PLOS ONE

Climate variability and cultural eutrophication at Walc Pond (Massachusetts, USA) during the last 1800 years

J. Curt Stager , Brendan Wiltse, J. Bradford Hubeny, Eric Yankowsky, David Nardelli, Richard Primack

Published: April 4, 2018 • https://doi.org/10.1371/journal.pone.0191755

Abstract

Recent shifts in the ecological condition of Walden Pond, MA, are of potentially wide interest du cultural, historical, and recreational resource in addition to its scientific value as an indicator of l change. Algal microfossils in six sediment cores document changes in hydroclimate and trophic 1800 years and extend two previous sediment core records of shorter length. Low percentages cores (WAL-3, WAL-15) indicate shallowing and/or greater water clarity associated with a relati Climate Anomaly, ca. A.D. 1150–1300, Cultural eutrophication of the lake since the A.D. 1920s *Asterionella* and *Synedra* to increase in relative abundance at the expense of *Cyclotella*, *Discos Mallomonas allorgei*. Percentages of *Asterionella* and *Synedra* have remained fairly stable sinc sediment core study was conducted, but scaled chrysophytes have become more numerous. T mitigation efforts have curtailed anthropogenic nutrient inputs to Walden Pond, the lake has not described by Henry David Thoreau and may become increasingly vulnerable to further changes possibly wetter future.

Citation: Stager JC, Wiltse B, Hubeny JB, Yankowsky E, Nardelli D, Primack R (2018) Clima eutrophication at Walden Pond (Massachusetts, USA) during the last 1800 years. PLoS ONE /10.1371/journal.pone.0191755

Editor: Hideyuki Doi, University of Hyogo, JAPAN

Received: November 11, 2017; **Accepted:** January 10, 2018; **Published:** April 4, 2018

Data Availability: The data underlying this study have been uploaded to NOAA and are acc https://www.ncdc.noaa.gov/paleo-search/study/23310.

Funding: The research upon which this study is based was funded by the U.S. National Scie #1358362 and #1126128 (www.nsf.gov).

Competing interests: The authors have declared that no competing interests exist.

Introduction

Best known as an inspiration for Henry David Thoreau's *Walden*: *or Life in the Woods* [1] during (Concord, MA) is also a heavily used recreational venue for hundreds of thousands of bathers, cabin site annually [2]. During the early 20th century, water clarity declined significantly due to a shoreline development and inputs of human wastes [2],[3]. Poisoning of the lake in 1968 with th repeated stocking with non-native sport fish, and regional climatic warming have also influenced the lake [2–4]. In recent decades, closure of a nearby town dump, shoreline stabilization, and u management of Walden Pond State Reservation have mitigated some of the changes, but relat of water clarity, lake levels, or other limnological parameters are available with which to assess Sediment cores, which can provide long, continuous records of phytoplankton community struct ecosystem, are therefore an important source of long-term perspectives on environmental cond our analyses focus on the remains of diatoms and chrysophytes, which are microscopic plant-lil resistant shells (known as "frustules" or "valves"), cysts, or scales that are often well preseved i possess diagnostic features that allow the identification of species which, in turn, aids in the dev chemistry, water clarity, and other features of the lake based upon the known habitat preference

Two previous studies of sediment cores from the deepest basin in Walden Pond yielded 600-ye pollen, microalgae, and geochemistry [7]. Both contained evidence of cultural eutrophication sir indicated by shifts in the carbon and nitrogen isotope composition of the sediments and by pron the genera *Asterionella* and *Synedra* that are often associated with enhanced phytoplankton pr

In this paper, we present diatom, chrysophyte, and geochemical records from six additional cor status and phytoplankton community of Walden Pond since A.D. 2000, when the last coring stu diatom records of our two longest cores to derive for the first time a qualitative reconstruction of variability in the watershed, which provides new insights into the climate history of the northeas relatively few such records are available.

