2012

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ABSTRACT

Current models of landscape response to Holocene climate change in midcontinent North America largely reconcile Earth orbital and atmospheric climate forcing with pollen-based forest histories on the east and eolian chronologies in Great Plains grasslands on the west. However, thousands of sand dunes spread across 12,000 km^2 in eastern upper Michigan (EUM), more than 500 km east of the present forest-prairie ecotone, present a challenge to such models. We use 65 optically stimulated luminescence (OSL) ages on quartz sand deposited in silt caps (n = 8) and dunes (n = 57) to document eolian activity in EUM. Dune building was widespread ca. 10–8 ka, indicating a sharp, sustained decline in forest cover during that period. This decline was roughly coincident with hydrologic closure of the upper Great Lakes, but temporally inconsistent with most pollen-based models that imply canopy closure throughout the Holocene. Early Holocene forest openings are rarely recognized in pollen sums from EUM because faint signatures of non-arboreal pollen are largely obscured by abundant and highly mobile pine pollen. Early Holocene spikes in nonarboreal pollen are recorded in cores from small ponds, but suggest only a modest extent of forest openings. OSL dating of dune emplacement provides a direct, spatially explicit archive of greatly diminished forest cover during a very dry climate in eastern midcontinent North America ca. 10–8 ka.

INTRODUCTION

Climates of north-central North America changed rapidly after ca. 20 ka, under the combined influence of the rapid retreat of the Laurentide Ice Sheet (Dyke et al., 2003), maximum solar radiation in the Northern Hemisphere, and increased concentration of atmospheric CO_2 (Kutzbach et al., 1998). Holocene climates in the forested midwestern United States have been largely interpreted from pollen data (e.g., Webb et al., 1983; Bartlein et al., 1984). West of the forest on the Great Plains, the study of Holocene climate history has focused on deposition of sand and dust, signals of drought-driven decline in grass cover (e.g., Muhs, 1985; Mason et al., 2004; Wolfe et al., 2006), and on various paleolimnological proxies interpreted from lake sediments (Fritz, 2008). The ecotone separating the Great Plains prairie from the boreal and temperate forests to the north and east has been studied by multiple means (e.g., vegetation change, McAndrews, 1966; eolian activity, Keen and Shane, 1990).

Thousands of currently forested sand dunes scattered across ~12,000 km^2 of interior eastern upper Michigan USA (EUM; Fig. 1), more than 500 km east of the current forest-prairie ecotone, present a paradox. Forests that quickly invaded the landscape as ice retreated (Brubaker, 1975) must have later broken down across large tracts to yield sand to dunes (Wasson and Nanninga, 1986). However, pollen-based studies infer no changes in forest cover, only mid-Holocene changes in forest composition and dominance (Brubaker, 1975; Futyma, 1982; Booth et al., 2002; Delcourt et al., 2002).

The dunes of interior EUM are far remote from wave action and storm surge that have continually driven dune building in Great Lakes coastal zones during the Holocene (Olson, 1958; Anderton and Loope, 1995). Natural disturbance of the interior mixed forest (e.g., blowdown, fire, herbivory, disease) has been periodic throughout the Holocene, but the contemporary forest is well adapted to such perturbations and quickly recovers (White, 1979; Wein and MacLean, 1983; Delcourt et al., 1983). The forest's position in the eastern midcontinent has afforded adequate moisture from the Gulf of Mexico during most of its Holocene history.

METHODS

In this paper we use optically stimulated luminescence (OSL) dating to assess the timing of eolian activity across EUM. OSL ages provide an estimate of the timing of the burial of quartz sand in dunes or silt caps after their exposure to light during wind transport (Aitken, 1998). Within the North American Great Plains, OSL has been used successfully to document eolian deposition during episodic aridity (Mason et al., 2004; Miao et al., 2007). Arbogast et al. (2002) used 8 OSL ages to place the timing of eolian activity across EUM between 7 and 5 ka (3 in Fig. 2A). In Loope et al. (2010), 20 OSL ages were used to suggest that eolian activity southwest of Whitefish Point (2 in Fig. 2A) was related to the abandonment of the shore of glacial Lake Minong ca. 9 ka. The disparity between these two efforts suggests that further assessment of dune age and origin in EUM is warranted.

