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Fire, Vegetation, and Water-level History from the Stockton Island Tombolo

Apostle Islands National Lakeshore

Natural Resource Report NPS/APIS/NRR—2021/2221

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ON THIS PAGE
View of Stockton Island Lagoon in June of 2018.

ON THE COVER
View on the western edge of the tombolo looking southward toward Presque Isle in June of 2018.

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Executive Summary

Great Lakes Barrens are a rare ecosystem type occupying sandy coastal settings of the upper Midwest and are dominated by scattered pines and an open understory of dune species. These ecosystems historically experienced periodic fires, but quantitative information on past fire regimes is sparse. Historical photographs from Great Lakes Barrens and associated red pine forest on Stockton Island in the Apostle Islands National Lakeshore (APIS) of Lake Superior reveal that tree cover has increased on the island since the 1930s. This observation led to questions about fire, vegetation, and climate history of the area and highlighted the need for historical information to inform fire management and conservation efforts. To provide this information, we developed paleoenvironmental records of fire, vegetation, and surface-moisture conditions from peat and sediment cores collected from two sites on the island, and we used these records along with previously collected data to provide a long-term perspective on fire, vegetation and island development, and hydrologic changes spanning approximately the past 5,000 years. The primary objective of this study was to provide APIS resource managers with information on fire frequency for the past several thousand years, as well as information on fire-vegetation and fire-climate relationships, so that this long-term perspective could inform fire management decisions.

Pine-dominated vegetation on Stockton Island is restricted to a tombolo, a sandy geomorphological feature that connects two former islands. Sediment and peat cores were collected from two sites on the tombolo: Stockton Bog and Stockton Lagoon. Standard methods were used for pollen analysis and the reconstruction of bog surface-moisture using testate amoebae, a group of moisture-sensitive protists that produce decay-resistant shells. Macroscopic and microscopic charcoal concentrations and accumulation rates were estimated and used to identify particularly large peaks in charcoal (fire episodes) using established methods. Fire frequency was expressed as the number of fire episodes per 500 years and summarized with a 500-year moving window to assess changes over time.

Our main findings include:

1. The area occupied by Stockton Bog was likely a shallow embayment of Lake Superior until about 5,000 years ago, when coastal sand deposition separated it from Lake Superior and it transformed into a sedge-dominated peatland and soon thereafter a *Sphagnum* bog. Sand-ridge deposition facilitated the eastward expansion of the tombolo over the past 4,000 years, and the tombolo likely reached its present-day configuration about 800 years ago.
2. Vegetation on the tombolo has been dominated by red pine, white pine, and paper birch since its formation, although tree density cannot be inferred with our data.
3. Frequent low-intensity fires and occasional higher-intensity or stand-replacing fires have been associated with the pine-dominated vegetation of the tombolo since its origin. Charcoal of all size classes was found in every centimeter of the peat and sediment cores.

4. Inferred fire frequencies based on the timing of fire episodes, likely representing either highly localized fires or stand-replacing fires of high intensity, ranged from about one to three major fire episodes per 500 years since tombolo formation, with the highest frequencies occurring about 3,000 years ago and during the past couple of centuries. Frequency of local fire episodes was less than recorded for inland pine barren communities of northwestern Wisconsin.
5. Major fire episodes were significantly more likely to occur during dry time periods.
6. Post-logging fires, particularly the widespread fires of the 1920s and 1930s, likely represent the most severe fire episode of at least the past 1,000 years.

Acknowledgments

Funding for this work came from the National Park Service, Apostle Islands National Lakeshore. In addition to co-authors R.K. Booth, M.A. Huff, and E.A. Lynch, we were assisted in the field by M. Schuster. D. Behe helped with the processing and analysis of macroscopic charcoal from the Stockton Island Lagoon. We are grateful to P. Burkman for transporting us to Stockton Island. P. Burkman and J. Van Stappen provided discussion and feedback on early drafts of the report. Constructive and thoughtful reviews by C.J. Long and C. Umbanhowar improved the final report.

Introduction

Knowledge of past fire regimes is a critical component of successful fire management (e.g., Gavin et al. 2007, Whitlock and Larson 2002), providing historical perspectives on fire variability and impacts on ecosystems (Marlon et al. 2012, 2013; McKenzie and Littell 2017; Noss et al. 2006). Paleoenvironmental records are a valuable source of information on fire history and can provide insight into how wildfire, human activities, climate change, and vegetation have interacted across a range of spatial and temporal scales (Bridge et al. 2005, Clifford and Booth 2015, Fletcher et al. 2014, Hotchkiss et al. 2007, Johnson et al. 2001, Long et al. 1998, Lynch et al. 2006, Marlon et al. 2006, Tweiten et al. 2015). Over the past two decades, theoretical and empirical studies have led to improvements in laboratory and analytical methods to assist with the development and interpretation of paleorecords of past fire, particularly those derived from sedimentary charcoal records collected from lakes and other depositional systems (Higuera et al. 2005, 2009, 2011; Power et al. 2008). For example, focusing analyses on defined size classes of charcoal allows fire inferences at particular spatial scales (i.e., regional versus local) (Umbanhowar 2004, Urrego et al. 2013), and recently developed peak-detection methods now allow the identification of fire episodes (one or more large fires occurring over a time period shorter than the sample resolution) while accounting for the effects of depositional processes like sediment focusing (i.e., movement of sediment from shallower to deeper areas) that can produce low-frequency changes unrelated to real changes in fire frequency (Conedera et al. 2009, Higuera et al. 2011). Application of these methods has facilitated the development of fire histories at spatial and temporal scales relevant to ecological management (e.g., Hotchkiss et al. 2007, Tweiten et al. 2015).

Great Lakes Barrens communities of the upper Midwest are a rare pine-barren ecosystem type dominated by scattered red and/or jack pine with a sparse understory of shrubs, grasses, forbs, and lichens (Epstein 2017). These communities occupy sandy, nutrient-poor soils in coastal settings and are characterized by severe storms, wind-blown sand, and storm waves (Epstein 2017). Periodic fires likely maintained these relatively open communities, but little quantitative information exists on historical fire frequency in these ecosystems, in contrast to inland pine barrens of the region (e.g., Hotchkiss et al. 2007; Jensen et al. 2007; Lynch et al. 2006, 2011, 2014; Tweiten et al. 2009, 2015).

One of the most undisturbed examples of a Great Lakes Barrens community is located on the sandy southeastern portion of Stockton Island in the Apostle Islands National Lakeshore of Lake Superior. This sandy portion of the island was deposited by coastal processes during the past several thousand years and consists of a series of sand ridges that accreted between two former islands, Stockton Island and Presque Isle, connecting them with a geomorphic feature referred to as a tombolo. Historical photographs reveal that the vegetation of the tombolo has become denser since the 1930s (Figure 1). The increase in vegetation cover during the 20th century coincides with the onset of laws that criminalized fire-based habitat management—including indigenous barrens community habitat management—by the State of Wisconsin and a policy of fire suppression by the National Park Service (NPS) since the early 1970s (Swain and Winkler 1983). Reintroduction of fire to the Great Lakes Barrens community on Stockton Island is believed to be necessary to preserve the species composition and structure of this rare community type. A small controlled burn was conducted on the

tombolo in 2017 to assess feasibility and impacts; however, only sparse information exists on the long-term fire history of the area (Swain and Winkler 1983, Kipfmueller 2019). Sediment-based records of fire history combined with a tree-ring based fire record (Kipfmueller 2019) can provide important context for the management this Great Lakes Barrens ecosystem.

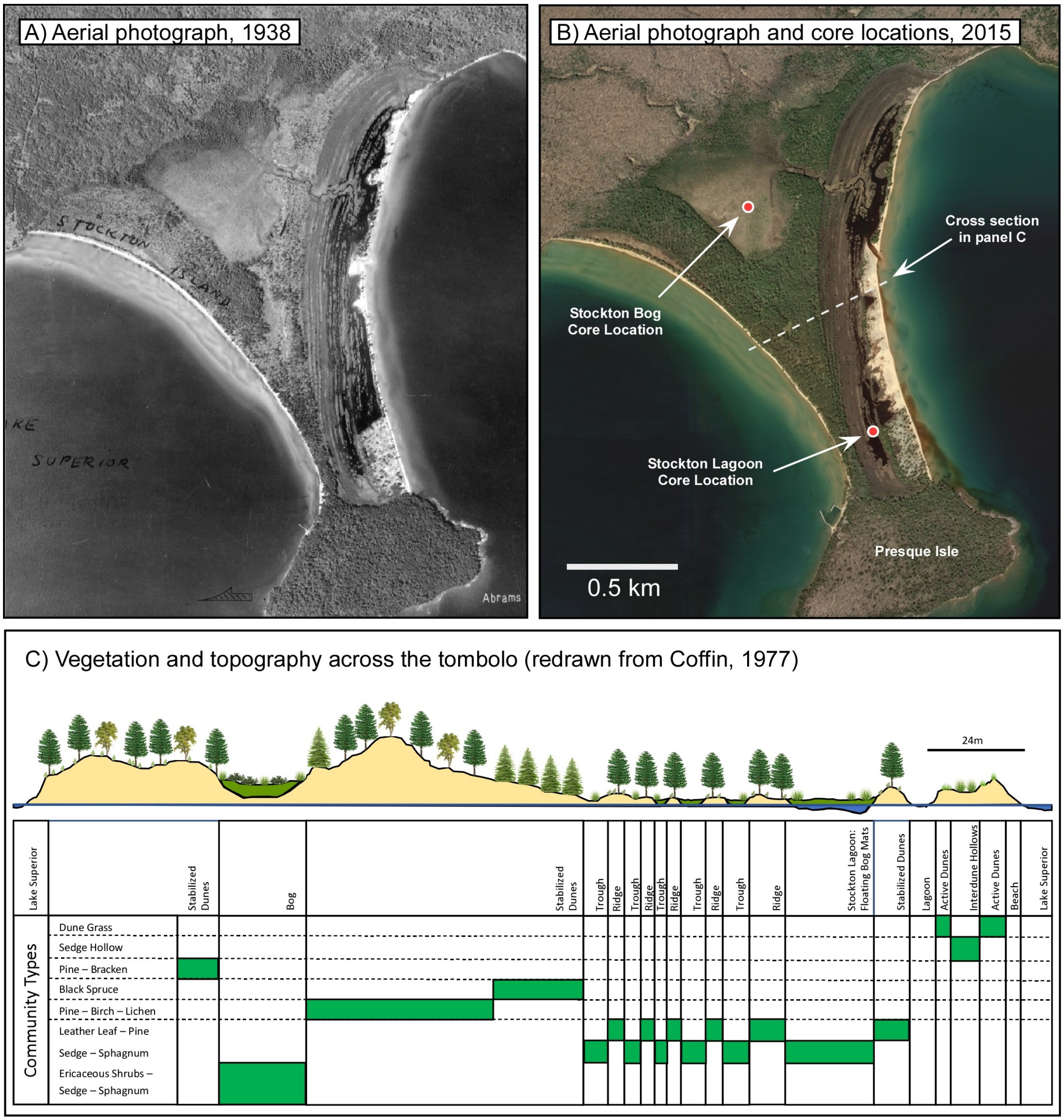

Figure 1. Aerial images and vegetation of the Stockton Island Tombolo, including A) aerial image from 1938, B) aerial image from 2015 showing the location of coring sites within Stockton Bog and Stockton Lagoon, and C) generalized vegetation and topography on the tombolo, as modified from Coffin (1977). Open Great Lakes Barrens occupies the area due east of the Stockton Lagoon coring site, whereas much of the rest of the tombolo is dominated by more dense red pine forest.

Stockton Island contains peatlands and shallow-water wetlands that potentially contain detailed records of past fire variability on the tombolo. In fact, previous paleoecological work at Stockton Bog (see Figure 1) demonstrated that high-resolution fire and vegetation records were likely obtainable from the site, with deposition rates averaging about 7 years/cm for much of its history (Figure 2) (Swain and Winkler 1983). A sediment core analyzed by Swain and Winkler (1983) found well-preserved pollen and charcoal and revealed that the site has been a *Sphagnum*-dominated peatland for the last 4,000 years. *Sphagnum*-dominated peatlands are also ideal for reconstructing past hydrological changes using testate amoebae, a group of moisture-sensitive protists that produce decay-resistant and morphologically distinct shells, referred to as tests, that have been used to reconstruct changes in past bog surface-wetness (e.g., Booth et al. 2004; Booth 2008; Clifford and Booth 2013, 2015). The combined investigation of past hydrology using testate amoebae and fire history using charcoal can provide insights into the sensitivity of fire to past climate changes (Clifford and Booth 2013, Galka et al. 2015). A record of water-level changes and fire from Stockton Bog would be valuable to understanding the history of the tombolo and contribute to the broader history of fire, climate, and vegetation change in the Great Lakes region.