Study site

Walden Pond (42°26.3'N, 71°20.4'W; Fig 1) occupies a glacial kettle depression that formed in granitic bedrock after the retreat of the Laurentide ice sheet [8]. It contains three basins of ca. 3 depending upon the water level, which can vary over several meters between years, and it is th Massachusetts (Fig 1) [3]. Walden is a flow-through seepage lake with no surface inlet or outlet receives about half of its volume from westward-flowing groundwater and the rest from direct pr showed that the hypolimnion (lower layer of the water column) was moderately oxygenated in A recently dissolved oxygen concentrations below 15 m depth have been typically at or close to 0 stratification period [3]. Secchi depth, a measure of water transparency, was reportedly within th century [1] and early 20th century [5], but more often within the lower end of the 2.5–9 m range values are low (65–93 μS/cm) [7] and pH varies from ca. 6.5 during the spring mixing period to summer. The higher pH values have been attributed in part to productivity by benthic meadows *Nitella*, that cover much of the lake bed between 6 and 13 m depths with a biomass 17 times th

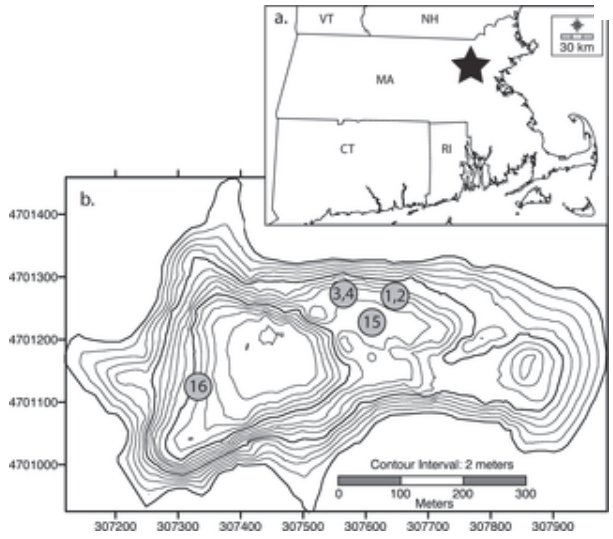

Fig 1. Location maps.
(a) Southern New England, with the location of Walden Pond indicated by a star. (b) Walden sites indicated. Numbers correspond to the numbers of the "WAL" cores discussed in the tex maps.com/carte.php?num_car=7175&lang=en under a CC BY license, with permission from 2007.
https://doi.org/10.1371/journal.pone.0191755.g001

Concord was settled by British colonists in A.D. 1635, and the forests surrounding Walden Pon extent over the next three centuries, during which time oak (*Quercus*) became less common in relative to birch (*Betula*) and pine (*Pinus*) [7]. A sequence of more recent human activities in the documented by Maynard [2] and summarized here, includes the building of a temporary shanty 1843 for workers during construction of the Fitchburg Railroad, which lies close to the western s since 1844. Sparks from steam engines frequently caused forest fires near the lake during the large fires in 1894 and 1896. Wood-cutting operations left hill-slopes along the eastern and nort 1840–1841, 1851–1852, and 1918, and high water levels killed many lake-side trees during the area and beach were operated on the western shore during the 1860s through the 1890s, but w usage of the lake increased further, underbrush and trees were cleared for walking along the wa more frequent.

After Walden Pond State Reservation was established in 1922, beach and bath-house facilities shore. By the early 1930s, hundreds of thousands of swimmers used the facility in summer, and site beside a cove on the northwestern shore caused large amounts of soil to wash into the lake and enlargement of the beach by county commissioners in 1957. More than half of the summer now be attributable to urine released by swimmers [3]. Stocking of the lake with game fish was has been frequently stocked with rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo* treated with rotenone in 1968. The Reservation has been managed since 1975 by the Massach and Recreation, during which time shoreline stabilization and restoration efforts have reduced s nearby Concord landfill during the early 1990s reduced the prevalence of waste-deposition by g

Materials and methods

Field permits for sampling in Walden Pond were provided by the Massachusetts Department of

June, 2015, two cores (WAL-1, WAL-4; 25 cm lengths) were collected with a UWITECH gravity basin, where two gravity-driven piston cores (WAL-2, WAL-3; 114 cm and 84 cm lengths, respe modified Kullenberg corer (Fig 1). Previous studies had focused on the deep western basin, but selected for this investigation in order to provide supporting information from that understudied for this choice was the likelihood that benthic diatoms associated with shallower microhabitats v in that location, thereby providing more robust time series of the ratios of planktonic to benthic t levels and hydroclimate [9–12].

As photosynthetic algae, benthic diatoms require sunlight, and their distribution on a lake bed is factors including water depth, clarity, and the proximity of littoral habitats [13]. Higher (lower) pe taxa in a core, for example, can reflect increased light penetration to the bottom due to the lowe dissolved organic carbon, a lateral shift of littoral habitats closer to the coring site, or a decrease planktonic productivity, all of which are likely to occur during prolonged droughts [9–14]. Variatic planktonic diatoms (referred to here as %PLANK) within the longer WAL-3 and WAL-15 cores a qualitative changes in effective moisture, with decreases of %PLANK representing generally dri to favor the growth of benthic taxa through changes in light penetration to the bottom. This inter significant relationships between modern-day water depth and %PLANK in the surface sedimer other North American lakes [9–12].

