Hydroclimate-primary production decoupling in a small, lake, Central Canada, over the last 900 years

Doyle, R.M; Liu, Z.; Walker, J.T.; Hladyniuk, R.; Moser, K.A.; and Longstaffe, F.J.

The University of Western Ontario (Canada)

A presentation for EGU 2020

Summary of abstract

1. Climate warming is expected to alter moisture regimes in temperate areas like southern Ontario, Canada, resulting in drier summers and wetter winters. Although it is understood that changes in moisture affect primary production, the exact links between these variables remain uncertain.

2. This study uses stable isotope science to elucidate connections between changes in effective moisture (the net of water inputs versus evaporative loss) and algal production in Barry Lake, a small kettle lake in Ontario, Canada.

3. During the Medieval Climate Anomaly (AD 1100-1300), effective moisture was lower than at present while, during the Little Ice Age (AD 1450- 1850), effective moisture was higher than at present. Our interpretation of effective moisture at Barry Lake is comparable with many, but not all, hydroclimatic records across the Great Lakes/St. Lawrence and northeastern USA region.

5. Despite changes in effective moisture, primary production remained relatively stable until AD 1850. This time period coincides with the intensification of European agriculture in the catchment.

Barry Lake (44°18’28”N, 77°55’17”W) is a small, dimictic kettle lake located in southeastern Ontario, Canada, 32 km east of Peterborough, Ontario, and 40 km north of Lake Ontario (Fig. 1). The main water body is surrounded by wetland with some forest, and adjacent to this is farmland.

The lake has two ephemeral inflows, probably derived from groundwater springs, and three ephemeral outflows. The area is characterized by hot, humid summers and cool, drier winters.

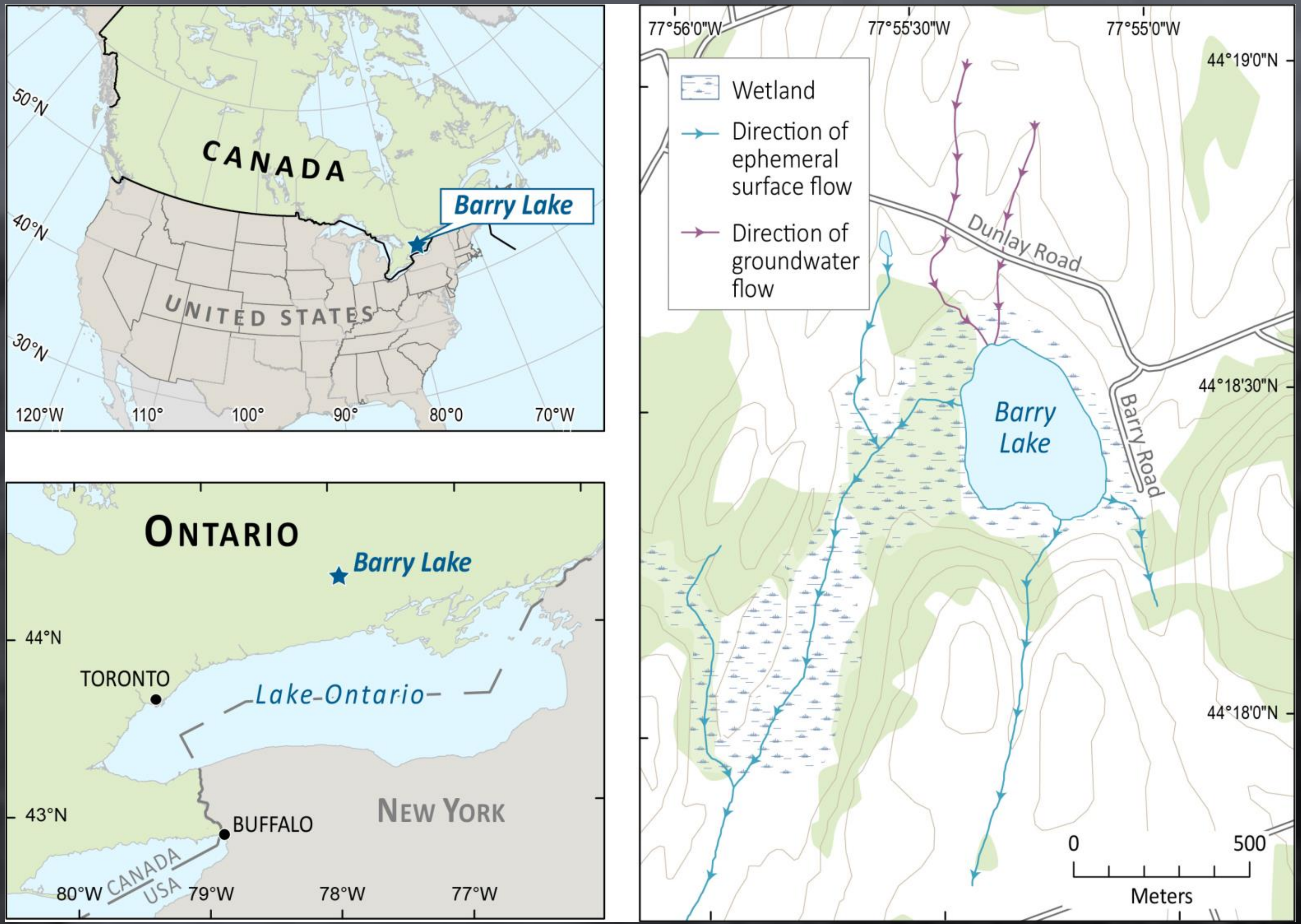


Figure 1. Maps of Barry Lake. (A) Location of Barry Lake within North America. (B) Location of Barry Lake and other well-studied lakes in southern Ontario. (C) Local hydrology in the vicinity of Barry Lake. The direction of surface flows are indicated by blue arrows, whereas the direction of groundwater is indicated by purple arrows.

