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Expanded spatial extent of the Medieval Climatic Anomaly revealed in lake-sediment records across the boreal region in northwest Ontario.

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Abstract

Multi-decadal to centennial-scale shifts in effective moisture over the past two millennia are inferred from sedimentary records from six lakes spanning a ~250-km region in northwest Ontario. This is the first regional application of a technique developed to reconstruct drought from drainage lakes (open lakes with surface outlets). This regional network of proxy drought records is based on individual within-lake calibration models developed using diatom assemblages collected from surface sediments across a water-depth gradient. Analysis of diatom assemblages from sediment cores collected close to the near-shore ecological boundary between benthic and planktonic diatom taxa indicated this boundary shifted over time in all lakes. These shifts are largely dependent on climate-driven influences, and can provide a sensitive record of past drought.

Our lake-sediment records indicate two periods of synchronous signals, suggesting a common large-scale climate forcing. The first is a period of prolonged aridity during the Medieval Climatic Anomaly (MCA, c. 900-1400 CE). Documentation of aridity across this region expands the known spatial extent of the MCA megadrought into a region that historically has not experienced extreme droughts such as those in central and western North America. The second synchronous period is the recent signal of the past ~100 years, which indicates a change to higher effective moisture that may be related to anthropogenic forcing on climate. This approach has the potential to fill regional gaps, where many previous paleo-lake depth methods (based on deeper centrally-located cores) were relatively insensitive. By filling regional gaps, a better understanding of past spatial patterns in drought can be used to assess the sensitivity and realism of climate model projections of future climate change. This type of data is especially important for validating high spatial resolution, regional climate models.

Introduction

Future extreme droughts, similar to or more extreme than the 'dust-bowl' 1930s, could be the most pressing problem of global warming (Romm, 2011). Droughts of unusually long duration or megadroughts (Cook *et al.*, 2010b), may be an omen for the future (Seager *et al*., 2007; Romm, 2011), but uncertainty about their spatial extent and severity remains. Mounting evidence suggests that the Medieval Climatic Anomaly (MCA, c. 900-1400 CE, common era) has a global signature (Seager *et al*., 2007; Trouet *et al*., 2009; Graham *et al.*, 2011). Regionally, however, the spatial extent, duration and magnitude of the MCA are not clearly defined. Understanding differences in the spatial extent and severity of the MCA between the arid west and the more humid east of North America (Cook *et al.*, 2010b) will lead to a better understanding of the MCA. Climate models suggest that a re-organization of the climate system occurred during the MCA, likely driven by changes in ocean circulation and sea-surface temperatures in both the Pacific and Atlantic Oceans (Trouet *et al*., 2009; Feng *et al*., 2011; Graham *et al.*, 2011; Oglesby *et al*., 2012). Although the MCA cannot be uniformly characterized, it has distinct regional expressions (Graham *et al.*, 2011) that are commonly manifested as a period of prolonged drought or megadrought (Helama *et al.*, 2009; Trouet *et al*., 2009; Cook

et al., 2010b). In North America, the MCA was characterized by elevated aridity in the western USA (Cook *et al.*, 2010b), and mobilized eolian dunes in the Great Plains (Miao *et al.*, 2007). The spatial patterns of MCA droughts in North America are thought to be similar to droughts witnessed in the 1930s; however, the MCA droughts lasted for several decades to centuries thus dwarfing modern-day droughts (Seager *et al*., 2007; Cook *et al.*, 2010b). Many studies suggest that these North American megadroughts were linked to persistent La Niña – like conditions in the Pacific Ocean and to a positive (warm) mode ofthe Atlantic Multidecadal Oscillation/North Atlantic Oscillation circulation pattern (Helama *et al.*, 2009; Trouet *et al*., 2009; Cook *et al.*, 2010b; Feng *et al*., 2011; Oglesby *et al*., 2012).

Lake sediment records have been widely used to infer past climatic conditions, but regional networks of proxy records from lakes are rare. Analysis of multiple lakes within a region is the best way to distinguish changes driven by climate forcing from intrinsic local influences (Fritz, 2008; Williams *et al.*, 2011). Water levels in many lakes are driven by changes in temperature and precipitation, and therefore can be important integrators of water balance and sentinels of water scarcity (Williamson *et al.*, 2009). Changes in precipitation can significantly impact the hydrological system, resulting in altered patterns of runoff and concurrent change in the chemistry of lakes, which in turn may affect the physical and biological processes, such as thermal structure, light transparency, algal productivity and community structure (Fee *et al*., 1996; Snucins & Gunn, 2000; Keller, 2007; Heino *et al*., 2009; Karlsson *et al*., 2009). Canada's boreal region contains ~80-90% of the country's freshwater (Schindler & Lee, 2010), and is predicted to be one of the biomes most affected by climate warming (Ruckstuhl *et al*., 2008; Schindler & Lee, 2010). One of the predictions of increasing temperatures is decreased lake levels and river flows (Schindler & Lee, 2010). Analysis of longer-term records of past water levels can provide a context for informing water managers on the inherent natural variability of lake levels and their sensitivity to climate change. Coherent shifts in past water levels of multiple lakes within a region would suggest climate as a dominant driver of change.

In the Experimental Lakes Area (ELA), located in the Winnipeg River Drainage Basin (WRDB) in the boreal region of northwest Ontario, reference lakes were shown to be sensitive to the droughts of the 1980s (Schindler *et al*., 1996). Additionally, limited long-term trends of drought from proxy records are available from the boreal region of northwest Ontario (Laird & Cumming, 2008). Analysis of a pollen dataset across the boreal region of Canada suggests that there is a warming signal in central Canada during the MCA

(Viau & Gajewski, 2009), although only 2 sites are close to the WRDB. Analysis of tree-rings within the WRDB over the past ~200 years suggests that low tree growth can be associated with warm/dry summers, but the signal is weak due to the generally cool, moist climate (St. George *et al*., 2008).

This study provides the first substantive evidence of decreased water availability during the MCA across a large region of the Winnipeg River Drainage Basin (WRDB) in northwest Ontario (Fig. 1), providing convincing evidence of how far north and east theMCA extended. Furthermore, this is the first regional application of the approach proposed by Laird and Cumming (2008) to reconstruct drought from lake sediment records in drainage lakes (open lakes with a surface outlet). This approach utilizes a sensitive relationship between changes in lake-water depth and changes in diatom assemblages derived from near-shore cores collected near the present-day ecological boundary between the shallower benthic and deeper planktonic (B:P) diatoms. A greater contribution of benthic diatoms implies shallower lake depths, and a larger contribution of planktonic diatoms infers deeper lake depths. Placement of cores near the B:P boundary can provide sensitive drought records over several millennia, and the method has the potential to be applied to numerous drainage lakes (Laird *et al*., 2011). In contrast, analyses of sediment records from deeper centrally-located cores from drainage lakes often do not yield clear signals of changes in water level and climate (Battarbee, 2000). Here we present six diatom-inferred drought records analyzed at ~ decadal-scale resolution over the past two millennia to provide a more comprehensive view of natural variability in water resources and the degree to which climate was an important driver of the patterns.