Care was taken to avoid sites where *Nitella* mats interfered with penetration of the core barrels preliminary core was rejected in the field due to partial clogging with *Nitella*. Twelve samples of collected from the central basin at 2 to 19 m depths, and a second field crew collected a gravity 19 m depth near the middle of the central basin (Fig 1). In 2016, a gravity core (WAL-16; 31 cm depth in the deep western basin in order to better document recent changes in the phytoplankto different sectors of the lake (Fig 1). All but one of the cores were extruded vertically in the field, increments, and stored in plastic sample bags under refrigeration. For WAL-15, the mud-water i for transport, and the core was split longitudinally for subsampling.

Radiocarbon ages of oven-dried organic sediments and sieved pollen fractions were obtained f WAL-2, WAL-3, and WAL-15 (Table 1), and calibrations were determined with CALIB version 7. ^{137}Cs and ^{210}Pb analyses on dried, powdered sediments were also performed by staff at the S Station (MN, USA).

Depth (cm)	^{14}C age (yr BP)	Calibrated Year A.D. 2-sigma (prob.)	Sample #
WAL-2			
27.5	1990 ± 30	x	134219
36.5	485 ± 30	x	134218
56.5	380 ± 2	x	134217
75.5	485 ± 35	x	134216
100.5	1330 ± 15	x	134215
111.5	1530 ± 20	x	131316
WAL-3			
40.5	345 ± 15	1472–1527 (0.40) 1554–1633 (0.60)	134223
51.5	490 ± 15	1416–1441	134222
69.5	1080 ± 15	899–923 (0.23) 946–1013 (0.77)	134221
78.5	1360 ± 20	645–678	134220
WAL-15			
35.5	535 ± 25	1322–1347 (0.19) 1392–1435 (0.81)	142334
47.5	980 ± 15	1017–1046 (0.72) 1090–1122 (0.24) 1139–1148 (0.04)	142335
57.5	1290 ± 20	668–726 (0.64) 738–768 (0.36)	142336
64.5	1660 ± 25	266–271 (0.01) 332–426 (0.99)	142337

https://doi.org/10.1371/journal.pone.0191755.t001

Table 1. Radiocarbon ages and calibrated age ranges of sediment samples from Walden Pond cores WAL-

The radiocarbon ages for WAL-2 denoted by "X" were not calibrated due to evidence of sedi
https://doi.org/10.1371/journal.pone.0191755.t001

An age model for core WAL-3 was constructed from the ^{137}Cs profile and the ^{210}Pb activity pro method [16], in combination with four accelerator mass spectrometry (AMS) dates on pollen fra radiocarbon ages on bulk organic sediment were used to develop an age model for WAL-15 (Ta were not obtained for the shorter cores due to cost constraints, which also prohibited additional other than WAL-3. Major changes in their microfossil stratigraphies were instead used for comp which radiometric dates were available.

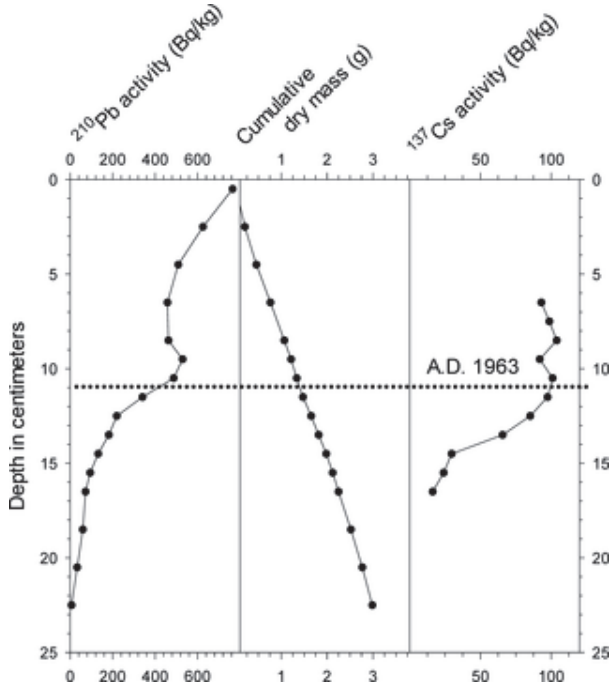

Fig 2. Lead-210 activity, cumulative dry mass, and ^{137}Cs activity profiles from core WAL-3.
Horizontal dotted line indicates the ca. A.D. 1963 interval as inferred from the ^{210}Pb and ^{137}
https://doi.org/10.1371/journal.pone.0191755.g002

