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Lacustrine records of post-glacial environmental change from the Nulhegan Basin, Vermont, USA

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ABSTRACT: The sedimentary records of Nulhegan Pond and Beecher Pond in the Nulhegan Basin of north-eastern Vermont were analyzed to yield a history of environmental change since the latest Pleistocene. Shoreline landforms indicate that part of the Nulhegan Basin was inundated by Glacial Lake Nulhegan (GLN), which was impounded behind a dam of glacial sediment. Outwash derived from stagnant ice forms the bottom 176 cm of the Nulhegan Pond core. Fine-grained inorganic sediment deposited between 13.4 and 12.2k cal a BP is interpreted as a deep-water facies representing GLN, while coarser sediment from 12.2 to 11.8k cal a BP records draining of the glacial lake. Rapid, simultaneous increases in organic matter and biogenic silica signal the onset of productivity following the Younger Dryas. Beecher Pond formed *c.* 11.3k cal a BP through surface collapse over a buried ice block; buried stagnant ice may have persisted in the vicinity of the pond into the early Holocene. From 8.9 to 5.5k cal a BP, sediment in both lakes became coarser and richer in aquatic organic matter, suggesting a low-water phase in which previously deposited lacustrine sediments were reworked and the littoral zone shifted basinward. Low water levels at this time are consistent with other records from Maine and southern Quebec, but contrary to records from ~325 km to the south.

KEYWORDS: Holocene; lake level; Nulhegan Basin; paleolimnology; Vermont.

Introduction

The region straddling the border between the north-eastern US and south-eastern Quebec has a rich late Quaternary history. The retreating Laurentide Ice Sheet interacted with the northern Appalachians generating a complex legacy of coexisting active and stagnant ice, large glacial lakes that reflect profound changes in drainage patterns, a prolonged incursion of marine waters into lowland valleys, and considerable isostatic uplift and regional tilting (Chapman, 1937; e.g. Koteff and Pessl, 1981; Parent and Occhietti, 1999; Ridge *et al.*, 1999; Rayburn *et al.*, 2005). Following retreat of the ice, different assemblages of forest vegetation migrated northward through the region, shifting precipitation patterns impacted lake levels and humans colonized the landscape (Boisvert, 1999; e.g. Shuman *et al.*, 2002; Shuman and Donnelly, 2006). Despite more than a century of study, many questions remain about these events and their timing. For instance, some recognized glacial lakes remain unstudied (Lougee, 1939), and it is likely that others have not yet been identified. The pattern of climatic changes during the Holocene, and the drivers that forced them, are also incompletely understood.

Multiproxy investigation of accurately dated sediment cores from small lakes can yield high-resolution paleoclimate records suitable for addressing some of these questions. While lakes have been cored and studied throughout the north-eastern US and southern Quebec, lake records, especially those from smaller basins, are inherently local and more studies are needed to fully understand the post-glacial environmental history of this region. In Vermont, in particular, most paleolimnological research has focused on records from the large glacial lakes that inundated the Champlain (Lake Vermont) and Connecticut River (Lake Hitchcock) Valleys (e.g. Chapman, 1937; Ridge and Toll, 1999; Rayburn *et al.*, 2007); little work has been published on records from smaller lakes in upland locations.

In an effort to provide new information from an area that has escaped prior scientific attention, this study focused on sedimentary records retrieved from two ponds in north-eastern Vermont. The ponds were selected with two main objectives: (i) to evaluate the evidence for a formerly extensive glacial lake in this region, and (ii) to reconstruct post-glacial environmental changes in an upland setting.

Study area

The ponds cored in this study are located in the Nulhegan Basin (NB), approximately 15 km west of the Connecticut River and 20 km south of the US/Canadian border (Fig. 1). The NB is a prominent circular depression with a diameter of 15 km surrounded by a mountain rim rising ~400 m (Fig. 2). The NB is underlain by a quartz monozodiorite pluton (Arth and Ayuso, 1997) whereas the rim is composed of schists of the early Devonian Gile Mountain Formation (Doll *et al.*, 1961). The floor of the NB is mantled by glacial sediment deposited by the last advance of continental ice, which arrived from the north-west (Munroe *et al.*, 2007; Munroe, 2007). Bedrock outcrops are common in the eastern half of the NB, whereas elsewhere glacial sediment is thick and bedrock outcrops are absent (Hodges and Butterfield, 1967; Munroe, 2007). The Nulhegan River originates on the south-western rim of the NB and flows eastward to join the Connecticut River.

Geomorphic features in the southern part of the NB suggest that the Nulhegan River was impounded at some point to form a lake, here named Glacial Lake Nulhegan (GLN), with a surface elevation of 358 m. Evidence includes a prominent spit, a delta on the north side of Notch Mountain, channels crossing the divide between the Nulhegan River drainage and the Clyde River to the west, and the low gradient of the Nulhegan River upstream from the gorge where the river leaves the NB and drops down to the Connecticut River (Fig. 2). Damming of the river was probably accomplished at the upstream end of this gorge by a ridge of glacial sediment spanning between two hummocks with modern elevations of 362 m (Fig. 2). Water rising to 358 m behind this dam would have inundated ~14 km^2 of the southern NB, and overtopped the divide leading westward to the Clyde River (Fig. 2).

Nulhegan Pond was selected for this study because its surface is ~6 m lower than the reconstructed elevation of GLN (Fig. 2).

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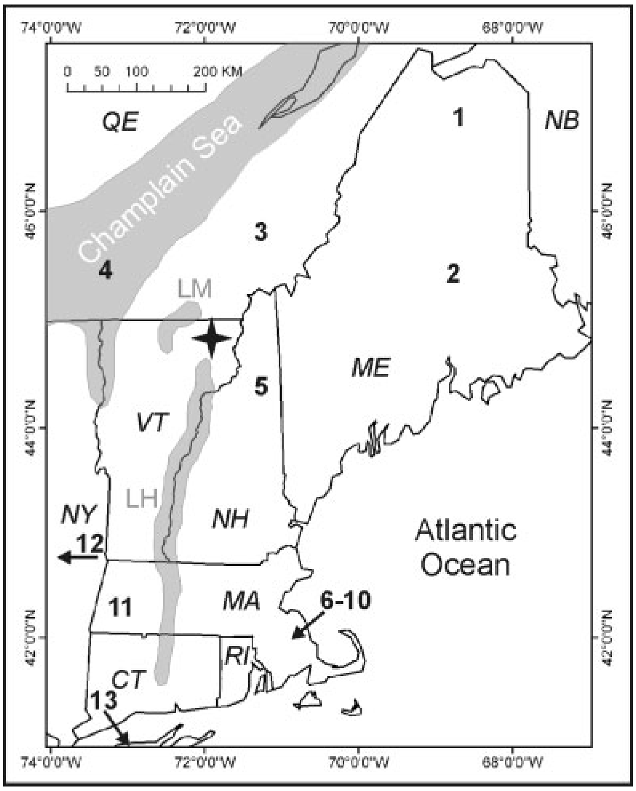