We established two age-depth models using ^{210}Pb and ^{14}C dating (Fig. 2). ^{210}Pb dates came from core BL-G11-01 while ^{14}C dates originated from core BL-G17-01. The cores were correlated so that depths from one core could be transferred to the other core.

In the sections of sediment dated using ^{210}Pb dating, proxy results from the two cores are very similar. In the sections of sediment dated using ^{14}C dating, however, proxy results sometimes disagree between the two cores.

At times when proxy results from these two cores disagree, emphasis is placed on BL-G17-01 since the ^{14}C dates originated from this core.

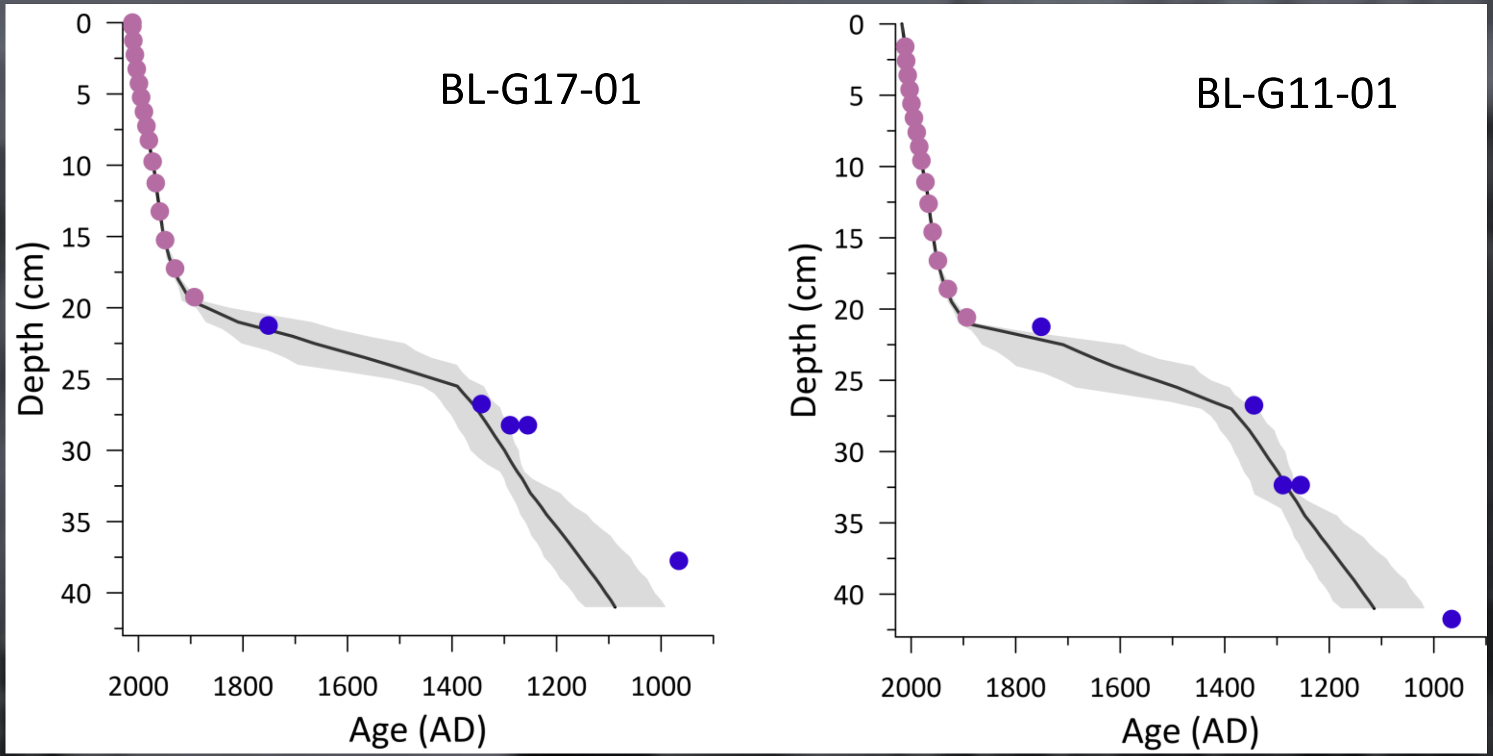


Figure 2. Age-depth model for BL-G17-01 (left) and BL-G11-01 (right) generated using the R package "Bacon". Filled purple circles represent ages obtained using ^{210}Pb dating whereas filled blue circles represent ^{14}C dates. Grey shading indicates the overall error associated with the age-depth model

Similarities between $\delta^{18}O_{marl}$ and records of hydroclimate offer evidence that $\delta^{18}O_{marl}$ is tracking effective moisture (Fig. 3).

The $\delta^{18}O_{marl}$ record from Barry Lake corresponds well with records of local July temperature and precipitation amounts, which provide an accurate measure of aridity during the summer months (Harris et al., 2014), and with the North American Drought Atlas (Cook et al., 2009), a measure of aridity (Fig. 3).