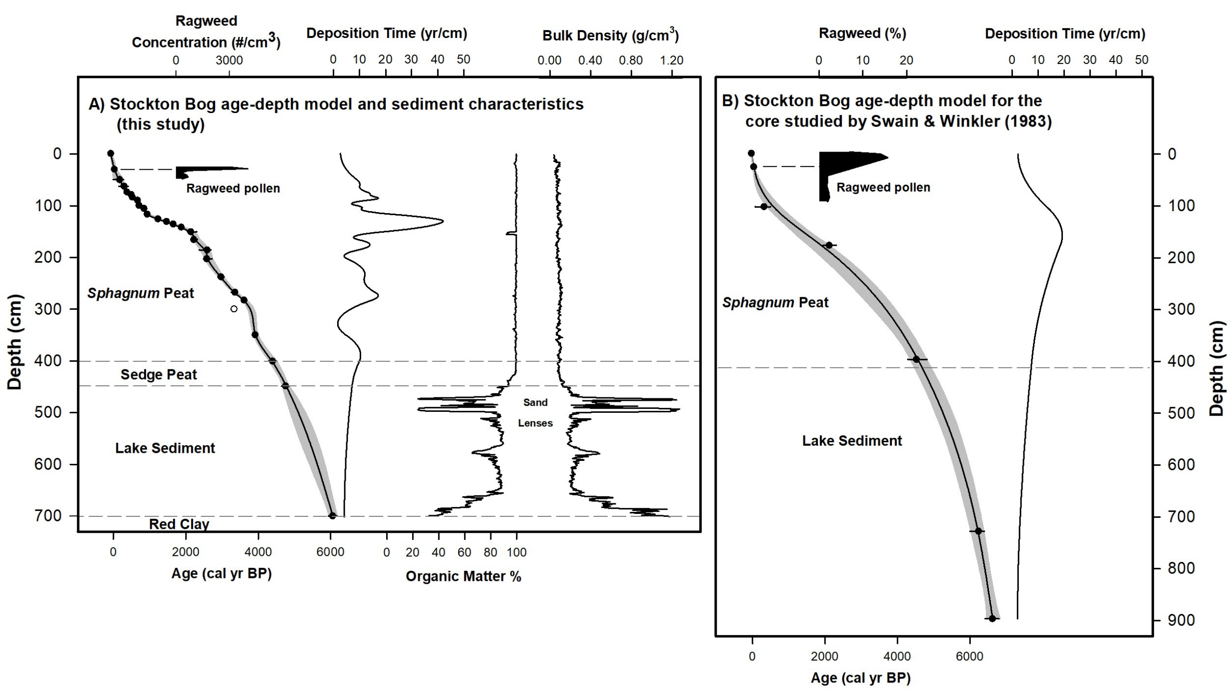

Figure 2. Age-depth models, sediment characteristics, and depositional history for sediment cores collected from Stockton Bog for A) the present study and B) the previous study by Swain and Winkler (1983). Calibrated radiocarbon ages are shown with black dots and two-sigma uncertainty. Black curve indicates the best fit age-depth model, and the gray area around it shows 2-sigma uncertainty. An outlier date not included in the age-depth model is shown with white fill. The top of the cores and the position of the ragweed pollen increase associated with European land clearance were used in the age-depth models along with radiocarbon dates.

In addition to Stockton Bog, the tombolo portion of the island contains shallow wetlands that occupy curvilinear, interridge depressions between sand ridges (see Figure 1). These interridge standing

water features are collectively referred to as the Stockton Lagoon, and similar coastal wetlands have been found to contain well-preserved paleoecological records (e.g., Lynch and Saltonstall 2002). However, given the location of the Stockton Lagoon within the younger, eastern edge of the tombolo, paleoenvironmental records from the area likely only capture recent centuries or millennia (Bona 1990). Paleoenvironmental records from both the bog and the lagoon on Stockton Island may provide a richly detailed characterization of fire and ecological history as well as spatially explicit perspectives on different portions of the tombolo during the past several centuries.

We developed fire history records from peat and sediment cores collected from Stockton Bog and Stockton Lagoon on the Stockton Island tombolo using standard paleoecological techniques (e.g., Higuera et al. 2005, 2009, 2011). We analyzed microscopic charcoal (<125 µm) and macroscopic charcoal (two size classes, 125–250 µm and >250 µm) continuously along sediment cores collected from the two locations. At Stockton Bog, we also analyzed testate amoebae continuously for the past 2,600 years of the record, comparing our inferred bog moisture history with fire reconstructions at both regional and local scales. Finally, we developed a pollen record from Stockton Lagoon and compared it with our fire record. Collectively, we use these data to provide a historical perspective on fire, hydrology, island development, and vegetation of the tombolo and the Great Lakes Barren community for resource managers.

Study Area

Stockton Island is located within the Apostle Islands National Lakeshore about 8 km northeast of the Bayfield Peninsula in Lake Superior. Mean annual temperature is 4.6°C (40.3°F), with average July and January temperatures of 19°C (66°F) and −11°C (12°F), respectively (National Climate Data Center, Madeline Island Weather Station, GHCND:USC00474953). Stockton Island receives an average of 84 cm of precipitation annually, with most of this precipitation (67%) occurring during the warmer months. The tombolo, referred to as the Presque Isle Tombolo or Stockton Island Tombolo, is located on the southeastern portion of the island, and the sandy substrate supports Great Lakes Barrens dominated by red pine (*Pinus resinosa*), eastern white pine (*Pinus strobus*), occasional paper birch (*Betula papyrifera*), as well as common juniper (*Juniperus communis*), early blueberry (*Vaccinium angustifolium*), huckleberry (*Gaylussacia baccata*), sand cherry (*Prunus pumila*), and bearberry (*Arctostaphylos uva-ursi*) (Coffin 1977). Along the southeastern margin of the tombolo the vegetation is particularly open, with sparse tree cover and large areas occupied by lichens, tickle grass (*Agrostis hyemalis*), crinkled hair grass (*Deschampsia flexuosa*), false-heather (*Hudsonia tomentosa*), and sand cress (*Arabidopsis lyrata*) (see Figure 1). Many of the species present are regionally rare, and collectively they represent a community of high conservation value (Coffin 1977). Great Lakes Barrens are listed as S1 or "critically imperiled" by the Wisconsin Department of Natural Resources due to their restricted range and recent decline (Epstein 2017). Elsewhere on Stockton Island and Presque Isle, glacial till soils support a dense, mixed deciduous forest community, characterized by yellow birch (*Betula alleghaniensis*), oak species (*Quercus* spp.), northern white cedar (*Thuja occidentalis*), and sugar maple (*Acer saccharum*) (Beal and Cottam 1960). Eastern hemlock (*Tsuga canadensis*) was also important prior to logging by Europeans in the early 1900s (Feldman 2011, Swain and Winkler 1983). Previous work indicates that vegetation differences between the tombolo and the glacial till of the original two islands have likely existed since the tombolo's formation (Swain and Winkler 1983).

Humans probably have influenced fire occurrence and vegetation on the tombolo for much of its history. Native Americans may have been present in the region as early as 11,000 years ago, and archeological evidence on Stockton Island suggests that people have been present on the island since at least 5,000 years ago (Busch 2008). The Ojibwe people inhabited the region at least as early as the 1500s (Warren 1984) and likely burned portions of the tombolo to increase blueberry yields, as has been indicated for edaphically similar areas and other red pine-dominated coastal forests in the region (Anderton 1999, Loope and Anderton 1998, Johnson and Kipfmueller 2016). Berry-picking and drying for storage was important to Ojibwe subsistence (Anderton 1999) and likely became even more widespread by the mid-to-late 1800s when it developed into a significant source of income (Norrgard 2009). Fires on Stockton Island were also associated with European logging throughout the early 1900s, with historical records of fires occurring in the 1910s, 1920s, and a particularly large fire that was started by blueberry pickers in 1934 (Ashland Daily News 1934, Feldman 2011). Occasional fires also occurred into the 1950s and 1960s (Feldman 2011). In 1970, the Apostle Islands National Lakeshore was established as a national park unit, and only limited fire activity has occurred since that time (Burkman 2008, Coffin 1977). In October 2017, a controlled burn was performed on a small portion of the tombolo (ca. 2 ha, or 5 acres) just east of Stockton Bog.

Both sites for fire history reconstruction were located on the Stockton Island Tombolo. Stockton Bog is a ca. 0.25 km^2 (ca. 273 yd^2) oligotrophic peatland on the northwestern edge of the tombolo that contains plant communities typical of nutrient-poor fens in northern Wisconsin and the Great Lakes region (Beal and Cottam 1960). Peatland vegetation is dominated by a carpet of *Sphagnum* moss and an overstory of ericaceous shrubs and sedges with scattered individuals of tamarack (*Larix laricina*) and black spruce (*Picea mariana*). Denser tree growth occurs at the margins of the peatland (see Figure 1). Stockton Bog drains into numerous, interconnected wetlands among the sand ridges on the eastern side of the tombolo (Coffin 1977), and standing water features in this area are collectively referred to as the Stockton Lagoon (see Figure 1). Floating *Sphagnum*-dominated peat mats occur within the lagoon area, and floating-leaved plants (e.g., *Nymphaea*, *Brasenia*) and submerged aquatic plants are common.

Methods

Field Methods

Field work on Stockton Island was conducted in June of 2018. The coring location at Stockton Bog was selected after an extensive peat-depth survey, and although our coring location was not quite as deep as that obtained by Swain and Winkler (1983), it was the deepest area encountered (Figure 2). A modified Livingstone piston-corer (10.5-cm diameter), with a serrated edge designed specifically for peatlands, was used to collect the upper ca. 3 meters of peat at Stockton Bog. The lower ca. 4 meters of peat and sediments at the bog were collected with a Russian-style corer (5-cm diameter). Peatland cores were described in the field, and wrapped in plastic wrap, tin foil, and PVC tubes. The peat-lake stratigraphic transition was found at the same depth in our study and the previous study of Swain and Winkler (1983), indicating that their longer core captured deeper lake sediment (Figure 2).

A ca. 60-cm-long sediment core was collected from the Stockton Lagoon after a sediment-depth survey to locate the deepest area, using a standard Livingston piston corer designed for finer organic sediments. A small inflatable boat was secured to the lagoon edges, and the core was collected using a plexiglass tube so that the integrity of the sediment-water interface was preserved and could be examined. The entire core was subsampled at 1-cm intervals in the field and placed in plastic bags so that stratigraphy was not disturbed. All cores and core samples from the two sites were returned to Lehigh University for cold storage and subsequent analyses.

Theoretical Basis for Size-Classes Used in Analysis of Charcoal

In this study we analyzed three charcoal size fractions, including microscopic charcoal (15 to ca. 125 µm) and two sizes of macroscopic charcoal (125–250 µm and >250 µm). Most studies of sedimentary charcoal have focused on a single size fraction (i.e., >125 µm); however, recent work has shown potential in using multiple size fractions to assess wildfire occurrence at different spatial scales (Florescu et al. 2018, Vachula et al. 2018). Microscopic charcoal fragments (<125 µm) are typically sourced from within about 125 km (ca. 77 miles) of a depositional basin, although much of this charcoal is likely derived from a source area similar to pollen, which reflects a distance-weighted source area of 20–30 km (12–19 miles) in forested regions (Davis 2000, Sugita 1994). In the original study of Stockton Bog by Swain and Winkler (1983), only microscopic charcoal was analyzed, and this size fraction likely reflects burning on Stockton Island, other islands, and even on the Bayfield Peninsula, although local fires can generate microscopic charcoal as well (Whitlock and Millspaugh 1996). Macroscopic fragments (>125 µm) generally reflect fire events that occur within ca. 3 km (<2 miles) of the basin (Vachula et al. 2018, Lynch et al. 2004), with the larger fragments likely more locally derived than the smaller fragments. For analysis of fire episodes, we combined both macroscopic size fractions (125–250 µm and >250 µm); however, we also plot them separately in this report to highlight differences in their abundance among identified fire episodes. Although other factors in addition to distance, such as fuel type and wind direction, likely affect the occurrence and abundance of different size fractions in the sediment record, the use of multiple size classes may allow the comparison of both local fire regimes on the tombolo as well as fire regimes of the surrounding mixed-deciduous forests on the island and broader region.

Laboratory Methods

Peat and sediment cores from the two sites were subsampled and analyzed using standard methods. The Stockton Bog core was subsampled contiguously at 1-cm resolution for loss-on-ignition (LOI), bulk density, and macroscopic charcoal analyses. Every centimeter of the upper ca. 4.5 m of peat was also sampled for testate amoebae and microscopic charcoal. Volumetric samples of 1 cm^3 were used for LOI, testate amoebae, and microscopic charcoal (15 to ca. 125 µm), and 2 cm^3 of peat/sediment was used for macroscopic charcoal analyses. Standard methods for LOI measurements were used to determine bulk density and organic matter content, including drying at 90°C for 24 hours and burning at 550°C for 4 hours (Dean 1974). The Stockton Lagoon core was subsampled for pollen and macroscopic charcoal (125–250 µm and >250 µm), using 1-cm^3 and 2-cm^3 volumetric samples, respectively. Macroscopic charcoal was analyzed at 1-cm intervals (i.e., continuously) along the Stockton Lagoon core, and pollen was examined at approximately 1–2 cm intervals for most of the core length.