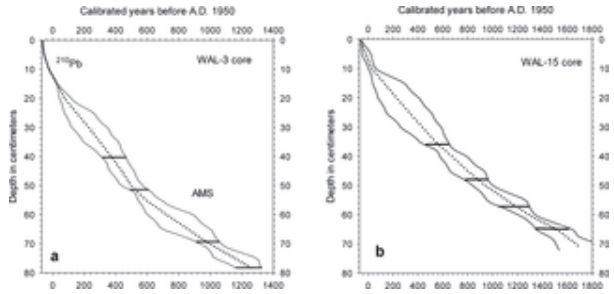

Fig 3. Age-depth relationships for Walden Pond cores WAL-3 and WAL-15.
Solid lines represent the upper and lower 95% confidence intervals of the BACON age mode

"best" model based on the weighted mean ages. Horizontal bars represent calibrated radioca
different age scales in the two charts.
https://doi.org/10.1371/journal.pone.0191755.g003

Age-depth relationships were constructed using Bayesian age modeling on ^{210}Pb and AMS dat
radiocarbon data alone for WAL-15 with the BACON version 2.2 modeling package in R (Fig 3)
dates were input into the model as uncalibrated dates with their appropriate error ranges as est
supply model. Pronounced inconsistencies in the radiocarbon ages of samples from core WAL-
construction and detailed microfossil analyses for that core unfeasible.

Because of the delicate nature of the microfossils and the disaggregated nature of the sedimen
extensive clumping or organic coatings was found in wet-mounted diatom samples, no chemica
preparation of microscope slides for diatom and chrysophyte analyses. Subsamples were dried
on glass slides with Permount™ mounting medium. Diatom valves and chrysophyte scales anc
under oil immersion, using standard references for identification [18–21]. At least 500 diatom va
species level in all cores at varying increments of 1–10 cm in order to characterize the general
the last 18 centuries. The common planktonic diatom *Cyclotella bodanica* has recently been cla
bodanica, *Handmannia bodanica*, and *Puncticulata bodanica* [22], but we refer to it here as *C. b*
of consistency with previously published records [7].

Sample intervals of 1 cm were employed throughout the long cores WAL-3 and WAL-15 in orde
conditions from the relative abundances of planktonic and benthic diatoms as determined from
per sample. The most abundant diatom taxa were also enumerated to species level at 1 cm inc
of cores WAL-1, WAL-3, WAL-4, WAL-15, and WAL-16, in order to examine the consistency of
multiple locations and thereby to better evaluate the degree to which the more rigorously dated
history of Walden Pond.

Changes in sediment organic content, as estimated by percent weight loss on ignition (%LOI) a
1 cm increments in all of the cores except for WAL-15, which was analyzed for total carbon usir
elemental analyzer. Carbon values for WAL-15 were converted to organic matter (%LOI) estima
assuming that elemental carbon comprises 44% of total organic matter [24].

Results

Radiometric analyses

Activity of ^{210}Pb in WAL-3 declined exponentially with depth with the exception of the 9–11 cm i
disturbance of the sediments and/or a shift in deposition rates during the A.D. 1960s to A.D. 19
reached in the ca. 22–23 cm depth interval (Fig 2). Activity of ^{137}Cs in WAL-3 displayed a broac
that was taken to represent the ca. A.D. 1963 global peak in atmospheric thermonuclear bomb
the peak might represent post-depositional migration of ^{137}Cs upward in the unconsolidated orc
makes the ^{137}Cs data less reliable as a tool to test the accuracy of the ^{210}Pb age model.

The age-depth profiles derived for WAL3 and WAL-15 displayed relatively little variability other t
increments per centimeter with depth (Fig 3). The radiocarbon ages of six subsamples from WA
reversals that made the core unsuitable for detailed analysis (Table 1). The lack of such reversa
depth profiles for WAL-3 and WAL-15 indicated that their stratigraphies were not significantly di
cores were roughly 1500 and 1800 calibrated radiocarbon years old, respectively (Table 1, Fig 3
stable in cores WAL-3 and WAL-15, and the prior distributions established for both accumulatio

the posterior distributions [17].

