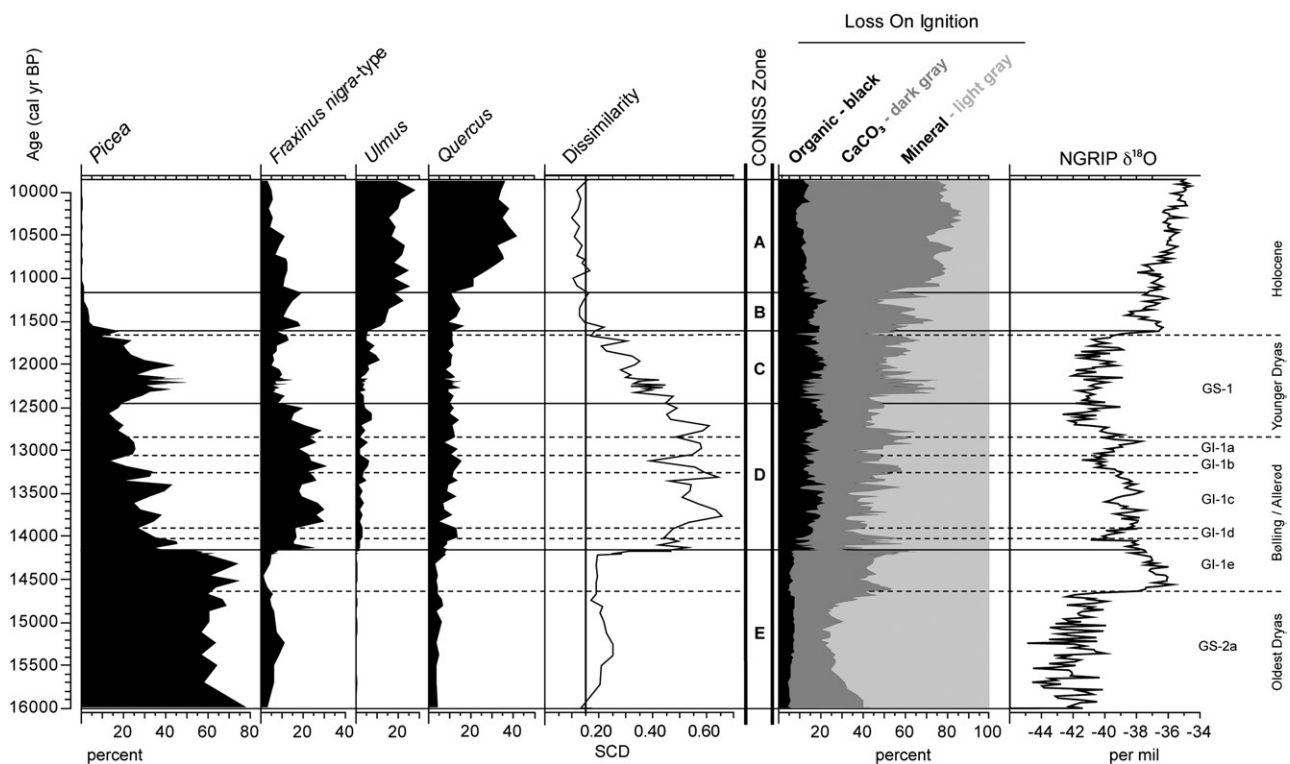
**Figure 1.** Bathymetric map of Crystal Lake (1 m contours; data courtesy of Tim Larson and Brandon Curry, Illinois State Geological Survey). Insets show the location of Crystal Lake in McHenry County as well as its location in the United States.

*Numerical analyses*

We used constrained incremental sum-of-squares analysis with the CONISS program (Grimm, 1987) to determine the zonation of vegetation assemblages at Crystal Lake. Pollen types with percentages

greater than 1% were divided into five clusters (A through E) (Figs. 2 and 3) that define the five major assemblage zones for the late-glacial/early Holocene record at Crystal Lake.

We used the squared-chord distance (SCD) metric to calculate the minimum dissimilarity of fossil pollen assemblages from modern



**Figure 2.** Summary of Crystal Lake vegetation during the late-glacial interval and early Holocene. The major pollen types are depicted here along side the dissimilarity analysis, CONISS vegetation zones, loss-on-ignition data, and the NGRIP ice-core data. Dashed lines mark NGRIP events and solid lines mark the vegetation zones defined by CONISS analysis. The thick line in the dissimilarity profile marks the threshold for non-analog vegetation. Dissimilarity values greater than 0.15 indicate vegetation had no modern analog.

pollen assemblages (Overpeck et al., 1985). We followed Overpeck et al. (1985) in defining samples that had modern analogs (SCD values  $<0.15$ ) because we used a similar number of taxa (20) and number of modern pollen samples (2882) in our analysis. This threshold agrees with Gavin et al.'s (2003) recommendation of 0.15 as an upper threshold for defining analogous vegetation assemblages at a regional scale.

We used 17 arboreal taxa (*Abies* East, *Acer* East, *Alnus incana* subsp. *rugosa*, *Betula*, *Carya*, *Celtis* East, *Corylus*, *F. nigra*, *Juglans cinerea*, *Larix* East, *Ostrya/Carpinus*, *Picea* East, *Pinus* Northeast, *Platanus*, *Quercus* East, *Salix*) and 3 herbaceous taxa (*Artemisia*, *Asteraceae*, *Chenopodiaceae/Amaranthaceae* Midwest) that represent the key taxa in the Crystal Lake record. The modern sample set was derived from the North American Surface Sample Pollen Database (Whitmore et al., 2005) version 1.6.1. Taxonomic splits for *Abies* East, *Acer* East, *Chenopodiaceae/Amaranthaceae* Midwest, *Larix* East, *Picea* East, *Pinus* Northeast were defined by Williams et al. (2001). In addition to these, we also split *A. incana* subsp. *rugosa* from other *Alnus* species and *F. nigra* from *F. quadrangulata* based on the Little range maps (Critchfield and Little, 1966; Little, 1971, 1976, 1977, 1978, <http://esp.cr.usgs.gov/data/atlas/little/>).

