ARTICLE IN PRESS

Journal of Great Lakes Research xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/ijglr

Fen development along the southern shore of Lake Ontario

Douglas A. Wilcox [a,*], Eli L. Polzer [a,1], Andie Graham [a], Robert K. Booth [b], Bradley Mudrzynski [a,2]

[a] *Department of Environmental Science and Ecology, SUNY Brockport, 350 New Campus Drive, Brockport, NY 14420, USA*
[b] *Earth & Environmental Sciences Department, Lehigh University, 1 West Packer Avenue, Bethlehem, PA 18015, USA*

ARTICLE INFO

Article history:
Received 13 July 2022
Accepted 3 October 2022
Available online xxxx
Communicated by Anett Trebitz

Keywords:
Hydrology
Modern vegetation
Paleoecology
Peatland development
Water chemistry

ABSTRACT

Fen development along a drowned-river-mouth tributary to Braddock Bay, Lake Ontario was studied to address its formation. Nested piezometers were installed to assess groundwater contributions and obtain water chemistry samples. Soil and geology information came from existing sources. We converted paleo lake levels from published reports to IGLD1985 and calendar years BP for use in analyzing vegetation changes over time using a combination of peat-core plant macrofossils and modern surveys. Piezometer data showed upward discharge, water at 3-m depth had pH 6.9, specific conductivity of 508 µS/cm, and alkalinity 206 mg/L as $CaCO_3$. Hydraulic head and mineralized water chemistry decreased at shallower depths. Vegetative development began 1790 cal yr BP with sedges and brown moss when land surface was 0.135 m above lake level. Lake levels increased, and by 1590 cal yr BP, water was 0.17 m deep and sedges were joined by shoreline emergent species. Water depth then increased to 0.525 m but began decreasing as lake levels fell. Peatland species appeared around 810 cal yr BP when water depth was reduced to 0.225 m. About 585 cal yr BP, additional peatland species appeared when land surface was 0.075 m above lake level. *Sphagnum* became prominent 80 cal yr BP (0.81 m above lake level), representing 67 % mean cover in modern vegetation. Isolation of the surface from calcareous groundwater resulted in transition from rich fen to poor fen. These wetlands are rare in the lower Great Lakes and deserve protection of their characteristic hydrology, water chemistry, and vegetation structure.

Introduction

In 2014, while performing ancillary wetland research in the Rochester Embayment Area of Concern of southern Lake Ontario, we discovered a discrete, lake-connected peatland resembling shoreline fens of more northerly Lake Superior (Wilcox et al., 2002; Epstein, 2017). The peatland (which we named Buttonwood Fen) was being actively invaded by hybrid cattail (*Typha* × *glauca*), as are most coastal wetlands of the lake (Wilcox et al., 2008; Wilcox and Bateman, 2018). However, the interior portion remained relatively uninvaded (Graham et al., 2021) and characteristic of fens, which are important wetland ecosystems for study in the temperate zone because they often contain diverse assemblages of plants, with rare and protected species (Johnson and Leopold, 1994; Amon et al., 2002).

Southern Lake Ontario seemed like an unusual location for such a peatland and generated the question sometimes asked among wetland scientists: “Why this kind of wetland here?” The answer generally involves hydrology and landscape position, underlying geology, soils, water chemistry, and climate that result in wetland plant communities. In the case of fen peatlands, the straightforward answer is often groundwater hydrology. Although similar peatlands are present on the eastern shore of Lake Ontario (Godwin et al., 2002; Bailey and Bedford, 2003; Distler 2010), little is known of their origin. To place Buttonwood Fen within an appropriate historical and ecological context and to understand the timing and means of its development, we pursued a multifaceted analysis including modern vegetation, hydrology, water chemistry, soils, geology, and paleoecology.

Definitions of fens sometimes have been associated with characteristic vegetation, but peatland plants often occur in both bogs and fens. Thus, source of water is used to separate precipitation-fed ombrotrophic bogs from groundwater-fed minerotrophic fens. Bedford and Godwin (2003) provided 11 fen definitions used by a variety of authors but concluded that fens are “wetlands that develop where a relatively constant supply of groundwater to the plant rooting zone maintains saturated conditions most of the time and the water chemistry reflects the mineralogy of the surrounding and underlying soils and geological materials.” How fens develop

---

[*] Corresponding author.
E-mail address: dwilcox@brockport.edu (D.A. Wilcox).
[1] Present address: U.S. Fish and Wildlife Service, 6578 Dogwood View Parkway, Suite A, Jackson, MS 39213, USA.
[2] Present address: 6982 Norton Rd., Elba, NY 14058, USA.

https://doi.org/10.1016/j.jglr.2022.10.005
0380-1330/© 2022 International Association for Great Lakes Research. Published by Elsevier B.V. All rights reserved.

Please cite this article as: D.A. Wilcox, E.L. Polzer, A. Graham et al., Fen development along the southern shore of Lake Ontario, Journal of Great Lakes Research, https://doi.org/10.1016/j.jglr.2022.10.005

in groundwater-fed locations differs by geomorphic setting in the landscape, such as shallow basins receiving groundwater discharge, ice-block depressions (kettle holes), small ravines, along rivers or streams in shallow valleys, large open-end basins, and topographic breaks that create hydrologic gradients causing groundwater to reach the land surface (Johnson, 1985; Amon et al., 2002). Examples of studies on development of various types of fens follow.

Wilcox et al. (1986) and Shedlock et al. (1993) used studies of hydrology, water chemistry, modern vegetation, topography, stratigraphy, and local geology at Cowles Bog (fen) in Indiana, USA to show the progression of sediment types and upward groundwater discharge. Stratigraphic studies using macrofossil and pollen analyses in wetlands of southern Ontario included both bog and fen development, largely in kettle holes (Bunting and Warner, 1998). McNamara et al. (1992) conducted a thorough assessment of hydrology, water chemistry, and stratigraphic fen development in a kettle hole in New York State. Many studies have addressed development of more northerly fens, including those by Foster and King (1984), Glaser (1992), and Bauer et al. (2003). However, water availability in some temperate zone areas may be less than in the boreal zone, making continuous groundwater discharge necessary to maintain saturation conducive to peat formation (Amon et al., 2002).

Bailey and Bedford (2003) conducted groundwater hydrology studies of a fen in the Deer Creek wetland complex that is intermittently connected to eastern Lake Ontario behind a barrier beach, where constant groundwater discharge into the peat occurred at all times. Correlations with modern lake-level change were also made. Although peat depths were measured, fen development was not assessed. Distler (2010) analyzed plant macrofossils from fens at Deer Creek and South Sandy Pond and assessed successional developmental history, including correlation with rising lake levels. However, paleo lake-level changes during fen development were not assessed, and groundwater studies were not conducted. Development of lake-edge fens on Lake Superior or other Great Lakes has not been addressed. Therefore, the objective of this study was to characterize modern vegetation at Buttonwood Fen, identify and measure the presence of groundwater discharge, characterize groundwater chemistry, assess the potential source of groundwater discharge, and determine possible fen development by analyzing radiocarbon-dated paleo vegetation changes using plant macrofossils and relate them to published paleo lake levels converted to the radiocarbon and lake-level scales used today.