Microfossil analyses

Below the 7–12 cm level in all of the cores, the most abundant diatom taxa were *Discostella ste* lato, and *Tabellaria flocculosa* var. IIIP, which together comprised roughly half to two thirds of th younger sediments of all of the cores, *Asterionella formosa* and *Synedra nana* were abundant, example, a rise in *A*. *formosa* to ca. 10–20% occurred above the 14 cm level, followed by a sim *Asterionella ralfsii* was rare in all cores, but represented up to 2% of the assemblage within the Percentages of *C*. *bodanica* reached minimal values within the 5–15 cm interval of WAL-3, ther cm of the core (Fig 4). A similar pattern of recent decline and recovery in *C*. *bodanica* was foun exception of WAL-4 which displayed no recovery at the core top (Fig 6).

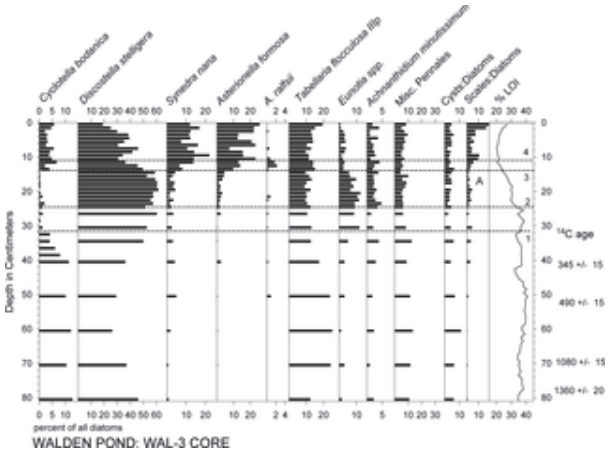

Fig 4. Percent abundances of the most common diatom taxa and %LOI in core WAL-3.
Horizontal dotted lines: (1) Onset of low *Cyclotella* percentages. (2) Decrease in %LOI indica content in the sediments. (3) Onset of increased *Asterionella and Synedra* percentages. (4) I abundances. Letter "A" indicates last occurrence of *Mallomonas allorgei*.
https://doi.org/10.1371/journal.pone.0191755.g004

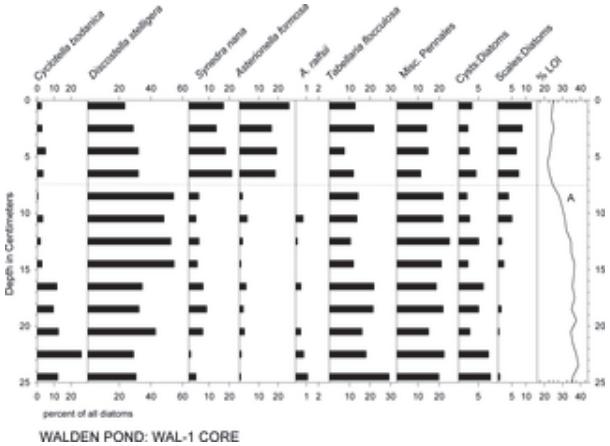

Fig 5. Percentages of the most common diatom taxa and %LOI in core WAL-1.
Horizontal dotted line indicates transition to high percentages of *Asterionella* and *Synedra*.
https://doi.org/10.1371/journal.pone.0191755.g005

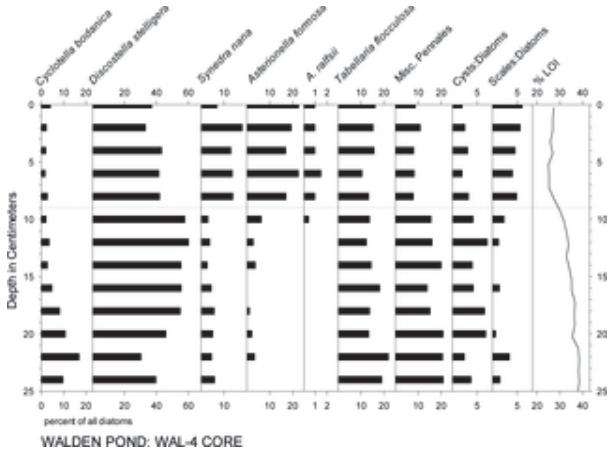

Fig 6. Percentages of the most common diatom taxa and %LOI in core WAL-4.
Horizontal dotted line indicates transition to high percentages of *Asterionella* and *Synedra*.
https://doi.org/10.1371/journal.pone.0191755.g006