Figure 1. Location map of the study area in northern Vermont, USA. QE, Quebec; NB, New Brunswick; ME, Maine; NH, New Hampshire; VT, Vermont; NY, New York; MA, Massachusetts; RI, Rhode Island; CT, Connecticut. The star marks the Nulhegan Basin (Fig. 2). The approximate outlines of the Champlain Sea, Glacial Lake Hitchcock in the Connecticut River Valley (LH) and Glacial Lake Memphremagog (LM) are shown in grey. Note that these features were time-transgressive and did not coexist temporally. Locations of other Holocene water-level reconstructions mentioned in the text and shown in Fig. 4 are also provided: 1, Dieffenbacher-Krall and Nurse (2005); 2, Almquist *et al.* (2001); 3, Lavoie and Richard (2000); 4, Muller *et al.* (2003); 5, Shuman *et al.* (2005); 6, Newby *et al.* (2000); 7, Shuman and Donnelly (2006); 8, Shuman *et al.* (2001); 9, Newby *et al.* (2009); 10, Shuman *et al.* (2009); 11, Newby *et al.* (2011); 12, Dwyer *et al.* (1996); 13, Oswald *et al.* (2010).

The pond therefore formed a deep sub-basin within the larger lake. Nulhegan Pond (44.79069°N, 71.81802°W) has an area of 11.2 ha and a maximum depth of 340 cm. The Nulhegan River flows through the pond, draining an upstream watershed of ~2500 ha. Measurements at the inlet and outlet of Nulhegan Pond revealed identical discharges, and thus the pond does not appear to be gaining or losing appreciable water to the groundwater system.

Beecher Pond is an isolated kettle selected because its surface is ~15 m above the former level of GLN. Beecher Pond (44.81189°N, 71.849622°W) has smaller surface area (7 ha), a greater maximum depth (410 cm) and a much smaller watershed (250 ha) than Nulhegan Pond.

Both ponds are surrounded by a boreal forest composed of *Abies balsamea*, *Picea rubens*, *Picea mariana* and *Larix laricina*. Shorelines are locally bordered by floating mats of northern bog vegetation including *Ledum groenlandicum*.

The modern climate of the NB is constrained by a weather station located 10 km east of Nulhegan Pond (Fig. 2). Annual temperatures averaged 5.4 °C for the period 2004–2010, with a summer (J/J/A) mean of 17.4 °C and a winter (D/J/F) mean of −8.6 °C. Annual precipitation averaged 1140 mm, with 387 mm (34%) falling in summer (J/J/A) and 172 mm (15%) in winter (D/J/F).

Methods

Sedimentary records from Nulhegan and Beecher Ponds were retrieved using a 5-cm-diameter Livingstone corer operated from the ice surface. Coring was started 100 cm below the sediment–water interface to ensure that the sediment would be dense enough to withstand extrusion. A casing of 4-inch diameter PVC pipe was employed to enable deeper penetration, and coring continued until the point of refusal. Beecher Pond was cored in March 2006, yielding six core sections that were assembled to create a composite record spanning 461 cm. Sixteen core sections were retrieved from Nulhegan Pond in March 2006, January 2007 and March 2007, and a surface core including an intact sediment–water interface was collected in November 2008. Together the cores from Nulhegan Pond yield a composite record spanning 1472 cm.

In the lab, the core sections were analyzed for loss-on-ignition (LOI) at 1-cm intervals in a Leco TGA-701 thermogravimetric analyzer. The TGA automatically dries the sample and then measures mass loss while heating to 550 °C for 3 h as a proxy for organic matter content (Dean, 1974; Heiri *et al.*, 2001). Subsamples at 2-cm (Beecher Pond) and 4-cm (Nulhegan Pond) intervals were subjected to analysis of carbon/nitrogen ratio (C:N), biogenic silica content (bSi) and grain size distribution (GS). Samples were freeze-dried (48 h) and ground before C:N and bSi analysis. Acidification was unnecessary because inorganic carbon was not detectable in appreciable quantities. C:N was measured with a CE Instruments NC 2500 Elemental Analyzer at the University of Vermont (Nulhegan Pond) and a Thermo Fisher Flash 2000 Elemental Analyzer at Middlebury College (Beecher Pond). The analyzers were calibrated with aspartic acid standards, and standard reference materials were run every 30 samples. Precision of the analyzers is approximately 1% for C and 0.5% for N. Biogenic silica content was determined through sequential extraction in NaOH for 5 h. After addition of reagents to generate a molybdate blue color development (Strickland and Parsons, 1965), silica content was measured by spectrophotometry (absorbance at 812 nm) calibrated by a 10-point standard curve. Analysis of replicates indicates that this method has a reproducibility of 10%. Grain size distribution was determined using laser scattering with a Horiba LA950 analyzer. Samples were pretreated with 35% H_2O_2 for ~10 days to remove organic matter, and leached for 1 h at 85 °C in 0.1 M NaOH to remove biogenic silica. Sodium hexametaphosphate (3%) was used as a dispersant and all samples were sonicated and mechanically mixed before analysis. The Horiba LA950 has an effective range of 50 nm to 3 mm. Ten per cent of samples were rerun as duplicates, and other samples exhibiting dramatic changes in grain size distribution were rerun for confirmation.