Testate amoebae and microscopic charcoal were isolated from the Stockton Bog core using standard sieving methods (Booth et al. 2010), and pollen was also isolated from the organic-rich sediments of Stockton Lagoon using the same methods. Samples were boiled in distilled water for 10 minutes and then passed through nested sieves of 300-µm and 15-µm mesh diameter, retaining the material on the 15-µm-diameter sieve for analyses. *Lycopodium* tablets with a known number of spores were added to each Stockton Bog sample in order to calculate microscopic charcoal concentration (Faegri and Iverson 1989). Glycerol was added to the samples and microscopic slides were scanned at 400× magnification, identifying and tallying testate amoebae or pollen until a count total of at least 100 was reached. In some cases, this count total was not obtainable for testate amoebae, and we only included samples with at least a total count of 50 individual tests in our subsequent analyses and estimates of water-table depth. Microscopic charcoal fragments and *Lycopodium* spores were tallied along with testate amoebae in the Stockton Bog core. Although our samples included material ranging from 15 µm to 300 µm in size, only microscopic charcoal fragments smaller than about 125 µm (the size of the largest testate amoebae encountered) were counted. Ragweed (*Ambrosia*) pollen was tallied in conjunction with testate amoebae in upper portions of the Stockton Bog core, and the total concentration was used to identify the stratigraphic horizon associated with European logging and land clearance. At Stockton Lagoon, the relative abundance of ragweed pollen, expressed as a percent of the total pollen tallied, was used to identify this post-European settlement horizon.

To isolate and quantify macroscopic charcoal fragments, samples of 2 cm^3 of sediment or peat were bleached using 6% H_2O_2 and heated to 50°C for 24 hours (Rhodes 1998). Bleached samples were sieved to isolate two size fractions: 125–250 µm and >250 µm. These size fractions were chosen because they represent the range of size classes used in previous studies focused on reconstructing local fire history (Vachula et al. 2018). Sieved samples were placed in petri dishes, dried using heat lamps, and all charcoal fragments were counted under a dissecting microscope.

Plant macrofossils or charcoal were collected from 25 horizons throughout the Stockton Bog core and five samples from the Stockton Lagoon core for radiocarbon dating (Table 1). Samples were sieved to remove material smaller than 300 µm, and then scanned to identify terrestrial plant remains

suitable for radiometric dating. These were picked, cleaned with distilled water, dried, and sent to Woods Hole National Ocean Sciences Accelerator Mass Spectrometry Lab for analysis using AMS ^{14}C dating techniques.

Table 1. Radiocarbon dates from Stockton Bog (SB) and Stockton Lagoon (SL) obtained as part of this study from Woods Hole—NOSAMS laboratory. Median probability and full two-sigma range shown for calibrated ages. Asterisks on lab sample numbers denote outlier samples not used in age-depth models.

Lab sample number	Site	Depth (cm)	Material Dated	^{14}C age (yr BP)	Calibrated Age (cal yr BP)
OS-144357	SB	50–51	*Sphagnum*	185 ± 15	180 (0–285)
OS-148657	SB	63–64	*Sphagnum*	260 ± 15	301 (157–416)
OS-144358	SB	74–75	*Larix laricina* needles, Cyperaceae, *Sphagnum*	340 ± 15	380 (316–471)
OS-148658	SB	79–80	*Sphagnum*	420 ± 20	497 (464–514)
OS-148659	SB	84–85	*Sphagnum*	515 ± 20	531 (512–547)
OS-144359	SB	90–91	*Larix laricina* needles, *Sphagnum*, *Kalmia* leaf	720 ± 15	673 (662–683)
OS-148660	SB	100–101	*Sphagnum*	800 ± 15	711 (687–732)
OS-143197	SB	106–107	Brown moss, *Sphagnum*	945 ± 15	849 (796–922)
OS-148661	SB	117–118	Charcoal	1,020 ± 15	939 (924–959)
OS-144360	SB	126–127	*Carex oligosperma*, Charcoal, Charred *Picea* needles	1,280 ± 15	1,235 (1,182–1,275)
OS-148662	SB	131–132	Charcoal	1,570 ± 15	1,471 (1,412–1,522)
OS-143198	SB	136–137	Charred *Picea* needles, *Sphagnum*	1,740 ± 15	1,658 (1,575–1,707)
OS-148762	SB	142–143	Sphagnum	1,930 ± 20	1,878 (1,826–1,923)
OS-144361	SB	151–152	Sphagnum	2,150 ± 25	2,143 (2,048–2,303)

Table 1 (continued). Radiocarbon dates from Stockton Bog (SB) and Stockton Lagoon (SL) obtained as part of this study from Woods Hole—NOSAMS laboratory. Median probability and full two-sigma range shown for calibrated ages. Asterisks on lab sample numbers denote outlier samples not used in age-depth models.

Lab sample number	Site	Depth (cm)	Material Dated	^{14}C age (yr BP)	Calibrated Age (cal yr BP)
OS-143199	SB	166–167	*Sphagnum*	2,230 ± 20	2,222 (2,156–2,327)
OS-143200	SB	186–187	*Sphagnum*	2,460 ± 20	2,593 (2,379–2,705)
OS-143201	SB	203–204	*Sphagnum*	2,500 ± 20	2,581 (2,491–2,723)
OS-143202	SB	238–239	*Sphagnum*, *Larix laricina* needle	2,860 ± 20	2,975 (2,829–3,059)
OS-144362	SB	268–269	*Sphagnum*	3,130 ± 20	3,361 (3,258–3,396)
OS-143203	SB	283–284	*Sphagnum*	3,370 ± 25	3,612 (3,570–3,684)
OS-143421*	SB	300–301	*Sphagnum*	3,110 ± 20	3,337 (3,251–3,380)
OS-143319	SB	350–351	*Larix laricina* needles	3,610 ± 25	3,918 (3,849–3,979)
OS-148763	SB	401–402	*Sphagnum*, *Larix laricina* needles	3,940 ± 25	4,398 (4,293–4,510)
OS-143422	SB	449–450	Cyperaceae leaves	4,220 ± 25	4,759 (4,651–4,849)
OS-143423	SB	700–701	*Pinus strobus* needles and *Betula papyrifera* seeds	5,270 ± 25	6,059 (5,942–6,178)
OS-151480	SL	32–33	*Pinus strobus needles and bud scales*	630 ± 15	593 (558–657)
OS-151481	SL	40–41	*Pinus strobus needles and bud scales*	485 ± 15	520 (508–533)
OS-148656	SL	49–50	*Pinus strobus needles and bud scales*	765 ± 15	688 (677–726)
OS-148655	SL	54–55	*Pinus strobus needles and bud scales*	735 ± 20	678 (670–692)
OS-143424*	SL	58–59	Cyperaceae leaves, *Cladium* seed, *Vaccinium oxycoccos* leaf	345 ± 20	386 (320–481)

Analytical Methods

Radiocarbon-age estimates were calibrated to calendar years before present (years before 1950) using Calib version 7.1 (Stuiver et al. 2017) and the INTCal13 calibration curve (Reimer et al. 2013). All dates in this report are in calendar years before present (cal yr BP), where present is defined as 1950 CE. In addition to radiocarbon dates, the top of the core and the position of *Ambrosia* (ragweed) pollen increase were used as chronological markers when developing age-depth models for the two sites. Logging on Stockton Island occurred later than nearby mainland regions, with major logging operations on the island from 1911–1920 CE (Feldman 2011). Given that substantial expansion of *Ambrosia* likely occurred after sufficient land area was cleared, the position of the *Ambrosia* pollen rise was assigned an age of 1918 ± 5 CE. An age-depth model was developed with the software package CLAM, which uses "classical" age-depth modeling techniques by fitting spline curves through the probability distributions of a sequence of calibrated radiocarbon dates (Blaauw 2010). Monte Carlo techniques were used to estimate uncertainty of the resulting age-depth model.

Testate amoeba counts were converted to percentages based on the total number of individual tests tallied, and these relative abundances were plotted using the program Tilia (Grimm 1991). To facilitate discussion of the record, compositional zones were identified by stratigraphically constrained cluster analysis using a Euclidean distance metric performed on untransformed data with the software CONISS (Grimm 1987). To assess the degree of similarity between fossil samples and modern testate amoeba communities of North American peatlands, non-metric multidimensional scaling (NMDS) was used to directly compare fossil samples with the almost 2,000 modern samples currently in the Neotoma Paleoecological Database (Amesbury et al. 2018). Water-table depths were also estimated from testate amoeba assemblages using this large modern dataset, with bootstrapped sample-specific error estimates (Amesbury et al. 2018). Negative values for water-table depths indicate standing water, whereas positive values indicate the depth of the water table beneath the peatland surface. To highlight shorter term wet and dry shifts (i.e., multidecadal-to-centennial scale) a LOESS curve was fit to the data and standardized water-table depth residuals were plotted. The detrended water-table depths provide a record of wet and dry deviations from the long-term, lower-frequency changes, similar to the way that fire episodes are typically defined as peaks above the low-frequency background influx values. Similar approaches have been applied to testate amoeba reconstructions in an effort to highlight multidecadal-to-centennial scale changes more confidently attributable to climatic effects (Booth et al. 2012, Charman et al. 2006, Clifford and Booth 2015). All correlations reported in this study were Pearson correlations.

Macroscopic and microscopic charcoal concentrations were converted to influx values (i.e., charcoal accumulation rates) using peat and sediment accumulation rates derived from the age-depth model, and these were used to identify fire episodes. Fire episodes identified in the macroscopic charcoal data likely reflect one or more fires burning near the site during the time represented by the centimeter of sediment, whereas peaks in the microscopic charcoal data may represent more distant fires, particularly when not associated with simultaneous peaks in macroscopic charcoal. However, the interpretation of microscopic charcoal peaks in this fashion has not been as well validated as it has for macroscopic charcoal. To identify fire episodes in both the microscopic and macroscopic charcoal influx records, we used the software package *CharAnalysis* version 0.9 (Higuera et al.

2009). *CharAnalysis* is a commonly used program for identifying peaks in charcoal accumulation rates above background levels, suggesting a fire episode (Higuera et al. 2011, Kelly et al. 2011). Charcoal accumulation rates were interpolated to the median sample resolution and smoothed using a 500-year window to remove the low-frequency background charcoal signal, and peaks in influx that exceeded a locally defined threshold were identified. Smoothing window width was selected based on several considerations, including examination of a signal-to-noise index (Kelly et al. 2011), keeping the window width the same size across sites and charcoal-size fractions, and using similar methods to those used on other pine barren ecosystems of the region (e.g., Tweiten et al. 2015). Fire frequency was expressed as the number of fire episodes per 500 years and summarized with a 500-year moving window to assess changes over time. Peak magnitude of fire episodes, a measure of relative intensity, was calculated as the number of charcoal fragments per cm^2 per fire episode (Higuera et al. 2009).

Relationships between bog moisture and fire history were examined visually and using chi-squared goodness-of-fit tests to assess whether the identified fire episodes were more or less likely during dry and wet time periods on the bog. To assess relationships between bog moisture and the probability of fire episodes, the detrended water-table depths were used to classify each sample in the record as either wet, average, or dry. A 0.5 standard deviation cutoff was used for these classifications because it resulted in similar sample sizes for the three moisture categories. The number of local and regional fire episodes was tallied for each moisture category, and chi-squared tests were performed to assess the null hypothesis that fire episodes were equally likely in all bog-moisture states. Similar analyses were performed to assess the null hypothesis that fire episodes were equally likely during the Medieval Climate Anomaly (1,000–600 cal yr BP) and the Little Ice Age (600–100 cal yr BP).

Results

Stockton Bog

Bog age-depth model and depositional history

The general stratigraphy of the Stockton Bog core captures three broad depositional stages (see Figure 2). Basal sediments, consisting of a red lacustrine clay similar to deposits found throughout western and southern Lake Superior (Lineback et al. 1979), occur in the lowermost 5 cm of the core below 685 cm. Bulk density is high (0.8–1.2 g/cm^3) and organic matter is relatively low (<50%) in this red clay. Above a depth of 685 cm, a brown lacustrine mud with somewhat higher organic matter (60%–90%) and lower bulk density (0.15–0.6 g/cm^3) occurs. Several prominent sand lenses occur within this lacustrine mud, and radiocarbon dating suggests that these were deposited between about 5,500 and 5,000 cal yr BP. At a depth of 451 cm, sedge-dominated peat occurs and transitions into a *Sphagnum*-dominated peat at about 400 cm depth. *Sphagnum* peat containing ericaceous shrub remains (e.g., leaves, seeds), sedges (e.g., achenes, leaves), and tamarack and spruce needles, continues to the top of the core. Organic matter is high in the peat portion of the record (>95%) and bulk density is low (0.04–0.12 g/cm^3). Radiocarbon dating indicates that the transition to a peatland occurred about 4,750 cal BP (4,650–4,850 cal BP), and the site became a *Sphagnum*-dominated peatland by about 4,400 cal BP (4,290–4,510). The age-depth model indicates relatively rapid accumulation rates prior to peatland establishment (ca. 5 yrs/cm), and more variable rates after peatland establishment. Deposition rates during the entire record ranged from 1.6 yrs/cm to 42.1 yrs/cm, with an average of 8.7 yrs/cm (see Figure 2). A period of slow accumulation occurred from about 1,000–2,000 cal yr BP (see Figure 2), and was also observed in the previous core studied by Swain and Winkler (1983).