Given the disconnect between widespread dune building and continuous Holocene forest cover, our goal is to use OSL to assess chronology of dune building across EUM on a broad scale. An ancillary goal is to compare emplacement of scattered silt caps within the study area with timing of dune building (Mason et al., 1999; Schaetzl and Loope, 2008).

We mapped dunes using 10 m digital elevation models (DEMs; for maps, see http://seamless.usgs.gov/website/seamless/viewer.htm) and digital orthophotos and selected sampling locations across EUM (12,000 km^2) to capture potential spatial and temporal variability of dune building (Fig. 1, sites 1–65).

We obtained samples from the upper C horizon at 65 different sites at the expense of attempting vertical resolution of dune chronology at individual locations. Samples of quartz sand were collected at depths of 1–2 m in 57 dunes and from the base of 8 thin silt caps (depths of 0.1–1.0 m). These criteria resulted in dune samples deep enough to avoid surface and near-surface bioturbation (e.g., tree throw) and shallow enough to record the most recent period of dune activity. Thin silt caps were sampled as close to their bases as possible. Each

Geology, April 2012; v. 40; no. 4; p. 315–318; doi:10.1130/G32937.1; 2 figures; Data Repository item 2012082.

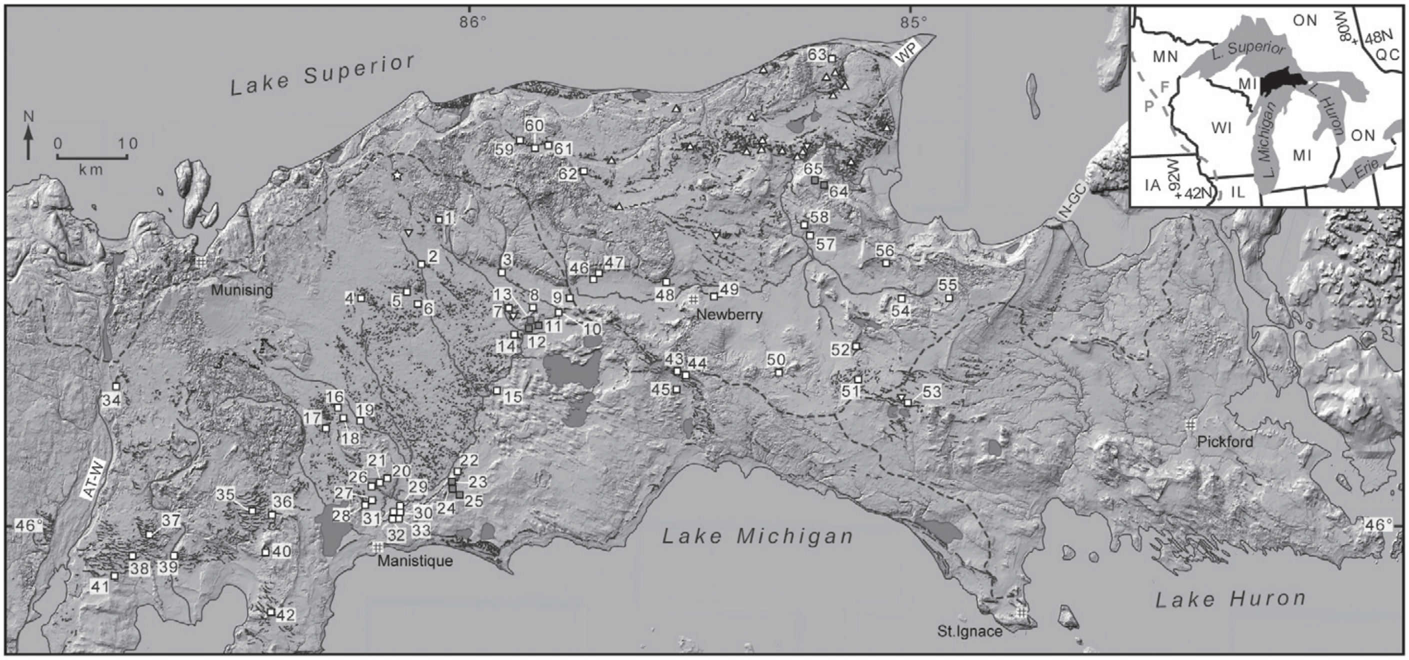


Figure 1. Hillshade (10 m) digital elevation model (DEM) of study area in eastern upper Michigan showing mapped dunes and optically stimulated luminescence sample locations from this and previous studies. Numbered white squares show dune samples from this study (n = 57); numbered gray squares show silt cap samples from this study (n = 8). White triangles show dune samples from former shore of Lake Minong (n = 20; Loope et al. 2010). Inverted white triangles show dune samples spread across eastern upper Michigan (EUM; n = 8; Arbogast et al., 2002) Watershed divides separating drainages of Lakes Superior, Huron, and Michigan are shown by dashed lines on DEM. Dashed line on locator at upper right denotes early Holocene (9 ka) prairie-forest (P, F) boundary (Webb et al., 1983). Other features referenced in text, west to east: AT-W—Au Train Whitefish Channel; WP—Whitefish Point; N-GC—Nadoway–Gros Cap Barrier.