Terrestrial macrofossils suitable for accelerator mass spectrometry ^{14}C dating were dried overnight at 60 °C and submitted for processing. Six samples were analyzed from Nulhegan Pond and four samples from Beecher Pond. All samples received standard acid–alkali–acid pretreatment before analysis. Radiocarbon ages were calibrated into calendar years with Calib 6.0 (Stuiver and Reimer, 1993) using the Intcal09 calibration curve (Reimer *et al.*, 2009). A prominent layer of decomposed sawdust near the top of the Nulhegan Pond core was assigned an age of AD 1890 after archival research revealed that a sawmill was present on the shore of the pond at that time. An abrupt transition from very coarse sand to fine silt ~2 m above the base of the Nulhegan

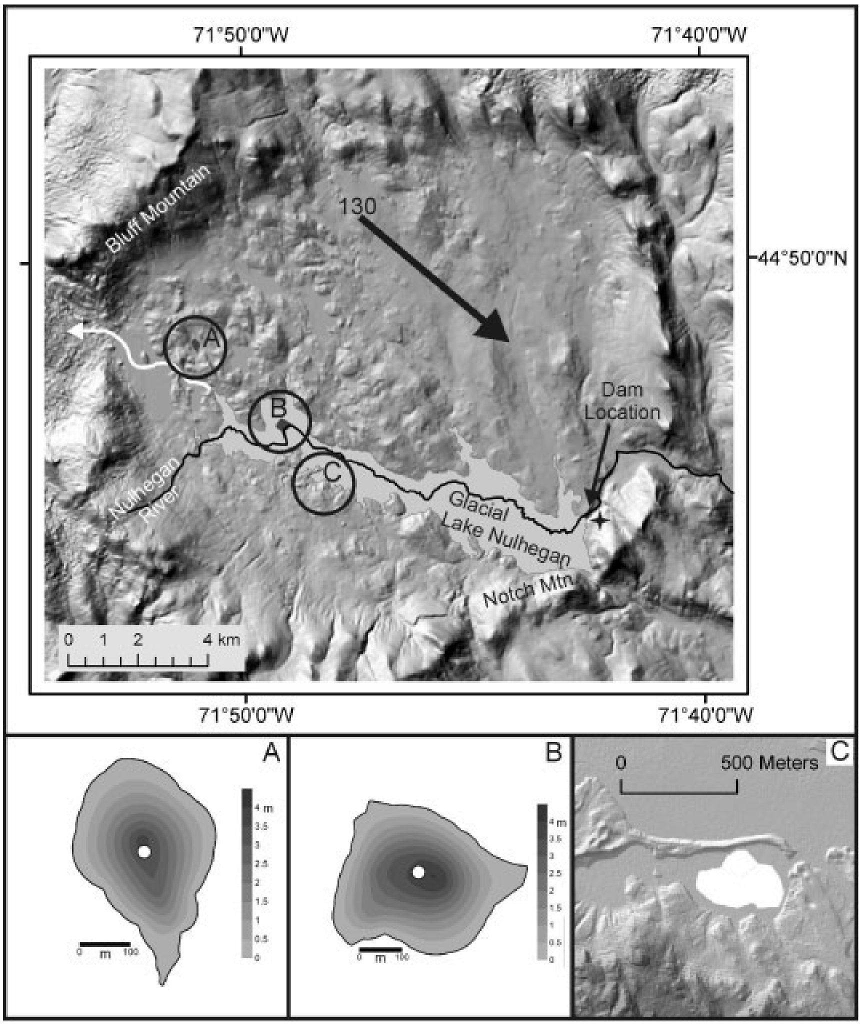

Figure 2. Detailed map of the Nulhegan Basin study area. Large upper figure shows a shaded relief image of the Nulhegan Basin including the Nulhegan River (black) and the area inundated by Glacial Lake Nulhegan at the 358-m level. The westward drainage route of the glacial lake to the Clyde River is shown in white. The locations of Beecher and Nulhegan Ponds are circled, and the prevailing ice-flow vector (130°) during deglaciation is shown. The star marks the location of the weather station constraining modern climate of the NB. Inset A presents a bathymetric map of Beecher Pond, while a map of Nulhegan Pond is shown in B. Coring locations are given by the white circles. Inset C is a hillshade derived from 1-m LIDAR data showing a prominent spit formed by eastward longshore transport in Glacial Lake Nulhegan. The white area is a pond.

Pond core was assigned the age (13.4k cal a BP) of the well-dated Columbia Bridge site located 20 km to the east in the Connecticut River Valley because this age is thought to closely limit the deglaciation of this region (Miller and Thompson, 1979; Ridge *et al.*, 1999). Depth–age models were developed for both records using these age constraints and the median probabilities within the 2-sigma calibration ranges.

Results

Lithology and chronology

The sedimentary record from Nulhegan Pond exhibits a three-part stratigraphy. The lowest unit (1472–1298 cm) is a coarse sand directly overlying stones. This unit is overlain abruptly by 115 cm of fine silt, extending to a stratigraphic depth of 1183 cm. Above this level, the sediment transitions over 10 cm into a massive gyttja that continues to the sediment–water interface.

The radiocarbon dates obtained for Nulhegan Pond indicate that this record extends back to the latest Pleistocene (Table 1). The lowest age of 11 170 cal a BP was obtained on a twig from 35 cm above the base of the gyttja, and the remaining ages are all in stratigraphic order. Figure 3 presents the depth–age model developed for this core by multiple linear interpolation between these ages, AD 2008 for the sediment–water interface, AD 1890 for the sawdust layer and 13.4k cal a BP (Miller and Thompson, 1979; Ridge and Toll, 1999; Ridge *et al.*, 1999) for the contact between the fine silt and the underlying coarse sand. Because the basal sand unit probably accumulated quickly, a sedimentation rate of 1 cm a^{-1} was arbitrarily assigned below this contact.

The composite record from Beecher Pond consists almost entirely of massive gyttja. However, the lowest 2 cm contained abundant, coarser, mineral grains directly overlying stones. An unidentified leaf fragment recovered from the core base constrains formation of the lake to 11.3k cal a BP. The other three radiocarbon dates are in stratigraphic order and a depth–age model was developed by multiple linear interpolation (Fig. 3). Extrapolation of this curve 41 cm above the uppermost age yields an age of ~1.0k cal a BP for the top of the retrieved section. Given these age models, resolutions range from 2 to 21 a cm^{-1} in Nulhegan Pond, and 11 to 43 a cm^{-1} in Beecher Pond.

Delineation of zones

Plotting the time-series for the two lakes on a common timescale revealed that major shifts in many proxies were synchronous between the two records. A succession of zones was therefore visually delineated to facilitate interpretation of the post-glacial environmental history. Zone boundaries were located at major shifts in the direction of proxy trends, points where local values crossed the period-of-record mean, and other places where the proxy time-series changed in visually distinct ways. No individual proxy was given greater weight in

Table 1. Radiocarbon Dates for Nulhegan and Beecher Ponds.