We analyzed the SCD values for our complete modern dataset and, because of potential taphonomic bias, for each depositional environment within our modern dataset as well (i.e., lacustrine, moss polster, peat, soil, and other/unknown). We closely examined the SCD values for the early Holocene (11,000–10,000 cal yr BP) because previous studies have indicated that the minimum dissimilarity for northeastern Illinois during this interval was 0.15 or less (Williams et al., 2001). Values from all depositional environments except lacustrine had SCD values  $>0.15$  during the early Holocene at Crystal Lake; however, their overall influence on the results from the total dataset were relatively minor because lacustrine records composed 61% of the dataset.

## Results

### Chronology

We obtained one conventional and 35 AMS radiocarbon dates from the Crystal Lake cores (Table 1, Fig. 4). We calibrated the dates to calendar years using the BCal calibration program (Buck et al., 1999) with the INTCAL04 calibration curve (Reimer et al., 2004). BCal uses Bayesian statistics with the *a priori* assumption that dates higher in the core are younger than dates lower in the core. When dates with overlapping calibrated probability distributions occur, BCal produces posterior probability distributions with non-overlapping modes, essentially wiggle-matching the dates to the calibration curve. It also statistically tests for outliers. Four dates from the basal trash layer in the Crystal Lake record had overlapping age ranges and were from material that was most likely deposited instantaneously as the basin collapsed. These dates were converted into a pooled mean before calibration. Three dates were rejected as outliers. One date (ISGS-A0051) on aquatic bryophytes was rejected *a priori* because it was clearly too old and showed a “hardwater effect” that particularly afflicts aquatic bryophytes (MacDonald et al., 1991). BCal identified two dates as outliers: CAMS-113597, which was too old, and UCIAMS-30993, which was too young. We used a linear interpolation age-depth model using the 50% median of the calibrated ages (Fig. 4).

The large number of radiocarbon dates from the Crystal Lake record provides excellent chronological control. Deposition time was relatively steady (averaging  $\sim 20$  yr/cm) from the Bølling-Allerød (GI-1) through the Holocene. Two intervals of rapid sediment accumulation rates are evident, with deposition times of  $\sim 2.5$  yr/cm, one during the Bølling (GI-1) (14,210–14,143 cal yr BP) and one during the Younger Dryas (GS-1) (12,322–12,147 cal yr BP). These intervals of increased sedimentation are concurrent with large peaks in carbonate LOI (Fig. 2).



Table 1

Accelerator mass spectrometer radiocarbon dates from Crystal Lake core and calibrated (calendar) ages.