Methods

Study site

Buttonwood Creek is a drowned river mouth wetland (Albert et al., 2005) tributary to Braddock Bay on the south shore of Lake Ontario near Rochester, New York, USA (Fig. 1). Physiographically, it is situated on the southern edge of the Erie/Ontario Lake Plain north of the flat inland agricultural areas of the Ontario Lowlands (Bryce et al., 2010). Buttonwood Fen (43.300°N, 77.728°W) is adjacent to Buttonwood Creek 1.2 km from the outlet to Braddock Bay. Because Buttonwood Creek is lake-connected, water-level regulation that began about 1960 with operation of the St. Lawrence Seaway under Plan 1958DD caused cattail invasion (Wilcox et al., 2008). Channels and potholes were excavated along Buttonwood Creek from December 2014 to March 2015 as part of a wetland restoration project to address cattail invasion (Polzer and Wilcox, 2022); restoration of Buttonwood Fen to reduce cattail cover was conducted in 2016–2018 (Graham et al., 2021). However, due to their timing and nature, neither restoration project affected results from this study.

Site delineation and elevation

We delineated the site in 2016 by mapping the extent of peatland vegetation using Real Time Kinematic GPS (RTK) (Trimble, Sunnyvale, CA). The 0.16-ha interior portion that was not invaded by *Typha* contained numerous taxa representative of temperate peatlands, such as *Phragmites australis* ssp. *americanus*, *Eriophorum virginicum*, *Drosera rotundifolia*, *Morella pensylvanica*, and *Sphagnum* spp. An area of approximately 4.25 ha (invaded fen) surrounded the interior fen and contained several peatland species in the understory but was being invaded along its outer edge by a moderately dense stand of cattails. The RTK GPS was also used to measure surface elevations at 78 randomly selected locations in the interior fen so they could be related to hydrologic data.

Modern vegetation

The plant community of the interior fen was sampled on 14–20 June 2016. Vegetation in 25 1-m^2 quadrats placed in a stratified random pattern (blind toss over shoulder) and a minimum of 2.5 m apart was sampled by identifying all plants to the lowest taxonomic level possible. Visual estimates of percent cover for each taxon were made at 1 % increments up to 5 % and then in 5 % increments. Mean percent cover for each taxon was then calculated.

Hydrology, water chemistry, soils, and geology

On 19 June 2017, three nested piezometers were placed adjacent to each other in the interior fen to assess vertical direction of groundwater flow. They were made from 2-cm inside diameter PVC tubing (outside diameter 2.5 cm) and capped at the bottom. The piezometer tubes were long enough to reach and anchor in soils at the bottom (approximately 3.2 m beneath the surface) so that they would not move if the fen mat moved up or down. Screens of 10-cm width created by drilling 1-mm holes were centered at 3 m, 2 m, and 1 m deep on the respective piezometers. Holes were created through the peat using a 2.5-cm diameter soil auger, and after insertion, the piezometers were driven to contact with the bottom and anchored using a short plank and mallet. A 12-volt peristaltic pump with polyethylene tubing was used to clear any sediment or debris from the piezometers, and they were allowed to settle for a day before water levels were measured by tape and chalk. Elevations of the piezometers were surveyed by RTK GPS on 22 June and corrected to International Great Lakes Datum 1985 (IGLD85) based on Lake Ontario water level on that date (75.75 m). Single piezometers were also placed at 3-m depths at two locations at the edge of the cattail-invaded portion of the fen. The peristaltic pump was used to evacuate each of the nested piezometers on 21 July 2017, and water samples were withdrawn for measuring field parameters of temperature, pH, specific conductance (SPC), and alkalinity. Since water could enter the nested piezometers only through screens at 1, 2, and 3 m, samples represented those elevations. Specific conductance in water samples from three 30-cm-deep excavations that were dug by hand within 2 m of the piezometers was also analyzed; the water table was 1–2 cm from the surface.

Elevations of lands surrounding the site were obtained from https://www.gmrt.org/GMRTMapTool/. Soils data from the area were obtained from https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx and underlying geologic information for the region from http://www.nysm.nysed.gov/research-collections/geology/gis and https://mrdata.usgs.gov/geology/state/.

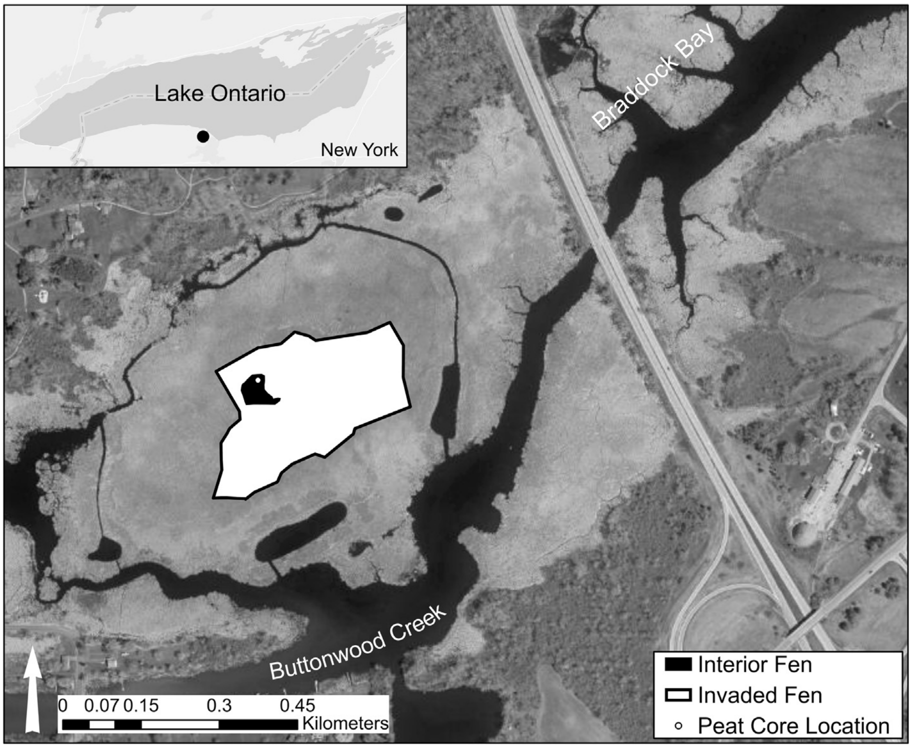

Fig. 1. Map of Buttonwood Fen, adjacent to the Buttonwood Creek drowned-river-mouth tributary to Braddock Bay on the southern shore of Lake Ontario near Rochester, NY. Shown are the Interior (0.16 ha) and cattail-Invaded (4.25 ha) portions of the peatland, as well as the location of the peat core and the nested piezometers.

Paleoecology

To assess long-term development of plant communities, a modified Livingstone piston-corer (10.5-cm diameter), with a serrated edge designed specifically for peatlands, was used to collect a 271-cm-long peat core from the approximate center of the open, *Sphagnum*-dominated, interior area at Buttonwood Fen on 6 April 2015. The peat core was collected in three drives, terminating at the contact zone with lake sediments, and was described in the field, wrapped in plastic wrap and aluminum foil, secured in PVC tubes, and returned to Lehigh University for cold storage and subsampling.

Plant macrofossils were subsampled and quantified every 6 cm along the length of the core. At each sampling location, a 40-cm^3 subsample was collected from a 1-cm slice of peat. Subsamples were disaggregated by gently wet-sieving, and all material greater than 300 μm in diameter was scanned under a standard dissecting microscope. Individual plant macrofossil types (e.g., leaves, seeds) were identified to the lowest taxonomic level possible and tallied. Plant macrofossil reference collections (R.K. Booth at Lehigh University and M.T. Distler at SUNY College of Environmental Science and Forestry), as well as reference literature (Montgomery, 1977; Martin and Barkley, 2000), were used for identification. Data were expressed as total counts for each macrofossil type per 40 cm^3 of peat. Leaves of mosses and sedges were too abundant to count in many samples, so qualitative notes on their abundance were made and used along with field notes to describe the general peat stratigraphy.