Materials and Methods

Study Region

The six study lakes are in the Winnipeg River Drainage Basin (WRDB) in northwest Ontario, forming a ~ 250-km transect across the region (Fig.1). The lakes to the west are within the Lake of the Woods/Rainy River watershed, and those to the east in the English River watershed. All lakes are unregulated with surface outlets (open drainage lakes). Five are 1st-order headwater lakes, whereas ELA Lake 442 is a 2nd-order lake (one small pond drains into it). The lakes range in surface area from ~17 to 78 ha, and maximum lake depth

from ~16-20 m (Table S1; Laird *et al*., 2011), with the exception of ELA Lake 239 which is 30 m deep (Laird & Cumming, 2008). Four lakes (Dixie, ELA Lake 239, ELA Lake 442 and Little Raleigh) are oligotrophic (low nutrients), with two lakes (Meekin and Gall) on the lower end of mesotrophic (moderate nutrients) (Table S1; Laird *et al*., 2011; Kingsbury *et al*., 2012).

Average annual precipitation in the WRDB varies from ~750 mm in the west to ~820 mm in the east (Fig. 2a), and mean annual (and summer temperature) varying from ~2.6(18.0) °C to ~1.5 (17.1) °C (Fig. 2b). Although average annual and summer temperatures are similar in the prairies to the west (~2.3 (18.3) °C in Winnipeg), average annual precipitation is much lower (~590 mm in Winnipeg). Our study area is predominantly covered with forests (over 70 %), and only has 0.5 to 3 % of the total land-use listed as settlement/development, with the remainder in lakes and wetlands (White, 2000). The eastern part of the WRDB consists of boreal forest comprising black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), and poplar (*Populus* spp.), along with white birch (*Betula papyrifera*), balsam fir (*Abies balsamea*), and larch (*Larix* spp.) (Ontario Ministry of Natural Resources, 2000). Gall Lake, Little Raleigh Lake and ELA lakes 239 and 442 are all located in this boreal forest zone (Kingsbury *et al.*, 2012). Dixie Lake lies within a transitional area between the east and west vegetation habitats and its dominant species are poplar, white oak (*Quercus alba*), black spruce, balsam fir, jack pine and white spruce (*Picea glauca*). Meekin Lake is located in the western-most vegetation zone which comprises black ash (*Fraxinus nigra*), poplar, white birch, red maple (*Acer rubrum*), and balsam fir (Kingsbury *et al.*, 2012).

Core location

The locations of the gravity and piston cores were chosen on the basis of the results from seismic profiling of the sediment that identified regions of gentle lake-bottom slope with sufficient sediment accumulation for decadal analysis over the past several thousand years. Seismic profiling was carried out using a Knudsen 320M marine sounder with 200 kHz and 28 kHz transducers. Lake floor and sub-bottom acoustic reflections were recorded graphically on thermal recording media. The cores were retrieved (Glew *et al*., 2001) ~1-2 m deeper than the depth of the present-day B:P diatom boundary (Fig. 3), as defined from a

surface-sediment calibration dataset from within each lake (Laird *et al.*, 2011). Data on the specific diatom assemblages that define the benthic and planktonic zones in the surface samples can be found in Kingsbury *et al*. (2012). Analysis of multiple transects from three different sub-basins of a large boreal lake in the WRDB with varying wind exposure and bottom slopes, indicated that a single, well-placed transect may be used to define this B:P diatom boundary within a lake (Laird *et al*., 2010). Cores were sectioned into 0.25-cm intervals, gravity cores in the field (Glew *et al*., 2001) and piston cores in the lab.

Laboratory procedures

For each core, ~0.2-0.3 g of wet sediment was sub-sampled and placed in 20-ml glass vials to which a 1:1 mixture by molar weight of concentrated nitric (HNO_3) and sulphuric (H_2SO_4) acid was used to remove organic matter. The samples were allowed to settle for 24 h before the acid above the sample was removed, and the sample was rinsed with distilled water. This procedure was repeated until the sample had the same pH as the distilled water (approximately eight rinses). Four successive dilutions for each sample were pipetted onto coverslips ensuring that each sample was well mixed. Samples on the coverslips were air-dried overnight, then heated on a warming plate to remove any remaining moisture,and subsequently mounted with Naphrax® onto glass microscope slides. Diatoms were identified and counted along transects on the prepared slide using a Leica (DMRB model) microscope fitted with a 100x fluotar objective (NA=1.3) and using differential interference contrast optics at 1000x magnification. Approximately 400 diatom valves were enumerated per slide. Diatoms were identified down to the species level or lower, using taxonomic references outlined in Laird *et al.* (2011).

Statistical models

Diatom-inferred (D-I) depth models were developed based on surface-sediment samples (~top 0.5-cm interval) collected along a depth gradient within each of the six small boreal lakes (Laird & Cumming, 2008;

Laird *et al*., 2011). A series of surface-sediment samples were collected along a gentle slope (<15%) from the near shore to the central deep basin for each study lake. Three samples were collected ~ every 1-m of water depth with a mini-Glew corer (Glew, 1989). The number of surface samples collected in each lake ranged from 51 to 87, depending on the maximum depth of each lake. The depth models were developed using the diatom taxa that achieved greater than 1% relative abundance from each of the surface-sample datasets using the computer program C2 v. 1.6.3 (Juggins, 2003). Analysis of the applicability and sensitivity of different models was evaluated (Laird *et al*., 2011), and a weighted-average partial-least-squares model (WA-PLS) with two components was appropriate in all lakes but Gall Lake, where a simple tolerance weighted-average model was deemed to be best for down-core application (Haig, 2011). Weighted-averaging (WA) methods provided strong models, with bootstrapped r^2 values ranging from 0.85 to 0.95, and root-mean-squared-errors of prediction (RMSEP) between 1.1 and 2.1 m, with the exception of ELA Lake 239 with r^2_{boot} of 0.72 and RMSEP of 4.6 m. The weaker statistics for ELA Lake 239 are likely the result of the lower taxonomic species designation for the sub-dominant and rarer diatom species that were identified and counted in this study (Laird & Cumming, 2008).

The significant diatom assemblage zones in the down-core analyses were defined by the broken-stick method using optimal zonation to establish the order of the splits and their significance using the program PSIMPOLL v 4.10 (Bennett, 1996). Those with the highest significance are considered the 'first order' or major zones, whereas those with lower significance are sub-zones.

Chronology

The time-depth relationships for each core were based on a composite model of ^{210}Pb for the topmost sediments and ^{14}C dating for the other sediments. The ^{210}Pb analysis was based on counts from a low-background gamma counter (Schelske *et al*., 1994) and estimates of chronology were calculated using a constant rate of supply model (Oldfield & Appleby, 1985). The overlap between the gravity and piston cores in each lake was determined through matching of percent organic content from loss-on-ignition analyses

(Dean, 1974), diatom assemblage data and ^{210}Pb activity near the tops of the piston cores, with the exception of ELA Lake 239 where all analyses are based on a longer gravity core. The material used for all ^{14}C dates of the age model were based on concentrated pollen grains processed at LacCore in the Limnological Research Center in Minneapolis, MN, and analyzed at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Lab (Table S2). All ^{14}C dates were calibrated to Calendar Years using the Calib 6.0.1 program and the INTCAL09 dataset (Stuiver & Reimer, 1993; Reimer *et al*., 2009).The calibrated ages that were used to determine chronology were based on the midpoint of the 2- sigma age range with the highest probability. Macrofossil dates from similar sediment levels correspond to the pollen-based dates in ELA Lake 239 (Laird & Cumming, 2008; Moos *et al.*, 2009) and in other cores from the lakes in this study (Haig, 2011). Average resolution between the analyzed samples for each lake varies from ~12-16 years, except Gall Lake which has an average resolution of ~19 years.