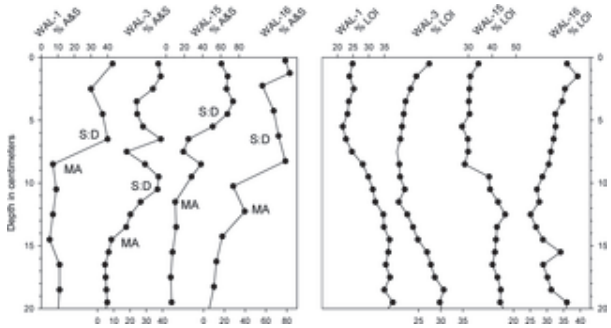

Fig 7. Comparison of microfossil and %LOI records in the uppermost 20 cm of four cores from Walden Po
Left panel: Combined percentages of *Asterionella* and *Synedra* (A&S) were interpreted as re
during the last century. The most recent presence of the oligotrophic indicator species, *Mallo*
a pronounced increase in the abundances of chrysophyte scales relative to diatoms are indic
respectively. Right panel: Organic content in the core sediments as represented by weight lo
https://doi.org/10.1371/journal.pone.0191755.g007

Percentages of diatom taxa that are typically found in planktonic habitats (%PLANK) fluctuated
WAL-3, with minimal %PLANK in the 52–63 cm interval and maximal values in the most recent
(Figs 4 and 8). In WAL-15, %PLANK typically ranged between ca. 80% and 90% in the lower pc
values within the 42–50 cm interval and maximal values above the 10 cm interval (Fig 8). Perce
highest in the upper ca. 20 cm of WAL-1 (Fig 5), WAL-3 (Fig 4), WAL-4 (Fig 6), and WAL-15 (Fi

upper half of deep-water core WAL-16. Percentages of planktonic taxa also increased significar sediment transect (r^2 = 0.86, P<0.0001).

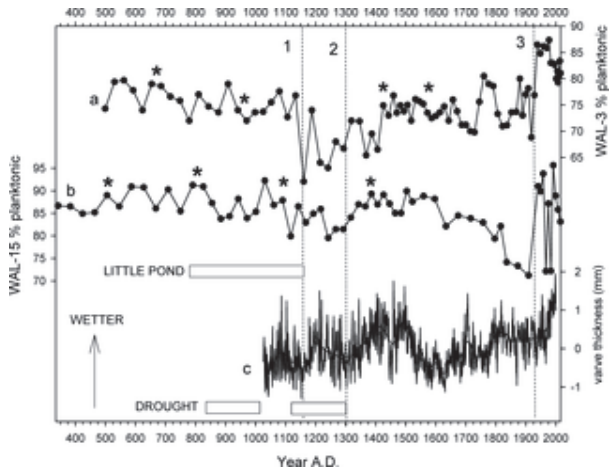

Fig 8. Comparison of sediment core records representing hydroclimate at Walden Pond and elsewhere in
a, b. Percent planktonic diatoms in Walden Pond cores WAL-3 and WAL-15, respectively. Da represent increased cultural eutrophication rather than climate alone. c. Composite hydroclin sediments of a lake and estuary in New York and Massachusetts, respectively [38]. Horizont at Little Pond, MA (upper)[36] and the New England region (lower)[34]. Vertical dotted lines # interval, line #3 indicates approximate onset of cultural eutrophication. Asterisks indicate cor radiocarbon ages.
https://doi.org/10.1371/journal.pone.0191755.g008

In all of the cores, abundances of chrysophyte scales relative to diatoms (S:D) were highest wit 4–6). Common chrysophyte taxa in those recent assemblages included *M*. *crassisquama*, *M*. *el* WAL-3, WAL-15, and WAL-16, S:D values approximately doubled again within the uppermost 4 WAL-1 or WAL-4 (Figs 5 and 6). Scales of *M*. *allorgei* were common in the older sediments but that were deposited after the rise in *Asterionella* and *Synedra* (7–12 cm range; Figs 3 and 7).

Geochemical analyses

Profiles of organic matter as represented by %LOI revealed a decline of varying magnitude and sediments of all cores (Figs 4–7). In WAL-3, %LOI values declined above the 24 cm level befor top (Fig 4). In most of the other cores, %LOI also declined and then increased within the upperr rise again in WAL-1 or WAL-4 (Figs 5–7). Core WAL-15, from a deeper part of the central basin average, than the cores from shallower sites that were situated closer to shore (WAL-1, WAL-3, values were found in core WAL-16 from the deep western basin (Figs 1 and 7).

Discussion

Consistency among the microfossil records

%LOI In general, the diatom stratigraphies of our cores were similar to those reported by Winkl confirm that major changes in the phytoplankton community occurred during the 20th century. A Walden Pond have recorded a pronounced increase in the prevalence of *A*. *formosa* and *S*. *nar*

large, sustained increase in the abundance of chrysophyte scales during the late 20th century.