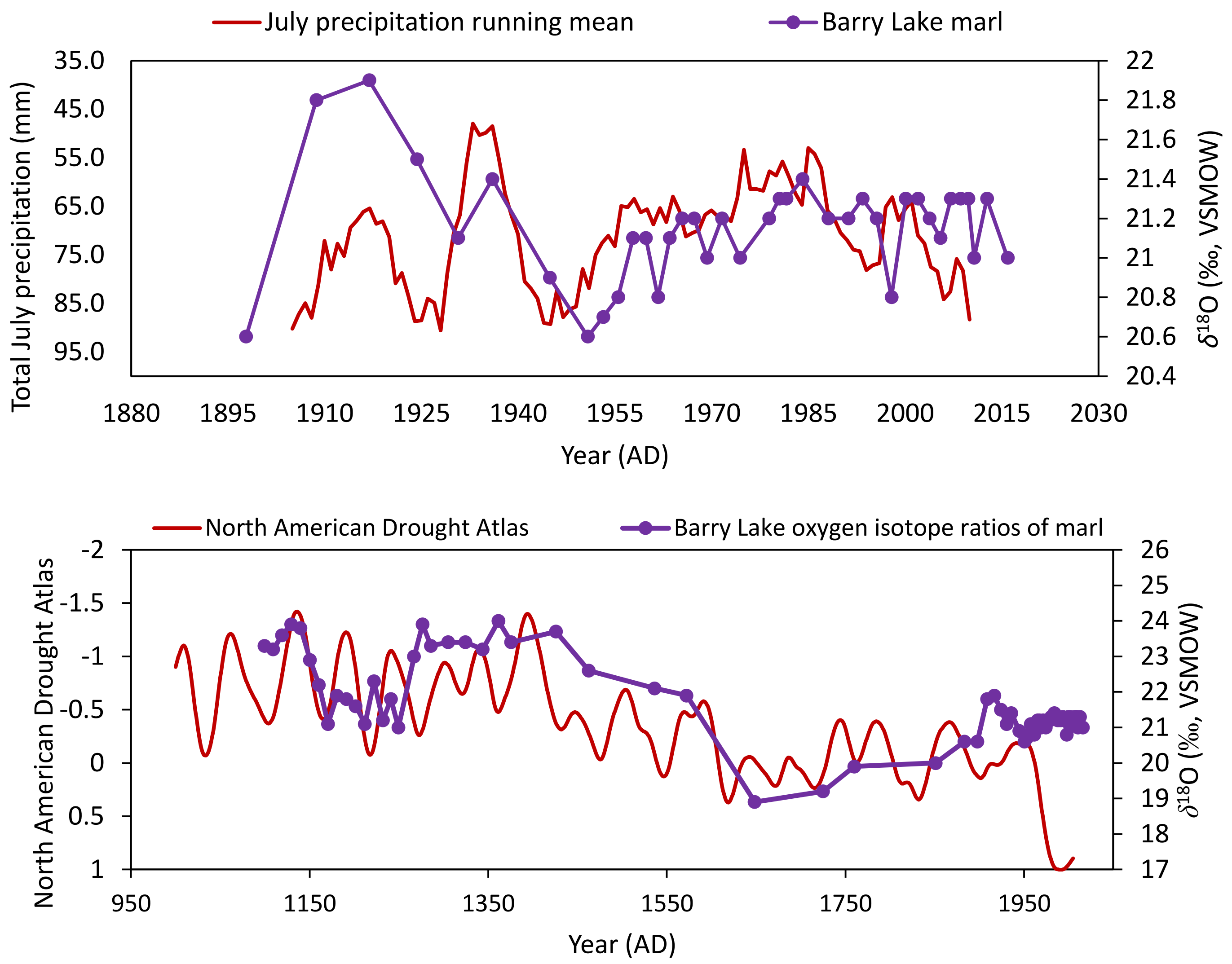


Figure 3. Comparisons of $\delta^{18}O_{marl}$ with instrumental July precipitation (top) and the North American Drought Atlas (bottom) over time.

Figure 4 (below) shows variations in proxies measured in BL-G11-01 and BL-G17-01 across time.