Eight samples of above ground plant remains or charcoal were selected, cleaned in deionized water, and submitted for AMS ^{14}C dating to the University of Georgia's Center for Applied Isotope Studies. All radiocarbon ages were calibrated using the INTCAL20 calibration curve (Reimer et al., 2020) and the CALIB 8.2 program (Stuiver et al., 2022), except for one young date that was calibrated using the NHZ1 post-bomb calibration curve and the CALIBOMB program (Reimer and Reimer, 2022). An age-depth model for the peat core was developed using the core surface age along with the calibrated radiocarbon dates using the program CLAM (Blaauw, 2010).

Results and discussion

Hydrology, water chemistry, soils, and geology

The peat surface across the interior fen ranged from 75.75 m (lake level) to 76.00 m IGLD85. At the piezometer site, the elevation was 75.92 m. Water level in all nested piezometers was above land surface: 76.005 m for the 1-m well, 76.040 m for the 2-m well, and 76.150 m for the 3-m well. The vertical hydraulic gradient $\Delta h/\Delta z$ (76.150 m-76.005 m/2.0 m) for comparison of 3-m and 1-m piezometers was +0.0725, thus demonstrating upward flow of groundwater at the site, and meeting the hydrologic definition of fen (e.g., Bedford and Godwin, 2003). Reduced hydraulic gradients from comparisons of 3-m vs 2-m (0.11 m/1.0 m = +0.11) and 2-m vs 1-m (0.035 m/1.0 m = +0.035) piezometers indicate that most of the head differential was lost closer to the surface. Water levels in the two deep piezometers at the outer edge of the cattail-invaded portion of the fen were 0.5 and 6.0 cm above the land surface, thus showing discharge but reduced hydraulic head.

Water withdrawn from the 3-m nested piezometer had temperature 14.8 °C, pH 6.9, SPC 508 μS/cm, and alkalinity 206 mg/L as $CaCO_3$, indicating groundwater discharge from a mineralized aquifer, as is common for fens in limestone-rich regions (e.g., Boelter and Verry, 1977; Wilcox et al., 1986; Bedford and Godwin, 2003; Vitt et al., 2005). Water from the 2-m piezometer had temperature 15.1 °C, pH 5.8, SPC 151 μS/cm, and alkalinity 27 mg/L as $CaCO_3$. Water from the 1-m piezometer had temperature 16.0 °C, pH 5.7, SPC 66 μS/cm, and alkalinity 13 mg/L as $CaCO_3$. The water samples from the excavations were likely diluted by precipitation and had SPC of 68, 57, and 64 μS/cm, respectively.

Water chemistry in the piezometers at Buttonwood Fen is characteristic of fens (e.g., Amon et al., 2002; Godwin et al., 2002; Bedford and Godwin, 2003; Vitt and Wieder, 2009), but bog/poor fen conditions are present nearer the surface (Vitt and Chee, 1990; Vitt and Wieder, 2009).

For comparison, at three coastal fen sites on the eastern shore of Lake Ontario (Rainbow Shores, South Sandy Pond, Deer Creek), Distler (2010) found surface water pH to range from about 5.2 to 5.9 and SPC from 91 to 102 μS/cm. In deep piezometers at Cranberry Pond Fen, later discovered near Buttonwood Fen on the southern shore of Lake Ontario, Kirkpatrick (2021) found water chemistry similar to Buttonwood Fen, with pH around 6.0 to 6.2, alkalinity ranging generally about 120 mg/L as $CaCO_3$, and much greater SPC, ranging as high as about 900 μS/cm. She also found that nested piezometers at Cranberry Pond Fen indicated groundwater discharge.

Large values for SPC and alkalinity for groundwater discharge at Buttonwood Fen indicate recharge and/or discharge through calcareous deposits. Soils adjacent to the fen location include areas with Hilton loam 0–3 % slope (HIA) and 3–8 % slope (HIB), both of which are about 11 % $CaCO_3$ (Fig. 2). A broad area from Lake Ontario inland to approximately 13 km from the fen (perpendicular to shore) is underlain by Queenston Shale (Oq) and from 13 to approximately 14 km by Thorold Sandstone (Sm) (Fig. 3). From 14 to 15 km, the underlying formation is Irondequoit Limestone (Sik) at an elevation 75 m greater than the fen, followed by Decew Dolostone (Sr) from about 15 to 16.5 km and Guelph Dolostone (Sl) from 16.5 to about 23 km. The mineralized groundwater discharge at the fen may be from waters recharged locally as suggested by the soils map. However, discharge is more likely from recharge in the limestone/dolostone formations to a deeper regional aquifer that discharges beneath Lake Ontario and the adjacent shoreline. Such was suggested by Crowe and Shikaze (2004) for Great Lakes wetlands and shown by Crowe and Meek (2009) for Lake Huron beaches and Wilcox et al. (2020) for a wetland complex on Lake Michigan.

Modern vegetation

Mean percent cover of plants found in quadrat sampling was dominated by *Sphagnum* spp. (67.2 %), followed by *M. pensylvanica* (23.6 %) and *Thelypteris palustris* (11.5 %) (Table 1). Less common but prominent species were *Lysimachia thyrsiflora*, *Osmundastrum cinnamomeum*, *Triadenum fraseri*, and *Juncus canadensis*. Of note were occurrences of *Boehmeria cylindrica, Calamagrostis canadensis, Comarum palustre, Decodon verticillatus, D. rotundifolia, Dulichium*