Testate amoebae and inferred water-table depth history

Forty-six taxa of testate amoebae were identified in the peatland portion of the Stockton Bog record, with considerable variability in assemblage composition throughout the core (Figure 3). In lower portions of the record, poor preservation and low count totals prevented quantitative analysis; however, adequate counts allowed for the analysis of the upper 194 cm spanning the last ca. 2,600 years. The record was divided into four major compositional zones using stratigraphically constrained cluster analysis.

Zone A4 (451 cm–387 cm, ca. 4,780–4,250 cal yr BP). Testate amoeba communities occupying the sedge-dominated peatland after its establishment included mostly minerotrophic taxa common to wet environments, with the lowest samples dominated by *Centropyxis aculeata* type and *Arcella vulgaris* type, morphological groupings of species that are common to both lake and wet peatland environments (Payne 2011). *Difflugia pristis* type became common in upper portions of this zone and became quite abundant immediately prior to the transition to Zone A3. Water-table depth estimates for the samples in this zone ranged from −3 cm to 45 cm, with an average of 5 cm below the peatland surface. However, these inferences should be interpreted with caution because other environmental factors may control testate amoeba distribution in minerotrophic settings (Booth 2002, Markel et al. 2010). Many samples throughout the zone yielded insufficient counts of testate amoebae for water-table depth estimates.

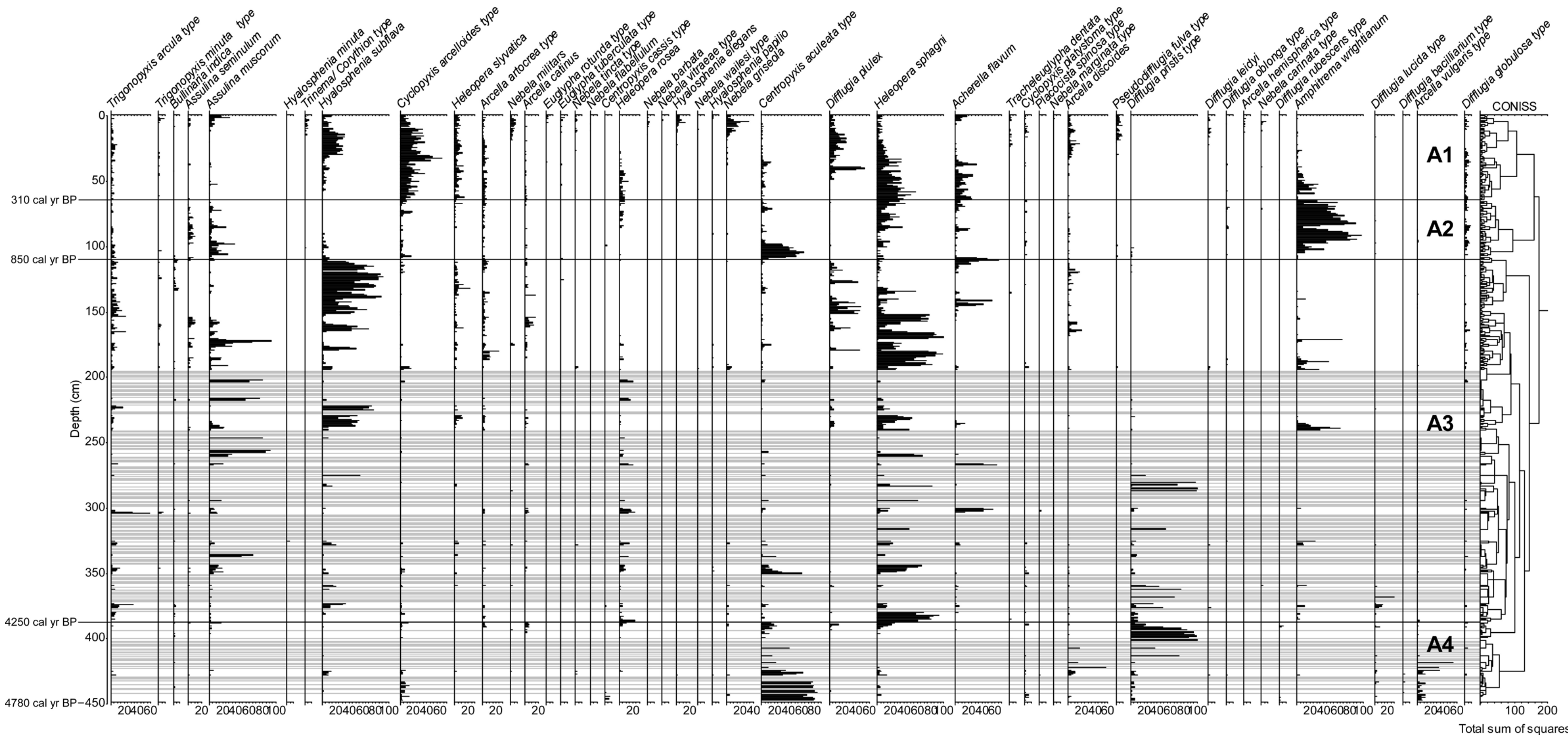

Figure 3. Testate amoeba stratigraphy in the Stockton Bog core, with relative abundances of taxa plotted against depth. Taxa organized by their moisture optima based on the ca. 2,000 North American samples in the Neotoma Paleoecology Database, with wetter taxa to the right. Gray horizontal bars indicate samples with insufficient numbers of testate amoebae for quantitative analysis. Zones defined by cluster analysis are shown on right, and approximate timing of zone transitions shown on left.

Zone A3 (387 cm–111 cm, 4,250–850 cal yr BP). The onset of this zone is characterized by abundant *Heleopera sphagni*, a mixotrophic testate amoeba common to nutrient-poor *Sphagnum* peatlands (Jassey et al. 2015). Poor recovery of testate amoebae in the lower samples of this zone led to many insufficient count totals. Lower portions of the zone were characterized by assemblages that alternated between abundant *Heleopera sphagni*, *Centropyxis aculeata* type, and *Difflugia pristis* type, likely indicating relatively moist conditions with varying amounts of minertrophic influence. *Assulina muscorum* and *Hyalosphenia subflava* appeared in the middle of the zone and became common in the assemblages, suggesting drier conditions; however, occasional increases of *Amphitrema wrightianum*, a species characteristic of very wet *Sphagnum* suggest occasional periods of wetter conditions. *Heleopera sphagni* increased in the upper portion of the zone, and its increase is associated with better recovery of testate amoebae, with count totals for all samples in the upper 194 cm sufficient for water-table depth estimates. Water-table depth estimates for the samples in this zone ranged from −7 cm to 50 cm, with an average of 23 cm below the peatland surface.

Zone A2 (111 cm–65 cm, 850–310 cal yr BP). Following the decline of *Hyalosphenia subflava*, a testate amoeba species associated with dry but variable conditions (Sullivan and Booth 2011), testate amoebae common to wetter and more stable environments become common in Zone A2. *Archerella flavum* increased at the base of the zone, but was quickly replaced by *Amphitrema wrightianum*, which dominated assemblages until the onset of Zone A1. Increases in *Centropyxis acuelata* preceded the dominance of *Amphitrema wrightianum*, suggesting a brief reversion to more minerotrophic conditions. Water-table depth estimates for the samples in this zone ranged from −10 cm to 19 cm, with an average of 3 cm below the surface.

Zone A1 (65 cm–0 cm, 310 cal yr BP to present). *Cyclopyxis arcelloides*, *Hyalosphenia subflava*, *Difflugia pulex*, and *Heleopera sphagni* appeared following the decline of *Amphitrema wrightianum*. These species occur in drier environments than *Amphitrema wrightianum*, although their variable abundance in the zone suggests considerable variability in moisture. Water-table depth estimates for the samples in this zone ranged from 8 cm to 41 cm, with an average of 23 cm below the peatland surface. Over this time interval there was a trend toward drier bog conditions.

Non-metric multidimensional scaling (NMDS) of Stockton Bog testate amoeba assemblages and modern testate amoeba communities collected from North American peatlands (Amesbury et al. 2018) produced a three-dimensional solution that represented 78% of the variance in community composition in the combined modern and fossil datasets, with the first two axes representing about the same amount of variability (31% and 29%, respectively) (Figure 4). Axis 1 and axis 2 captured compositional changes in modern samples associated with measured water-table depths (r^2=0.12 and 0.29 for axes 1 and 2, respectively). Inferred water-table depths for the fossil samples were also correlated with position of the samples along the two axes (r^2=0.12 and 0.32 for axes 1 and 2, respectively). However, some Stockton Bog samples were positioned outside the space occupied by the modern samples, indicating that good modern analogues are lacking for these samples. These "no-modern analogue" samples all came from the sedge-dominated Zone A4 and the lower portions of Zone A3, and were characterized by very abundant *Difflugia pristis* type, a morphologically diverse species group of somewhat uncertain ecology. In a few samples, 100% of the testate amoebae

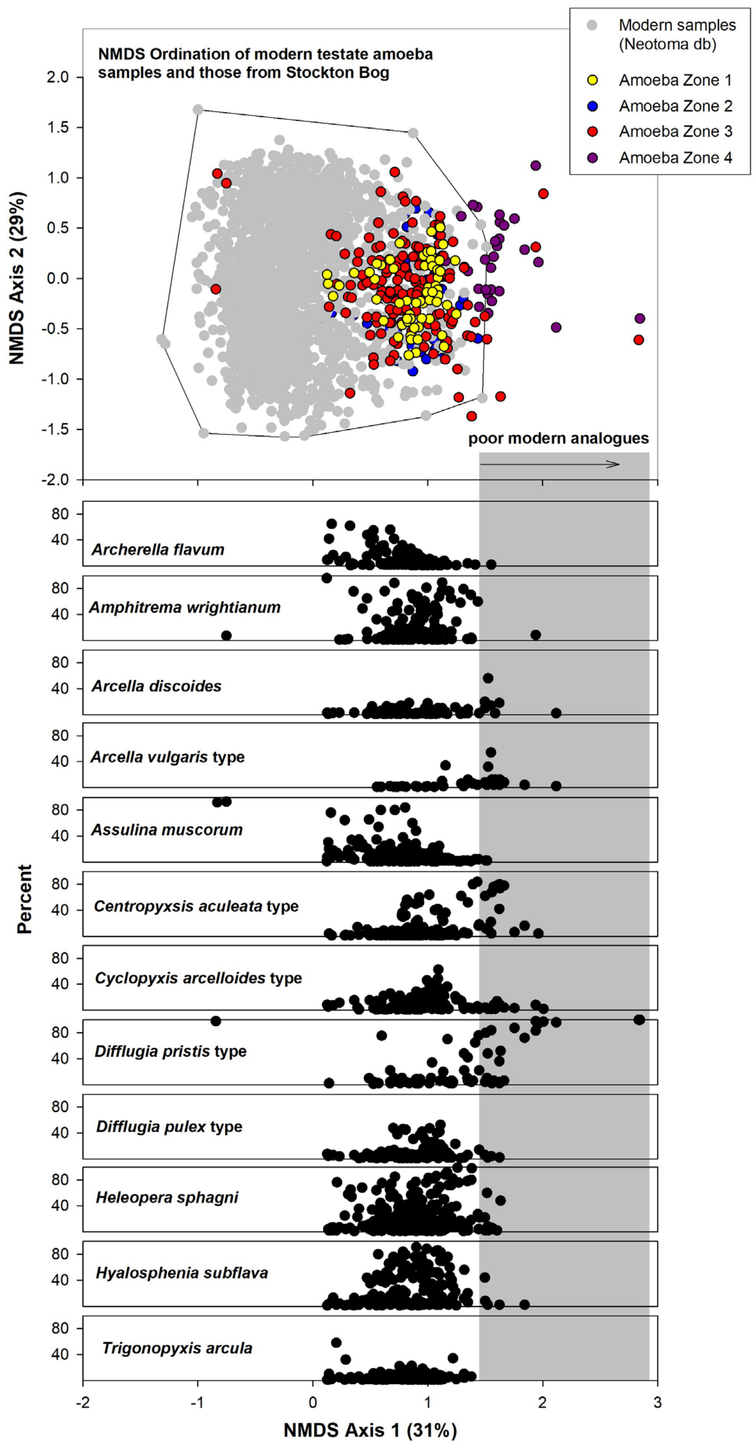

Figure 4. Non-metric multidimensional scaling (NMDS) ordination of fossil testate amoeba samples from Stockton Bog alongside modern samples from North American peatlands. Note that samples from Amoeba Zone 4 and some samples from Zone 3 fall outside the distribution of the modern samples, indicating poor modern analogues in the calibration dataset. Panels below the ordination show the abundance of common taxa in the Stockton Bog core, highlighting that the samples with poor modern analogues have abundant *Difflugia pristis* type and/or abundant *Centropyxis aculeata* type.

identified were this taxon (Figure 4). Because of the poor modern analogues in portions of A3 and A4, and the lack of continuous data from these zones because of variable preservation, quantitative analysis of the water-table depth reconstruction was restricted to the upper 194 cm of the core.