Results

Climate records

Correlation of the annual precipitation records ranged from 0.51 to 0.69 (Table 1) between the four climate stations which span ~450 km, from Winnipeg (~200 km west of Kenora) to Sioux Lookout (~250 km east of Kenora) (Fig. 1). Correlation of the annual temperature records were much higher between the four climate stations, ranging from 0.89 to 0.97 (Table 1). These results illustrate higher spatial variability in precipitation in comparison to temperature, a result expected at this spatial scale because precipitation, if it occurs, does so in discrete events. This spatial variability in precipitation can also be observed in the instrumental time-series records, where the 1930s drought is evident in the two western sites, the 1950s only in Kenora and the 1980s in all sites (Fig. 2a). The 1980s drought was interrupted with higher precipitation in all sites but Kenora, which had consistently lower precipitation throughout this decade. All sites indicated generally higher precipitation since the 1980s drought, but only two sites (Kenora and Sioux Lookout) indicate a significant

increase in precipitation since 1910. The lack of a trend in precipitation at the Dryden site may in part be due to the record of the adjusted and homogenized dataset (Mekis & Vincent, 2011) extending to only 2003. In contrast, all four climate stations indicate a significant increase in temperature since 1910 (Fig. 2b).

Chronology

Three to five radiocarbon dates, tied into ^{210}Pb dates from the topmost sediments, provided the chronology for the sediment records for the past ~2000-3000 years (Table S2). A simple linear interpolation model was used between the bottom ^{210}Pb and the radiocarbon dates, except in the case of Gall Lake where a linearregression model was used (Fig. 4). Radiocarbon dates for four of the lakes suggest that sedimentation rates have remained relatively constant, whereas, sedimentation rates decreased during the last ~1000 years in Meekin Lake, and increased slightly in Gall Lake. Overall, the strong chronology in all cores provides a framework to infer decadal-to-centennial scale changes in all of our records.

Diatom assemblages

Changes in the percent abundance of planktonic diatoms has varied over the last two millennia in all lakes (Fig. S1), greatly influencing the inferred depths (Fig. 5). The dominant planktonic taxa in all lakes included *Discostella stelligera*, with *Discostella pseudostelligera* also abundant in the more western lakes, *Cyclotella bodanica v. lemanica* in Little Raleigh Lake (Ma, 2011) and *Aulacoseira tenella* in Gall Lake (Haig, 2011). Other planktonic taxa present at lower abundances included: *Asterionella formosa*, *Cyclotella michiganiana*, *Cyclotella ocellata*, *Cyclotella tripartita*, *Fragilaria nanana*, *Fragilaria tenera,* and *Tabellaria flocculosa* (Table S3).

One of the most dominant benthic taxa in the cores associated with mid-depth habitats was *Staurosirella pinnata* (Laird *et al*., 2011; Kingsbury *et al.*, 2012). Other abundant mid-depth taxa included *Nupela vitiosa*, *Navicula rotunda*, *Pseudostaurosira brevistriata*, *Staurosira construens*, and *Aulacoseira distans* (Table S4). Numerous other rare *Navicula* taxa (sensu lato) comprised this mid-depth benthic

assemblage. Benthic taxa associated with near-shore habitats (Kingsbury *et al*., 2012) were generally of lower abundance, with one of the most common being *Achnanthidium minutissimum*. Many other rare near-shore benthic taxa include genera of *Achnanthes* (sensu lato), *Cymbella* (sensu lato) and *Nitzschia*.

Diatom-inferred depth

Diatom-inferred depths over the past 2000 years in five of the lakes ranged ~5-6 m within each lake, whereas the range in ELA Lake 239 was ~12 m (Fig. 5). This is likely due to the much greater maximum depth of Lake 239 and thus the potentially greater overestimation of inferred depth once the assemblage is dominated by planktonic taxa (Laird & Cumming, 2008). The mean inferred depths of the major zones for each lake (defined by the diatom assemblage) have shifted over time, with the mean shift between adjacent zones typically being ~1-2 m, with the exception of ELA Lake 239 with shifts from ~ 1 to 5 m (Fig. 5). The timing and direction of these shifts varied between the lakes. However, a period of lower inferred depth, that was consistently lower than the mean of the zone, can be identified in all lakes during the period known as the Medieval Climatic Anomaly (MCA) (Fig. 5). For four of the lakes (Meekin, Lake 239, Lake 442, Little Raleigh) the MCA low-water stand lasted ~200 years, although for Lake 239 it was punctuated by episodes of greater inferred depth. In Gall Lake the lower water levels persisted for ~300 years (albeit punctuated by short episodes of greater inferred depth, particularly between ~1000-1100 CE) and for over 400 years in Dixie Lake. These low-water stands correspond to periods in which there was a higher abundance of benthic diatoms in the cores (Fig. S2). The timing of the onset of lower water levels in the more western lakes was at ~900 CE, whereas the onset in the eastern lakes was slightly later at ~1000 CE in Gall Lake and ~1100 CE in Little Raleigh Lake. In four lakes (Meekin, Dixie, Gall, Little Raleigh) the shallowest inferred depths over the last 2000 years occurred during the MCA, whereas in the ELA lakes lower inferred lake levels occurred within a period of generally higher lake levels (Fig. 5). In three of the lakes (Dixie, Lake 239, Little Raleigh), the low-water stand was marked at the beginning and end by a change in diatom assemblage, which was identified by PSIMPOLL as a sub-zone. Sub-zones are defined as having diatom assemblage composition different from a random assemblage, as defined by the broken-stick method, but are of lower significance

(smaller difference) than the major diatom assemblage zones. In Dixie, the shallower inferred depths extended beyond the sub-zone. In two lakes (Lake 442, Gall), a change in diatom assemblage occurred at the end of the MCA, whereas in Meekin Lake, the shallower inferred depths did not correspond with a significantly different diatom assemblage.

The only other period during the past 2000 years that was similar in all six lakes, was a shift ~100 years ago to a period of higher water levels. All shifts were defined by a major change in diatom assemblages, with the exception of Dixie which was defined by a sub-zone, with the largest changes in Meekin Lake and ELA Lake 442 (Fig. 5).