= wet periods

= arid periods

= core BL-G11-01

= core BL-G17-01

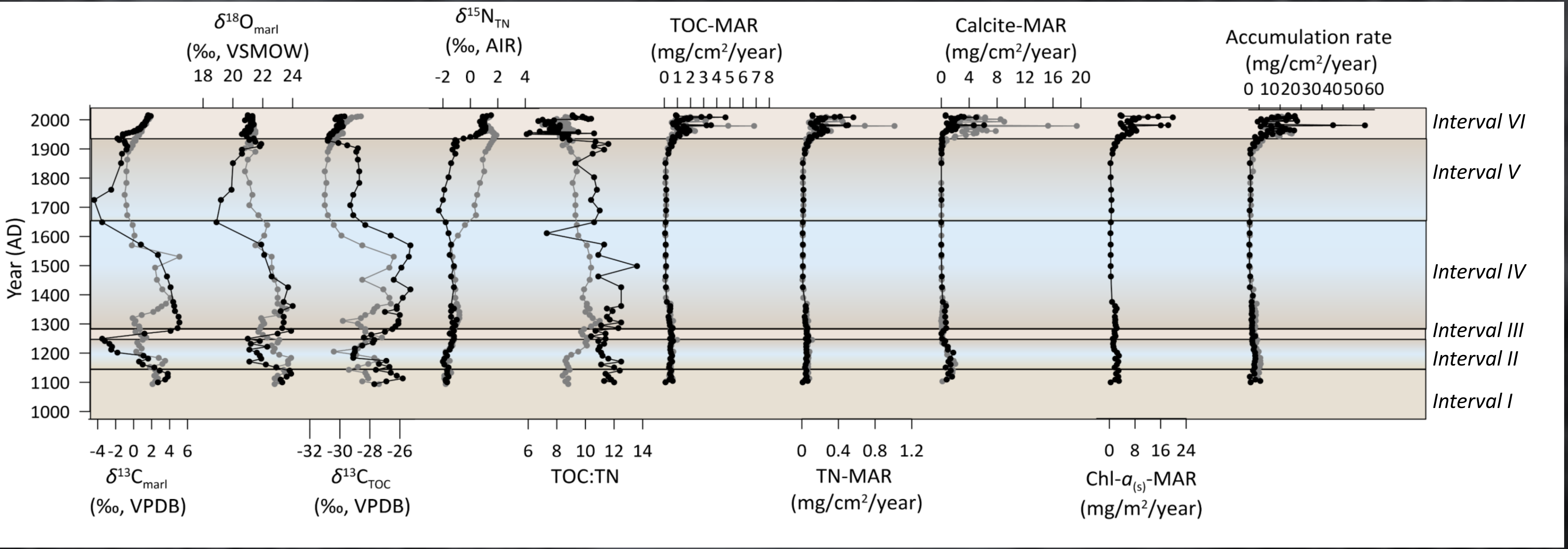
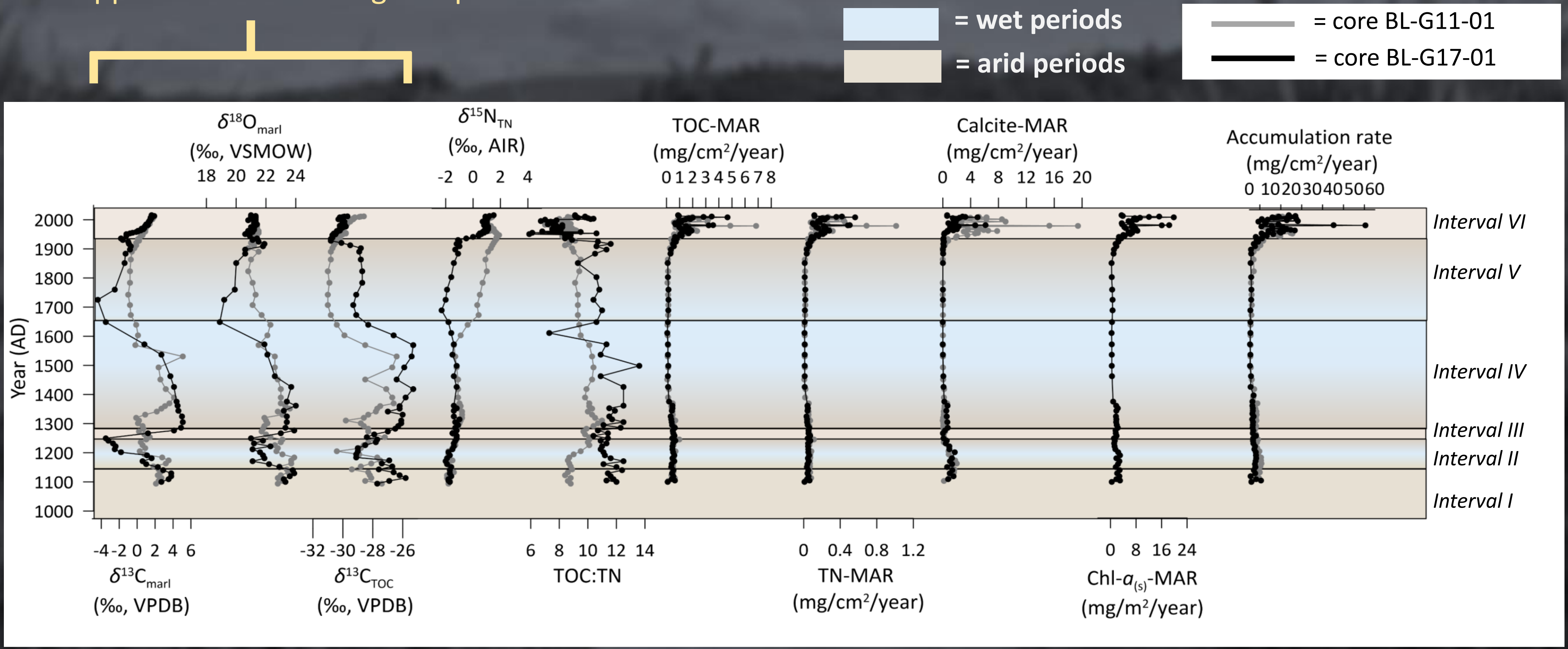
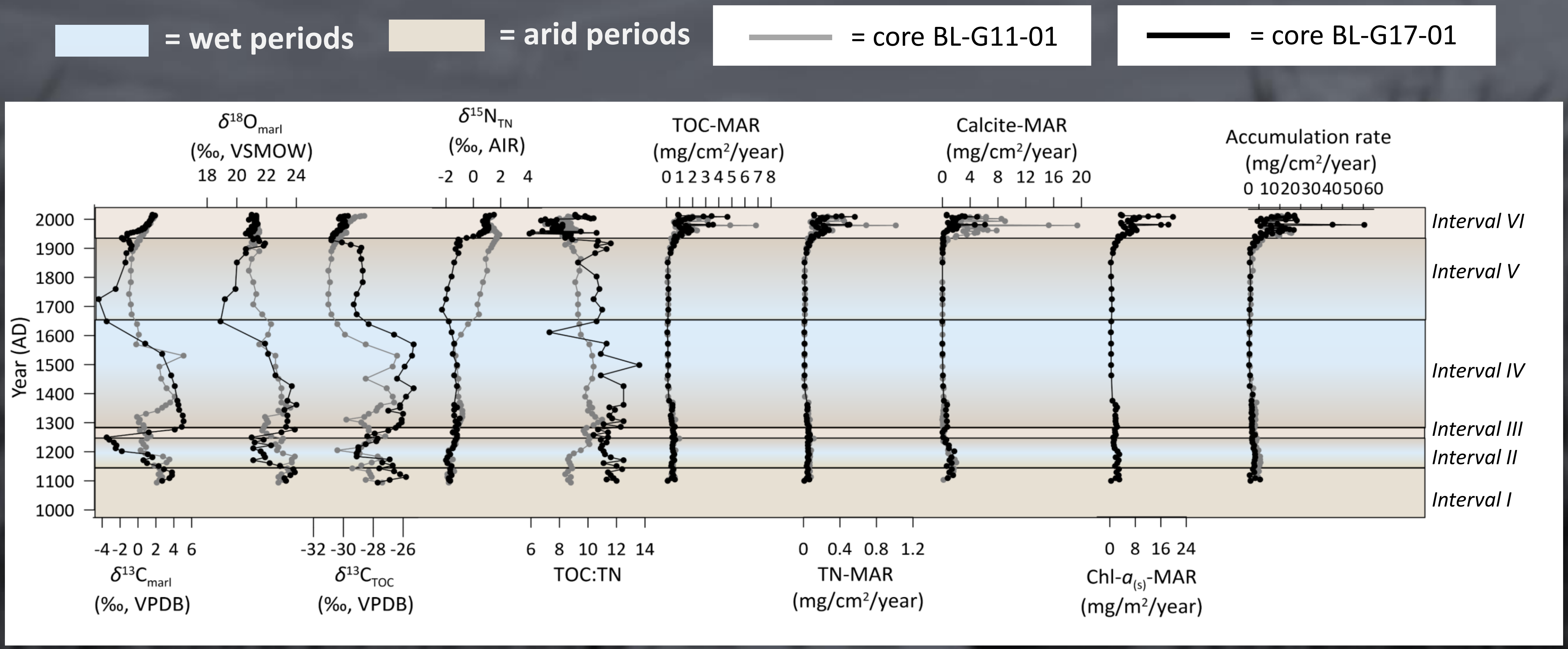