Lab. no.	Sample ID*	Description	$\delta^{13}C$ (‰)	Stratigraphic depth (cm)	^{14}C age (a)	Error (a)	2σ max (a)	2σ min (a)	Prob.	Cal. Midpoint (a)
OS-55721	NP_40-42.5	Wood	−25.8	140.5	1250	20	1269	1167	0.90	1215
OS-56165	NP_1072.5-1075	Misc	−25.0	733.5	4990	140	6008	5449	0.97	5742
Beta-231100	NP_877	Wood	−26.2	877	6500	40	7483	7319	1.00	7419
Beta-227711	NP_1350	Plant material	−27.0	1010.5	7890	40	8793	8591	0.85	8697
OS-60423	NP_985	*Picea* needles	−27.4	1061	8600	110	9923	9401	0.98	9610
OS-60083	NP_1072	Twig	−29.7	1148	9750	50	11250	11088	0.98	11190
OS-55402	BP_40-42.5	Misc	−26.7	141	1800	40	1825	1611	0.99	1735
OS-60107	BP_257	Seeds	−24.2	257	3350	40	3647	3477	0.90	3588
OS-60102	BP_414	Twig	−26.8	414	5040	45	5903	5706	0.92	5806
OS-55401	BP_Base	Leaf	−27.1	560	9810	55	11328	11138	1.00	11227

* NP, Nulhegan Pond; BP, Beecher Pond.

this process, and zone boundaries were intentionally positioned to capture simultaneous changes in as many of the proxies as possible. The stratigraphic depths and ages of the zone boundaries are presented in Table 2. Summary statistics for the proxies in each zone are presented in Table 3, and zone boundaries are overlain on the proxy time-series in Fig. 3.

Discussion

Interpretation of environmental changes from physical proxies

The suite of physical proxies considered in this study supports the interpretation of paleoenvironmental changes responsible

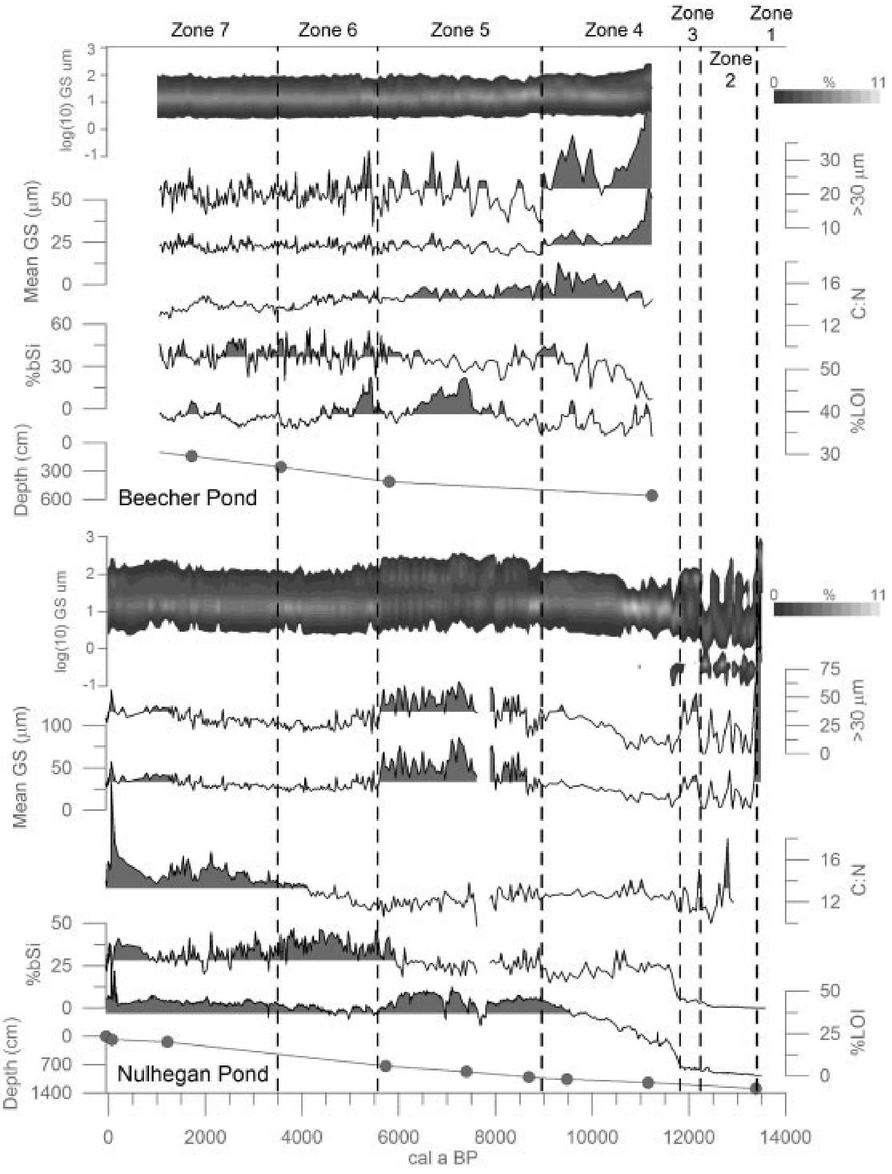

Figure 3. Plot of multiproxy time-series for the sedimentary records from Nulhegan and Beecher Ponds. Control points for the depth–age models are shown with circles (see Table 1). Ages are given in cal a BP. %LOI is loss-on-ignition at 550 °C; %bSi is biogenic silica content determined through sequential extraction with NaOH; C:N is the ratio of carbon to nitrogen determined with an elemental analyzer; mean GS is the mean particle diameter (in μm) determined with laser scattering; >30 μm is sum of abundance of particles from coarse silt through coarse sand. Time-series plots are filled above their mean values. The grain size maps show the frequency (from 0 to 11%) of all measured grain sizes (on a $\log_{10}$ scale). Zone boundaries are represented by dashed vertical lines, and zones are labeled at the top.

Table 2. Bounding depths and ages for stratigraphic zones.