Discussion

The Winnipeg River Drainage Basin (WRDB) provides the source water for a major portion of the hydropower produced in Manitoba (St. George, 2007), some of which is exported to neighbouring provinces and mid-west states. Issues of water availability in the semi-arid prairies to the west are exacerbated by anthropogenic land-use and climate change (Schindler & Donahue, 2006). In contrast, in northwest Ontario increased precipitation during the last decade (Fig. 2a; Parker *et al.*, 2009) and increased stream flow suggest that this region may not have major water supply issues over the next few decades (St. George, 2007). However, the increasing trend in temperature (Fig. 2b) could decrease overall effective moisture, thereby offsetting any increases in precipitation. Furthermore, seasonal changes in precipitation, with higher rainfall from April to October and lower snowfall from November to March (Parker *et al.*, 2009), may significantly influence the hydrological budget and recharge of lakes (Winter & Woo, 1990). Although parts of the WRDB have experienced drought during the 1930s, 1950s and 1980s, the spatial variability was large with few synchronous droughts across all sites (Fig. 2). In the absence of any large-scale forcing, precipitation is inherently very variable in both time and space as it depends on discrete events, which accounts for the large spatial variability observed today. This spatial variability is in sharp contrast to the generally synchronous aridity during the MCA (Fig. 5). It is this synchronicity that makes these new reconstructions so important –

they suggest that large-scale climate forcing has occurred (which does not occur at present), and drought can be widespread and ubiquitous across the region. Not only will this data enable a better understanding of the controls on the MCA, it also serves as an indicator of a possible climate outcome in the future.

The longer-term perspective of the sediment records enabled the identification of the MCA at all sites examined in this region. Location of the sediment cores near the benthic to planktonic (B:P) diatom boundary provided a sensitive means of inferringlower depths as a proxy for drought conditions, whereas deeper cores in drainage lakes are much less sensitive (Laird and Cumming, 2009). Some caution must however be used in interpreting the magnitude of change, particularly when inferring higher water levels, due to the lower sensitivity and larger errors associated with the models at the deeper depths (Laird & Cumming, 2009; Laird et al., 2011). The key to this approach is to define the location of the B:P boundary within each of the study lakes, and then core in a region deeper than this boundary where there is sufficient sediment accumulation to provide an adequate temporal resolution.

Benthic to planktonic (B:P) diatom boundary

The benthic to planktonic (B:P) diatom boundary is the water depth at which there is a distinct assemblage shift in the lake surface sediments from primarily benthic diatoms (shallower water) to an assemblage dominated primarily by planktonic diatoms (deeper water) (Kingsbury *et al.*, 2012). The depth of the B:P diatom boundary varies greatly among our study lakes from ~6 to 14 m (Table S1; Laird & Cumming, 2008; Laird *et al*., 2011). Availability of light is one of the dominant variables in the zonation between the benthic and the planktonic algal assemblages in nutrient-poor lakes where benthic algae are limited primarily by light (Karlsson *et al.*, 2009). Many studies have concluded that the concentration of dissolved organic carbon (DOC) in boreal Canadian Shield lakes is the major driver determining lake clarity and the depth of the euphotic zone (Keller, 2007). DOC also appears to be a factor in the location of the B:P diatom boundary, with lower (higher) DOC lakes having deeper (shallower) boundaries (Kingsbury *et al.*, 2012). Variation of the depth of the euphotic zone within a lake is influenced by climate and will influence the region occupied by benthic taxa. For example, DOC concentrations decreased in boreal ELA lakes during the drier years of

the late 1980s (Schindler *et al*., 1996), which resulted in increases in both the epilimnetic depth (average ~1 m) and euphotic zone depth (~0.5 m) (Findlay *et al*., 2001). A six-year study of 20 lakes in northern Michigan also indicated substantial declines of DOC during periods of drought which were sufficient to cause changes in light penetration (Pace & Cole, 2002). If light penetration increases significantly, the B:P boundary will move towards the deeper regions of the lake (Laird *et al.*, 2011).

In addition to light, changes in lake level through time will change the location of the B:P diatom boundary (Laird *et al.*, 2011). As lake level declines, the boundary of the transition from benthic to planktonic diatomassemblages will move towards deeper parts of the lake (Fig. 3). Sediment cores retrieved near the present-day depth of the B:P diatom boundary can be used to track this movement. For example, during arid conditions increases in benthic taxa and declines in planktonic taxa would be archived in the sediment cores, leading to inferences of lower lake level (Fig. 3). This approach is similar to tracking the physical depositional boundary depth that will move towards the deeper center of the lake as lake level declines (Dearing, 1997). However, our approach to reconstruct droughts can be applied to a single well-placed core (Laird & Cumming, 2008; Laird & Cumming, 2009; Laird *et al.*, 2011) and provides a continuous record at ~ decadal resolution. As a result of the interactions between changes in lake level and light penetration, which move in concert during droughts, our down-core depth inferences from cores retrieved near the present-day B:P diatom boundary are recording the temporal movement of this ecological boundary. Because this boundary is highly influenced by climatic conditions, tracking the changes in diatom assemblages can provide a sensitive indicator of drought over millennia.

Regional network of proxy records and comparison to other sites during the MCA (c. 900-1400 CE)

The chronological control of our sedimentary records is strong (Fig. 4), thereby allowing us to make multi-decadal to centennial comparisons across sites. Our sediment core results from northwest Ontario suggest that during the last 2000 years several shifts in the mean depth of individual lakes have taken place, with some synchronous periods (Fig. 5). Two such periods of synchronous change occur across all lakes: the MCA with reduced water levels, and the last ~100 years with generally higher water level. Four of the sites show that MCA droughts were the most extreme of the last 2000 years, whereas at ELA lakes 239 (Laird & Cumming, 2009) and 442, the MCA was manifested as a low-water stand within a period of higher water levels. The

general synchrony across sites suggests an extrinsic climate forcing (Williams *et al.*, 2011), with the MCA being part of inherent natural fluctuations, whereas the recent change during the last 100 years more likely has an anthropogenic influence.

Regional networks of paleolimnological records are more apt to distinguish ecological changes driven by extrinsic forcing, such as climate, from more intrinsic local influences (Fritz, 2008; Williams *et al.*, 2011). Spatial and temporal variability in lake sediment records can be due to the individual responsiveness of the lakes to climate forcing mediated by the geological, vegetation and hydrological setting and/or spatial variability in climate (Fritz, 2008). With just six sites spanning ~250 km, it is difficult to determine, with any certainty, what particular chemical or physical characteristics determined the magnitude and length of the lake response during the MCA. The two lakes with the longest apparent low-water stands (Dixie, Gall) are the two smallest in both surface area and volume (Table S1), albeit the magnitude of change was similar across all lakes (~1-m decline, with up to ~2-m in Dixie). Such declines may have resulted in the lakes becoming closed (no surface outlet); however, because of the low concentration of ions in these lakes, there is no change in the diatom assemblage, such as the presence of more sub-saline taxa, that suggest a significant change to conductivity. Deciphering the cause of the different pattern in the two ELA lakes (a low stand within an overall higher-water stand) is difficult; although they are spatially adjacent and similar in chemical composition, they are in different sub-watersheds and have very different morphology (Kingsbury *et al*., 2012). The magnitude of the high-water stand of Lake 239 is likely, in part, an artifact of overestimation of the model at depths > ~ 15 m (Laird & Cumming, 2008, 2009), and the complexities of the potential for ELA Lake 239 coalescing with adjacent ELA Lake 240 with increasing depth. A widespread external forcing must be large enough for regional patterns to emerge, despite the potential heterogeneity and intrinsic complexities of local ecosystems and internal dynamics (Williams *et al.*, 2011). In the Nebraska Sandhills (one of the few other regions with a paleolimnological-drought network), an analysis of five topographically-closed lakes indicated relative coherency over the last 4000 years, particularly during the MCA with all lakes indicating lake-level decline (Schmieder *et al*., 2011). Our sites in the WRDB indicate some temporal variability, with an earlier onset in the west (~900 CE) versus somewhat later in the east (~1000-1100 CE), indicating a potential time-transgressive response, although these periods nearly overlap when errors in radiocarbon are taken into account. Our data indicates the MCA penetrated at least as far as

our easternmost lake, but without sites further east we cannot clearly define the eastward extent.