Figure 4. Age-dependent variation in climate proxies for cores BL-G11-01 (grey) and BL-G17-01 (black). The paleoclimatic record is subdivided into intervals (right) based on major shifts in δ^{18}Omarl. Brown shading indicates a warmer- and drier-than-average period (defined by above-average $\delta^{18}O_{marl}$), whereas blue shading denotes a cooler- and wetter-than-average period (defined by below-average $\delta^{18}O_{marl}$). After AD 1850, the $\delta^{13}C_{TOC}$ and $\delta^{13}C_{marl}$ record have been corrected for the Suess Effect, following Verburg (2007).

Like $\delta^{18}O_{marl}$, $\delta^{13}C_{marl}$ and $\delta^{13}C_{TOC}$ are tracking effective moisture. Increased aridity results in more evaporation, which causes dissolved inorganic carbon (DIC) to become enriched in ^{13}C, thereby increasing $\delta^{13}C_{marl}$ and $\delta^{13}C_{TOC}$. The opposite occurs during wet periods.



Mass accumulation rates of total organic carbon (TOC-MAR), total nitrogen (TN-MAR), calcite (calcite-MAR) and sedimentary chlorophyll-*a* (Chl-$a_{(s)}$-MAR) are indicators of primary production in this system.



Key messages:

1. Primary production was relatively constant until AD 1850 when it began to slowly rise. Primary production further accelerated around AD ~1915. This increase could be the result of European agriculture, anthropogenic climate change or a combination of both factors.
2. Trends in effective moisture do not correspond with variations in primary production, so it is unlikely that shifts in effective moisture are driving primary production in Barry Lake.

A regional view of hydroclimate across the last ~900 years

- A comparison of hydroclimatic records from across the region (Fig. 5) demonstrates that many sites were indeed drier-than-average during the MCA and modern period, and wetter-than-average during the LIA. Not all sites responded in this fashion, however. Of note is that hydroclimate was more heterogeneous during the MCA and modern periods than during the LIA.
- The fact that hydroclimate was heterogeneous during the MCA and modern periods is to be expected since the factors governing moisture are complex and often produce microclimates (Ljungqvist et al., 2020; Shinker, 2010).
- We speculate that the position of the polar jet stream, a key driver of effective moisture in the Great Lakes region, influenced this relatively uniform increase in effective moisture during the LIA. The polar jet stream, currently located at a mean latitude of ~41.8 °N, has occupied higher latitudes in the past (Kirby et al., 2002). It is therefore possible that the polar jet stream did not intersect the region during the LIA, resulting in more uniform delivery of moisture to the sites shown in Figure 8. In contrast, the polar jet stream’s intersection of the region during the MCA and modern periods would cause moisture availability to differ between the western and the eastern halves of the region.

Figure 5. A regional view of hydroclimate across the MCA (AD 1000-1350), LIA (AD 1450-1850) and the modern period (AD 1850-present). The sites shown here were (*i*) located between 40-55 °N and 60-100 °W and (*ii*) available from the National Oceanic and Atmospheric Administration (NOAA) paleoclimate database (https://www.ncdc.noaa.gov/paleo-search/). Data obtained from bogs were detrended using a 1000-year LOESS smooth to account for bog growth (Clifford & Booth, 2013). All records were averaged into three bins: AD 1000-1350, AD 1450-1850 and AD 1850-2005 and converted into z-scores. Shades of blue denote wetter-than-average conditions while shades of orange indicate more arid-than-average conditions. NWO stands for "northwestern Ontario". A full list of references is provided in Table 1.