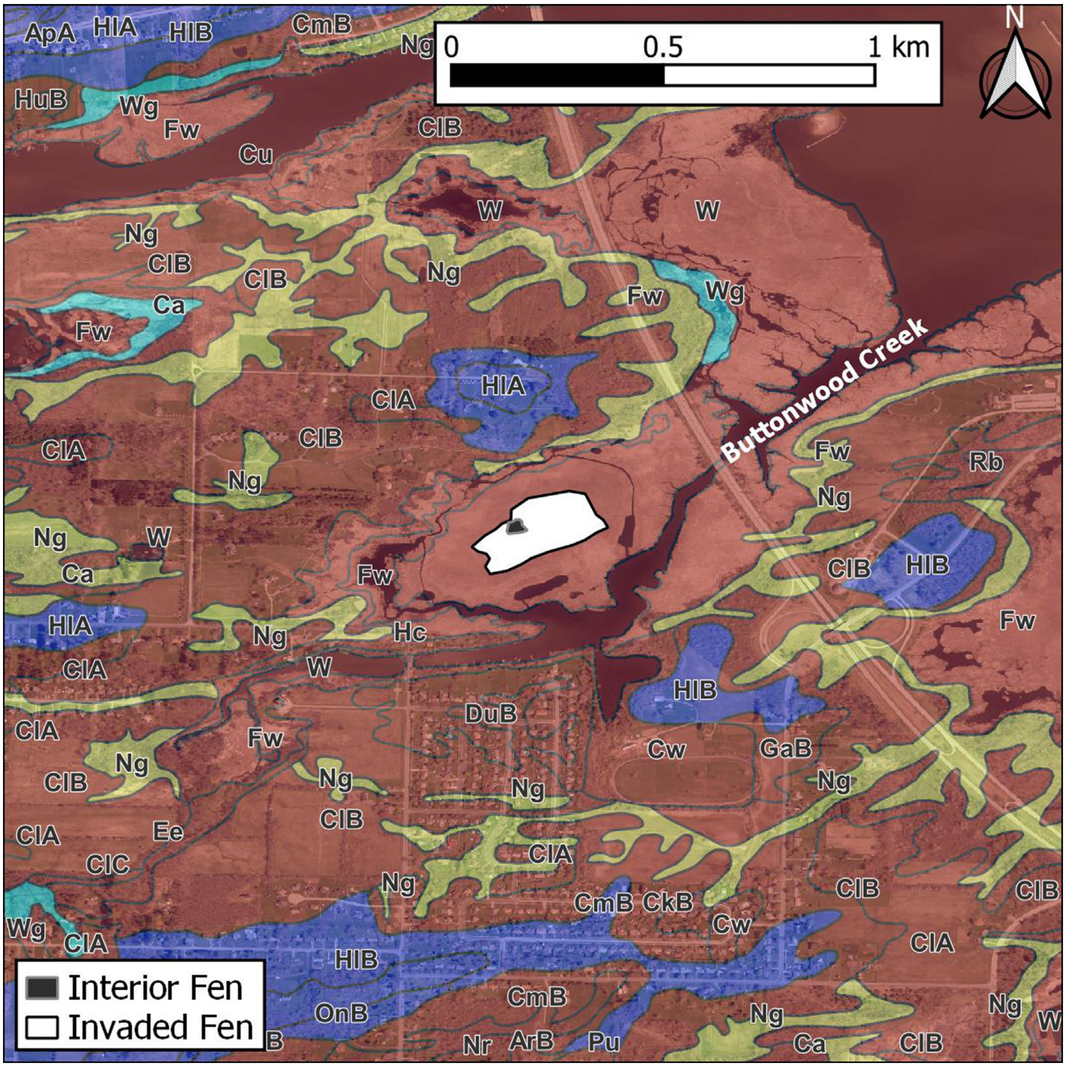

Fig. 2. Map of the soils adjacent to Buttonwood Fen showing Hilton loam 0–3% slope (HIA) and 3–8% slope (HIB), both of which are about 11% $CaCO_3$ and thus reflect the calcareous nature of groundwater discharge. Other soil types are not calcareous. As depicted in Fig. 1, the sweeping arc across the map is a highway.

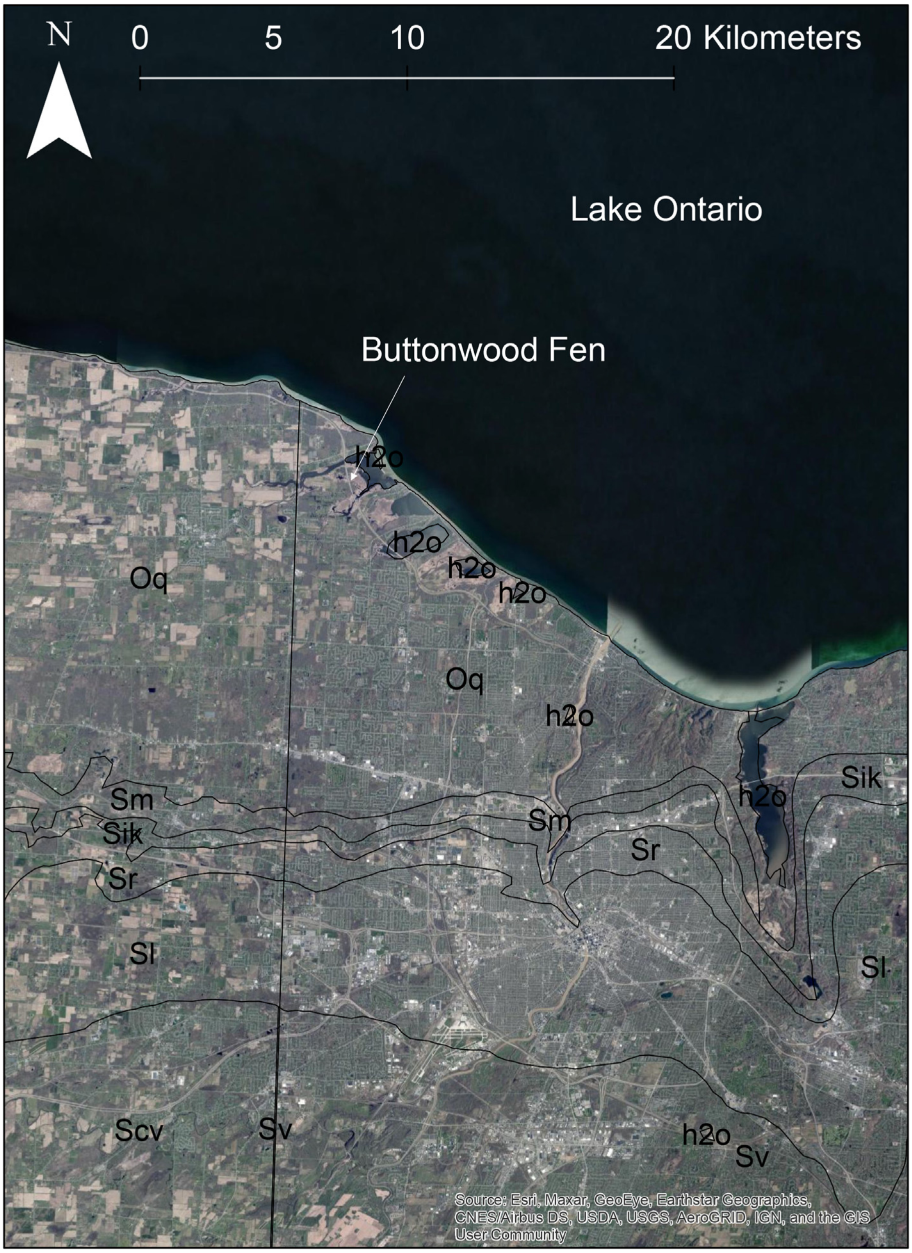

Fig. 3. Map of underlying regional geology potentially sourcing calcareous groundwater to Buttonwood Fen, with Irondequoit Limestone (Sik), Decew Dolostone (Sr), and Guelph Dolostone (Sl) ranging from 14 to 23 km from the fen at an elevation 75 m greater than the study site**.** Other bedrock formations shown are Queenston Formation (Oq), Thorold Sandstone (Sm), Vernon Formation (Sv), and Camillus Shale (Scv). The black vertical line is where the Niagara and Finger Lakes maps join.

arundinacea, *E. virginicum*, *Osmunda regalis*, *P. australis* ssp. *americanus*, *Sphagnum* spp., and *Spiraea alba* (Table 1). These taxa are often found in peatlands in the Great Lakes region (Swink and Wilhelm, 1979; Chadde, 2012; Voss and Reznicek, 2012). *Vaccinium macrocarpon* was also observed but not captured in our sampling effort.

In much more extensive sampling of coastal fen habitat at three sites (South Sandy Pond, Rainbow Shores, Deer Creek) on the eastern shore of Lake Ontario in 2004 and 2005, Distler (2010) found these and many additional peatland species. Sampling of fen habitat at South Sandy Pond in 2011 and Rainbow Shores in 2012 and 2017, as well as (eastern shore) Cranberry Pond in 2013 and 2018, as part of the Great Lakes Coastal Wetland Monitoring Program (Uzarski et al., 2017) noted most of the same additional species (https://www.greatlakeswetlands.org).

In addition to taxa found at Buttonwood Fen, at (southern shore) Cranberry Pond Fen, Kirkpatrick (2021) also found peatland species *Carex canescens*, *Carex echinata*, *Carex lasiocarpa*, *Menyanthes calyculata*, *Drosera intermedia*, *Larix laricina*, *Sarracenia purpurea*, and *Vaccinium oxycoccos*. Greater species richness at fens on the eastern shore may relate to a greater sampling effort; however, it could be due to a slightly more northerly location or greater isolation from human activities far from the Greater Rochester area.