In the Canadian and northern U.S. prairies to the west of the WRDB, there is high variability in diatom-inferred effective moisture during the MCA interval (Laird *et al.*, 2003). This may be due to complex interactions between groundwater and climate in this region, as well as differences in the spatial pattern of precipitation and drought depending on the position and configuration of the jet stream and high-pressure ridges (Laird *et al.*, 2003). Other proxy records from regions adjacent to the WRDB suggest intervals of drought within the MCA interval. In Minnesota, sand deposits in Mina Lake indicate large declines in lake level during the 1300s (St. Jacques *et al.*, 2008), high eolian deposition occurred from ~ 1280 to 1410 CE in Elk Lake (Dean, 1997) and $\delta^{18}O$ from calcite indicated an arid period from ~ 1100 to 1400 CE in Steel Lake (Tian *et al*.,2006). In Manitoba, the cellulose $\delta^{18}O$ record from the southern basin of Lake Winnipeg indicated severe dry conditions between 1180 and 1230 CE, and a less-severe dry period from 1320 to 1340 CE (Buhay *et al*., 2009). Relative warm conditions during the MCA in comparison to the Little Ice Age (LIA) have been inferred from pollen records in the central boreal region of Canada and in Wisconsin (Viau & Gajewski, 2009; Viau *et al*., 2012; Wahl *et al.*, 2012).

Many studies now suggest that the MCA was of global extent, with many regions indicating dry conditions, while others were wet (Seager *et al*., 2007; Helama *et al*., 2009; Trouet *et al*., 2009; Graham *et al*., 2011). These conclusions are based on proxy records around the world and climate models that suggest a re-organization of the climate system. While many of these studies point to conditions in the Pacific Ocean being in a persistent La Niña mode, others also indicate that conditions in the North Atlantic (Feng *et al.*, 2011; Oglesby *et al.*, 2012), and Indian Ocean (Graham *et al.*, 2011) also played a role in this re-organization. Observational and modeling studies also suggest that these same sea-surface temperature (SST) patterns play a major role in present-day droughts across central North America, including our study region (e.g., Hu et al. 2011). It is not that an entirely different set of controls accounted for the drought; rather the SST patterns favoring drought appear to have prevailed during much of the MCA, whereas they are much more sporadic at present.

Recent signal (last ~100 years)

Recent studies show that anthropogenic forcing has a detectable influence on climate, being implicated in precipitation trends across large latitudinal bands (Zhang *et al.*, 2007), as well as trends in river flow, winter air temperature and snow pack (Barnett *et al*., 2008). At the ELA, a significant upward trend in average annual temperature (mostly due to temperature increases in the winter) is accompanied by increasingrainfall, particularly between April to October (Parker *et al*., 2009). These recent increases in precipitation in our study region (Fig. 2a) may be related to anticipated increased poleward moisture transport into the Great Lakes region related to greenhouse-gas induced warming (Kutzbach *et al.*, 2005). An increase in precipitation is certainly a factor in the most recent increases in the inferred depth of our lakes. However, warming air temperatures can also be associated with a warmer epilimnion in lakes which can lead to increased stratification (Schindler *et al.*, 1996), conditions that would favour the small planktonic *Discostella* (formerly *Cyclotella*) taxa (Rühland *et al.*, 2008), the dominant planktonic diatoms in all of our lakes (Fig. S1, Table S3). In three of our lakes (Meekin, ELA L442, Gall), the percentages of *Discostella* taxa are at their highest during the last 100 years of the 2000-year records. Thus the magnitude of the inferred highs of these lakes was likely amplified, in part, by increased stratification. Nonetheless, this does not negate the fact that all lakes show a similar increasing trend in inferred depth over the last 100 years, even though the degree of change may be a result from complex interaction of climatic influences on the physical properties of lakes. In Meekin Lake, there were also concurrent small increases (~2%) in two other planktonic taxa, *Asterionella formosa* and *Fragilaria nanana* (Laird *et al.*, 2011), which may imply either increased nutrients in the metalimnion (Ruhland *et al.*, 2010) or increased stratification (Longhi & Beisner, 2009). Although nutrients could potentially be a confounding influence on our inferred water-depth changes, we found that even in our moderate nutrient status lakes (Meekin and Gall, ~10-12 µg/L total phosphorus, TP) that the assemblages were dominated by oligotrophic taxa (including planktonic *Discostella*), with only small percentages of more mesotrophic taxa, and the assemblages had a similar distribution with changes in lake depth in all other lakes studied (Kingsbury *et al.*, 2012). Gall Lake has the highest TP levels (~12 µg/L) of our study lakes, but the percent abundance of more mesotrophic taxa, such as *A. formosa* has changed little over the past 2000 years and never exceeded 10% of the assemblage (Haig, 2011), suggesting nutrient status in this lake has not

changed substantially over this time period. Potential multiple stressors on lakes from anthropogenic influences again highlights the necessity of a regional network of sites to help decipher intrinsic factors from external forcings.

Application of this approach to other regions

Regional networks of proxy lake records provide a means of distinguishing climate driven signals from more local influences. Our approach of utilizing near-shore sediments, as a sensitive method to track changes in diatom assemblages near the benthic to planktonic (B:P) boundary, led to the documentation of an arid MCA across the WRDB in northwest Ontario, providing convincing evidence on the northward spatial extent of this megadrought. The ability to develop robust diatom-inferred depth models across many lakes and a well-defined B:P boundary, makes this approach potentially applicable to regions dominated by drainage lakes. Consequently, this approach can provide a method to estimate changes in effective moisture in comparison to conditions today, in more humid regions where such data have been extremely difficult to acquire.

Tracking changes in diatom assemblages near the B:P diatom boundary in lake sediment cores provides a means of retrieving a drought signal from dilute lakes with outlets; however, this approach is most appropriate in small lakes (< 100-200 ha) with a gently sloping bottom that has sufficient near-shore sediment accumulation. The location of the core near the present-day depth of the B:P diatom boundary (Fig. 3) makes this technique especially sensitive to detecting even low-intensity droughts (Laird *et al.*, 2011), but needs to be based on a high-resolution (~1 m) calibration of diatom assemblages in surface sediments across a water-depth gradient in each study lake (Kingsbury *et al.*, 2012). Although lower sedimentation rates are generally associated with near-shore cores, comparison across lakes is still realistic at multi-decadal to centennial scales. Given these caveats, this approach can provide a powerful means to reconstruct climate where more traditional paleolimnological methods based on a central core from drainage lakes are inadequate (Battarbee, 2000).