sampling pit was photographed and stratigraphy at the sample point was briefly described.

OSL ages were determined at the Luminescence Geochronology Laboratory at the University of Nebraska-Lincoln using the single aliquot regenerative protocol (Murray and Wintle, 2000). (For details of sample collection, preparation, and treatment, see the GSA Data Repository[1].) Optical ages are reported as thousands of years before 2007 (ka; Grün, 2008).

RESULTS

Optical ages of dune samples range from 11.8 to 5.6 ka, and average 9.0 ka (±0.6 at 1σ; Fig. 2A1; Table DR1 in the Data Repository). Of 57 ages, 44 are between 10.2 and 7.8 ka (±2σ of the 9.0 ka mean), implying a sharp decline of forest cover across that time period. Most dunes are parabolic with arms open to the northwest, but composite dunes (i.e., in-line arrangement, sites 35–38 in Fig. 1; David, 1977) and low-relief dome dunes (e.g., sites 4–6) are also present. Parabolic morphology suggests effective winds from the northwest in the presence of some vegetation. Continuous forest cover and limited exposure precludes finer-scale assessment of dune morphology, sedimentary structures, and stratigraphy (e.g., David, 1977), but eolian cross-bedding was observed in or adjacent to all sampling pits. OSL age of dune samples are temporally correlated with recently discovered hydrologic closure of the upper Great Lakes ca. 9 ka (e.g., Lewis et al., 2008; Fig. 2C, sites 8–11). Mapping shows that the spatial distribution of dunes is strongly correlated with the former extent of glacial Lake Algonquin and that dunes are sourced from sandy sediments <~290 m above sea level (asl) (Table DR2; Fig. DR3). The absence of paleosols within the study area (see Arbogast et al., 2002) suggests a single period of eolian activity.

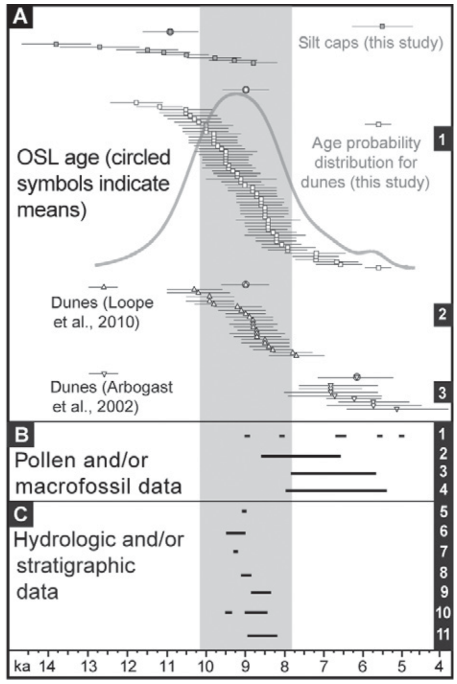
Optical ages of silt caps range from 13.8 to 8.8 ka and average 10.9 ka (±0.8 at 1σ). There are six silt caps near 245 m in the Manistique River drainage (Fig. 1, sites 11–13 and 23–25); two are above ~290 m in the Tahquamenon River drainage (Fig. 1, sites 64–65).