Lab #	Depth (cm)	<sup>14</sup> C Date	1σ	Calibrated age	Material dated
CAMS-99091 <sup>a</sup>	1398–1403	1000	60	786 (921) 1059 <sup>b,c</sup>	Charcoal
CAMS-99032 <sup>a</sup>	1449–1451	1720	40	1533 (1629) 1716 <sup>b, c</sup>	Charcoal
CAMS-99033 <sup>a</sup>	1498–1507	2340	45	2177 (2360) 2680 <sup>b, c</sup>	Charcoal
CAMS-99034 <sup>a</sup>	1549–1551	3080	40	3166 (3299) 3385 <sup>b, c</sup>	Charcoal
CAMS-99035 <sup>a</sup>	1599–1601	3775	40	3988 (4147) 4287 <sup>b, c</sup>	Charcoal
CAMS-99036 <sup>a</sup>	1647–1652	4590	60	5046 (5294) 5468 <sup>b, c</sup>	Charcoal
CAMS-99037 <sup>a</sup>	1698–1702	5810	45	6496 (6611) 6730 <sup>b, c</sup>	Charcoal
CAMS-18870 <sup>a</sup>	1731–1732	6625	35	7440 (7515) 7572 <sup>b, c</sup>	Charcoal
CAMS-113597 <sup>a</sup>	1738–1739	8150	35	9008 (9082) 9247 <sup>b</sup>	<i>Cornus drummondii</i> seed
UCIAMS-30988 <sup>d</sup>	1735–1742	7190	20	7960 (7994) 8028 <sup>b, c</sup>	Charcoal, 1 Cyperaceae seed
CAMS-113598 <sup>a</sup>	1744–1745	7595	30	8358 (8398) 8433 <sup>b, c</sup>	3 <i>Schoenoplectus</i> seeds
CAMS-99038 <sup>a</sup>	1748–1751	7860	60	8542 (8677) 8977 <sup>b, c</sup>	Charcoal
CAMS-99039 <sup>a</sup>	1787–1789	8520	50	9432 (9511) 9559 <sup>b, c</sup>	Charcoal
CAMS-99040 <sup>a</sup>	1830–1838	9490	45	10,591 (10,755) 11,072 <sup>b, c</sup>	Charcoal
UCIAMS-30989 <sup>d</sup>	1865–1867	9995	35	11,285 (11,462) 11,619 <sup>b, c</sup>	<i>Larix</i> needles, <i>Betula papyrifera</i> seed and fruit scale
UCIAMS-30990 <sup>d</sup>	1913–1916	10,360	25	12,052 (12,143) 12,292 <sup>b, c</sup>	<i>Picea</i> seed wing, <i>Picea</i> seed, <i>Larix</i> needle, 3 charcoalized <i>Picea</i> needle fragments, charcoal
UCIAMS-38362 <sup>d</sup>	1947–1948	10,320	110	12,096 (12,227) 12,356 <sup>b, c</sup>	<i>Picea</i> needles, charcoal
UCIAMS-30991 <sup>d</sup>	1970	10,375	25	12,159 (12,322) 12,546 <sup>b, c</sup>	<i>Abies</i> seed
UCIAMS-38363 <sup>d</sup>	2004	10,930	45	12,832 (12,885) 12,943 <sup>b, c</sup>	<i>Picea</i> needle fragments
UCIAMS-38364 <sup>d</sup>	2022	11,330	30	13,125 (13,200) 13,258 <sup>b, c</sup>	2 charcoalized <i>Picea</i> needle tips, charcoal
UCIAMS-30992 <sup>d</sup>	2025–2026	11,375	50	13,183 (13,256) 13,335 <sup>b, c</sup>	<i>Picea</i> needle, <i>Picea</i> seed wing
UCIAMS-38365 <sup>d</sup>	2037–2038	11,520	120	13,250 (13,401) 13,633 <sup>b, c</sup>	<i>Picea</i> and <i>Larix</i> needle fragments, <i>Picea</i> seed wing
UCIAMS-30993 <sup>d</sup>	2051	11,020	35	12,878 (12,937) 13,045 <sup>eb</sup>	<i>Picea</i> needle, <i>Picea</i> seed wing
UCIAMS-38366 <sup>d</sup>	2064	12,025	40	13,780 (13,877) 13,983 <sup>b, c</sup>	<i>Picea</i> needle fragments
UCIAMS-30994 <sup>d</sup>	2070	12,180	30	13,938 (14,028) 14,111 <sup>b, c</sup>	<i>Picea</i> needle fragments, <i>Picea</i> seed wing, <i>Larix</i> needle fragment
UCIAMS-38367 <sup>d</sup>	2079–2080	12,295	35	14,034 (14,105) 14,174 <sup>b, c</sup>	<i>Picea</i> and <i>Larix</i> needle fragments, <i>Picea</i> seed wing
UCIAMS-38368 <sup>d</sup>	2081–2083	12,255	25	14,070 (14,140) 14,212 <sup>b, c</sup>	<i>Picea</i> and <i>Larix</i> needle fragments, 3 <i>Picea</i> seed wings
UCIAMS-30995 <sup>d</sup>	2110	12,320	35	14,106 (14,210) 14,403 <sup>b, c</sup>	<i>Larix</i> seed, <i>Picea</i> seed, <i>Larix</i> needles
UCIAMS-38369 <sup>d</sup>	2115–2117	12,310	120	14,168 (14,434) 14,757 <sup>b, c</sup>	<i>Picea</i> and <i>Larix</i> needle fragments
UCIAMS-38370 <sup>d</sup>	2141–2143	12,620	220	14,390 (14,890) 15,355 <sup>b, c</sup>	<i>Larix</i> needle fragments, <i>Picea</i> seed wing
UCIAMS-38371 <sup>d</sup>	2161–2164	13,175	30	15,326 (15,560) 15,859 <sup>b, c</sup>	<i>Larix</i> and <i>Picea</i> needle fragments, <i>Picea</i> seed wing fragment
ISGS-4367 <sup>e</sup>	2169–2175	13,560	90	15,717 (16,130) 16,580 <sup>g, h</sup>	Wood
OxAW864.13 <sup>f</sup>	2172	13,427	126	15,468 (15,948) 16,454 <sup>g, h</sup>	<i>Picea</i> needles
OxAW864.14 <sup>f</sup>	2222	13,377	123	15,406 (15,882) 16,377 <sup>g, h</sup>	Wood
OxAW864.16 <sup>f</sup>	2238.5	13,533	126	15,617 (16,089) 16,597 <sup>g, h</sup>	Wood
OxAW864.15 <sup>f</sup>	2258	17,143	173	–	Bryophytes
–	2169	–	–	15,683 (15,987) 16,308 <sup>c</sup>	Pooled Mean

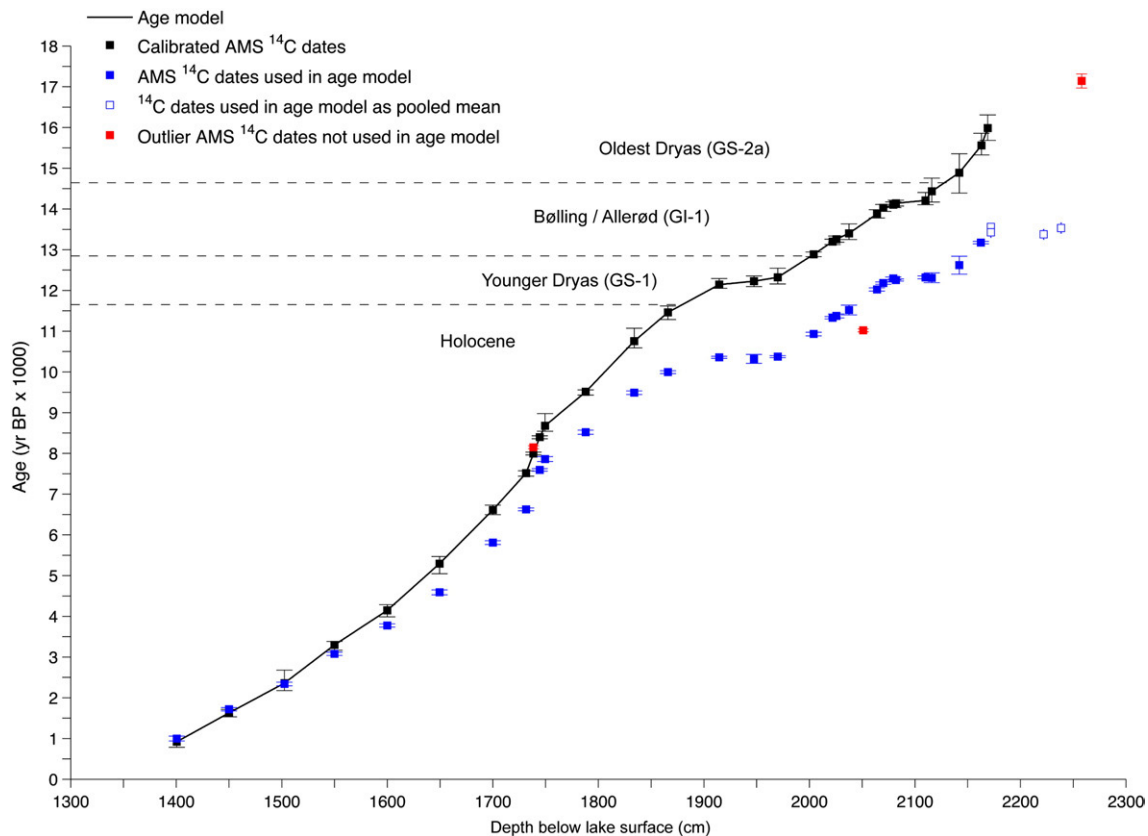
Note that depth is measured from the surface of the lake.