Future implications

Empirical evidence for the penetration of the MCA drought into northwest Ontario, fills a geographical gap

that climate models can strive to mimic for a better mechanistic understanding of the spatial pattern of the MCA. The models must now be able to simulate this expanded region of drought if they are to be considered useful in understanding how the MCA came to be. This is especially important for high spatial resolution (4-12 km), regional climate models. Current increasing trends in precipitation in northwest Ontario suggest that water scarcity may not be an issue in the near future. However, if the concurrent increasing trends in temperature continue, this could result in declines of overall effective moisture. If trends in effective moisture were to decrease, this could lead to the return of aridity, resulting in significant declines in hydropower generation, and other environmental and socioeconomic impacts.

Expanding our knowledge of the spatial extent and severity of past megadroughts provides plausible scenarios for water-resource management and societal impacts. Past megadroughtshave been implicated in the decline, abandonment and collapse of societies. The collapse of the classic Maya in Mexico and the Tiwanaku in the Bolivian-Peruvian altiplano was coincident with prolonged drought (deMonocal, 2001). Large population declines and abandonment of Puebloan and Cahokia settlements in North America occurred during the megadroughts of the MCA (Cook *et al*., 2007). Recent tree-ring records in Asia suggest that drought may also have contributed to the fall of the Ming Dynasty (Cook *et al*., 2010a). What the future climate may hold for regions of North America due to global warming is unclear, but a return to the aridity of the MCA would have significant ecological, environmental and social impacts to this region.

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Supporting information legends

Figure S1. Percentage of planktonic diatoms in the cores retrieved from the six study lakes. The thick dashed horizontal lines represent the highest significant splits based on species composition (Bennett, 1996). The dotted horizontal lines are splits of lower significance, but which generally highlight the distinct species composition of the Medieval Climatic Anomaly (MCA). The MCA signal for each of the study lakes (highlighted) occurs within the general MCA time period of c. 900-1400 CE (Seager *et al*., 2007; Trouet *et al*., 2009; Graham *et al*., 2011). A list of the dominant and sub-dominant planktonic taxa for each lake are provided in Table S3.

Figure S2. Percentage of benthic diatoms in the cores retrieved from the six study lakes. The thick dashed horizontal lines represent the highest significant splits based on species composition (Bennett, 1996). The dotted horizontal lines are splits of lower significance, but which generally highlight the distinct species

composition of the Medieval Climatic Anomaly (MCA). The MCA signal for each of the study lakes (highlighted) occurs within the general MCA time period of c. 900-1400 CE (Seager *et al*., 2007; Trouet *et al*., 2009; Graham *et al*., 2011). A list of the dominant and sub-dominant benthic taxa for each lake are provided in Table S4.

Table S1. Summary of some physical and chemical characteristics for each of the study lakes.

Table S2. Results of AMS radiocarbon dates processed at the Center for AMS at Lawrence Livermore National Laboratory). All dates are based on pollen isolated from sediment samples processed at LacCore in the Limnological Research Center in Minneapolis, MN. All ^{14}C dates were calibrated to Calendar Years (Cal yr) CE, with the midpoint of the 2-sigma range used for the age model.

Table S3. List of dominant and sub-dominant planktonic diatom taxa for each of the six lakes.

Table S4. List of dominant and sub-dominant benthic diatom taxa for each of the six lakes.

Tables

Table 1. Correlations between temperature (in ***bold italics***) of the years in common between the different climate stations, and annual precipitation (regular font) in northwest Ontario.

	Winnipeg	Kenora	Dryden	Sioux LO
Winnipeg	1.0	***0.92***	***0.89***	***0.89***
Kenora	0.59	1.0	***0.95***	***0.96***
Dryden	0.51	0.58	1.0	***0.97***
Sioux LO	0.56	0.62	0.69	1.0

Figure legends

Figure 1. Location of the study lakes (black dots) and climate stations (black stars) within the Winnipeg River Drainage Basin (WRDB). Sub-basins within the WRDB are outlined. Study sites are numbered: 1) Meekin Lake, 2) Dixie Lake, 3) ELA Lake 442, 4) ELA Lake 239, 5) Little Raleigh Lake and 6) Gall Lake.

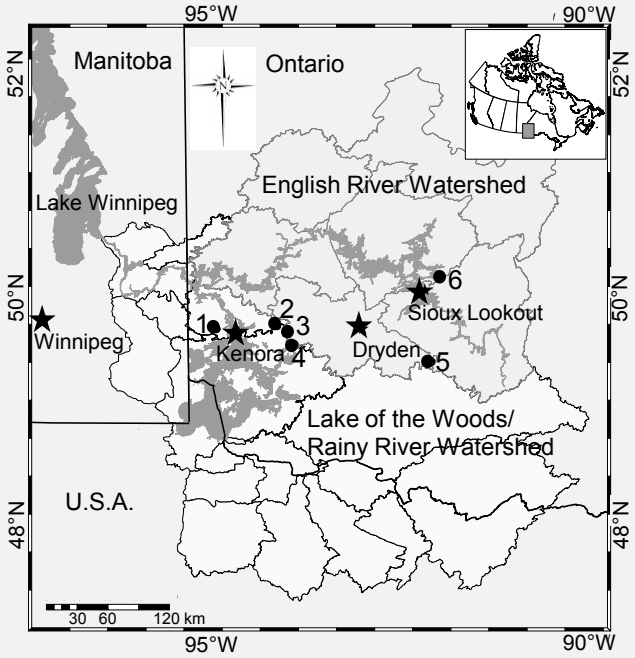
Figure 2. Precipitation (a) from 1915 to 2009 and temperature records (b) from 1915 to 2010 for Winnipeg, Manitoba and climate stations closest to our study sites in Ontario: Kenora, Dryden and Sioux Lookout. The dashed line indicates the mean of the record. The solid line indicates the linear trend, with p-values indicated for those records with significant trends. The 1930s, 1950s and 1980s are highlighted for ease of comparison. All data are from the Adjusted and Homogenized Canadian Climate Data archive (http://ec.gc.ca/dccha-ahccd). The Winnipeg and Dryden records from this dataset only extended to 2006 and 2003, respectively.

Figure 3. Schematic of the sensitivity of core location for tracking the movement of lake depth associated with the benthic:planktonic (B:P) diatom boundary under different climate scenarios: (a) wetter conditions, precipitation (P) > evaporation (E); and (b) more arid conditions, P < E. The solid lines indicate the present-day B:P boundary, the dotted lines indicate the direction of movement of the B:P boundary. Under climate scenario (a) as lake level rises, the B:P boundary moves toward shore. Under climate scenario (b) as lake-level declines, the B:P boundary moves toward the deeper center areas. Figure is modified from Laird *et al*., 2011.