DISCUSSION

We interpret our dune ages as reflecting a roughly synchronous appearance of large openings within a forest matrix upwind of sample sites ca. 10–8 ka (Figs. 1 and 2A). In contrast with the episodic eolian activity documented on the Great Plains, major eolian activity in EUM appears to be restricted to a single broad time frame (Fig. 2, gray bar). Periods of heightened dune building may have occurred during the ca. 10–8 ka time frame, but these are not resolvable within errors associated with our optical dating. Disturbance agents must have continually created gaps in forests, but high effective moisture in the eastern midcontinent permitted rapid recovery during most of the Holocene (Brugam et al., 2004). Forest gaps ca. 10–8 ka must have been large and persistent enough to permit surface deflation. This breakdown of forest resilience is roughly coincident with rapid regional drying (Williams et al., 2010) that culminated with hydrologic closure of the upper Great Lakes (Lewis et al., 2008; Boyd et al., 2010; McCarthy and McAndrews, 2010; Fig. 2C, sites 8–11). Because deflation of sand is greatly restricted as vegetation cover exceeds ~40% (Wasson and Nanninga, 1986), dune age directly records time periods when ground cover was significantly reduced. The broad spatial distribution of dunes suggests that openings in forest cover were widespread. The height of dunes (up to 10 m) indicates that openings were large enough to permit saltation. Our data contrast with those of Arbogast et al. (2002; Fig. 2A) in that they suggest an early, rather than a mid-Holocene, peak in eolian activity. This disparity may be a function of sample size. However, the differences in results are difficult to explain, and additional work is needed.

[1]GSA Data Repository item 2012082, OSL methodology, ages, and supporting data; Tables DR1–DR2; Figures DR1–DR3; and references, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Figure 2. A: Optically stimulated luminescence (OSL) data from eastern upper Michigan. Thin dark lines show ±1σ for each sample; cumulative probability distribution is shown for dune data from this study (n = 57). Number 1 shows data from this study; numbers 2 and 3 show data from other studies referenced on left. B: Horizontal dark lines 1–4 show periods of peak drought interpreted from paleoecological proxies: 1—presence of barrens vegetation on the Kingston Plains (northwest of site 1 in Fig. 1; Lytle, 2005); 2—changes in wetland composition that signal water-table decline (Booth et al., 2002); 3, 4—shifts in pollen stratigraphy that signal drought-tolerant forests (Futyma, 1982; Delcourt et al., 2002). C: Horizontal dark lines 5–11 show interpretation of key hydrologic events in upper Great Lakes Basin: 5—peak meltwater receipt in Superior Basin (Breckenridge et al., 2004); 6—12 m transgression of Lake Minong (Breckenridge et al., 2010); 7—breach in southeast rim of Lake Minong (N-GC in Fig. 1; Yu et al., 2010); 8—hydrologic closure of the Superior Basin (Boyd et al., 2010); 9, 10—hydrologic closure of Huron-Michigan Basin (Lewis et al., 2008; Brooks et al., 2010); 11—hydrologic closure of Georgian Bay (McCarthy and McAndrews, 2010). Vertical gray bar (±2σ bracketing of mean dune age) highlights close correlation of OSL signals of eolian activity from this study (A) with signals of rapid hydrologic change and extreme regional drought (C). Eolian activity is not well correlated with paleoecological proxies of drought based on pollen and macrofossils (B).