Fen development

Paleoecological analysis of the 271-cm peat core suggested that vegetation development at Buttonwood Fen began at an elevation nearly three meters below modern lake levels at about 1790 calen-

Table 1
Mean percent cover of plant taxa sampled in the interior portion of Buttonwood Fen in 2016. Asterisks denote taxa that are often found in peatlands in the Great Lakes region (Swink and Wilhelm, 1979; Chadde, 2012; Voss and Reznicek, 2012); others are wetland generalists.

Taxa	Mean Percent Cover	Taxa	Mean Percent Cover
Andropogon virginicus	1.4	*Morella pensylvanica* *	23.6
Boehmeria cylindrica	0.3	*Osmunda regalis*	0.6
Calamagrostis canadensis	0.8	*Osmundastrum cinnamomeum*	6.1
Carex spp.	0.4	*Parthenocissus quinquefolia*	0.1
Comarum palustre *	0.4	*Phragmites australis* ssp. americanus	2.6
Decodon verticillatus	0.6	*Rosa palustris*	0.1
Drosera rotundifolia *	0.1	*Scirpus cyperinus*	0.1
Dulichium arundinacea	0.1	*Solidago rugosa*	1.1
Eriophorum virginicum *	0.3	*Sphagnum* spp. *	67.2
Impatiens capensis	0.1	*Spiraea alba*	0.2
Juncus canadensis	4.1	*Thelypteris palustris*	11.5
Lycopus americanus	0.2	*Toxicodendron radicans*	0.2
Lycopus uniflorus	1.0	*Triadenum fraseri*	5.4
Lysimachia terrestris	0.6	*Typha* × *glauca*	2.2
Lysimachia thyrsiflora	7.2	*Viburnum dentatum*	0.9
Lythrum salicaria	0.1		

dar yrs BP. Early peatland and shallow emergent marsh would thus require that Lake Ontario water levels were much lower at that time, necessitating paleo lake-level data for analysis of paleoecological results.

Dalrymple and Carey (1990) assessed early lake levels dating back to 4200 BP by collecting sediment cores in the Cataraqui River lagoon near Kingston, Ontario in northeastern Lake Ontario. They compared organic matter content vs water depth to determine depositional environments and then compared the relations to those developed from a study using modern sediments. They graphed the elevations of sediment surfaces vs radiocarbon dates from the cores and converted them to lake-level elevations vs radiocarbon years (Fig. 4a). The results showed relatively low lake levels from estimated dates of 4200 to 3300 BP, a rapid increase at 3100 BP that lasted until 2400 BP, and a reduction in lake level at 2100 BP. Lake levels then rose rapidly and continued to rise until modern levels. To corroborate their results, Dalrymple and Carey (1990) compared their assessment of paleo lake levels to those from previous studies (Flint et al., 1988; McCarthy and McAndrews, 1988); both were considered as broadly synchronous with the Cataraqui River lagoon.

To make comparisons between the Dalrymple and Carey (1990) hydrograph and our data from Buttonwood Fen, we needed to make conversions from “meters asl” (Fig. 4a) to meters IGLD85 and from “radiocarbon years before present” to calendar years BP. With those conversions made, we plotted a new hydrograph (Fig. 4b) and identified lake-level elevations (converted to IGLD85) for each of our radiocarbon dates, which were in calendar years BP. We also converted cm depths in the peat core to meters IGLD85. Eight radiocarbon dates were obtained from the peat core (Table 2). The lowest dated level, derived from charcoal fragments, yielded an age of c. 1820 cal yr BP.

The paleoecology diagram shows lake sediments from the bottom of the 271-cm core to 260 cm (Fig. 5). These sediments were mostly inorganic and devoid of charcoal and plant macrofossils, suggesting open waters. Sedge peat and small amounts of brown moss appeared in the core at 260 cm; brown moss extended upward in varying amounts to 29 cm. From the age-depth model, it seems that vegetation development began just before 1790 cal yrs BP (Fig. 5). The 256-cm dated sample was on charcoal, suggesting presence of fire. During this time, indigenous communities

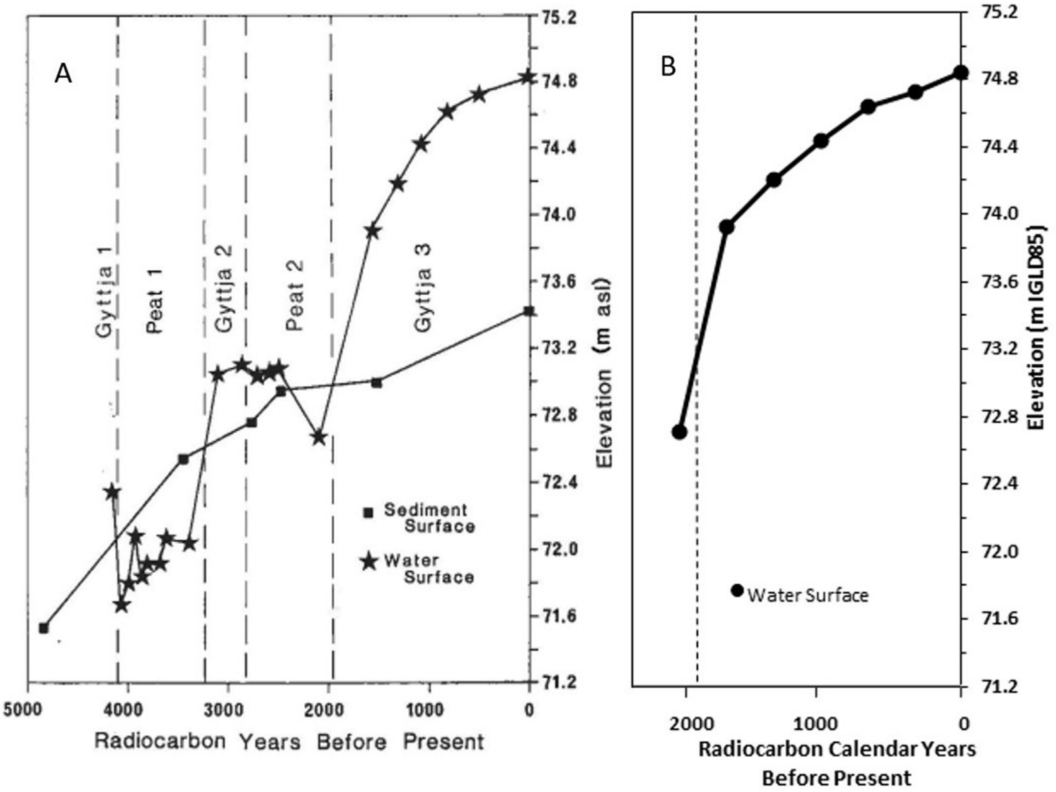

Fig. 4. Paleo water levels of Lake Ontario derived from sediment cores in the Cataraqui River lagoon near Kingston, Ontario (Dalrymple and Carey, 1990) A) in meters above sea level and radiocarbon years; B) converted to meters IGLD85 and calendar years BP.

Table 2
Radiocarbon dating results from peat core at Buttonwood Fen. The ±1σ represents one standard deviation reported lab uncertainty.