Figure 4. Age models for the six study lakes based on a composite of ^{210}Pb dates (solid squares) from gravity core samples and ^{14}C dates (open squares) based on concentrated pollen from piston core samples (Table S1). The shaded open square represents the anchor point between the ^{210}Pb and ^{14}C analyses. A simple linear model was used between the dates, with the exception of Gall Lake where the ^{14}C dates were not as consistent with a simple model (Haig, 2011); the dashed line indicates the age

model used in this case. The star in Dixie Lake profile indicates a macrofossil date that helped confirm the validity of the pollen-derived dates.

Figure 5. Diatom-inferred (D-I) depth relative to the depth of coring for the six study lakes based on their individual lake calibration models (Laird *et al*., 2011) and plotted according to the calibrated age models. All cores were retrieved ~1-2 m deeper than the present-day near-shore B:P diatom boundary between primarily benthic taxa and primarily planktonic taxa, and thus changes in the diatom assemblages track the movement of this climatically-sensitive region (Laird *et al*., 2011). The thick dashed horizontal lines represent the highest significant splits based on species composition (Bennett, 1996). The solid vertical lines indicate the average D-I depth of these major zones. The dotted horizontal lines are splits of lower significance, but which generally highlight the distinct diatom species assemblages of the Medieval Climatic Anomaly (MCA). The MCA signal for each of the study lakes (highlighted) occurs within the general MCA time period of c. 900-1400 CE (Seager *et al*., 2007; Trouet *et al*., 2009; Graham *et al*., 2011), shown at right. In four of the lakes, the D-I depths during the MCA are the lowest of the past two millennia, whereas in ELA lakes 239 (Laird & Cumming, 2009) and 442 the MCA inferred depths are lows within a generally higher stand.