Results obtained by one of us (Lytle, 2005) shed some light on the disparity between OSL and pollen-inferred records of EUM vegetation history (Fig. 2B, sites 1–4). In evaluating localized Holocene vegetation change (e.g., Calcote, 1995; Sugita et al., 1999), several peaks in nonarboreal pollen (sum > 20%) were found (Lytle, 2005) in cores from small lakes ~30 km northeast of Munising (star symbol in Fig. 1). From these peaks, the presence of small forest openings (barrens) was inferred, usually associated with peaks in charcoal accumulation. While congruence of barrens vegetation, peaks in charcoal accumulation, and regional dune building (our data) occur ca. 8.9 ka and ca. 8.1 ka, the largest spike in nonarboreal pollen (6.5 ka) and several later spikes are outside the dune chronology (compare Figs. 2A1 with 2B1). This implies that significant change in forest cover and composition and increase in fire occurred at multiple times when the threshold required for deflation of sand (<40% vegetation cover; Wasson and Nanninga, 1986) was not reached. A more precise method to use pollen stratigraphy to detect and measure forest openings is, at present, problematic (Sugita et al., 1999). In addition, Futyma (1982) and Delcourt et al. (2002) did not report nonarboreal pollen in EUM.

Fire is associated with dune building along the tundra-forest boundary east of Hudson Bay (Filion, 1984), but contemporary northern forests respond to fire by stem sprouting and reproductive strategies that generally increase ground cover (Wein and MacLean, 1983). Those adaptations were apparently overwhelmed ca. 10–8 ka.

Dunes are widely distributed across the study area where fine to medium sand is abundant in the upper regolith. They are sourced primarily from sandy glaciolacustrine sediments of glacial Lake Algonquin (Whitney et al., 1992). The paucity of dunes along the crest of the Munising moraine northeast of Munising appears to reflect coarse-grained substrate near heads of outwash that mark the Marquette advance of the Laurentide Ice Sheet (Blewett and Rieck, 1987; Lowell et al., 1999). Dunes are absent from glaciolacustrine silt and clay plains at the eastern edge of the study area near Pickford (Fig. 1). Landscape segments that supplied sand in the early Holocene now support wetlands whose growth began as effective moisture increased after ca. 7 ka (Booth et al., 2002; Brugam et al., 2004).

We speculate that some dune building in the Superior Basin below ~245 m asl (Fig. 1; Fig. DR3) could be related to flooding of forests driven by transgressions of Lake Minong (Phillips and Fralick, 1994; Breckenridge et al., 2010). The transgressions must have ascended the Tahquamenon River Valley and may even have driven meltwater across the interbasin divide to the Manistique River Valley (near site 9, Fig. 1). Forests killed by flooding during these events would have been slow to recover during the severe drought that followed the rapid decline in Lake Minong ca. 9.0 ka (Loope et al., 2010; Yu et al., 2010). Almost all dunes in the Michigan Basin and those in the Superior Basin above the zone of possible flooding attest to large tracts where moisture stress alone drove tree death in large patches. Drought that led to such biogeomorphic failure of forest vegetation in EUM must have been significantly more severe than that associated with periodic failure of grass cover on the northern Great Plains (Hugenholtz and Wolfe, 2005). We assume that mobilization of silt and very fine sand deposited in thin silt caps ca. 13.8–11.5 ka (Fig. 1, sites 64–65) and 12.7–9.8 ka (Fig. 1, sites 23–25) was coincident with growth of upwind sand dunes (Mason et al., 1999). The older set may reflect dune building that followed final retreat of the Laurentide Ice Sheet ca. 11.5 ka (Lowell et al., 1999; Schaetzl and Loope, 2008). The younger set of ages may be associated with the major episode of early Holocene dune building described here.

CONCLUSIONS

We conclude the following. (1) Dune building within EUM was concentrated ca. 10–8 ka, coincident with drought-driven hydrologic closure of the upper Great Lakes. (2) Pollen-based models of vegetation history do not accommodate early Holocene dune building because the forest openings required for sand mobility are poorly detected. (3) While multiple periods of eolian activity occurred in the Great Plains during the Holocene, our data suggest a single broad period across EUM. (4) OSL dating of sand deposition in dunes comprises an unambiguous signal of decline in forest cover during the early Holocene.