<sup>a</sup> Date from the Lawrence Livermore National Laboratory Center for Accelerator Mass Spectrometry.<sup>b</sup> Date calibrated with BCal (Buck et al., 1999) using the BCal calibration curve (<http://bcal.shef.ac.uk/>). Shown is the 2σ age range with the 50% median probability age in parentheses.<sup>c</sup> Date used in age model.<sup>d</sup> Date from the Keck-Carbon Cycle AMS facility (KCCAMS) – University of California, Irvine.<sup>e</sup> Date from the ISGS Radiocarbon Laboratory – Champaign, Illinois: conventional <sup>14</sup>C date.<sup>f</sup> Date from the ISGS Radiocarbon Laboratory – Champaign, Illinois: AMS <sup>14</sup>C date.<sup>g</sup> Date calibrated with CALIB 5.0.2 (Reimer et al., 2004; Stuiver and Reimer, 1993) using the INTCAL 2004 calibration curve (<http://radiocarbon.pa.qub.ac.uk/calib>). Shown is the 2σ age range with the 50% median probability age in parentheses.<sup>h</sup> Date used in pooled mean in age model.

### Pollen stratigraphy and vegetation reconstruction

The cluster analysis identified five pollen zones, which we label A–E from youngest to oldest (Figs. 2 and 3). Basal zone E (~16,000–

14,160 cal yr BP) is characterized by high values of *Picea* averaging about 60% and the highest values of *Larix* (>6%) in the pollen record. Percentages of pollen from deciduous taxa are generally low as are pollen values from herbaceous taxa. However, herbaceous taxa have



**Figure 4.** Age-depth graph and age model for Crystal Lake core. AMS  $^{14}\text{C}$  (blue squares) and calibrated dates (black squares) are shown with their 2s error bars. Each  $^{14}\text{C}$  date used in the age model has a calibrated age. The four AMS  $^{14}\text{C}$  dates indicated by open blue squares had their mean ages pooled for use in the calibrated age model. The three  $^{14}\text{C}$  dates indicated by red squares are not used in the age model. Two dates were rejected because they were either too old (1738 cm) or too young (2051 cm). The third date (2258 cm) was rejected because it showed the “hard water” effect. NGRIP age boundaries are depicted with horizontal lines.

their highest values in this zone, compared to the other pollen zones. The pollen assemblage represents a forest dominated by *Picea* and *Larix*. *Larix* is a very poor pollen producer, and its pollen percentages in zone E likely represent a significant presence in the vegetation (Janssen, 1966; Ritchie, 1987; Penalba and Payette, 1997). Values of *F. nigra*-type to >10% indicate that *F. nigra* was also present. The low percentages of *Ostrya*-type and *Quercus* may represent low abundances of these taxa in the vegetation, or their pollen may be derived from long-distance transport. SCD values are consistently above 0.15, indicating a no-analog vegetation type. Compared to the modern boreal forest, this vegetation lacked *Pinus* and *Betula*, which were either absent or present only in very small numbers.

A sharp decline in *Picea* marks the transition from zones E to D. *Picea* continues to decline throughout zone D (~14,160–12,400 cal yr BP); however, it remains a dominant member of a much more diverse forest than that which existed previously. Among the conifers, *Larix* values are low in zone D, and *Abies* increases to ~10%. The deciduous taxa *F. nigra*-type, *Ulmus*, *Ostrya*-type, and *Quercus* all increase and were certainly present in the vegetation. *F. nigra*-type attains values of >30%, which are far greater than any modern values for this taxon (Williams et al., 2006). Zone D has the highest SCD values in the record and represents the late-glacial vegetation most different from any modern type. *P. mariana* was the dominant *Picea* species. This species prefers poorly drained soils as does *F. nigra*. Whether *P. mariana* and *F. nigra* were growing in different landscape positions or whether they were growing together in the same stands is unknown. The dominant taxa of zone D (*Picea*, *Abies*, *F. nigra*-type, *Ulmus*, *Ostrya*-type, and *Quercus*) all occur together in the northern Great Lakes region today; however, *F. nigra* does not reach nearly the abundances in the modern vegetation of this region as it does in zone D. Additionally, where *Picea* overlaps the range of *F. nigra* today, *F.*

*nigra* does not occur in such high abundances as in zone D. Moreover, *Pinus* and *Betula* dominate the northern Great Lakes pollen assemblages (Williams et al., 2006), but occur in very low abundances in zone D.

*Picea* declines to its minimum value of 13% near the top of zone D, then increases to a peak of nearly 50% in zone C (~12,400–11,600 cal yr BP), before declining gradually to the top of the zone. *F. nigra*-type decreases in zone C, while other deciduous tree-taxa either decline or remain steady. *A. incana*-type increases in zone C. Among the conifers, *Larix* increases, and *Abies* continues to maintain its high values. The increase of *Picea* is mainly that of *P. mariana*. Zone C represents the re-establishment of a *Picea*-dominated forest with a significant presence of *Larix* and *Abies*. Some deciduous elements are still present, but in lower numbers than in the previous zone D.