Bog charcoal records

Charcoal in all size fractions was abundant throughout the bog core, with all samples containing charcoal in each of the size classes (Figure 5). Plotting both charcoal concentrations and charcoal influx allows assessment of how sensitive the long-term patterns and peaks are to the sediment accumulation rate, which is an inferred variable sensitive to the age-depth model (Figure 5). Concentrations of the two size classes of macroscopic charcoal (125–250 µm and > 250 µm) were generally correlated with each other during the lake developmental phase prior to 4,750 cal yr BP ($r=0.35$), but not during the entire peatland phase ($r=0.05$). Some peaks in total macroscopic charcoal concentration were characterized by large relative quantities of >250 µm charcoal, whereas other peaks had greater relative amounts of 125–250 µm-sized charcoal. For example, the largest macroscopic charcoal concentration peak occurred at 2,300 cal yr BP and was associated with charred *Sphagnum* leaves, yet was not characterized by an increase in >250 µm fragments (Figure 5). Conversely, the second largest peak in the record occurred at 850 cal yr BP and almost entirely consisted of >250 µm fragments; this horizon and surrounding depths also contained abundant charred spruce (*Picea*) needles. Presumably, differences in the relative abundance of the charcoal size classes reflect fire proximity, fuel type, wind characteristics, and other differences (Figure 5).

Macroscopic charcoal influx highlights most of the same peaks evident in the concentration data; however, the effect of changing sediment accumulation rates had a large influence on peak heights (Figure 5). *CharAnalysis*, performed using the median sampling resolution of 7 years, identified 56 local fire episodes from the ca. 6,000 year-long macroscopic charcoal record. Estimated local fire frequency ranged from ca. 0.5 to 4.3 fires per 500 years throughout the record, and from 2.0 to 3.6 fires per 500 years over the past 300 years (Figure 5). Microscopic charcoal concentration was greatest during the time of slow peat accumulation, associated with the charred spruce needles between about 1,000 and 2,000 cal yr BP (Figure 5). However, microscopic charcoal influx during this time was not particularly elevated due to the slow accumulation rate (Figure 5). *CharAnalysis* identified 32 fire episodes from the microscopic charcoal record, and fire episodes inferred from this more regionally sourced charcoal ranged from about 0.5 to 3.5 fire episodes per 500 years.

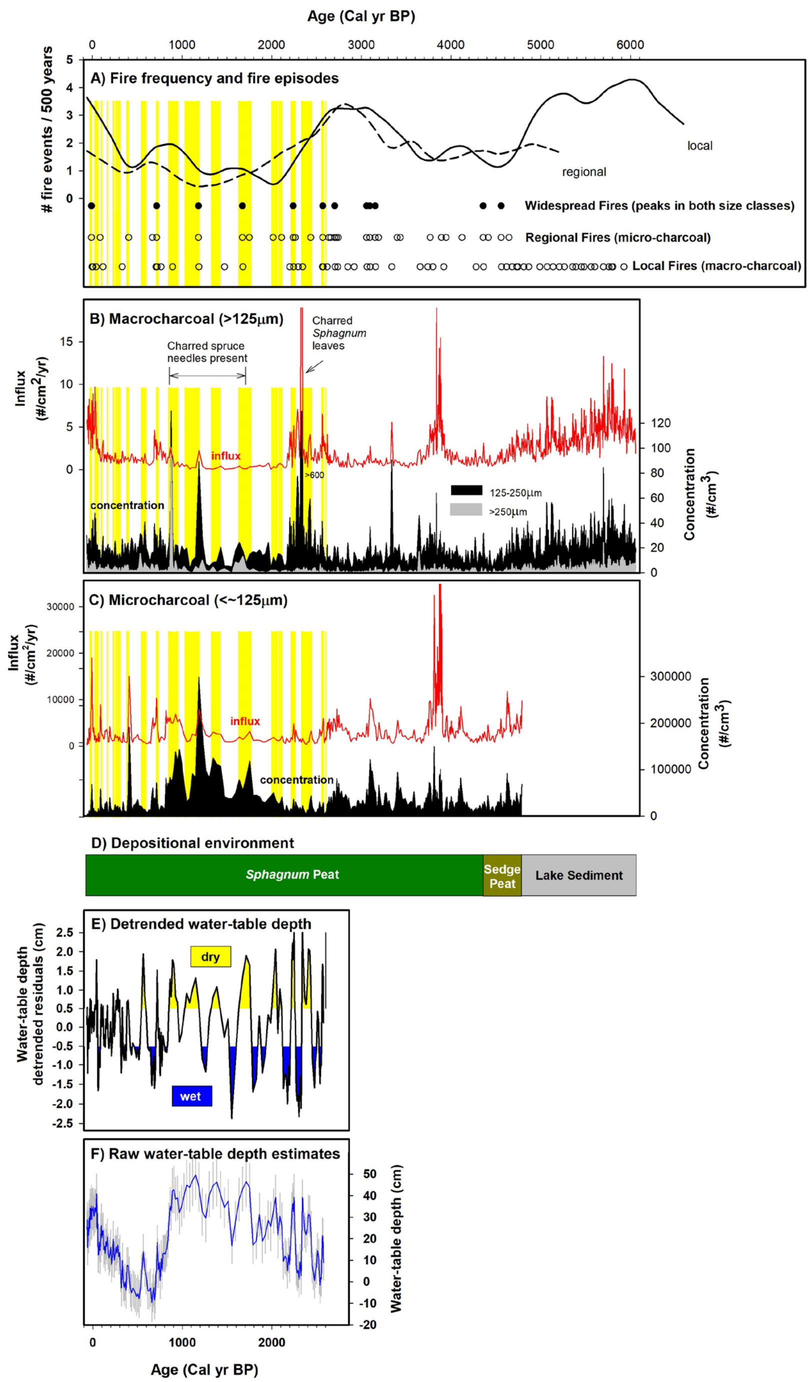

Figure 5. Paleoenvironmental reconstructions from the Stockton Bog sediment core, including A) inferred fire frequency and major fire episodes indicated with dots, B) macroscopic charcoal data, C) microscopic charcoal data, D) depositional history, E) detrended water-table depths highlighting multidecadal-to-centennial scale moisture shifts, and F) raw water-table depth estimates and testate amoeba zones highlighting overall changes in bog hydrology. Yellow vertical bars in the top three panels highlight the major shifts to drier conditions inferred from testate amoebae. In panel A, “widespread fires” refers to samples with *CharAnalysis*-identified peaks in both microscopic and macroscopic size fractions, whereas “local fires” and “regional fires” indicate peaks identified in the macroscopic and microscopic charcoal data, respectively.

Bog hydrology and fire reconstructions
Several interesting relationships between the inferred bog hydrology and charcoal records are apparent at both millennial and shorter timescales over the past 2,600 years. For example, changes in the raw (i.e., not detrended) water-table depths broadly corresponded to the concentration of charcoal, particularly changes in the concentration of microscopic charcoal (see Figure 5). The driest conditions on the bog, between 1,000 and 2,000 years ago, were associated with the highest microscopic charcoal concentration. High concentration of microscopic charcoal at this time was likely in part due to very slow peat accumulation rates (see Figure 2) that resulted from enhanced decomposition during this dry time period (see Figure 5). At multidecadal-to-centennial timescales, associations between the detrended water-table depths and the timing of fire episodes revealed that shifts to drier conditions on the bog were characterized by a greater number of identified fire episodes, in both the microscopic and macroscopic charcoal datasets (see Figure 5). Although fire episodes occurred during both wet and dry time periods on the bog, the probability (frequency) of fire episodes was significantly and substantially higher during drier times as compared to average and wet times (Figure 6). Six samples during the past 2,600 years recorded both macroscopic and microscopic charcoal peaks in the same sample, with five of these occurring during dry time periods, one during average conditions, and no charcoal peaks were associated with wet conditions (Figure 6).

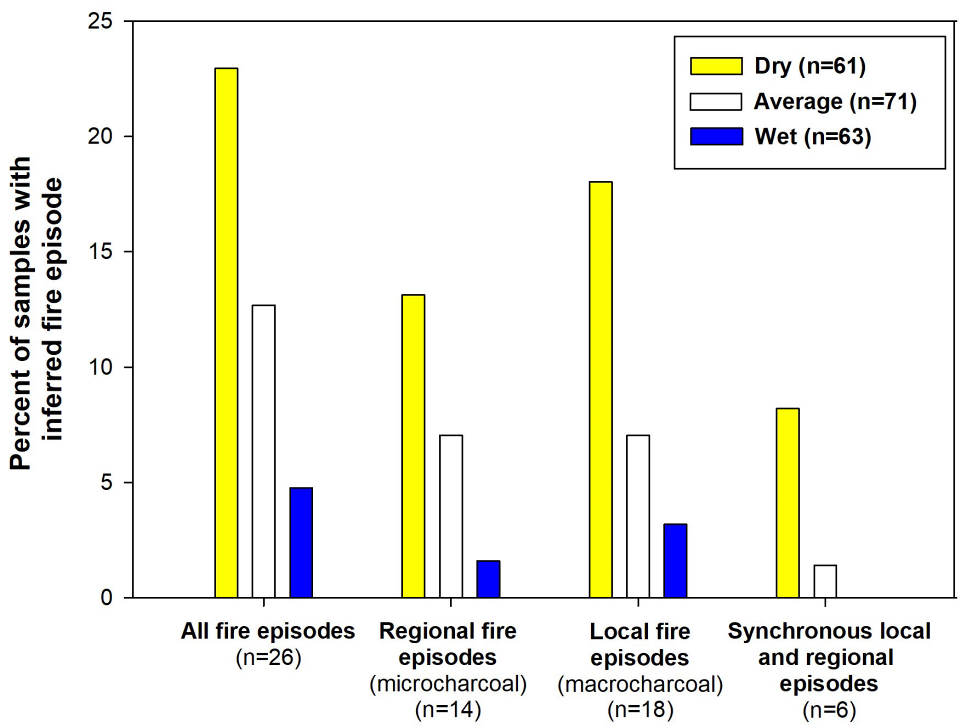

Figure 6. Relationship between bog-surface moisture and the probability of fire episodes for all inferred fire episodes (micro- and macrocharcoal), regional fire episodes (microcharcoal), local fire episodes (macrocharcoal), and for fire episodes that were recorded in both regionally (microcharcoal) and locally (macrocharcoal). Chi-squared tests assessed whether the number of fire episodes was different across the three categories of bog surface-moisture moisture. Results indicate that all comparisons were statistically significant ($p<0.05$). Local and regional fire episodes occurred more frequently during drier periods.

Stockton Lagoon

Lagoon age-depth model and depositional history

An age-depth model for the 60-cm-long core from the Stockton Lagoon indicated variable accumulation rates and the possibility of a gap in the record (i.e., a depositional hiatus) (Figure 7). The lagoon formed and began accumulating organic matter about 750 years ago in the area of the coring site, similar to the timing of organic matter deposition in similar settings elsewhere in the Apostle Islands (Long Island) (Bona 1990). Relatively rapid accumulation rates, with deposition times of less than 10 years/cm, characterized the next couple of centuries of sediment accumulation (ca. 750–500 cal yr BP) until about 30 cm in depth in the sediment core (Figure 7). At this point in the record, much slower accumulation rates, or a depositional hiatus when no record was preserved, occurred. In other words, little-to-no sediment is preserved between about 500 years ago and the early 20th century. A rise in *Ambrosia* pollen associated with logging and land clearance on the island occurred at about 22 cm. Rapid accumulation rates then characterized the last 100 years. A number of small age reversals with depth, one clear radiocarbon-age outlier, and the period of slow accumulation or depositional hiatus required using two age-depth models, linear interpolation from 0–22 cm and a smoothed spline (Blaauw 2010) from 22–60 cm to provide age-depth relations. One outlier radiocarbon age was not incorporated into the age-depth model (Figure 7, and see Table 1).