ACKNOWLEDGMENTS

Gregg Bruff and Lora Loope commented on early drafts of the manuscript. Brody Block, Jim Waybrant, and Les Homan provided logistical assistance, field insight, and helpful discussions. Tony Williams provided an aerial flight across the study area. Conversations with Alan Arbogast, Daniel Feinstein, Robert Regis, and Catherine Yansa helped to frame and clarify issues. Thanks to Kerry Keen, Mike Lewis, and an anonymous reviewer for comments that improved the manuscript. This paper is Contribution 1668 of the U.S. Geological Survey, Great Lakes Science Center.

REFERENCES CITED

Aitken, M.J., 1998, An introduction to optical dating: The dating of Quaternary sediments by the use of photon stimulated luminescence: Oxford, UK, Oxford University Press, 267 p.

Anderton, J.B., and Loope, W.L., 1995, Buried soils in a perched dune-field as indicators of late Holocene lake-level change in the Lake Superior basin: Quaternary Research, v. 44, p. 190–199, doi:10.1006/qres.1995.1063.

Arbogast, A.F., Wintle, A.G., and Packman, S.C., 2002, Widespread middle Holocene dune formation in the eastern Upper Peninsula of Michigan and the relationship to climate and outlet-controlled lake level: Geology, v. 30, p. 55–58, doi:10.1130/0091-7613(2002)030<0055:WMHDFI>2.0.CO;2.

Bartlein, P.J., Webb, T., III, and Fleri, E.C., 1984, Holocene climatic change in the northern Midwest: Pollen-derived estimates: Quaternary Research, v. 22, p. 361–374, doi:10.1016/0033-5894(84)90029-2.

Blewett, W.L., and Rieck, R.L., 1987, Reinterpretation of a portion of the Munising moraine in northern Michigan: Geological Society of America Bulletin, v. 98, p. 169–175, doi:10.1130/0016-7606(1987)98<169:ROAPOT>2.0.CO;2.

Booth, R.K., Jackson, S.T., and Thompson, T.A., 2002, Paleoecology of a northern Michigan lake and the relationship among climate, vegetation and Great Lakes water levels: Quaternary Research, v. 57, p. 120–130, doi:10.1006/qres.2001.2288.

Boyd, M., Teller, J.T., Yang, Z., Kingsmill, L., and Shultis, C., 2010, An 8,900 year-old forest drowned by Lake Superior: Hydrological and paleoecological implications: Journal of Paleolimnology, doi:10.1007/s10933-010-9461-1.

Breckenridge, A., Johnson, T.C., Beske-Diehl, S., and Mothersill, J.S., 2004, The timing of regional Lateglacial events and post-glacial sedimentation rates from Lake Superior: Quaternary Science Reviews, v. 23, p. 2355–2367, doi:10.1016/j.quascirev.2004.04.007.

Breckenridge, A., Lowell, T.V., Fisher, T.G., and Yu, S., 2010, A late Lake Minong transgression in the Lake Superior basin as documented by sediments from Fenton Lake, Ontario: Journal of Paleolimnology, doi:10.1007/s10933-010-9447-z.

Brooks, G.R., Medioli, B.E., and Telka, A.M., 2010, Evidence of early Holocene closed-basin conditions in the Huron-Georgian basins from within the North Bay outlet of the Upper Great Lakes: Journal of Paleolimnology, doi:10.1007/s10933-010-9408-6.

Brubaker, L.B., 1975, Postglacial forest patterns associated with till and outwash in north central Upper Michigan: Quaternary Research, v. 5, p. 499–527, doi:10.1016/0033-5894(75)90013-7.

Brugam, R.B., Owen, B., and Kolesa, L., 2004, Continental-scale climate forcing factor and environmental change at Glimmerglass Lake in the Upper Peninsula of Michigan: The Holocene, v. 14, p. 807–817, doi:10.1191/0959683604hl761rp.

Calcote, R., 1995, Pollen source area and pollen productivity; evidence from forest hollows: Journal of Ecology, v. 83, p. 591–602, doi:10.2307/2261627.

David, P.P., 1977, Sand dune occurrences of Canada: A theme and resource inventory study of the eolian landforms of Canada: Ottawa, Canada, Department of Indian and Northern Affairs, National Parks Branch, Contract 74-230, 183 p.