*Picea* declines and then essentially disappears in zone B (~11,600–11,100 cal yr BP). This transitional zone is marked by peaks in *Pinus* and *Betula* and increases in *F. nigra*-type and *Ulmus*. *Abies* remains at fairly high values. The peak in *Pinus* (primarily *P. subg. Pinus*) is unusual for sites in northeastern Illinois (King, 1981; Curry et al., 2007), and it must represent a local presence on the outwash plain around Crystal Lake. Otherwise, the pollen assemblage represents a deciduous forest with a significant admixture of *Abies* and some *Picea*, perhaps somewhat similar to forests in northwestern Minnesota (Buell and Martin, 1961), but with more *F. nigra* and less *Pinus*. SCD values drop below 0.15 in this zone, indicating correlation with modern analogs.

*Picea*, *Larix*, and *Abies* disappear completely from the Crystal Lake record at the base of zone A (~11,100–9800 cal yr BP), and *Pinus* decreases to background levels. *Betula* and *A. incana*-type also decrease and essentially disappear early in the zone. *Quercus* and *Ostrya*-type increase, *Ulmus* maintains the high values attained in

zone B, and *F. nigra*-type gradually declines. Other minor deciduous types, such as *Carya*, *Acer saccharum*, *Tilia*, and *J. cinerea* increase, some perhaps appearing in the vegetation for the first time. Zone A represents a diverse deciduous forest dominated by *Ulmus*, *Quercus*, *Ostrya* (or *Carpinus*), and *F. nigra*, with an admixture of other mesic deciduous trees.

## Discussion

The late-glacial and early Holocene vegetation history of Crystal Lake is generally similar to other Midwestern records (Wright, 1964; Schweger, 1969; King, 1981; Webb et al., 1983, 1993; Shane and Anderson, 1993; Grimm and Maher, 2002; Grimm and Jacobson, 2004). However, the exceptional chronological control for Crystal Lake allows us to correlate the vegetation changes at Crystal Lake with the major changes evident in the NGRIP ice-core record at the century scale. The event stratigraphy in the pollen and LOI data from Crystal Lake closely track  $\delta^{18}\text{O}$  shifts in the NGRIP record, but with some apparent lags (Fig. 2).

### Climatic and ecological implications

Whereas previous studies have suggested that conditions in the Midwest were relatively dry (Bryson and Wendland, 1967; Yu and Wright, 2001), our results indicate wet late-glacial and early Holocene conditions in northeastern Illinois. Although there may have been spatial variability in precipitation patterns throughout the Midwest, the widespread presence of *F. nigra* throughout the southern Great Lakes region suggests wet conditions throughout the region (Jacobson et al., 1987). Existing evidence indicates that kettle lakes formed in the region between 18,000 and 16,500 cal yr BP (Curry et al., 2007), 2500 yrs before the advent of very wet conditions at Crystal Lake. Therefore in this case, the suggestion by Yansa (2006) that melting ice blocks were source of soil moisture does not seem plausible.

At Crystal Lake, climatic interpretation is hampered by the no-analog pollen assemblages. However, some conclusions based on autecology may be drawn. The very high abundance of *F. nigra* in pollen zone D, which is coeval with the Allerød and early Younger Dryas, is especially notable. *F. nigra* grows in swamps and on poorly drained soils (Wright and Rauscher, 1990), thus implying high soil moisture. Also of note is the high percentage of *Abies* in zones D–B. *Abies* thrives with abundant precipitation (Webb et al., 1983; Prentice et al., 1991), especially winter precipitation (Williams et al., 2006). The great abundance of *F. nigra* and *Abies*, together with the absence of boreal post-fire taxa, specifically *Betula* and *Pinus*, suggest very wet conditions, probably with heavy winter snows. The increase in sediment carbonate at the beginning of the Bølling suggests increased lake productivity and warmer climate (Yu, 2000), but little change is seen in the vegetation. However, an increase in sediment organic matter is concomitant with sudden increases in *F. nigra*, as well as other deciduous taxa including *Ulmus*, *Quercus*, *Ostrya*-type, and *Humulus*, suggesting warmer conditions. The range of *Picea* today spans a wide temperature gradient; with mean a mean January temperature gradient of  $-35$  to  $-5^\circ\text{C}$  and mean July temperature gradient of  $3$  to  $20^\circ\text{C}$ . It is possible that the warming at the beginning of the Bølling was from the colder to the warmer tolerances of *Picea*, and it was not until the end of the Bølling that temperatures become warm enough for deciduous taxa. The implication is that the Allerød was warmer than the Bølling. However, this trend is opposite than that implied by  $\delta^{18}\text{O}$  in the Greenland ice cores, which indicates greater warmth during the Bølling.

During the first  $\sim 300$  yr of the Younger Dryas Chronozone, *Picea* drops to its lowest late-glacial values, *F. nigra*-type begins to decline, but other deciduous types remain steady and *Ostrya*-type peaks, all of which suggest the warmest conditions of the late-glacial interval. *Picea*, primarily *P. mariana*, then peaks during the mid-Younger Dryas

and declines towards the end of the Younger Dryas. The pollen data indicate a cold interval that is coeval with the Younger Dryas. However, this cold interval starts several hundred years after the onset of the Younger Dryas Chronozone and begins to ameliorate prior to the end of the Younger Dryas, as indicated by the decline of *Picea* well before the end of the chronozone. The Marquette re-advance of the Laurentide ice sheet into Wisconsin and the Upper Peninsula of Michigan ended at the termination of the Younger Dryas (Drexler et al., 1983; Farrand and Drexler, 1985; Lowell et al., 1999; Larson and Schaetzl, 2001), but the timing of the onset of this advance is unknown, and conditions may have begun to warm before the advance terminated. The termination of the Younger Dryas Chronozone does coincide with a major shift in vegetation as recorded by the pollen at Crystal Lake. The prevalence of *P. mariana* during the Younger Dryas, together with continued abundance of *Abies*, a reduced but still significantly present *F. nigra*, and increased *A. incana*-type, all indicate wet (albeit cooler) conditions during the Younger Dryas Chronozone in northeastern Illinois.