Zone	Top age (k cal a BP)	Top depth (cm) Nulhegan	Top depth (cm) Beecher
1	13.4	1299	–
2	12.2	1212	–
3	11.8	1184	561*
4	8.9	1036	499
5	5.6	720	401
6	3.5	444	254
7	Present	0	100†

*Base of recovered core, dated to 11.2k cal a BP. †Top of recovered core, extrapolated age of 1k cal a BP.

for shifts in the lacustrine sedimentary environment. While each of these proxies is equivocal in insolation, their use in an ensemble permits more focused reconstructions. Collective consideration of all four proxies from both lakes also helps mitigate some of the ambiguities that can hinder interpretations made from single cores. For example, measurements of organic matter content by LOI analysis can provide a signal of in-lake productivity (e.g. Kurek *et al*., 2004), delivery of terrestrial material (e.g. Corbett and Munroe, 2010) or changes in water level that shift the proximity of the littoral zone relative to the coring site (e.g. Shuman, 2003). Yet when combined with C:N, this ambiguity is reduced because terrestrial organic matter exhibits a higher ratio (Meyers and Ishiwatari, 1995). Increases in LOI associated with elevated values of C:N are therefore considered to provide evidence of increased inputs of terrestrial organic matter, possibly driven by greater effective precipitation. The concurrent appearance of larger mean grain sizes would be additional support for such an interpretation (Noren

Table 3. Descriptive statistics for zones in the Nulhegan and Beecher Pond cores.

	Nulhegan Pond					Beecher Pond				
Statistic	Mean	CV	Min.	Max.	*n*	Mean	CV	Min.	Max.	*n*
Zone 7 (3.5k cal a BP to present)										
% LOI	43.8	5.1	34.3	66.8	420	38.9	3.3	36.3	42.7	153
C/N	14.9	7.7	13.5	23.4	104	13.8	3.2	12.7	14.8	77
% bSi	31.7	16.1	19.6	45.2	104	38.8	16.0	22.3	50.2	77
Mean size (μm)	32.9	20.0	23.4	57.6	104	22.9	12.3	17.7	30.2	77
% >30 μm	32.5	19.4	21.5	56.4	104	20.0	14.5	14.0	27.7	77
Zone 6 (5.6–3.5k cal a BP)										
% LOI	39.3	4.7	33.2	42.6	276	39.7	6.7	36.1	48.2	147
C/N	12.7	6.1	11.2	13.9	68	14.3	3.7	13.4	15.3	73
% bSi	38.3	13.2	25.6	47.2	68	39.7	19.6	20.1	57.5	73
Mean size (μm)	28.1	19.2	20.6	46.2	68	23.1	11.2	16.8	29.6	73
% >30 μm	26.3	20.5	17.7	43.3	68	20.6	17.9	10.6	32.8	73
Zone 5 (8.9–5.6k cal a BP)										
% LOI	44.4	9.0	29.9	52.6	316	40.8	6.8	36.2	47.9	98
C/N	12.2	6.1	9.8	13.9	73	15.0	3.4	14.1	15.9	49
% bSi	26.8	17.4	18.5	41.8	73	34.7	17.9	20.4	51.8	49
Mean size (μm)	51.3	29.4	17.3	86.1	73	22.1	13.1	16.9	30.5	49
% >30 μm	43.8	26.1	14.1	63.9	73	19.9	23.3	11.5	32.6	49
Zone 4 (11.8–8.9k cal a BP)										
% LOI	30.0	28.7	11.0	44.6	148	37.1	5.5	34.3	42.6	43
C/N	12.8	3.4	12.1	14.2	37	15.7	6.1	13.7	17.9	32
% bSi	22.3	20.7	12.0	35.2	37	28.4	40.9	6.7	46.7	32
Mean size (μm)	22.1	34.1	3.7	35.5	37	29.3	27.1	17.4	58.7	32
% >30 μm	21.4	55.5	0.3	43.2	37	29.5	29.1	11.3	55.1	32
Zone 3 (12.2–11.8k cal a BP)										
% LOI	4.9	24.4	3.5	8.6	28	–	–	–	–	–
C/N	11.7	8.4	11.0	13.4	7	–	–	–	–	–
% bSi	4.9	21.4	3.0	6.0	7	–	–	–	–	–
Mean size (μm)	30.5	34.2	15.3	41.7	7	–	–	–	–	–
% >30 μm	34.5	43.8	13.5	53.6	7	–	–	–	–	–
Zone 2 (13.4–12.2k cal a BP)										
% LOI	1.8	59.6	0.2	5.1	87	–	–	–	–	–
C/N	13.8	40.8	0.0	28.0	22	–	–	–	–	–
% bSi	1.0	91.1	0.1	3.3	22	–	–	–	–	–
Mean size (μm)	15.8	82.6	1.9	47.1	22	–	–	–	–	–
% >30 μm	16.1	94.0	0.0	54.7	22	–	–	–	–	–
Zone 1 (pre-13.4k cal a BP)										
% LOI	0.1	82.4	0.0	0.3	36	–	–	–	–	–
C/N	0.0	–	0.0	0.0	41	–	–	–	–	–
% bSi	0.0	–	0.0	0.0	41	–	–	–	–	–
Mean size (μm)	536.2	92.5	103.0	1868.3	41	–	–	–	–	–
% >30 μm	90.3	9.0	61.9	95.4	27	–	–	–	–	–

et al., 2002; Parris *et al.*, 2010). On the other hand, if elevated LOI and mean grain size were concurrent with lower C:N values, this would be interpreted as evidence of a lowered water level that moved the littoral zone (larger grain size) closer to the coring site and allowed previously deposited lacustrine organic matter (lower C:N) to be eroded and reworked basinward (elevated LOI). Interpretation of bSi changes is challenging without specific study of the diatom taxa involved, which was beyond the scope of this project. Nonetheless, bSi is a valuable indicator of aquatic productivity (Colman *et al.*, 1995), which is controlled to a large extent by the area of shallow water for benthic diatom habitat, and water turbidity. Depending on bathymetry, decreases in bSi during inferred episodes of low water is consistent with emergence of shallow shelves (Stone and Fritz, 2004), and increases in bSi during intervals of rising LOI is a signal of enhanced in-lake productivity, perhaps due to increased water clarity (Bradbury *et al.*, 1994).