Delcourt, H.R., Delcourt, P.A., and Webb, T., III, 1983, Dynamic plant ecology: A spectrum of vegetational change in time and space: Quaternary Science Reviews, v. 1, p. 153–175, doi:10.1016/0277-3791(82)90008-7.

Delcourt, P.A., Nester, P.L., Delcourt, H.R., Mora, C.I., and Orvis, K.H., 2002, Holocene lake-effect precipitation in northern Michigan: Quaternary Research, v. 57, p. 225–233, doi:10.1006/qres.2001.2308.

Dyke, A.S., Moore, A., and Robertson, L., 2003, Deglaciation of North America: Geological Survey of Canada Open File Report 1574, http://geopub.nrcan.gc.ca/moreinfo_e.php?id=214399.

Filion, L., 1984, A relationship between dunes, fire and climate recorded in the Holocene deposits of Quebec: Nature, v. 309, p. 543–546, doi:10.1038/309543a0.

Fritz, S.C., 2008, Deciphering climatic history from lake sediments: Journal of Paleolimnology, v. 39, p. 5–16, doi:10.1007/s10933-007-9134-x.

Futyma, R., 1982, Post-glacial vegetation history of eastern Upper Michigan [Ph.D. thesis]: Ann Arbor, University of Michigan, 426 p.

Grün, R., 2008, Editorial: Quaternary Geochronology, v. 3, p. 1, doi:10.1016/j.quageo.2007.09.001.

Hugenholtz, C.H., and Wolfe, S.A., 2005, Biogeomorphic model of dunefield activation and stabilization on the northern Great Plains: Geomorphology, v. 70, p. 53–70, doi:10.1016/j.geomorph.2005.03.011.

Keen, K.L., and Shane, L.C.K., 1990, A continuous record of Holocene eolian activity and vegetation change at Lake Ann, east-central Minnesota: Geological Society of America Bulletin, v. 102, p. 1646–1657, doi:10.1130/0016-7606(1990)102<1646:ACROHE>2.3.CO;2.

Kutzbach, J., Gallimore, R., Harrison, S., Behling, P., Selin, R., and Laarif, F., 1998, Climate and biome simulations for the last 21,000 years: Quaternary Science Reviews, v. 17, p. 473–506, doi:10.1016/S0277-3791(98)00009-2.

Lewis, C.F.M., and 16 others, 2008, Dry climate disconnected the Laurentian Great Lakes: Eos (Transactions, American Geophysical Union), v. 89, p. 541–542, doi:10.1029/2008EO520001.

Loope, H.M., Loope, W.L., Goble, R.J., Fisher, T.G., Jol, H.M., and Seong, J.C., 2010, Early Holocene dune activity linked with final destruction of Glacial Lake Minong, eastern Upper Michigan, USA: Quaternary Research, v. 74, p. 73–81, doi:10.1016/j.yqres.2010.03.006.

Lowell, T.V., Larson, G.J., Hughes, J.D., and Denton, G.H., 1999, Age verification of the Lake Gribben forest bed and the Younger Dryas advance of the Laurentide Ice Sheet: Canadian Journal of Earth Sciences, v. 36, p. 383–393, doi:10.1139/e98-095.

Lytle, D.E., 2005, Palaeoecological evidence of state shifts between forest and barrens on a Michigan sand plain, USA: The Holocene, v. 15, p. 821–836, doi:10.1191/0959683605hl856ra.

Mason, J.A., Nater, E.A., Zanner, C.W., and Bell, J.C., 1999, A new model of topographic effects on the distribution of loess: Geomorphology, v. 28, p. 223–236, doi:10.1016/S0169-555X(98)00112-3.

Mason, J.A., Swinehart, J.B., Goble, R.J., and Loope, D.B., 2004, Late Holocene dune activity linked to hydrological drought, Nebraska Sand Hills, U.S.A.: The Holocene, v. 14, p. 209–217, doi:10.1191/0959683604hl677rp.

McAndrews, J.H., 1966, Postglacial history of prairie, savanna and forest in northwestern Minnesota: Torrey Botanical Club Memoir 22, 72 p.