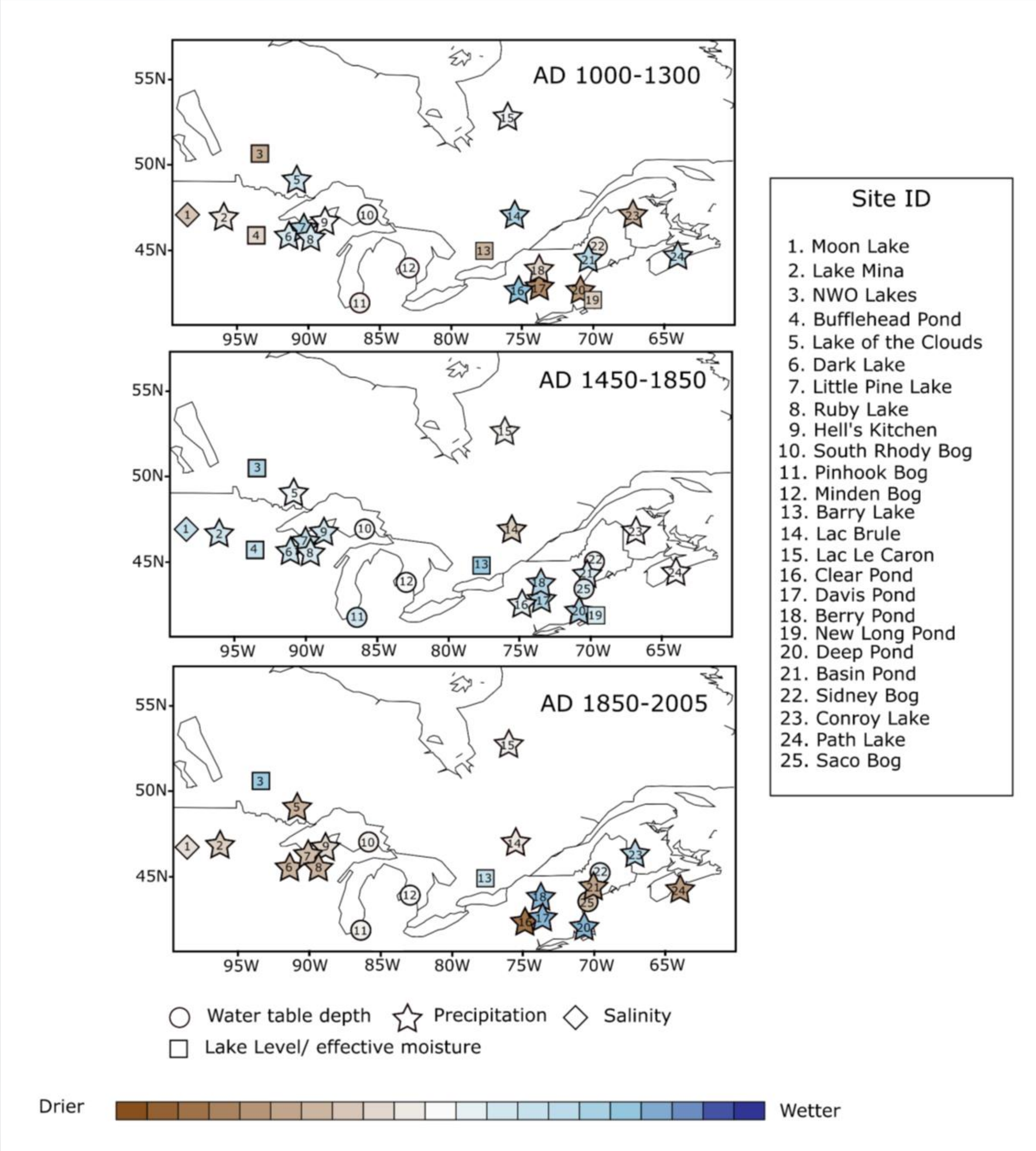


Table 1. A summary of data used to generate Figure 5. The sites shown here were (*i*) located between 40-55 °N and 60-100 °W and (*ii*) available from the National Oceanic and Atmospheric Administration (NOAA) paleoclimate database (https://www.ncdc.noaa.gov/paleo-search/).

Site ID	Main proxy used	Inferred variable	Source
1. Moon Lake	Diatom assemblages	Salinity	Laird et al., 2003
2. Lake Mina	Pollen assemblages	Effective moisture	St. Jacques et al., 2008
3. Northwestern Ontario (NWO)	Diatom assemblages	Lake level	Laird et al., 2012
4. Bufflehead Pond	Ground penetrating radar (GPR)	Lake level	Shuman et al., 2009
5. Lake of the Clouds	Pollen assemblages	Precipitation	Gajewski, 1987
6. Dark Lake	Pollen assemblages	Precipitation	Gajewski, 1987
7. Lake of the Clouds	Pollen assemblages	Precipitation	Gajewski, 1987
8. Ruby Lake	Pollen assemblages	Precipitation	Gajewski, 1987
9. Hell's Kitchen	Pollen assemblages	Precipitation	Gajewski, 1987
10. South Rhody Bog	Testate amoeba assemblages	Water table depth	Booth et al., 2012
11. Pinhook Bog	Testate amoeba assemblages	Water table depth	Booth et al., 2012
12. Minden Bog	Testate amoeba assemblages	Water table depth	Booth et al., 2012
13. Barry Lake	Oxygen isotope ratios of marl	Effective moisture/lake level	This study
14. Lac Brule	Pollen assemblages	Precipitation	Lafontaine-Boyer & Gajewski, 2014
15. Lac Le Caron	Testate amoeba assemblages	Water table depth	Loisel & Garneau, 2010
16. Clear Pond	Pollen assemblages	Precipitation	Gajewski, 1988
17. Davis Pond	Ground penetrating radar (GPR)	Effective moisture/lake level	Newby et al., 2011
18. Berry Pond	Pollen assemblages	Precipitation	Whitehead, 1979
19. New Long Pond	Ground penetrating radar (GPR)	Effective moisture/lake level	Newby et al., 2009
20. Deep Pond	Ground penetrating radar (GPR)	Effective moisture/lake level	Marsicek et al., 2013
21. Basin Pond	Pollen assemblages	Precipitation	Gajewski, 1988
22. Sidney Bog	Testate amoeba assemblages	Water table depth	Clifford & Booth, 2013
23. Conroy Lake	Pollen assemblages	Precipitation	Gajewski, 1987
24. Path Lake	Pollen assemblages	Precipitation	Neil et al., 2014
25. Saco Bog	Testate amoeba assemblages	Water table depth	Clifford & Booth, 2013

1. The Barry Lake hydroclimate record shows remarkable similarities with site 3 (Northwestern Ontario Lakes) and site 25 (Saco Bog) shown in figures 5 and 6.