Deglacial implications

The sediment representing Zone 1 of the Nulhegan Pond core supports an emerging picture of the deglacial process in this relatively high-relief area. Given its grain size, fining-upward trend and general lack of organic matter, this sediment is interpreted as glacial outwash, probably derived from stagnant ice. The hummocky landscape in the western part of the NB (Fig. 2) indicates that blocks of stagnant ice were present during the latest Pleistocene deglaciation, and previous surficial mapping noted the abundance of ice-contact deposits along the Nulhegan River (Hodges and Butterfield, 1967; Doll, 1970). Formation of stagnant ice during deglaciation is predictable given the morphology of the western NB. Munroe (2007) reported striations indicating an ice flow azimuth of 130° during deglaciation (Fig. 2). Given this flow direction, at some point lowering of the ice surface would have revealed Bluff Mountain as a nunatak, causing ice in the western sector of the NB to stagnate (Fig. 2). Similar processes have been invoked for the deglaciation of the northern White Mountains in New Hampshire based on modern observations of retreating glaciers in south-eastern Alaska (Goldthwait and Mickelson, 1982). Given the relief of Bluff Mountain above the Nulhegan River, the thickness of stagnant ice could have been as much as 500 m, consistent with the great amounts of hummocky ice-contact stratified drift mantling the NB floor.

The contact between the outwash of Zone 1 and the overlying finer sediment comprising Zone 2 is abrupt, implying a nearly instantaneous change in sedimentary environment. The location of Nulhegan Pond may have originally been a buried ice block that collapsed to form a kettle. Deposition of outwash could have started above this ice block, with later collapse dropping the surface below the water table and switching the system instantaneously to lacustrine sedimentation.

Glacial Lake Nulhegan

An important result for the latest Pleistocene is that the proxies in Zone 2 support the geomorphic evidence for GLN. This lake represented a major change in the regional drainage pattern, shifting almost 200 km^2 from the south-flowing Connecticut River system, which was occupied by Glacial Lake Hitchcock (Ridge *et al.*, 1999) to the west-flowing Clyde River, which drained into Glacial Lakes Memphremagog and Candona, a precursor to the Champlain Sea (Parent and Occhietti, 1999) (Fig. 1). During the time represented by Zone 2 (13.4–12.2k cal a BP) the coring site in Nulhegan Pond would have been submerged beneath >22 m of water, and located >1 km from the nearest shoreline or point of focused sediment delivery. The fine sediment comprising this zone (with maximum silt contents of 75%) is consistent with deposition in a deep, large lake, although pulses of coarser sediment were occasionally delivered to the coring site, as revealed by short-term increases in sand content (Fig. 2). Values of bSi are extremely low throughout Zone 2, suggesting cold turbid water, which would be expected in a setting where stagnant glacial ice was melting. The age of this zone also overlaps with the Younger Dryas cold interval 12.9–11.7k cal a BP, during which lower temperatures drove regional readvance of the Laurentide Ice Sheet (LaSalle and Shilts, 1993; Borns *et al.*, 2004). Temperature depression would have shortened the ice-free season, further impacting the diatom population. Nonetheless, there may still have been an ecosystem within and around GLN. Pioneering fish species were living in similar conditions at the north end of Lake Hitchcock in the Connecticut River Valley by ~13k cal a BP (Benner *et al.*, 2009), so it is possible that fish were present in GLN if a suitable upslope migration route existed. Detectable values of LOI and elevated values of C:N in Zone 2 also indicate that vegetation was becoming established in the NB during this interval. This inference is supported by the rich assemblage of late Pleistocene tundra vegetation reported from the lower elevation Columbia Bridge site east of the NB (Hollick, 1931; Miller and Thompson, 1979), and pollen and macrofossil data from a higher elevation site in the White Mountains of New Hampshire indicating that spruce was present in the region by the start of the Holocene (Miller and Spear, 1999). If the NB was vegetated during the Zone 2 interval, shorelines of GLN might be fruitful locations in which to search for archeological sites given that there is evidence of a regional Paleoindian presence at this time (Boisvert, 1999).

The dramatic coarsening of the sediment in Zone 3 probably reflects the end of GLN. As this deep water body draining westward converted to a shallower pond draining eastward, currents within the lake would have redistributed coarser sediment into the deeper parts of the basin. If the water level fell to near its modern value, the total drop was 6 m. Draining of GLN may have been a catastrophic event because mean GS, and the abundance of fine sand, very fine sand and coarse silt all increase three- to four-fold at the start of this interval, and then decrease through the overlying 24 cm. This fining-upward stratigraphy suggests a pulse of coarser sedimentation that tapered as the energy of the sedimentary environment decreased, consistent with breaching of a dam followed by rapid lowering of water level. On the other hand, downstream from the inferred dam location the Nulhegan River flows through a gorge up to 30 m deep and 1 km long, and erosion of this feature, even in unconsolidated sediments, might have taken several centuries, especially if the water discharges were modest. Given the uncertainty surrounding this event, and the minor thickness of this zone within the Nulhegan Pond record (24 cm out of 1472 cm, <2%) the depth–age model was not adjusted to treat this interval as an instantaneous event. However, study of the sedimentary record of Glacial Lake Colebrook (Lougee, 1939) downstream from the NB might reveal a signal of this draining event that would allow its duration to be determined.

Post-Younger Dryas ecosystem response

The boundary between Zones 3 and 4 corresponds to the onset of gyttja deposition in Nulhegan Pond. This shift in the style of sedimentation, combined with rapid increases in LOI and bSi, indicates that the aquatic environment became markedly more productive following the higher-energy event recorded in Zone 3. The simultaneous onset of these changes at 11.8k cal a BP is consistent with an ecosystem response to the end of the Younger Dryas cold interval known to have affected this region (Levesque *et al.*, 1993; Cwynar and Spear, 2001) where numerous lacustrine records exhibit similar, rapid increases of LOI at the Pleistocene–Holocene transition (Borns *et al.*, 2004; Kurek *et al.*, 2004; Oswald and Foster, 2012). The start of Zone 4 also corresponds with a dramatic decrease in the abundance of coarse particles. Values at this time fell to below modern levels, implying that water depths remained greater than they are today even after draining of GLN, consistent with the position of the Zone 4 sediments within the Nulhegan Pond stratigraphy (11 m below the modern lake bottom).