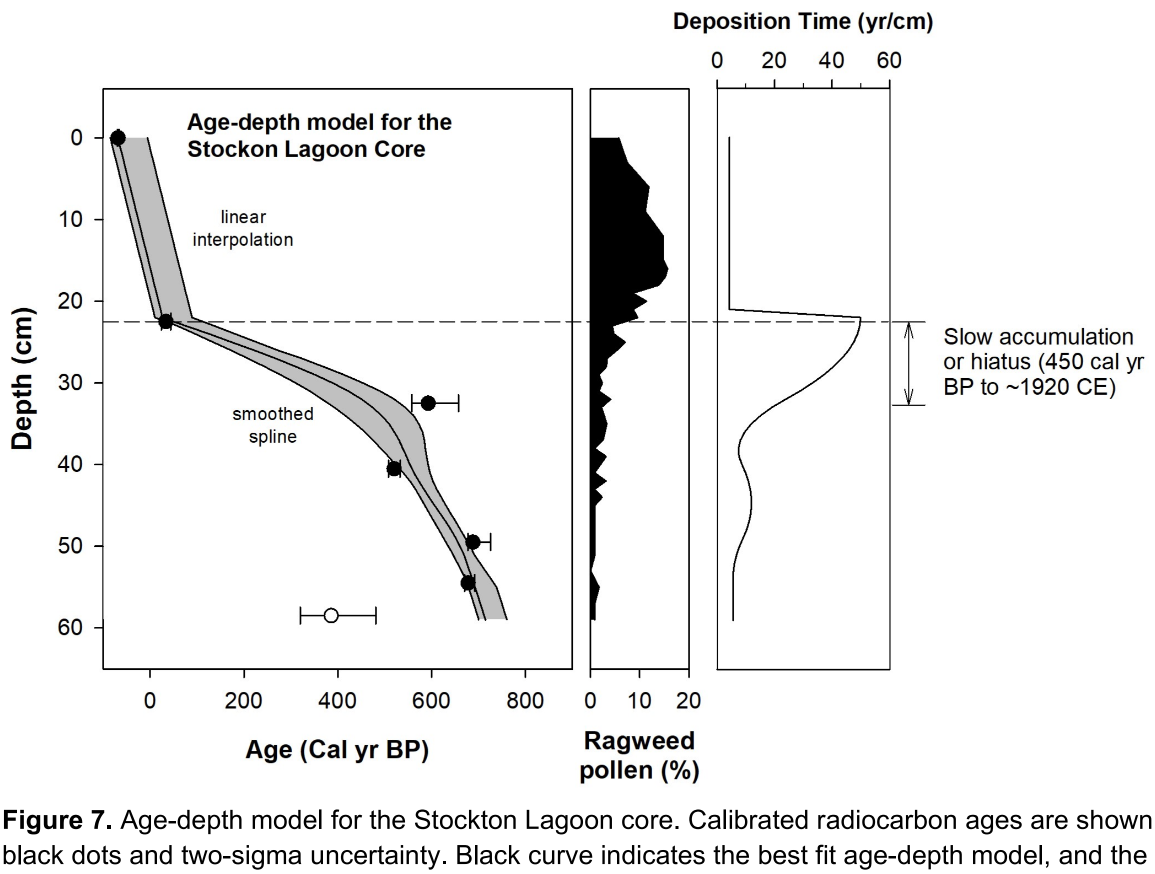

Figure 7. Age-depth model for the Stockton Lagoon core. Calibrated radiocarbon ages are shown with black dots and two-sigma uncertainty. Black curve indicates the best fit age-depth model, and the gray area shows 2-sigma uncertainty. An outlier date not included in the age-depth model is shown with white fill. The top of the cores, the position of the *Ambrosia* pollen increase at 22cm, and radiocarbon dates were used in the age-depth model.

Lagoon charcoal and pollen record

Interpretation of the Stockton Lagoon charcoal record from ca. 50 to 500 cal yr BP is complicated by the slow accumulation rate or depositional hiatus, which resulted in low and relatively stable influx estimates during this time period (Figure 8). However, between 750 and 500 cal yr BP, two major fire episodes were identified using *CharAnalysis*, and three were identified during the past century (Figure 8). A fire episode at 550 cal yr BP was characterized by abundant large charcoal fragments (>250 µm), suggesting a local fire (Figure 8). The largest peak in both concentration and influx occurred a centimeter above the *Ambrosia* rise, and likely reflects known historical fires in the 1920s and 1930s. The two other recent fire episodes were both relatively small in terms of peak magnitude (Figure 8).

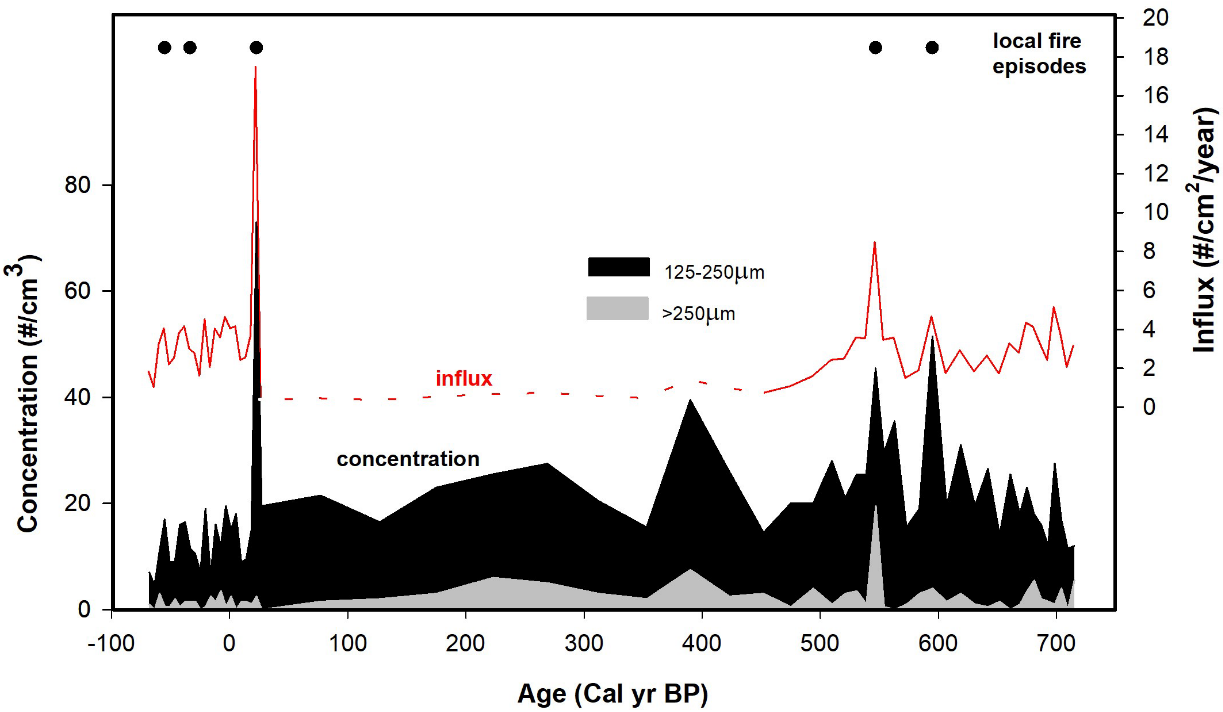

Figure 8. Charcoal data and fire reconstructions from the Stockton Lagoon sediment core. Dashed influx line denotes the time period that may be missing from the record or characterized by extremely slow accumulation. Dots indicate fire episodes identified with *CharAnalysis*.

The two fire episodes with the largest peaks in charcoal influx were associated with transient changes in the pollen data from the Lagoon (Figure 9). The fire event at 550 cal yr BP was followed by a brief decline in white pine pollen and a corresponding increase in birch pollen. The 1920s–1930s fire episode was followed by the opposite pattern, with a short-term decrease in birch and a transient increase in pine (Figure 8). Fires in the 1920s and 1930s occurred shortly after widespread logging of the island, which is also reflected in the pollen record by decreasing white pine and hemlock pollen percentages and higher oak pollen percentages that have persisted until today (Figure 9). Over the entire 750-year-long record, there was a slight trend toward decreasing percentages of pollen from wetland and aquatic taxa and increasing relative amounts of pollen from upland herbaceous taxa (see

Figure 8). The raw water-table estimates from Stockton Bog indicate that over the same time period that there has been a trend toward increasingly drier conditions (see Figure 5).

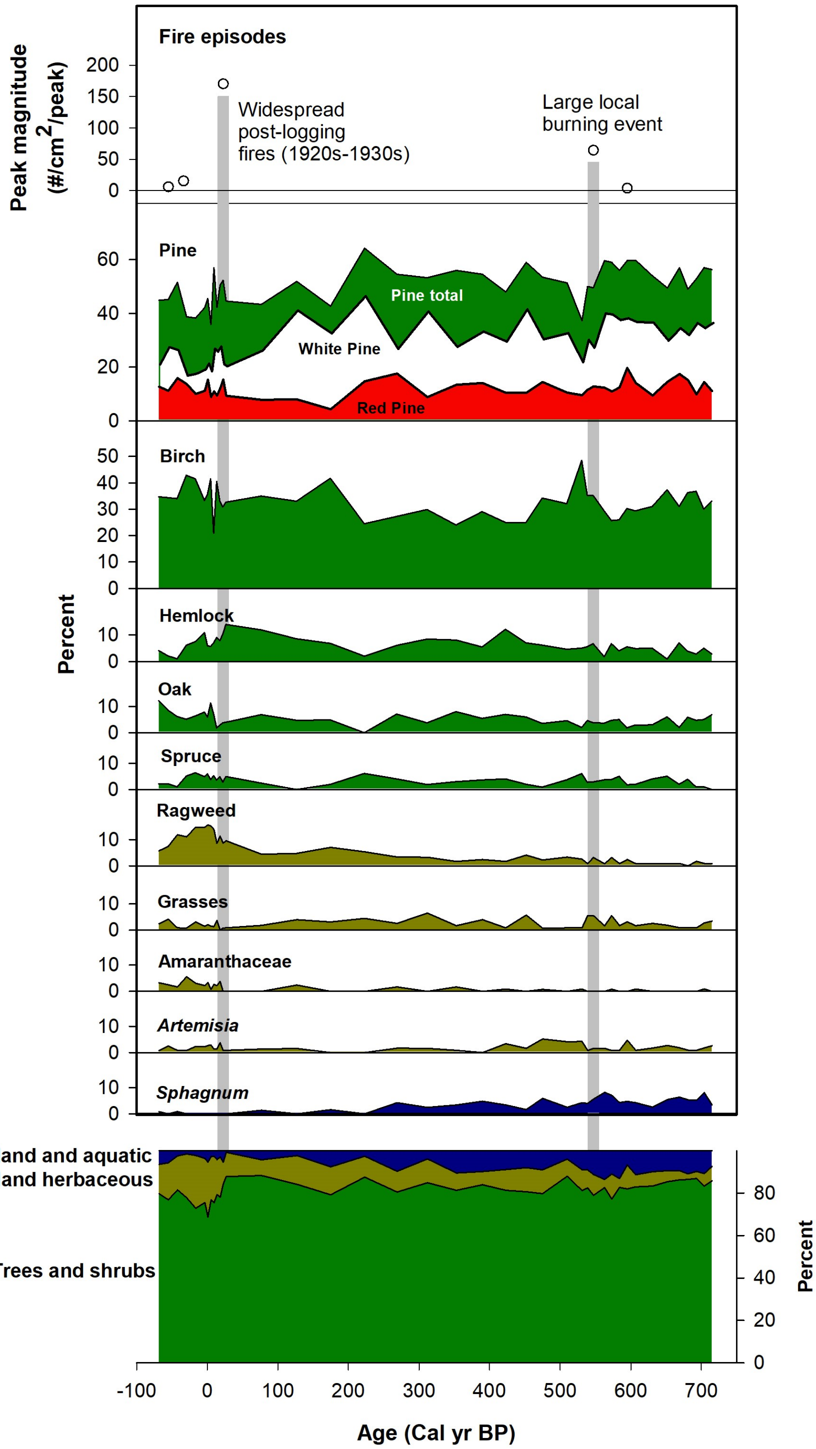

Figure 9. Selected pollen data (taxa with maximum abundance >5%) from the Stockton Lagoon sediment core, with gray vertical boxes highlighting the timing of the two largest fire episodes.

Discussion

Development of the Stockton Island Tombolo

Most of the Apostle Islands bedrock is Precambrian sandstone, and the current size and shape of the islands has been molded through glacial and coastal dynamics (Thornberry-Ehrlich 2015). Stockton Island formed about 12,000 years ago as two separate islands—Stockton Island and Presque Isle—as water-levels rose and the Laurentide Ice Sheet retreated. Water levels in the Great Lakes rose again in the mid-Holocene as differential isostatic rebound raised the North Bay outlet of the upper Great Lakes, resulting in the high-water levels of the Nipissing Great Lakes (Lewis 1970, Fisher and Whitman 1999). Two mid-Holocene peaks in water levels occurred, at about 6,000 cal yr BP and again at about 4,500 cal yr BP (Fisher and Whitman 1999, Johnson et al. 2007, Lewis 1970). These water-level fluctuations influenced the development of the area now occupied by Stockton Bog. The site became a lake or embayment of Lake Superior about 6,000 years ago during the first high-water level phase, accumulating lacustrine sediments similar in characteristics to those found in some coastal areas of the Lake Superior basin today (see Figure 2). Coastal sand deposition occurred between about 5,500 and 5,000 years ago, perhaps associated with falling water levels from the first Nipissing highstand, and a sedge-dominated peatland became established by about 4,700 cal yr BP as the basin became isolated from Lake Superior. Our sediment record from the peatland suggests that the peatland then transitioned into a *Sphagnum* bog within a few hundred years, indicating increasing isolation from groundwater and surface flows as Lake Superior water-levels dropped rapidly from the second Nipissing highstand (see Figure 2) (Baedke and Thompson 2000, Johnson et al. 2004). The formation of the tombolo via the accumulation of north-south oriented ridges between the two original islands occurred sometime after the bog formed. The spatial sequences of beach ridges east and southwest of the bog formed in response to fluctuating lake levels, with our radiocarbon dating of the lagoon sediment indicating that the easternmost ridge near the open Great Lakes Barrens was established by about 800 years ago (see Figure 7). The modern spatial extent and configuration of the tombolo was likely established by this time.