The herbaceous taxa *Artemisia*, Poaceae, and Cyperaceae occur at low abundances generally  $<5\%$  in late-glacial zones C–E and then virtually disappear at the beginning of the Holocene in zone B. Cyperaceae could be derived from wetland sources, but *Artemisia* is an upland plant, and Poaceae is primarily an upland plant. These taxa may represent small openings in the forest or a relatively open understory on parts of the landscape. The decline of these taxa at the close of the Pleistocene with the extinction of proboscideans suggests that these large herbivores may have been responsible for forest openings. Both mastodons (*Mammuth americanum*) and mammoths (*Mammuthus* spp.) lived in the late-glacial forests of northern Illinois (Pasenko and Schubert, 2004; Saunders et al., 2007). In Africa, elephants are “keystone species” known to cause widespread destruction of woody vegetation (Laws, 1970; McNaughton et al., 1988; Owen-Smith, 1988; Western and Maitumo, 2004), and it is not improbable that Pleistocene proboscideans would have had similar ecological impacts. If so, the presence of these herbaceous taxa may have resulted from openings caused by megafaunal disturbance.

*Pinus* and *Betula* peak in zone B at the transition from the Younger Dryas to the Holocene, while both *F. nigra* and *Ulmus* increase. In the modern boreal forest, *Pinus* and *Betula* are post-fire successional taxa, and the peaks in their abundance may suggest more frequent fires and drier conditions during this interval. Without a charcoal record from Crystal Lake we cannot verify this hypothesis. However, whereas we found considerable charcoal fragments when sieving for macrofossils for AMS dates in the Holocene section of the core, we found very little charcoal in the late-glacial section suggesting that relative to the Holocene, fires in the late-glacial interval were infrequent (Table 1). On the other hand, the increases in *F. nigra* and *Ulmus*, both of which prefer poorly drained soils, suggest wet conditions. An alternative to the fire hypothesis is that *Pinus* and *Betula* exploited open areas created by the death of *Picea* stands, particularly on the sandy outwash plain around Crystal Lake. Meanwhile *F. nigra* and *Ulmus* expanded on poorly drained soils on nearby moraines, with *Ulmus* becoming more abundant than *F. nigra* during the warmer Holocene than Allerød. Thus, the successional phase of *Pinus* and *Betula* was possibly due to disturbance caused by rapid climate change, and perhaps associated outbreaks of insects, as is happening in Alaska today (Logan et al., 2003), rather than by fire.

About 500 yr after the end of the Pleistocene, *Quercus* increased, along with *Ostrya*-type, *Carya*, *A. saccharum*, *Tilia* and other mesic deciduous trees. *Ulmus* remained abundant, while *F. nigra*-type slowly decreased. This mesic deciduous forest indicates warm and moist conditions.

### Timing of climatic shifts in northeastern Illinois

The sediment record at Crystal Lake begins at  $\sim 16,000$  cal yr BP during the Oldest Dryas (GS-2a, 16,000–14,642 cal yr BP). *Picea* is high



during this interval and remains high until near the end of the Bølling (GI-1e, 14,642–14,025 cal yr BP), when *Picea* suddenly declines. Mineral LOI is high (~56–80%) during the Oldest Dryas, but carbonate deposition suddenly increases at the onset of the Bølling. The ~400-year delay in the decline of *Picea* after the onset of the Bølling may indicate that temperatures did not warm in northeastern Illinois coevally with the Bølling; however, the increase in carbonate deposition does indicate an environmental change coincident with the onset of the Bølling.

At least two hypotheses may explain the increase in carbonate deposition. The first is that carbonate deposition increased due to an increase in lake productivity as a response to increased water temperatures. Inasmuch as photosynthetic productivity is a summer phenomenon, carbonate is then a summer temperature signal. Winters may still have been too cold for deciduous trees, and in this highly seasonal environment, *Picea* continued to dominate. The second hypothesis is that groundwater flow into the lake increased at the beginning of the Bølling delivering more bicarbonate and carbonate ions, which then precipitated as calcium carbonate. The climatic implication is that climate became wetter at the beginning of the Bølling, but not necessarily warmer; thus *Picea* continued to dominate until the end of the Bølling, when conditions suddenly became warmer. These hypotheses are not mutually exclusive, and limnological data from ostracodes or diatoms could potentially resolve them.

Pollen zone D is essentially coeval with the Allerød (GI-1a to GI-1c, 13,904–12,846 cal yr BP) but extends ~300 yr into the Younger Dryas (GS-1, 12,846–11,653 cal yr BP). Several fluctuations in *Picea* may correspond with the ~100-yr-long Older Dryas (GI-1d) and ~200-yr-long Intra-Allerød Cold Period (GI-1b); however, given the 300–400 year offsets of the major pollen zones with the onsets of the Bølling and Younger Dryas and given some error in the age models for both Crystal Lake and NGRIP, any correlations with these shorter stadials would be tenuous. The transition from zone C to B corresponds closely with the end of the Younger Dryas and the beginning of the Holocene.

Overall, the pollen data indicate warm and wet conditions during the Bølling-Allerød Chronozone and colder conditions during the Younger Dryas. However, the Bølling-Allerød shift in vegetation does not occur until near the end of the Bølling. Similarly, a shift to colder conditions, as registered in the vegetation, does not occur until ~300 yr after the beginning of the Younger Dryas Chronozone. At least three hypotheses could explain the apparent 300–400 yr lagged response of northeastern Illinois vegetation to the NGRIP record: (1) age-model errors, (2) vegetation change lagging climate change, or (3) climate change in northern Illinois lagging North Atlantic Event Stratigraphy.