The WAL-15 diatom record appears to indicate a slightly later increase in the eutrophication-ind the core analyzed by Köster et al. [7] (Fig 9). However, its age-depth model lacks support from profiles that were available for WAL-3, and we therefore interpret the timing of the recent microf greater caution.

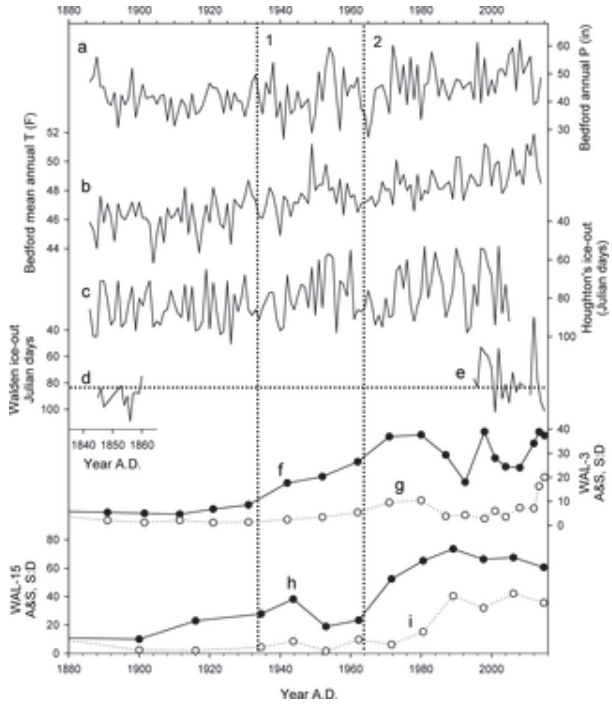

Fig 9. Comparison of temperature and precipitation in eastern Massachusetts since A.D. 1880 with ice-out Pond.

(a, b) Precipitation and temperature, respectively, at Bedford, MA. (c) Ice-out dates at Hough ice-out dates at Walden Pond recorded by Thoreau [1],[4],[48] and Primack [4], respectively. and *Synedra* (A&S) in cores WAL-3 and WAL-15, respectively. (g,h) Ratios of chrysophyte sc WAL-3 and WAL-15, respectively. Horizontal dotted line indicates mean ice-out date at Wald dotted lines (1,2) indicate approximate onset of main increase in A&S percentages in cores \ https://doi.org/10.1371/journal.pone.0191755.g009

The relative abundances of *C*. *bodanica* declined to near zero across the A&S transition in all c [7], but the timing of the onset of the decline was not consistent. Köster et al. [7] dated the chan WAL-3 and WAL-15 records it apparently occurred during the 17th and 18th centuries, respectiv *C*. *bodanica* rose again within the A.D. 1960s intervals of the Köster et al. [7] core, WAL-3, and WAL-4. In addition, %PLANK values declined within the A.D. 1600–1900 interval of the WAL-15 The reasons for these stratigraphic inconsistencies are unclear, but they show that single cores history of an entire lake with perfect precision.

Although the age-depth relationships reported by Köster et al. [7] are consistent with those in ou age of 530 +/- 70 yr BP obtained by Winkler [6] for a sediment sample from 75–81 cm depth in younger than those determined for corresponding intervals in WAL-3 and WAL-15 (Table 1, Fig

age model for the microfossil records reported by Winkler [6] might therefore require re-evaluati

The lack of rising values of %LOI and % *C*. *bodanica* along with the presence of rare but distinc top of core WAL-4 suggest that the upper section of its sediment record was missing and/or phy with problematic radiometric age discrepancies in core WAL-2, the causes of such stratigraphic with certainty but could include disturbances by boat anchors, contact with the bottom by free-d turtles which are common in the pond.

The upper sediments of WAL-15 (0–18 cm) and WAL-16 (0–14 cm) were dark brown to black, r brown sediments below, but there was little to no apparent color variability in the other cores co darkening is likely due to higher concentrations of dissolved oxygen at their shallower collection depth limit of summer hypoxia in the lake and the lower depth limit of oxygen-producing *Nitella*

Hydroclimate history

Climatic interpretation of %PLANK in sediment cores can be problematic where anthropogenic also influence diatom communities [7],[12]. However, historical and paleolimnological records in on Walden Pond before the late 19th century [1–7]. We therefore interpret %PLANK in the older a qualitative indicator of hydroclimate variability before the late 19th century.