2. Each of these records record drier-than-average conditions during the Medieval Climate Anomaly (AD 1000- 1350) and cooler-than-average conditions during the Little Ice Age (AD 1450-1850)

3. The fact that variations in $\delta^{18}O_{marl}$ from Barry Lake correspond with these other two hydroclimatic records suggests that the changes in effective moisture observed at Barry Lake are not simply a reflection of local hydrologic variations but are recording regional variations in atmospheric moisture.

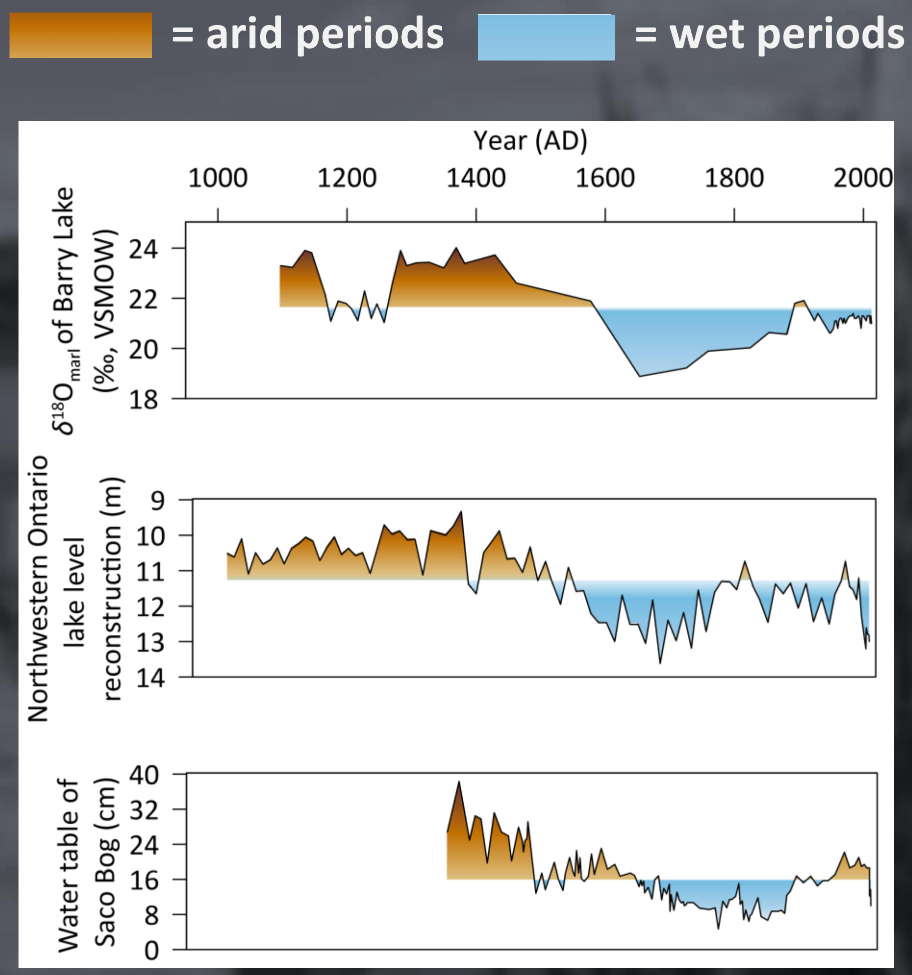


Figure 6. A comparison of (top) the $\delta^{18}O_{marl}$ record from BL-G17-01, (middle) a diatom-based reconstruction of lake level from lakes in northwestern Ontario (Site 3 in Figure 5; Laird et al., 2012) and (bottom) a reconstructed water table record from Saco Bog, Maine (Site 25 in Figure 5), derived from testate amoebas (Clifford & Booth, 2013). Drier-than-average values are depicted in orange while wetter-than-average values are coloured blue.

Conclusions

- Effective moisture at Barry Lake, southeastern Ontario, Canada, inferred mainly from $\delta^{18}O_{marl}$, has changed substantially over the past ~900 years, with more arid conditions during the Medieval Climate Anomaly and wetter conditions during the Little Ice Age.
- The Barry Lake $\delta^{18}O_{marl}$ record is similar to other proxy records of lake level from northwestern Ontario, Canada (diatoms) and water table depths from Saco Bog, Maine, USA (testate amoebae), but different from hydroclimatic records at other sites, particularly during the MCA and modern period (AD 1850-2017). These comparisons indicate that hydroclimate has been more heterogeneous across the Great Lakes/St. Lawrence and northeastern USA during arid periods than during wetter periods, likely due to variations in the position of the polar jet stream.
- Effective moisture, as inferred from the Barry Lake record, remains within the range of natural variation observed over the last ~900 years. Inferences of primary production in the last 150 years are greater than the range of natural variation observed over the last ~900 years, despite only small changes in effective moisture since 1850.
- Therefore, shifts in effective moisture are unlikely to drive increases in primary production in small, dimictic lakes such as Barry Lake. Instead, the driver of the recent increase in primary production is likely related to ACW and/or land-use changes.