Both Crystal Lake and NGRIP have errors in their age models. The estimated maximum counting error in the NGRIP chronology is 125 yr at 12,500 cal yr BP and 167 yr at 14,000 cal yr BP (Rasmussen et al., 2006). The pollen zone E/D boundary is bracketed by two closely spaced radiocarbon dates with  $1\sigma$  errors of 25 and 35 yr and 95% highest posterior density (HPD) regions of 142 and 300 yr (Table 1, UCIAMS-38368, UCIAMS-30995). Pollen zone D/C is bracketed by two dates with  $1\sigma$  errors of 25 and 45 yr and 95% HPD regions of 387 and 111 yr, respectively (UCIAMS-30991, UCIAMS-38363).

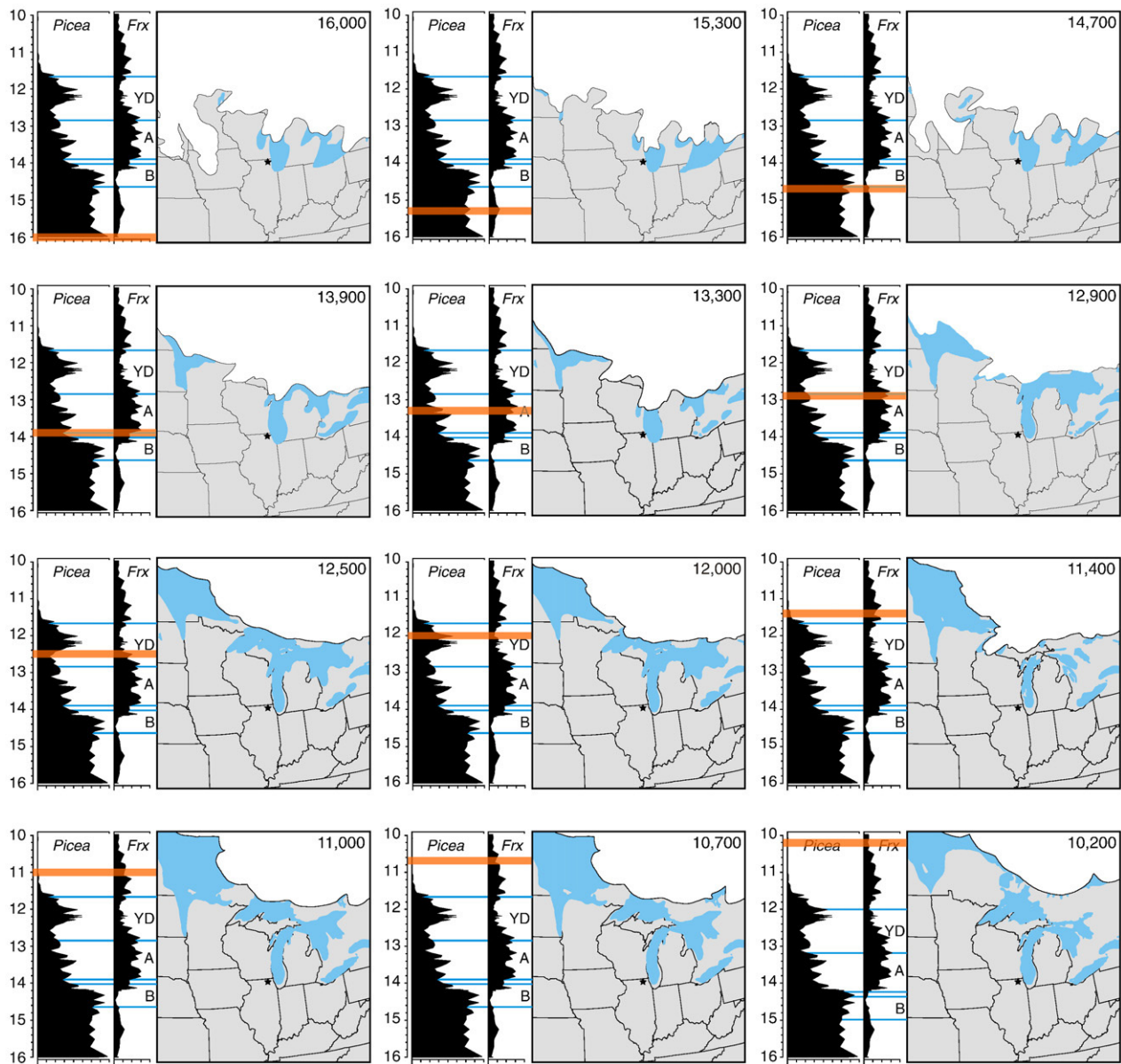
Age-model errors thus could account for some of the offset between NGRIP events and Crystal Lake pollen zones, but the temporal offset appears too large to be explained entirely by age-model errors. Furthermore, the close correlation of the C/B pollen zone boundary and the NGRIP Younger Dryas/Holocene boundary and the sharp change in LOI at the beginning of the Bølling suggest that the age models are not offset by centuries. The sharpness of the E/D pollen boundary and correlation of this boundary with a sudden increase in organic LOI argue against a significant lag in vegetation response to climate change. Migrational lag cannot be invoked as an explanation

for lagged vegetation response because the primary taxa involved in the major vegetation shifts were already present in the vegetation. Thus, the most probably hypothesis is that major late-glacial climate shifts in northeastern Illinois lagged the North Atlantic Event Stratigraphy by a few centuries.