Depth (cm)	Lab number	Material dated	^{14}C yr BP ± 1σ	Median probability and 95 % confidence interval of calibrated age (cal yr BP)
34–35	UGAMS-28393	Plant fragments	60 ± 25	133 (−5 to 255)
58–59	UGAMS-28389	Plant fragments	180 ± 25	183 (0–292)
100–101	UGAMS-28394	Plant fragments	390 ± 25	465 (328–505)
112–113	UGAMS-28390	Plant fragments	650 ± 25	593 (557–667)
154–155	UGAMS-28387	Plant fragments	940 ± 25	850 (789–917)
184–185	UGAMS-28391	Plant fragments	970 ± 25	853 (793–927)
214–215	UGAMS-28388	Plant fragments	1200 ± 25	1118 (1059–1242)
256–257	UGAMS-28392	Charcoal	1910 ± 30	1819 (1736–1922)

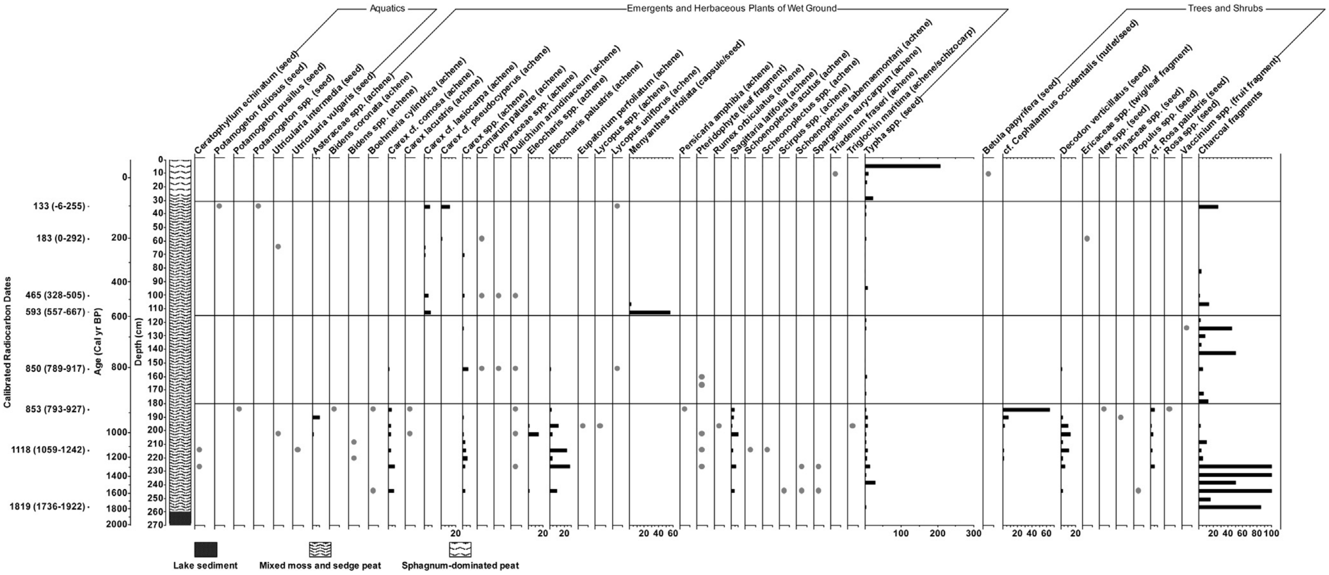

Fig. 5. Plant macrofossil concentration data for the Buttonwood Fen core, with numbers of macrofossils per 40 cm^3 plotted against depth. The position of calibrated radiocarbon dates (cal yr BP) along the core is shown on the left. An age scale is also shown next to the depth scale and was estimated from the age-depth model. Closed gray circles indicate presence for taxa with low abundance.

Table 3
Estimated age, core depth, and dated elevation from peat cores collected at Buttonwood Fen that were used to determine paleo lake levels of Lake Ontario.

Estimated Age (cal yr BP)	Core Depth (cm)	Dated Elevation (m IGLD85)	Paleo Lake Level (m IGLD85)	Dated Elevation vs Lake Level (m IGLD85)
1790	256	73.355	73.22	0.135
1590	245	73.47	73.64	−0.17
1500	240	73.52	73.84	−0.32
1130	214	73.775	74.3	−0.525
890	184	74.075	74.52	−0.445
805	154	74.375	74.6	−0.225
670	125	74.67	74.68	−0.01
590	112	74.795	74.72	0.075
490	100	74.915	74.74	0.175
210	58	75.335	74.8	0.535
110	34	75.575	74.81	0.765
80	29	75.63	74.82	0.81

were occupying nearby coastal wetland sites along Lake Ontario, such as Princess Point (Cootes Paradise Marsh) (Finkelstein et al., 2005; Haines et al., 2011). That sample, having poor macrofossil preservation, came from an elevation of 73.355 m IGLD85 (Table 3), and the paleo lake level from Fig. 4b was 73.22 m, so the sedge and moss peat that had begun forming at 260 cm was already 0.135 m above lake level. This suggests that groundwater discharge provided water to the site, as shown by our piezometer data.

Lake levels were on the rise, however (Fig. 4b), and by 1590 cal yr BP, the water was 0.17 m deep (Table 3). While *Carex* was present at 245 cm in the core, the stratum was dominated by a suite of emergent taxa characteristic of exposed shorelines and mudflats, such as *Eleocharis palustris*, *Sagittaria latifolia*, *Schoenoplectus tabernaemontani*, *Scirpus* spp., *Sparganium eurycarpum*, and *Decodon verticillatus* (Fig. 5), thus indicating a transition from a sedge marsh phase to a robust emergent marsh.

Lake levels kept rising (Fig. 4b), and by 1500 cal yr BP, water depth was 0.32 m; at 1130 cal yr BP, the water was 0.525 m deep (Table 3). Water depth then began decreasing, and at 890 cal yr BP, depth was 0.445 m. The reappearance of *Carex* and other shallow emergents (*Typha* spp., *E. palustris*, *D. verticillatus*, and *S. latifolia*) from 245 to 185 cm in the core corresponds to slight fluctuations in water levels (Fig. 5). This mixed assemblage of emergent and graminoid marsh plants, with an abrupt appearance of floodtolerant shrub *Cephalanthus occidentalis*, indicates that shallow emergent marsh (Swink and Wilhelm, 1979; Chadde, 2012; Voss and Reznicek, 2012) continued to persist in Buttonwood Fen until 890 cal yr BP or later.

At 155 cm (805 cal yrs BP), water depth was reduced to 0.225 m (Table 3), and *C. palustre* made a brief appearance, as did *Vaccinium* spp. at 125 cm (670 cal yrs BP) (Fig. 5) when water depth was reduced to 0.01 m (Table 3). These taxa are common in temperate peatlands (Swink and Wilhelm, 1979; Chadde, 2012; Voss and Reznicek, 2012). Few other macrofossils were found between 155 and 115 cm, but an increase in charcoal indicates local/regional fire activity.

At 590 cal yr BP, the dated sample originated from 112 cm in the core or 74.795 m IGLD85 (Table 3). The paleo lake level from Fig. 4b was 74.72 m, so the early phases of upper peatland development starting after 115 cm in the macrofossil record occurred on brown moss/sedge peat that was 0.075 m above lake level. Our piezometer data demonstrate that groundwater discharge, albeit with a reduced hydraulic gradient, was still occurring near this depth at one meter. Peatland species *M. trifoliata* increased in frequency at 113 cm in the core (Fig. 5), and presence of *C. lasiocarpa* suggests development of a floating mat (Chadde, 2012; Voss and Reznicek, 2012). At 490 cal yr BP (100 cm), the peat surface was 0.175 m above the paleo lake level, and *D. arundinaceum* was found at 101 cm. At 210 cal yr BP (58 cm), the surface was 0.535 m above lake level, and Ericaceae spp. was found at 59 cm.