McCarthy, F., and McAndrews, J., 2010, Early Holocene drought in the Laurentian Great Lakes basin caused hydrologic closure of Georgian Bay: Journal of Paleolimnology, doi:10.1007/s10933-010-9410-z.

Miao, X., Mason, J.A., Swinehart, J.B., Loope, D.B., Hanson, P.R., Goble, R.J., and Liu, X., 2007, A. 10,000 year record of dune activity, dust storms, and severe drought in the central Great Plains: Geology, v. 35, p. 119–122, doi:10.1130/G23133A.1.

Muhs, D.R., 1985, Age and paleoclimatic significance of Holocene sand dunes in northeastern Colorado: American Association of Geographers Annals, v. 75, p. 566–582, doi:10.1111/j.1467-8306.1985.tb00094.x.

Murray, A.S., and Wintle, A.G., 2000, Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol: Radiation Measurements, v. 32, p. 57–73, doi:10.1016/S1350-4487(99)00253-X.

Olson, J.S., 1958, Lake Michigan dune development. 3. Lake-level, beach and dune oscillations: Journal of Geology, v. 66, p. 473–483, doi:10.1086/626530.

Phillips, B.A.M., and Fralick, P.W., 1994, A post-Minong transgressive event on the north shore of Lake Superior, Ontario: Possible evidence of Lake Agassiz inflow, circa 9.5 ka BP: Canadian Journal of Earth Sciences, v. 31, p. 1638–1641, doi:10.1139/e94-145.

Schaetzl, R.J., and Loope, W.L., 2008, Evidence for an eolian origin for the silt-enriched soil mantles on glaciated uplands of eastern Upper Michigan: Geomorphology, v. 100, p. 285–295, doi:10.1016/j.geomorph.2008.01.002.

Sugita, S., Gaillard, M.-J., and Brostrom, A., 1999, Landscape openness and pollen records: A simulation approach: The Holocene, v. 9, p. 409–421, doi:10.1191/095968399666429937.

Wasson, R.J., and Nanninga, P.M., 1986, Estimating wind transport of sand on vegetated surfaces: Earth Surface Processes and Landforms, v. 11, p. 505–514, doi:10.1002/esp.3290110505.

Webb, T., III, Cushing, E.J., and Wright, H.E., Jr., 1983, Holocene changes in the vegetation of the Midwest, *in* Wright, H.E., Jr., ed., Late-Quaternary environments of the United States, Volume 2: The Holocene: Minneapolis, University of Minnesota Press, p. 142–165.

Wein, R.W., and MacLean, D.A., eds., 1983, The role of fire in northern circumpolar ecosystems: Scientific Committee on Problems of the Environment Volume 18: New York, John Wiley and Sons, 322 p.

White, P.S., 1979, Pattern, process and natural disturbance in vegetation: Botanical Review, v. 45, p. 229–299, doi:10.1007/BF02860857.

Whitney, G.D., Anzalone, W., Kroell, M.L., Rodock, S.E., Neilson, R., Perreault, L., and Hausler, K., 1992, Soil survey of Chippewa County, Michigan: U.S. Department of Agriculture Soil Conservation Service, 383 p.

Williams, J.W., Shuman, B., Bartlein, P.J., Diffenbaugh, N.S., and Webb, T., III, 2010, Rapid, time-transgressive, and variable responses to early Holocene mid-continental drying in North America: Geology, v. 38, p. 135–138, doi:10.1130/G30413.1.

Wolfe, S.A., Ollerhead, J., Huntley, D.J., and Lian, O.B., 2006, Holocene dune activity and environmental change in the prairie parkland and boreal forest, central Saskatchewan, Canada: The Holocene, v. 16, p. 17–29, doi:10.1191/0959683606hl903rp.

Yu, S.-Y., Colman, S.M., Lowell, T.V., Milne, G.A., Fisher, T.G., Breckenridge, A., Boyd, M., and Teller, J.T., 2010, Freshwater outburst from Lake Superior as a trigger for the cold event 9300 years ago: Science, v. 328, p. 1262–1266, doi:10.1126/science.1187860.

Manuscript received 18 October 2011
Manuscript accepted 3 November 2011

Printed in USA