Stagnant ice persistence and the formation of Beecher Pond

The basal date from Beecher Pond indicates that this basin formed in the earliest Holocene. In contrast, compilation of lake-bottom dates indicates that other ponds in northern New England formed 2000 years earlier (Thompson *et al.*, 1999). Furthermore, incursion of marine waters to form the Champlain Sea *c.* 13.0k cal a BP (Fig. 1) requires that the southern margin of the Laurentide Ice Sheet was located ~200 km north of the NB on the north side of the St Lawrence valley by this time (Richard and Occhietti, 2005). Given its location in a landscape of hummocky topography, it seems likely that Beecher Pond formed as a kettle produced by surface collapse over a melting ice block. Thus, the ice that melted to form the depression holding Beecher Pond appears to have persisted for at least 2000 years after retreat of active ice from this region. This is an unexpected result, and it is possible that coring efforts failed to retrieve the deepest material from this basin, as has been reported from some other sites in the region (Davis and Davis, 1980). However, multiple attempts to drive to stratigraphically deeper levels encountered rocks at the same depth, suggesting that the basal date is accurate. Persistence of buried ice until 11.3k cal a BP may have been aided by low temperatures during the Younger Dryas, the size and depth of burial of the ice block beneath thick ice-contact stratified debris, and the relatively high elevation of the Nulhegan Basin.

It is also notable that the bottommost sediment of the Beecher Pond core contained abundant organic matter, including the leaf that provided the ^{14}C age. This characteristic is in stark contrast to the 3 m of inorganic sand and silt below the gyttja in the Nulhegan Pond core. A possible explanation is that the land surface in the vicinity of Beecher Pond was vegetated by the time at which the collapse occurred, which is supported by the rising LOI and bSi values in Nulhegan Pond at the onset of Zone 4.

Values of mean GS, the abundance of the >30-μm size fraction and C:N reach record values in Beecher Pond toward the end of Zone 4, suggesting that abundant terrestrial material (clastic and organic) was mobilized into the water. In contrast, proxy trends in Nulhegan Pond continue essentially unchanged from their trajectories earlier in the zone. This discrepancy may reflect landscape instability associated with final melt-out of buried ice in the vicinity of Beecher Pond. Because the pond lacks connection to a major inflowing stream, it is unlikely that changes in surface water hydrology were responsible for delivering increased amounts of terrestrial material. And a lowering of water level, which might be inferred from the increased grain size, fails to explain the above-average LOI values that accompany the peaks in grain size. Final melt-out of buried ice may correspond to maximum summer insolation values (Berger and Loutre, 1991).

Evidence for low water

The proxy shifts during Zone 5 (8.9–5.6k cal a BP) constitute one of the most striking signals seen in the records from both ponds. Values of LOI and grain size are consistently high in Nulhegan Pond and generally above average in Beecher Pond. Values of C:N are below average in Nulhegan and greatly reduced from Zone 4 levels in Beecher, and bSi is below average in both records. Collectively these shifts are best explained by a sustained interval of low water in both lakes. Exposure of pre-existing, organic-rich lacustrine sediment by a drop in water level would lead to elevated LOI and decreased C:N as that material was reworked basinward. A reduction in the area of shallow water would negatively impact the population of benthic diatoms, lowering the overall bSi content of the sediment. And shifting of the higher energy littoral zone closer to the coring sites in each pond would increase the abundance of coarser grain sizes in the records (Shuman, 2003).

Other alternatives fail to adequately explain the entire suite of proxy shifts. For instance, an increase in precipitation could explain the larger grain sizes, but increased surface water inputs would deliver terrestrial organic matter with a higher (not lower) C:N. Increased inflow could also explain the decrease in bSi if the lakes became more turbid, yet mean grain size would decrease (not increase) as the abundance of silt was elevated. The prominent rise in LOI in Nulhegan Pond could be attributed to a decrease in inflow that reduced the amount of terrigenous material available for diluting the organic matter in the sediment. However, it is unclear how this change would lead to an increase in the abundance of coarser grains unless water level also dropped. Similarly, an increase in lake level could also reduce the influence of terrigenous clastic material, which could lead to an apparent increase in the abundance of organic matter. But greater water depth and distance from shore are inconsistent with the increases in grain size.

Numerous studies have reconstructed Holocene lake level change in the north-eastern US and south-eastern Canada (Fig. 1). Some concluded that lake levels were low in the middle Holocene, while others concluded that levels were relatively high at this time (all ages have been converted to calendar years BP with Calib 6.0). For instance, studies in Maine documented low water from 9.0 to 5.6k cal a BP (Almquist *et al.*, 2001), as well as 9.0 to 8.0k cal a BP and 7.3 to 6.5k cal a BP (Dieffenbacher-Krall and Nurse, 2005). Low water was also reported at sites in southern Quebec including Lac Hertel from 9.0 to 8.0k cal a BP and 7.6 to 6.6k cal a BP (Muller *et al.*, 2003), and Lac Albion from 11.0 to 6.9k cal a BP and 6.1 to 4.4k cal a BP, which overlaps with Zone 5 (Lavoie and Richard, 2000). In contrast, numerous studies from southern Massachusetts reported prolonged intervals of low water levels during the early and late Holocene (Newby *et al.*, 2000, 2009, 2011; Shuman *et al.*, 2001; Shuman and Donnelly, 2006). Recent, higher-resolution investigations have revealed shorter episodes of low water in the middle Holocene in some of these lakes, but the overall suggestion is that the lake levels were generally high during the middle Holocene in southern Massachusetts (Newby *et al.*, 2009; Shuman *et al.*, 2009). Similar results were reported from the Finger Lakes region in western New York where an early Holocene lowstand was centered on ~10k cal a BP (Dwyer *et al.*, 1996) and from Echo Lake in north-central New Hampshire where water levels were low from ~11.0 to 8.0k cal a BP and high from ~8.0 to 5.0k cal a BP (Shuman *et al.*, 2005).

When these water level reconstructions are considered spatially, a pattern emerges with generally low water levels during the middle Holocene in northern lakes (Maine, Vermont and southern Quebec), and high water levels during this time in southern (Massachusetts) and western (New York) lakes (Fig. 4). One outlier is the record from Echo Lake in New Hampshire (Shuman *et al.*, 2005), which resembles the southern signal despite its northern latitude, but overall the pattern suggests an intraregional dichotomy in lake level change with time. Almquist *et al.* (2001) concluded that Holocene moisture variations in this region were controlled by shifts in the relative dominance of cold/dry Arctic air, mild/dry Pacific air and warm/moist tropical air leading to locally divergent precipitation patterns. However, the mechanism responsible for the shifting influence of these air masses is unclear. Dwyer *et al.* (1996) suggested that intensified monsoons during the middle Holocene, possibly enhanced by latitudinal shifts in the position of the jet stream, may have been responsible for the observed offset in the timing of lake highstands between the north-eastern and central US. Shuman and Donnelly (2006) proposed that lake level fluctuations in the north-eastern US could have been driven by changing seasonality of precipitation, perhaps as a response to atmospheric reorganization accompanying final collapse of the Laurentide Ice Sheet. Modeling experiments reveal that shifting precipitation from winter to summer would reduce groundwater recharge and lower lake levels (Shuman and Donnelly, 2006), so perhaps the relatively low water at northern sites in the middle Holocene reflects a decrease in winter precipitation relative to summer. Given its relatively high elevation, surrounding ring of mountains and permeable surficial aquifer, water levels in the NB should be particularly susceptible to changes in winter snowfall. Whatever the cause, the results of this study indicate that the mechanism(s) responsible for fluctuations in lake level during the Holocene was capable of driving divergent responses at subregional scales. Future efforts involving multi-core studies (e.g. Shuman and Donnelly, 2006; Newby *et al.*, 2011) and isotopic data (Kirby *et al.*, 2002) should be aimed at more precisely delineating the pattern of Holocene lake level fluctuations in the north-eastern US and southern Quebec.