At 110 cal yr BP (34 cm), the surface was 0.765 m above lake level (Table 3). The presence of *Potamogeton foliosus* and *Potamogeton* spp. and lack of emergent species at 35 cm (Fig. 5) suggest increased depth or proximity to open water habitat during this period. This was perhaps related to Lake Ontario water levels exceeding 75.6 m IGLD85 in 1870, 1886, and 1908 (https://www.lre.usace.army.mil/missions/great-lakes-information/great-lakes-water-levels/water-level-forecast/monthly-bulletin-of-great-lakes-water-levels/).

The peat surface at 80 cal yr BP (core depth 29 cm) was 0.81 m above lake level (Table 3). Thus, the peatland community developing after 590 cal yr BP, as shown in the macrofossil record, was capable of greater peat deposition rates (approximately 0.14 cm/yr) as rise of lake levels decelerated (Fig. 4b). The upper 29 cm of the core contained *Sphagnum*-dominated peat, demonstrating a system having undergone an ecophysiological transition from brown mosses at some point within the previous century. *Typha* spp. became prominent (Fig. 5), especially in the top 5 cm, as the fen had been invaded by cattail (Graham et al. 2021), similar to current conditions in nearly all Lake Ontario wetlands (Wilcox et al., 2008; Wilcox and Bateman, 2018; Smith et al., 2021).

Although the modern peat surface was only 0.17 m above survey date lake level of 75.75 m, the long-term average lake level when coring was done in summer was 75.05 m IGLD85 (https://www.lre.usace.army.mil/missions/great-lakes-information/great-lakes-water-levels/water-level-forecast/monthly-bulletin-of-great-lakes-water-levels/), which would place the 75.92 m peat surface at 0.87 m above average lake level and within reasonable proximity to the 0.81 m calculated for 80 cal yr BP.

During the first 700 years, the peat-accumulation rate was relatively low at approximately 0.07 cm/yr (14 yr/cm) on average. By contrast, in the last c. 100 years, peat (largely *Sphagnum*) accumulated at a much greater average rate of ~0.25 cm/yr (4 yr/cm).

So why this kind of wetland here? Development of Buttonwood Fen began along a shallow stream channel adjacent to Lake Ontario receiving calcareous groundwater discharge (3-m piezometer: pH 6.9, SPC 508 µS/cm, alkalinity 206 mg/L as $CaCO_3$). As lake water levels rose, the site began supporting sedges and emergent taxa in shallow water and accumulating the sedge peat of a rich fen. (Vitt and Chee, 1990; Amon et al., 2002; Godwin et al., 2002; Bedford and Godwin, 2003). Increasing elevations of peat resulted in shallower water, and more species characteristic of peatlands appeared. Groundwater discharge was still influencing peat pore water (2-m piezometer: pH 5.8, SPC 151 µS/cm, alkalinity 27 mg/L as $CaCO_3$), but the chemistry suggests beginning development of poor fen conditions. When peat elevation rose above water levels, additional peatland species began to occur and a floating *C. lasiocarpa* mat may have developed. Water chemistry (1-m piezometer: pH 5.7, SPC 66 µS/cm, alkalinity 13 mg/L as $CaCO_3$) clearly signaled poor fen.

Sphagnum later appeared, followed by brown moss, at which time, fostered by temporary high lake levels, submersed aquatic vegetation appeared. Reduction of lake levels following the temporary highs eliminated the submersed aquatics and likely anchored any *C. lasiocarpa* mat. Reappearance of *Sphagnum* signaled further reduction of groundwater influence, as already shown by much-reduced alkalinity in the 1-m-deep piezometer.

Transitions from emergent marsh to rich fen to poor fen have been documented by others (e.g., Kuhry et al., 1993; Bauer et al., 2003). In Buttonwood Fen, build-up of sedge peat isolated the growing surface from calcareous groundwater, resulting in transition from rich fen to poor fen water chemistry. Alkalinity was eventually reduced sufficiently to allow *Sphagnum* to grow and survive, with a modern mean cover of greater than 65 % (Table 1). Wetlands of this type are rare in the lower Great Lakes and deserve protection of their characteristic hydrology, water chemistry, and vegetation structure.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Funding for paleoecological work was provided by a SUNY Brockport Provost's Post-Tenure Fellowship Award to D. Wilcox and SUNY Brockport Distinguished Professor Award for Graduate Student Research to E. Polzer. Nate Jones, Tyler Ohle, and Robert Tyler assisted in hydrology and water chemistry field studies.

References

Albert, D.A., Wilcox, D.A., Ingram, J.W., Thompson, T.A., 2005. Hydrogeomorphic classification for Great Lakes coastal wetlands. J. Great Lakes Res. 31 (Suppl. 1), 129–146.

Amon, J.P., Thompson, C.A., Carpenter, Q.J., Miner, J., 2002. Temperate zone fens of the glaciated Midwestern USA. Wetlands 22, 301–317.

Bailey, K.M., Bedford, B.L., 2003. Transient geomorphic control of water table and hydraulic head reversals in a coastal freshwater peatland. Wetlands 23, 969–978.

Bauer, I.E., Gignac, L.D., Vitt, D.H., 2003. Development of a peatland complex in boreal western Canada: lateral site expansion and local variability in vegetation succession and long-term peat accumulation. Can. J. Bot. 81, 833–847.

Bedford, B.L., Godwin, K.S., 2003. Fens of the United States: distribution, characteristics, and scientific connection versus legal isolation. Wetlands 23, 608–629.

Blaauw, M., 2010. Methods and code for 'classical' age-modelling of radiocarbon sequences. Quat. Geochronol. 5, 512–518. https://doi.org/10.1016/J.QUAGEO.2010.01.002.

Boelter, D.H., Verry, E.S., 1977. Peatland and water in the northern lake states. General Technical Report NC-31, USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Bryce, S.A., Griffith, G.E., Omernik, J.M., Edinger, G., Indrick, S., Vargas, O., Carlson, D., 2010. Ecoregions of New York (color poster with map, descriptive text, summary tables, and photographs), map scale 1:1,250,000. U.S. Geological Survey, Reston, VA.

Bunting, M.J., Warner, B.G., 1998. Hydroseral development in southern Ontario: patterns and controls. J. Biogeogr. 25, 3–18.

Chadde, S.W., 2012. A Great Lakes Wetland Flora: a Complete Guide to the Wetland and Aquatic Plants of the Midwest. Steve W, Chadde.

Crowe, A.S., Meek, G.A., 2009. Groundwater conditions beneath beaches of Lake Huron, Ontario, Canada. Aquat. Ecosyst. Health Manage. 12, 444–455.

Crowe, A.S., Shikaze, S.G., 2004. Linkages between groundwater and coastal wetlands of the Laurentian Great Lakes. Aquat. Ecosyst. Health Manage. 7, 199–213.

Dalrymple, W.R., Carey, J.S., 1990. Water-level fluctuations in Lake Ontario over the last 4000 years as recorded in the Cataraqui River lagoon, Kingston, Ontario. Can. J. Earth Sci. 27, 1330–1338.

Distler, M.T., 2010. The Influences of Landscape Position and *Typha* (cattail) on Dominance, Diversity, and Long-Term Dynamics in Central New York Lakeside Fens. SUNY College of Environmental Science and Forestry, Syracuse, NY. PhD dissertation.

Epstein, E.E., 2017. Natural communities, aquatic features, and selected habitats of Wisconsin; Great Lakes shore fen. In: The Ecological Landscapes of Wisconsin: an Assessment of Ecological Resources and a Guide to Planning Sustainable Management. Wisconsin Department of Natural Resources PUB-SS-1131H. Chapter 7. pp. H122–H128. https://p.widencdn.net/exmng9/1805Ch7.