Peatland and Lake Records of Past Fire History

Temporal changes in the charcoal records from the two sediment records on Stockton Island reflect changes in fire frequency, intensity, proximity, and fuel characteristics as well as changes in depositional environment, charcoal source area, and accumulation rates. Given that the bog and lagoon represent quite different depositional environments, and that the bog went through an open-water phase before becoming a peatland about 4,800 years ago, some discussion of the differences in how peatlands and lakes record past fire history is warranted.

Previous studies have suggested that peatland records contain a more local record of past fire events than lakes (Conedera et al. 2009, Mooney and Tinner 2011, Feurdean et al. 2012), may contain less noisy charcoal variations (Feurdean et al. 2012, Rius et al. 2011), and have little to no background signal from charcoal redeposition because all inputs are atmospherically deposited (Florescu et al. 2018). Comparing the peat and lacustrine portions of the Stockton Bog macroscopic charcoal influx record provides confirmation of some of these conclusions (see Figure 5). The background influx values were higher during the lacustrine portion of the record, with more short-term variability than

the peat portion of the record, leading to the identification of more fire episodes during the lacustrine developmental phase. These patterns are consistent with redeposition or surface inflows contributing charcoal when open-water conditions existed and connection with Lake Superior would have brought charcoal to the site from a greater distance. Thus, the record at this time may integrate fire history across a much broader area. Therefore, changes in charcoal influx across the lithological transition are unlikely to be related to real changes in fire activity, as noted by Florescu et al. (2018). However, after establishment of peatland, charcoal reaching the bog would have only come via atmospheric deposition or from burning of the peatland. During the peatland phase, the potential controls on temporal patterns of charcoal abundance include 1) changing fuel composition and density related to vegetation changes in the upland surrounding the peatland, 2) changing size of the tombolo, and therefore potential burn area, as it developed through time, and 3) changes in the frequency, size, and intensity of fires in the upland and/or the peatland.

Bog charcoal records provide advantages over lake records because they are atmospherically derived and minimize the effects of charcoal redeposition, but they also present certain complications not applicable to lake records. Bogs can burn, generating charcoal from fires occurring on their surface (Ohlson et al. 2006, Sillasoo et al. 2007, Turetsky et al. 2004); consequently, making inferences about upland fires is potentially confounded by local fires on the peatland. Furthermore, during particularly dry times, the peat itself can sometimes burn, removing a portion of the peat record (Clifford and Booth 2015, Martin 1999). The vegetation of Stockton Bog burned on multiple occasions between 2,300 and 800 cal yr BP. The largest peak in macroscopic charcoal concentration and influx occurred at 2,300 cal yr BP and was associated with burned *Sphagnum* leaves, clearly indicating that the bog vegetation burned. This was the only sample in the core where burned *Sphagnum* was observed, although high accumulation rates at this depth suggest that only the surface vegetation burned and not the peat itself. Numerous horizons between 1,800 and 800 cal yr BP also contained burned *Picea* needles, suggesting fires were common on the bog surface during this time, and there may have been denser woody cover on the bog during this dry time period (see Figure 5). A particularly large bog fire occurred at 850 cal yr BP, leaving abundant large macroscopic fragments (>250µm) and abundant charred *Picea* needles in the peat record. Given the much slower estimated accumulation rates during this interval of the peat core, a depositional hiatus (i.e., missing time) spanning a century or two cannot be ruled out.

One additional caveat to make about bog records is that changes in charcoal influx near the top of the core may be difficult to interpret because of incomplete decomposition and the loose, uncompacted peat. For example, charcoal influx increases at the top of the Stockton Bog core, which is likely due to so little time being represented by each centimeter (see Figure 5). Concentration of charcoal may offer a more accurate depiction of fire history during these upper centimeters of peat, and it suggests several peaks in the early-to-mid 20th century followed by lower charcoal concentrations.

Long-Term Fire and Vegetation History of the Tombolo

A previously developed pollen record from Stockton Bog and our record from Stockton Lagoon both suggest that vegetation on the tombolo has been relatively stable and dominated by red pine, white pine, and paper birch for the last 6,000 years (Swain and Winkler 1983) (Figure 10). A possible trend

toward increasing birch and decreasing pine occurred over this time period (Figure 10); however, the record likely integrates changes occurring on both the glacial till and the tombolo, so it is unclear whether these trends reflect long-term changes on the tombolo itself. For example, increasing birch pollen during the late Holocene (last ca. 3,000 years) was also observed in a paleoecological study of Brander Bog, located further north on the glacial soils of Stockton Island, where yellow birch was probably a greater contributor to the total birch pollen (Swain and Winkler 1983). Hemlock also increased about 2,000 years ago on northern portions of the island. The relative stability of vegetation on the tombolo suggests high resilience of the red pine forest to climate changes of the past.

Our charcoal records reveal that fire has clearly been an important and persistent feature of the Stockton Island Tombolo since its establishment. The occurrence of charcoal of all size fractions in every centimeter of the bog and lagoon cores—particularly at the bog, where it was atmospherically deposited—suggests that fires on the tombolo were frequent throughout its history, and many fires were likely too small in size and/or intensity (e.g., ground fires) to generate significant charcoal peaks above background levels (see Figure 5). Studies of fire scars from other coastal red pine forests in the upper Great Lakes have suggested that light ground fires every 5–20 years were typical of these ecosystems for at least a few centuries prior to European land clearance (Johnson and Kipfmueller 2016, Loope and Anderton 1998), and recent work on the tombolo itself suggests similar fire frequencies (Kipfmueller 2019). The continual presence of macroscopic charcoal in bog and lagoon sediments, even during time periods where each sample represents less than 6 years of accumulation, suggests that fire regimes on the tombolo were likely similar throughout its history.

No obvious long-term trends were observed in the charcoal records from the bog and lagoon (see Figures 5 and 8), which is consistent with the interpretation of the occurrence of frequent low intensity fires and occasional stand-replacing fires since the tombolo's origin (see Figure 5). The inferred local and regional fire frequencies, based on the timing of charcoal peaks, reflect the occurrence of only the very largest fire episodes and likely represent either highly localized fires or stand-replacing fires of high intensity. The frequency of these large fires ranged from about 1-to-3 major fire episodes per 500 years since the mid Holocene (see Figures 5 and 8), with the highest frequencies occurring about 3,000 years ago and during the past 200 years (see Figure 5). The vegetation of Stockton Bog burned during several fire episodes, particularly at 850 cal yr BP and 2,300 cal yr BP (see Figure 5). Frequent low-intensity fires and occasional higher intensity or stand-replacing fires has been the inferred fire regime in the pine-dominated vegetation of the tombolo since its origin (Swain and Winkler 1983) (see Figure 10).

The shorter pollen record from Stockton Lagoon also attests to the pre-1900s stability of the Great Lakes Barren community, although the higher resolution of the analyses and direct comparability to the fire history (i.e., both datasets collected within the same core) provide insight into shorter term changes (see Figure 9). For example, the patterns following the local fire event at 550 cal yr BP are consistent with paper birch sprouting and growth within a decade or two after the fire, but after 40–50 years white pine pollen percentages returned to pre-fire levels. Red pine abundance appears to have been relatively unaffected (see Figure 9). In contrast, the fires and logging in the early 1900s

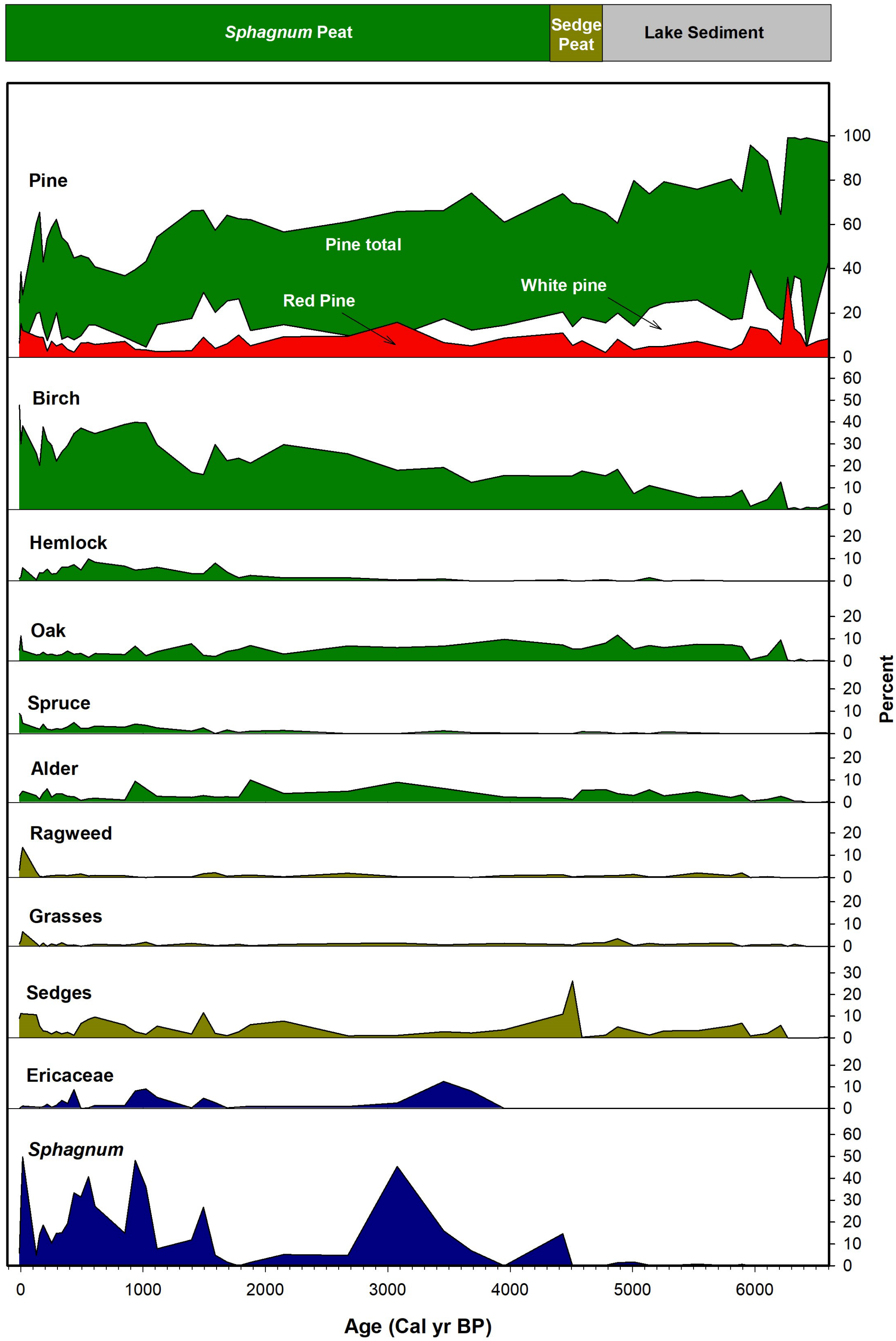

Figure 10. Selected pollen data (taxa with maximum abundance >5%) from the Stockton Bog sediment core collected by Swain and Winkler (1983). The age-depth model developed in this study (see Figure 2) was used to plot the Swain and Winkler (1983) pollen data.

were associated with transient decreases in birch pollen and increases in pine pollen, although Swain and Winkler (1983) noted that the red pine-dominated tombolo vegetation may have been less affected by logging than vegetation elsewhere on the island. Logging and fires on the glacial till landscape of Stockton Island near Brander Bog resulted in decreased abundance of hemlock and increased abundance of oak, a pattern that remains on the landscape today, whereas the tombolo vegetation appears to have been less altered by these events (Swain and Winkler 1983) (see Figure 9).