These lags may be related to the position and height of the Laurentide ice sheet, the southern margin of which was located in the Great Lakes basin during the entire late-glacial interval (Fig. 5). At the beginning of the Bølling, the Lake Michigan lobe was positioned well south into the Lake Michigan basin, potentially exerting a significant control on climate in northeastern Illinois. It then retreated, but remained within the basin until ~13,900 cal yr BP. The shift from pollen zone E to D occurred during this retreat. Ice re-advanced until ~13,300 cal yr BP, a date that corresponding with a small peak in *Picea* during the Allerød. The ice sheet retreated to its northernmost late-glacial position at 12,500 cal yr BP (Dyke et al., 2003), coeval with the lowest values of *Picea* at the top of zone D. The ice sheet then re-advanced to the Younger Dryas Marquette moraine.

Thus, we suggest that the position of the Laurentide ice sheet was the primary control on late-glacial climate of northeastern Illinois, perhaps through its influence on the positions of frontal boundaries and the jet stream. Bromwich et al. (2005) indicate that during the last glacial maximum strong temperature gradients developed in the summer months as cold air flowing along the southern margin of the Laurentide ice sheet converged with warm air from the heated adjacent land surface. These temperature gradients have been documented up to 240 km south of the ice sheet margin by Levesque et al. (1997) from fossil midge assemblages. During summer the ice sheet would have fixed the position of the polar front over northern Illinois, where warm Gulf air converged with colder air, producing increased storm frequency and ample precipitation throughout the summer months (Bromwich et al., 2005). Considering that the Laurentide ice sheet was only a few hundred kilometers north of Crystal Lake during the Bølling, it is very probable that Crystal Lake was situated in the storm track flowing along the southern margin of ice sheet. High values of *Abies* pollen, similar to that of the maritime provinces in Canada, also suggest heavy snowfall and incursion of Gulf air during the winter months.

Another possible influence of the ice-sheet position could have been an enhanced lake effect, particularly in summer. Today during summer, lake breezes cool temperatures for several kilometers inland (Changnon et al., 2004). Average maximum summer surface water temperature of Lake Michigan varies annually from ~20 to 24°C (<http://coastwatch.glerl.noaa.gov/statistic/>). However, from the beginning of the Crystal Lake record ~16,000 cal yr BP to the late Allerød, the Laurentide ice sheet terminated in the Lake Michigan basin (Fig. 5). Calving icebergs may have significantly cooled the surface water temperatures of then glacial Lake Chicago. At the beginning of the Bølling, ice still extended far south into the basin, and surface water temperatures may not have been much above freezing (~20°C cooler than today). Thus, this may have greatly enhanced the lake effect on summer temperature and potentially delayed warming at Crystal Lake, which is ~45 km from the Lake Michigan basin. Modeling studies of Lake Agassiz, albeit a larger lake than glacial Lake Chicago, indicate suppressed summer temperatures due to lake effect up to 225 km east of the lake (Hostetler et al., 2000). At the beginning of the Younger Dryas, the ice sheet terminated in the Lake Superior basin, and glacial Lake Algonquin occupied the Superior, Michigan, and Huron basins (Hansel et al., 1985; Larson and Schaeztl, 2001). The shallow sill at the northern end of the Lake Michigan basin may have impeded icebergs, but cold water would nevertheless have spilled into the basin. As ice advanced to the Marquette Moraine, the Lake Michigan basin was isolated from the Superior Basin, lake level dropped at least 60 m, and Lake Chippewa, which occupied the basin, was much smaller than modern Lake Michigan (Hansel et al., 1985). The isolation of the Lake



**Figure 5.** Time series of panels showing the graphs for *Picea* and *Fraxinus nigra*-type from Crystal Lake and the location of the Laurentide ice sheet from Dyke et al. (2003). The Younger Dryas (YD), Allerød (A), and Bølling (B) Chronozones are shown on the pollen graphs. Age in cal yr BP for each panel is shown in the upper left corner of the ice-position map and by the broad orange line on the pollen graphs. The  $^{14}\text{C}$  yr BP ages on the Dyke et al. (2003) maps were converted to cal yr BP with the INTCAL04 calibration curve. The star on each map marks the location of Crystal Lake.

Michigan basin from the ice margin could explain the gradual decline in *Picea* and implied warming seen at Crystal Lake before the end of the Younger Dryas.

## Conclusions

The high-resolution Crystal Lake record, with its large number of AMS radiocarbon dates, allows direct temporal correlation of the vegetation changes at Crystal Lake with millennial-scale changes in the NGRIP ice record. *Picea* dominated the record until the late Bølling Chronozone, when *F. nigra* increased dramatically. *P. mariana*, *F. nigra*, and *Abies* dominated the record during the Allerød Chronozone. The very high values of *F. nigra* and the absence of *Pinus* and *Betula* set apart this pollen assemblage from any modern assemblage. Nevertheless, the autecology of the dominant species suggests very wet conditions during the Allerød. *F. nigra* declined and *Picea* increased during the Younger Dryas Chronozone. The prevalence of *P. mariana* together with the persistence of *Abies* and an increase in *Larix* suggest

that climate cooled but remained relatively wet. During the early Holocene, the increase in *Quercus* along with other mesic deciduous trees such as *Ulmus* suggests that conditions became warm and moist.

The Laurentide ice sheet may have influenced frontal boundary conditions and lake-effect temperature, especially when the ice margin was in the Lake Michigan basin. The polar front was probably fixed over northern Illinois during summer, where cold air flowing from the ice sheet converged with Gulf air masses and producing abundant precipitation. The pollen assemblages also imply deep snow and ample winter precipitation.

Vegetation changes at Crystal Lake lagged the major climate changes evident in the NGRIP ice core by 300–400 yr at the beginning of both the Bølling and Younger Dryas chronozones. These lags may be due to the influence of the Laurentide ice sheet on the climate in northeastern Illinois, whether it be through its influence on frontal boundary conditions or lake-effect temperature, and the slow response of the massive ice sheet to rapid climate changes that may have been coeval with changes in the North Atlantic Event Stratigraphy.

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