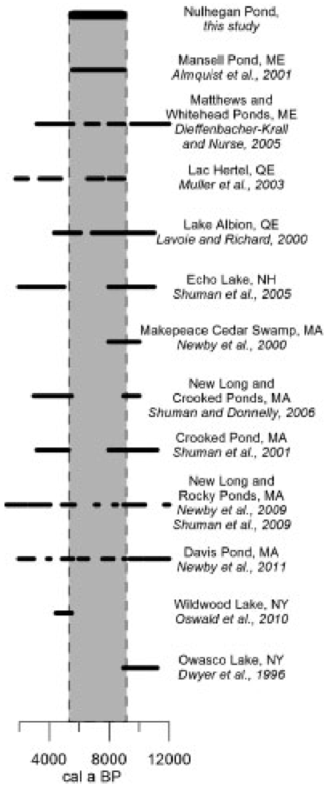

Figure 4. Durations of low-water stages reported for lakes in southern Quebec and the north-eastern US arranged roughly from north to south. Locations are given in Fig. 1. Northern sites, including this study from the Nulhegan Basin, generally experienced low water during the middle Holocene, while prolonged lowstands occurred in southern sites during the early (and late) Holocene. Recent high-resolution studies from south-eastern Massachusetts (Newby *et al.*, 2009; Shuman *et al.*, 2009) reveal short-lived fluctuations throughout the Holocene.

Late Holocene water-level rise and drainage integration

Following the end of Zone 5, bSi rises in both lakes, reaching record values in Nulhegan Pond, while LOI falls. A possible explanation is that an increase in effective moisture raised water levels, expanding the area of shallow shelves suitable for abundant diatom growth. A return to deeper water conditions is also indicated by the pronounced decrease in mean grain size in Nulhegan Pond. Alternative explanations, such as a reduction in streamflow that decreased dilution of bSi by clastic sediment, are unable to explain the divergent directions of LOI and bSi in Nulhegan Pond, and the simultaneous changes in Beecher Pond during this zone.

This hydrologic shift was apparently driven by an overall increase in precipitation volume, or winter snowfall, that raised the water table, rather than by an increase in precipitation intensity, because mean grain size values in Beecher Pond, which are controlled by overland flow, remain similar to those in Zone 5. This interpretation is consistent with reconstructions of Holocene storminess in this region that exhibit a general low between ~6 and ~4k cal a BP (Noren *et al.*, 2002; Parris *et al.*, 2010). An exception in the Beecher Pond record is a brief spike in the abundance of >30-μm particles at *c.* 5k cal a BP. This coarsening coincides with a major transient rise in LOI and a less dramatic rise in C:N, suggesting that a short-lived interval of intense precipitation events increase enhanced overland delivery of terrestrial sediment to the pond.

Finally, the prolonged interval of above-average LOI and C:N values, and at (or above) average sediment coarseness, in Nulhegan Pond during Zone 7 suggests increasing sediment delivery from the Nulhegan River. Explanations for the LOI rise involving increased in-lake productivity fail to explain the simultaneous rise in mean grain size, as well as increases in C:N to record values. In contrast, the lack of an obvious increase in sediment coarseness during Zone 7 in Beecher Pond indicates that the volume of overland flow to the pond remained low, and low (and decreasing) values of C:N indicate that the amount of terrestrial organic matter entering the pond was decreasing over time. These opposing trends can be explained by evolution of the Nulhegan River system. As the river and its tributaries became increasingly well integrated in the late Holocene, larger flows of water could be conveyed through Nulhegan Pond from the surrounding watershed. Furthermore, an extensive wetland located 500 m upstream from Nulhegan Pond may represent a former kettle that has been nearly filled by sediment. Final filling of this kettle during the last 3000 years would have allowed increasing amounts of coarser sediment and terrestrial organic matter to continue downstream into Nulhegan Pond. None of these changes would have affected Beecher Pond because it is not connected with the Nulhegan River.

Conclusions

Multiproxy study of well-dated, high-resolution sediment cores from two ponds supports reconstruction of the post-glacial environmental history of the NB in north-eastern Vermont. Major findings include:

1. Glacial outwash derived from stagnant ice blocks accumulated in the NB following deglaciation at *c.* 13.4k cal a BP.
2. After the Nulhegan River was blocked by glacial debris, water inundated 14 km^2 of the NB floor, forming GLN. This lake existed from 13.4 to 12.2k cal a BP and had maximum water depths in excess of 22 m.
3. GLN drained between 12.2 and 11.8k cal a BP, possibly as a catastrophic event driven by collapse of an ice-cored dam.
4. Organic proxies in Nulhegan Pond record simultaneous and dramatic increases in productivity at *c.* 11.8k cal a BP following draining of GLN and the end of the Younger Dryas.
5. Beecher Pond formed through collapse at *c.* 11.3k cal a BP of a vegetated surface over a melting ice block that persisted for ~2000 years after deglaciation of the Nulhegan Basin.
6. A sustained period of low water levels occurred in both ponds from 8.9 to 5.6k cal a BP. Middle Holocene aridity is consistent with records from elsewhere in the extreme north-eastern US and southern Quebec, but is out of phase with records from southern Massachusetts and New York.
7. Increased inputs of terrestrial organic matter and coarse sediment into Nulhegan Pond during the late Holocene reflect enhanced integration of the Nulhegan River system.

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Abbreviations. bSi, biogenic silica; GLN, Glacial Lake Nulhegan; GS, grain size distribution; LOI, loss-on-ignition; NB, Nulhegan Basin.

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