Finkelstein, S.A., Peros, M.C., Davis, A.M., 2005. Late Holocene paleoenvironmental change in a Great Lakes coastal wetland: integrating pollen and diatom datasets. J. Paleolimnol. 33, 1–12.

Flint, J.E., Dalrymple, R.W., Flint, J.J., 1988. Stratigraphy of the sixteen Mile Creek lagoon, and its implications for Lake Ontario water levels. Can. J. Earth Sci. 25, 1175–1183.

Foster, D.R., King, G.A., 1984. Landscape features and developmental history of a patterned mire complex on the Eagle Plateau, southeastern Labrador, Canada. J. Ecol. 72, 115–143.

Glaser, P.H., 1992. Ecological development of patterned peatlands. In: Wright, H.E. Jr., Aaseng, S.E (Eds.) The Patterned Peatlands of Minnesota. University of Minnesota Press, Minneapolis, MN. pp. 27–42.

Godwin, K.S., Shallenberger, J.P., Leopold, D.J., Bedford, B.L., 2002. Linking landscape properties to local hydrogeologic gradients and plant species occurrence in minerotrophic fens of New York State, USA: a hydrogeologic setting (HGS) framework. Wetlands 22, 722–737.

Graham, A., Mudrzynski, B., Polzer, E., Wilcox, D.A., 2021. Restoration of a Lake Ontario-connected fen through invasive *Typha* removal. Restor. Ecol. 29, 13562.

Haines, H.R., Smith, D.G., Galbraith, D., Theymeyer, T., 2011. The Point of Popularity: a summary of 10,000 years of human activity at the Princess Point Promontory, Cootes Paradise Marsh, Hamilton. Ontario. Can. J. Archaeol. 35, 232–257.

Johnson, A.M., Leopold, D.J., 1994. Vascular plant species richness and rarity across a minerotrophic gradient in wetlands of St. Lawrence County, New York, U.S.A. Biodivers. Conserv. 3, 606–662.

Johnson, C.W., 1985. Bogs of the Northeast. University Press of New England, Hanover, NH. Kirkpatrick, S., 2021. Evaluating restoration techniques for a coastal fen on Lake Ontario degraded by *Typha* × *glauca* and shrub encroachment. MS thesis, SUNY Brockport, Brockport, NY.

Kuhry, P., Nicholson, B.J., Gignac, L.D., Vitt, D.H., Bayley, S.E., 1993. Development of *Sphagnum*-dominated peatlands in boreal continental Canada. Can. J. Bot. 71, 10–22.

Martin, A.C., Barkley, W.D., 2000. Seed Identification Manual. Blackburn Press, Caldwell, NJ. McCarthy, F.M.G., McAndrews, J.H., 1988. Water levels in Lake Ontario 4230–2000 years B.P.: evidence from Grenadier Pond, Toronto, Canada. J. Paleolimnol. 1, 99–133.

McNamara, J.P., Siegel, D.I., Glaser, P.H., Beck, R.M., 1992. Hydrogeologic controls on peatland development in the Malloryville Wetland, New York (USA). J. Hydrol. 140, 279–296.

Montgomery, F.H., 1977. Seeds and Fruits of Plants of Eastern Canada and Northeastern United States. University of Toronto Press, Toronto, ON.

Polzer, E.L., Wilcox, D.A., 2022. Testing restoration methods for Lake Ontario wetlands at a wetland scale. J. Great Lakes Res. 48, 756–767.

Reimer, R.W., Reimer, P.J., 2022. CALIBomb [WWW program] at http://calib.org accessed 2022-03-14.

Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Ramsey, C.B., Butzin, M., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer, J.G., Pearson, C., van der Plicht, J., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., Wacker, L., Adolphi, F., Buentgen, U., Capano, M., Fahrni, S.M., Fogtmann-Schulz, A., Friedrich, R., Koehler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo, S., 2020. The Intcal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62, 725–757. https://doi.org/10.1017/RDC.2020.41.

Shedlock, R.J., Wilcox, D.A., Thompson, T.A., Cohen, D.A., 1993. Interactions between ground water and wetlands, southern shore of Lake Michigan, USA. J. Hydrol. 141, 127–155.

Smith, I.M., Fiorino, G.E., Grabas, G.P., Wilcox, D.A., 2021. Wetland vegetation response to record- high Lake Ontario water levels. J. Great Lakes Res. 47, 160–167.

Stuiver, M., Reimer, P.J., Reimer, R.W., 2022. CALIB 8.2 [WWW program] at http://calib.org, accessed 2022-3-14.

Swink, F., Wilhelm, G., 1979. Plants of the Chicago Region. The Morton Arboretum, Lisle, IL.

Uzarski, D.G., Brady, V.J., Cooper, M.J., Wilcox, D.A., Albert, D.A., Axler, R.P., Bostwick, P., Brown, T.N., Ciborowski, J.H., Danz, N.P., Gathman, J.P., Gehring, T.M., Grabas, G.P., Garwood, A., Howe, R.W., Johnson, L.B., Lamberti, G.A., Moerke, A.H., Murry, B.A., Niemi, G.J., Norment, C.J., Ruetz, C.R., Steinman, A.D., Tozer, D.C., Wheeler, R., O'Donnell, T.K., Schneider, J.P., 2017. Standardized measures of coastal wetland condition: implementation at a Laurentian Great Lakes basin-wide scale. Wetlands 37, 15–32.

Vitt, D.H., Bayley, S.E., Tai-Long, J., 2005. Seasonal variation in water chemistry over a bog–rich fen gradient in continental western Canada. Can. J. Fish. Aquat. Sci. 52, 587–606.

Vitt, D.H., Chee, W.L., 1990. The relationships of vegetation to surface water chemistry and peat chemistry in fens of Alberta, Canada. Vegetatio 89, 87–106.

Vitt, D.H., Wieder, R.K., 2009. The structure and function of bryophyte-dominated peatlands. In: Goffinet, B., Shaw, A.J. (Eds.), Bryophyte Biology. second ed. Cambridge University Press, Cambridge, pp. 357–392.

Voss, E.G., Reznicek, A.A., 2012. Field Manual of Michigan Flora. University of Michigan Press, Ann Arbor, MI.

Wilcox, D.A., Baedke, S.J., Thompson, T.A., 2020. A complicated groundwater flow system supporting ridge-and-swale wetlands in a Lake Michigan strandplain. Wetlands 40, 1481–1493.

Wilcox, D.A., Bateman, J.A., 2018. Photointerpretation analysis of plant communities in Lake Ontario wetlands following 65 years of lake-level regulation. J. Great Lakes Res. 44, 1306–1313.

Wilcox, D.A., Shedlock, R.J., Hendrickson, W.H., 1986. Hydrology, water chemistry, and ecological relations in the raised mound of Cowles Bog. J. Ecol. 74, 1103–1117.

Wilcox, D.A., Meeker, J.E., Hudson, P.L., Armitage, B.J., Black, M.G., Uzarski, D.G., 2002. Hydrologic variability and the application of index of biotic integrity metrics to wetlands: a Great Lakes evaluation. Wetlands 22, 588–615.

Wilcox, D.A., Kowalski, K.P., Hoare, H., Carlson, M.L., Morgan, H., 2008. Cattail invasion of sedge/grass meadows and regulation of Lake Ontario water levels: photointerpretation analysis of sixteen wetlands over five decades. J. Great Lakes Res. 34, 301–323.