Potential Fire-Climate-People Interactions

The level of influence that indigenous people had on fire regimes in North American ecosystems is widely debated (e.g., Abrams and Nowacki 2019, Oswald et al. 2020), and our records of fire history cannot address the relative importance of lightning versus humans as ignition sources. There is abundant evidence and traditional knowledge indicating that the Ojibwe people used fire to clear land; maintain early successional plant communities; promote paper birch, which was extensively used for shelter and canoes; and stimulate berry production (Anderton 1999, Berkes and Davidson-Hunt 2006, Guyette et al. 2016). These sorts of human activities happened against the backdrop of climate change, including changes associated with the Medieval Climate Anomaly (ca. 1,000–600 cal yr BP) and Little Ice Age (ca. 600–100 cal yr BP), as well as considerable variability in multidecadal-to-centennial scale drought and pluvial episodes (e.g., Booth et al. 2012). Furthermore, spatial complexity in vegetation and edaphic conditions likely led to spatial variability in both the use of fire by humans and the climate sensitivity of fire regimes across the landscape (Tweiten et al. 2015). However, the small size of the tombolo and its isolation by water and more mesic, less-flammable vegetation suggests that local ignition sources must have been frequent, given the continual presence of locally sourced charcoal (i.e., fragments >125 µm) throughout the record.

Although fire-climate-people interactions on Stockton Island and the surrounding region were likely complex, our coupled bog moisture and charcoal records provide a unique perspective on the historical sensitivity of inferred fire episodes to climate variability, particularly whether the largest fire events occurred more frequently during particular climatic conditions. Our analyses revealed no significant differences in the frequency of inferred local or regional fire episodes between the Medieval Climate Anomaly and the Little Ice Age, time periods characterized by relatively warm and cool conditions, respectively. However, major local and regional fire episodes occurred more frequently during drier short-duration time periods (see Figure 6). Although these patterns are consistent with both lightning and human ignition sources, they do indicate that at least in a probabilistic sense, the largest fire episodes likely reflected widespread and/or stand-replacing fires that were more common during dry time periods (see Figure 6). Furthermore, although major regional and local fire episodes rarely occurred at the same time, when they did it was almost exclusively when the tombolo was dry (see Figure 6). It is worth noting that Stockton Bog has generally been getting drier for the past 1,000 years, although whether this pattern is due to climate or drainage dynamics through the ridge-swale topography east of the bog is unclear.

Tombolo Fire History For the Last Few Centuries and Millennium

A summary of the last several centuries of fire history on the tombolo is likely particularly relevant to management, given that the tombolo was near its present spatial configuration during this time period. Historical fires on the island have been documented for the past hundred years (APIS personnel, personal communication), and studies of fire scars on dead stumps provide a spatially explicit and chronologically precise fire history record for the last few centuries (Kipfmueller 2019). A comparison of historical records, fire-scar data, and our sediment-based records from Stockton Bog and Lagoon confirms that the identified fire episodes in our sediment-based records only reflect the largest and/or most local fires, and not surprisingly, they do not capture all of the known fire events on the tombolo for the past several centuries (Figure 11). However, only three historically documented fires were larger than about a hectare in size, and both the bog and lagoon recorded about three fire episodes in the past century. Both sites recorded the widespread fires that occurred after logging, with much of the charcoal likely coming from the widespread fires in the 1920s and 1934 (Figure 11). Fires of the mid-1800s are clearly documented in fire scars obtained from dead stumps on the tombolo, and these are also associated with a peak in charcoal at Stockton Bog (Figure 11). Fire-scar studies reveal that fire frequency was particularly high in the mid-1800s, likely greater than what would be expected based on natural ignition sources alone (Kipfmueller 2019). Unfortunately, the lagoon does not preserve a clear record at this time due to slow accumulation or a depositional hiatus.

The records from Stockton Bog and Stockton Lagoon highlight how anomalous the intensity of the post-logging fires of the 1920s and 1930s were in the context of fire variability of the past millennium (Figure 11). It is worth noting that the 1938 aerial photograph (see Figure 1) was taken only a few years after the largest fire episode of the last 1,000 years on the tombolo. Vegetation density on the tombolo in 1938 was likely substantially reduced by previous decades of logging as well as the extensive fires. Although the lagoon record is limited in its temporal coverage, the only clear example of synchronous fires at both the bog and the lagoon were these post-logging fires of the 1920s and 1930s. This pattern, and the documentation of numerous smaller fires during the past several centuries by tree-ring and historical records, suggests that most fires on the tombolo historically were patchy and heterogenous, with landscape features like the extensive lagoon, wetlands, and ridge-swale topography limiting their spread.

Comparison to Inland Pine Barren Ecosystems of the Region

Although structurally similar to the more extensive pine barrens ecosystems occupying sandy, glacial outwash deposits of the upper Midwest, the fire history of the Stockton Island Tombolo might be expected to differ. Its small size, proximity to the moderating climatic influence of Lake Superior, and isolation from other fire-prone vegetation types might lead to less frequent fires than on the more widespread pine barren ecosystems on the mainland. Extensive work describing the fire and vegetation history of the past several thousand years has been conducted on the northwestern Wisconsin sand plain (NWSP) over the last few decades, using similar methods to those of the present study. One of the key observations of this work was that there has been considerable variability among vegetation and fire regimes, even on a relatively homogeneous sandy outwash

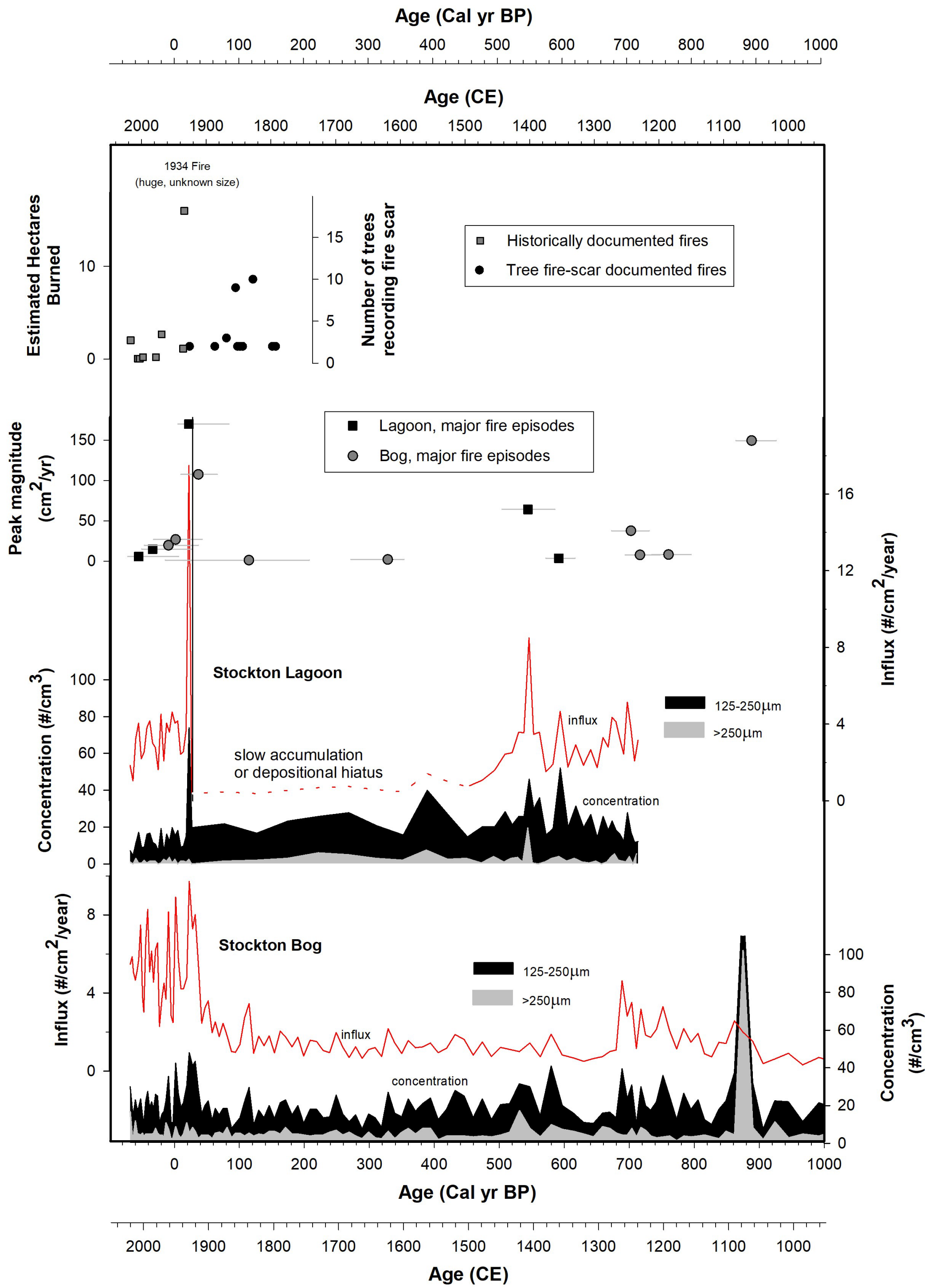

Figure 11. The last millennium of sediment-based fire history compared with historically documented fires (APIS personnel, personal communication) and those identified on fire scars on tree stumps (Kipfmueller 2019). Sediment-based fire episodes are shown with 2-sigma chronological uncertainty based on the age-depth models.

plain. Likely these differences arise from soil and vegetation differences, as well as lake position within the surrounding landscape and along climatic gradients (Tweiten et al. 2015, Lynch et al. 2014).

Given that the NWSP should have experienced a similar climatic history to that of Stockton Island over the past several thousand years, it provides a useful comparison to consider how fire in Great Lakes Barrens might differ from that of inland pine- and oak-dominated systems. Comparison of fire histories suggests differences in the two areas. For example, charcoal concentrations and peak frequency generally dropped at inland sites on the NWSP at the onset of LIA conditions (Lynch et al. 2011), whereas fire regimes on Stockton Island appear to have been less sensitive to this climatic transition, possibly because of the moderating influence of Lake Superior. Over the past 2,000 years, fire frequencies inferred from the sites on the Stockton Island tombolo were also at the very low end of the range observed on the northwestern sandplain (Figure 12), indicating that the records from Stockton Island generally contain fewer large charcoal peaks, relative to background levels, than those from the NWSP. Background charcoal levels in the Stockton Island records are also on the low end of the range observed from the NWSP (Lynch et al. 2011). The bog and lagoon records likely integrate charcoal from a smaller area than lakes on the sandplain—not surprising given their island location—and past fires on the tombolo were likely small, occurring within a heterogenous mosaic of wetlands and sandy uplands.

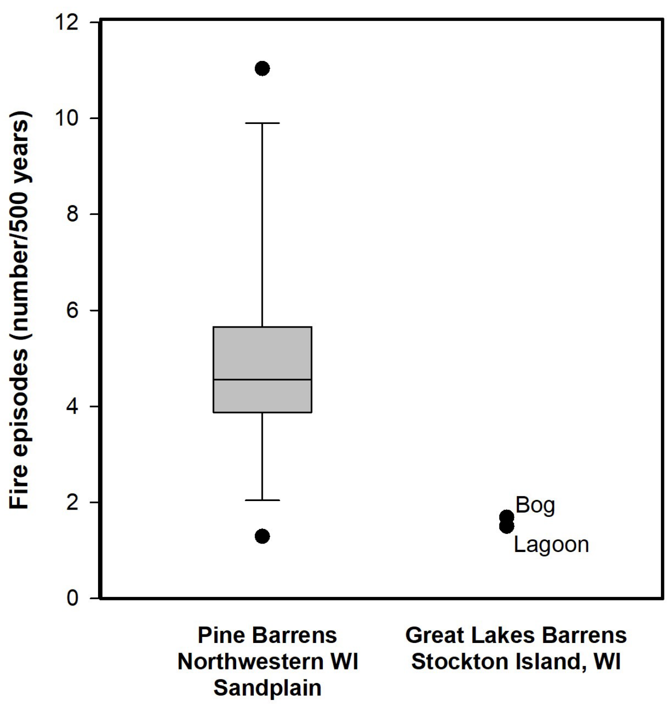

Figure 12. Frequency of large fire episodes for the 2,000 years prior to European settlement inferred from twelve lakes on the northwestern Wisconsin sandplain (Tweiten et al. 2015), compared with estimates for same time period at Stockton Bog and the last 750 years at Stockton Lagoon.

Conclusions

The Stockton Island Tombolo has a long history of burning, and it likely experienced heterogenous and patchy fires since its formation sometime after about 5,000 years ago. Surface fires were probably similar in frequency to other studied coastal red pine forests of the region (Kipfmueller 2019, Loope and Anderton 1998). However, our long-term records indicate that significantly larger or more intense fires occurred about 1–3 times per 500 years since the mid-Holocene, and that these major fire episodes were significantly more likely to occur during drier time periods. Several of these larger fires burned the peatland vegetation of Stockton Bog, particularly during a time when the bog was dry between 1,000 and 2,000 years ago. However, large fire episodes were less frequent than those of inland pine barren communities of northwestern Wisconsin (Tweiten et al. 2015, Lynch et al. 2011), which likely had greater connectivity with the surrounding fire-prone landscape and may have experienced more extreme climatic variability than island sites. The vegetation of the tombolo has been relatively stable and pine-dominated since its formation, likely in part due to the stable fire regime. Post-logging fires, particularly the widespread fires of the 1920s and 1930s, likely represent the most severe fire episode of at least the last 1,000 years.

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