95°W
90°W
52°N
50°N
48°N
Manitoba
Ontario
Lake Winnipeg
English River Watershed
Winnipeg
Kenora
Dryden
Sioux Lookout
1
2
3
4
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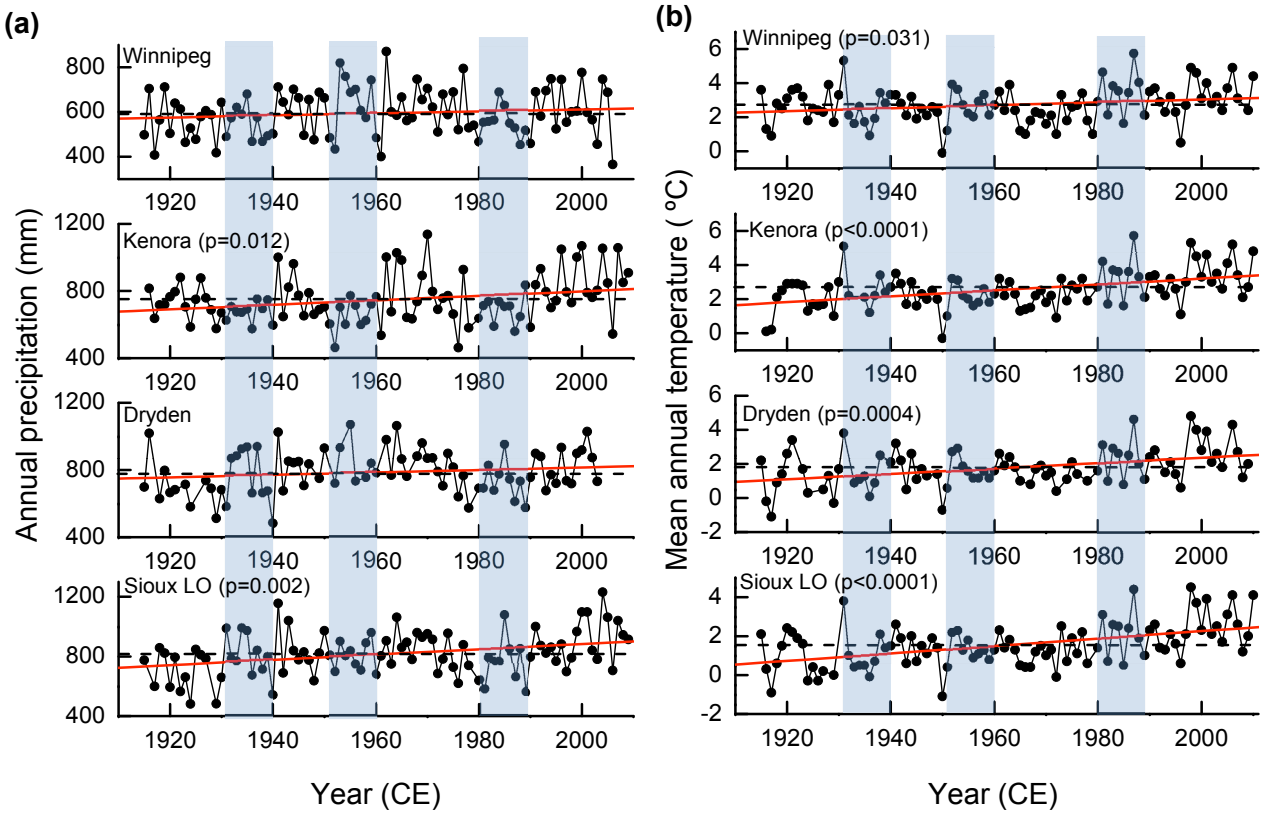
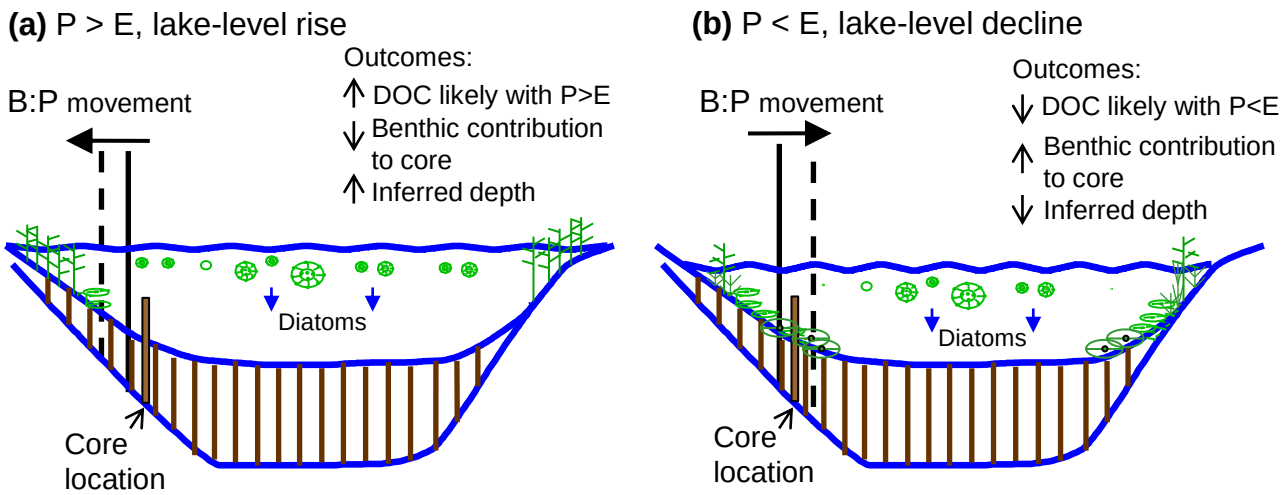
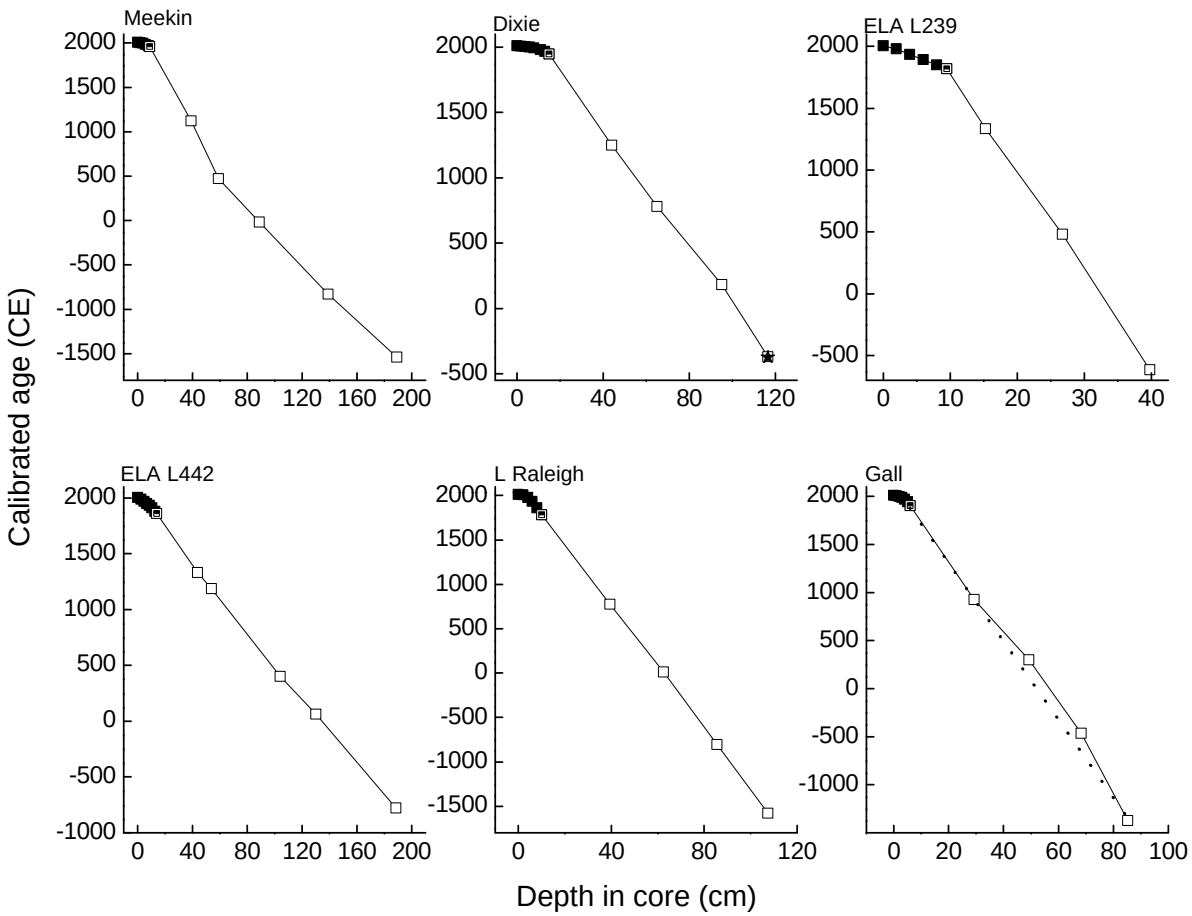
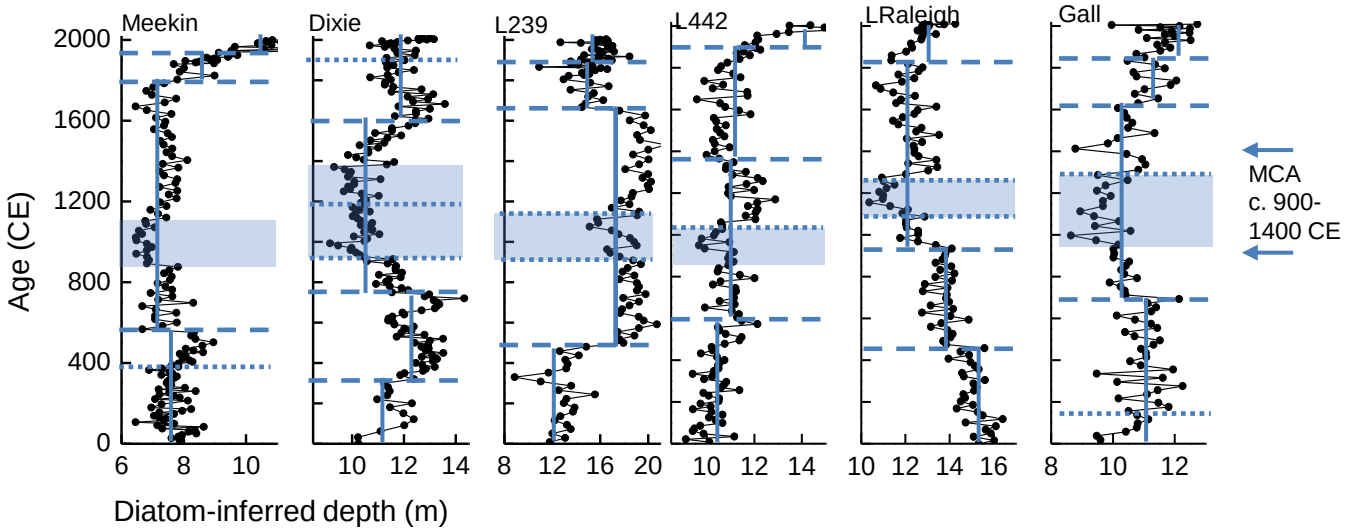
Lake of the Woods/
Rainy River Watershed
U.S.A.
30 60 120 km


(a)
Winnipeg
Kenora (p=0.012)
Dryden
Sioux LO (p=0.002)
Annual precipitation (mm)
Year (CE)
(b)
Winnipeg (p=0.031)
Kenora (p<0.0001)
Dryden (p=0.0004)
Sioux LO (p<0.0001)
Mean annual temperature (°C)
Year (CE)


(a) P > E, lake-level rise
B:P movement
Outcomes:
DOC likely with P>E
Benthic contribution to core
Inferred depth
Diatoms
Core location
(b) P < E, lake-level decline
B:P movement
Outcomes:
DOC likely with P<E
Benthic contribution to core
Inferred depth
Diatoms
Core location


Meekin
Dixie
ELA L239
ELA L442
L Raleigh
Gall
Calibrated age (CE)
Depth in core (cm)


Meekin
Dixie
L239
L442
LRaleigh
Gall
Age (CE)
2000
1600
1200
800
400
0
6 8 10
10 12 14
8 12 16 20
10 12 14
10 12 14 16
8 10 12
Diatom-inferred depth (m)
MCA
c. 900-
1400 CE