Acknowledgements

- George Archer and family
- PEARL Lab at Queen's University for help with measuring Chl-$a_{(s)}$
- Laboratory for Stable Isotope Science (LSIS)
- Lake and Reservoir Systems Research Facility (LARS)
- Field Assistance: Amanda Philavong, Maria Sia, Carolyn Hill
- Karen Vankerkoerle for assistance with figures.
- Financial support: NSERC Discovery Grant (FJL), Canada Research Chair Program (FJL), Canada Foundation for Innovation (FJL), Ontario Research Fund (FJL), NSERC Discovery Accelerator Grant (FJL), NSERC Canada Graduate Scholarship: Doctoral (RMD)

Western LARS Research Facility

LABORATORY for STABLE ISOTOPE SCIENCE

Ontario Research Fund

NSERC CRSNG

Western UNIVERSITY · CANADA

References (A-M)

Booth, R.K., Jackson, S.T., Sousa, V.A., Sullivan, M.E., Minckley, T.A., Clifford, M.J., 2012. Multi-decadal drought and amplified moisture variability drove rapid forest community change in a humid region. Ecology 93, 219–226.

Clifford, M.J., Booth, R.K., 2013. Increased probability of fire during late Holocene droughts in northern New England. Clim. Change. 119, 693–704.

Cook, E.R., Seager, R., Heim, R.R., Vose, R.S., Herweijer, C., Woodhouse, C., 2009. Megadroughts in North America: placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context. J. Quat. Sci. 25, 48–61.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.H., Stahle, D.W., 2004. Long-term aridity changes in the western United States. Science. 306, 1015–1018.

Gajewski, K., 1988. Late Holocene climate changes in eastern North America estimated from pollen data. Quat. Res. 29, 255–262.

Gajewksi, K., 1987. Climatic impacts on the vegetation of eastern North America during the past 2000 years. Quat. Sci. Rev. 68, 179–190.

Harris, D., Horwath, W. R., VanKessel, C., 2001. Acid fumigation of soils to total organic carbon. Soil Soc. Am. J. 65, 1853–1856.

Kirby, M., Patterson, W., Mullins, H., Burnett, A., 2002. Post-Younger Dryas climate interval linked to circumpolar vortex variability: Isotopic evidence from Fayetteville Green Lake, New York. Clim. Dyn. 19, 321–330.

Lafontaine-Boyer, K., Gajewski, K., 2014. Vegetation dynamics in relation to late Holocene climate variability and disturbance, Outaouais, Québec, Canada. Holocene 24, 1515- 1526.

Laird, K.R., Fritz, S.C., Grimm, E.C., Mueller, P.G., 2003. Moon Lake 11,000 year diatom inferred salinity data. Papers in the Geosciences 23.

Laird, K.R., Haig, H.A., Ma, S., Kingsbury, M. V., Brown, T.A., Lewis, C.F.M., Oglesby, R.J., Cumming, B.F., 2012. Expanded spatial extent of the Medieval Climate Anomaly revealed in lake-sediment records across the boreal region in northwest Ontario. Glob. Chang. Biol. 18, 2869–2881.

Ljungqvist, F.C., Piermattei, A., Seim, A., Krusic, P.J., Büntgen, U., He, M., Kirdyanov, A. V., Luterbacher, J., Schneider, L., Seftigen, K., Stahle, D.W., Villalba, R., Yang, B., Esper, J., 2020. Ranking of tree ring based hydroclimate reconstructions of the past millennium. Quat. Sci. Rev. 230, 106074.

Loisal, J., Garneau, M., 2010. Late Holocene paleoecohydrology and carbon accumulation estimates from two boreal peat bogs in eastern Canada: Potential and limits of multi proxy archives. Palaeogeogr. Palaeoclimatol. Palaeoecol. 291, 493–533.

Marsicek, J.P., Shuman, B., Brewer, S., Foster, D.R., Oswald, W.W., 2013. Moisture and temperature changes associated with the mid-Holocene *Tsuga* decline in the northeastern United States, Quat. Sci. Rev. 80, 129–142.

References (M-Z)

Marsicek, J.P., Shuman, B., Brewer, S., Foster, D.R., Oswald, W.W., 2013. Moisture and temperature changes associated with the mid-Holocene *Tsuga* decline in the northeastern United States, Quat. Sci. Rev. 80, 129–142.

Neil, K., Gajewski, K., Betts, M., 2014. Human-ecosystem interactions in relation to Holocene environmental change in Port Joli Harbour, southwestern Nova Scotia, Canada. Quat. Res. 81, 203-212.

Newby, P.E., Shuman, B.N., Donnelly, J.P., MacDonald, D., 2011. Repeated century-scale droughts over the past 13,000 yr near the Hudson River watershed, USA. Quat. Res. 75, 523-530.

Newby, P.E., Donnelly, J.P., Shuman, B.N., MacDonald, D., 2009. Evidence of centennial-scale drought from southeastern Massachusetts during the Pleistocene/Holocene transition. Quat. Sci. Rev. 28, 1675–1692.

Schuman, B., Henderson, A.K., Plank, C., Stefanova, I., Ziegler, S.S., 2009. Woodland-to-forest transition during prolonged drought in Minnesota after ca. AD 1300. Ecology 90, 2792- 2807.

Shinker, J.J., 2010. Visualizing spatial heterogeneity of western U.S. climate variability. Earth Interact. 14, 1–15.

St. Jacques, J.M., Cumming, B.F., Smol, J.P., 2008. A 900-year pollen-inferred temperature and effective moisture record from varved Lake Mina, west central Minnesota, USA. Quat. Sci. Rev. 27, 781–796.

Verburg, P., 2007. The need to correct for the Suess effect in the application of $\delta^{13}C$ in sediment of autotrophic Lake Tanganyika, as a productivity proxy in the Anthropocene. J. Paleolimnol. 37, 591–602.

Whitehead, D.R., 1979. Late-glacial and postglacial vegetational history of the Berkshires, western Massachusetts. Quat. Res. 12, 333-357