We focus here on an interval of reduced %PLANK within the WAL-3 and WAL-15 cores (Fig 8) reduced effective moisture ca. A.D. 1150–1300 during the Medieval Climate Anomaly (MCA; A. record also includes a secondary decline that might extend the period to ca. A.D. 1420, but it is WAL-3 was collected from a site that was both closer to shore and shallower than that of WAL- pre-19th century sediments contain higher percentages of benthic diatoms than WAL-15 and gr 20–40% and 8–20%, respectively). Köster et al. [7] did not provide data on benthic taxa in their compared to our own records, but the relatively low percentages of benthic taxa in WAL-16 (ca. assemblages in the deeper sectors of the lake may be less sensitive indicators of hydroclimate coring sites in the shallower central basin.

Other paleoecological records have documented aridity in the northeastern United States during of its timing and duration vary. Drought conditions were inferred from pollen and charcoal data f around A.D. 800–1300 [29], and Sidney Bog, ME, registered relatively dry conditions ca. A.D. 1 A.D. 900–1400 have also been inferred from records in northwest Ontario [31], the Great Lakes United States [33],[34].

In contrast, lake level records from Deep, Davis, and New Long Ponds, MA, revealed no evider instead placed a shorter period of low lake levels earlier, ca. A.D. 650–750 [35]. At Little Pond, from ca. A.D. 750–1150 as indicated by increased abundances of spores of the benthic plant *Is* content (Fig 8) [36]. A high-resolution diatom record from Wolf Lake, NY, registered a low stand 1150–1300 [12]. Dendroclimatological records registered severe droughts throughout much of A.D. 1122–1299 (Fig 8) [37] but relatively little change in New England then, a conclusion that t support. A composite time series based on varved sediment records from Rhode Island and Ne wetter conditions during the A.D. 1100–1300 interval (Fig 8)[38]. That increase in precipitation not strongly registered in the New York record and could presumably represent a maritime micr rather than the region as a whole. The Walden core data lack sufficient temporal resolution to ri decadal-scale variability during that period, but the WAL-3 diatom record more closely resemble than WAL-15 (Fig 8).

At present, the limitations of radiocarbon dating and a need for more high-resolution paleolimnc

make it difficult to determine whether these differences represent true regional variability or unc
Precipitation is spatially variable, particularly in complex terrain such as that which characterize
and lakes of different forms and hydrological settings can respond differently to it, so more reco
nature of hydroclimate variability in this region during the late Holocene can be more fully chara

The large increase in %PLANK that occurred in cores WAL-3 and WAL-15 within the uppermos
result of cultural eutrophication than climate [3],[7], and is discussed below.

Recent changes in the phytoplankton community

Phytoplankton productivity in Walden Pond has increased notably since the A.D. 1920s, followi
shoreline [2],[3],[5],[7]. Other recent nutrient inputs included erosion of sediment from the lakesl
also contributed to declines in %LOI within the cores through dilution with inorganic mineral gra
such as stabilization of the shoreline and trails and improvement of public sanitary facilities hav
nutrient inputs to the lake, but their more recent effects on the lake remain to be evaluated with
provided by sediment cores.

The previous core studies at Walden Pond documented an abrupt decline in the abundance of
century, probably due to shading from enhanced planktonic productivity [6],[7]. Köster et al [7] a
starting around A.D. 1930 in which *C*. *bodanica* and *D*. *stelligera* were ljoined by abundant *A*. *fo*
commonly associated with cultural eutrophication in North American lakes [39–43]. That transiti
abundances of chrysophytes during the late 20th century.

The diatom and chrysophyte records of our cores corroborate those previous studies and exten
In WAL-1, WAL-3, WAL-15, and WAL-16, scales of the chrysophyte *M*. *allorgei* were present thr
cores but were not found above the A&S transition (Fig 7). This species is typically found in olig
disappearance from the sediment assemblages probably reflects the eutrophication that is so p
records.

We further examine the microfossil records of Walden Pond here in qualitative terms in order to
the condition of the lake in recent times: What caused the recent changes in the phytoplankton
returning to its pre-impact condition or developing a new "no-analog" state?

Climatic warming can affect plankton communities by enhancing thermal stratification which, in
sediment-bound nutrients through hypoxia at the bottom of the lake [45]. Increased precipitatior
through erosion of nearby soils and lake-shore deposits [12],[46]. However, the rise in A&S duri
by several decades the notable increases in temperature and precipitation that occurred in Mas
(Fig 9). No significant changes are evident in the duration of lake ice cover, an indirect indicator
from Houghton's Pond, MA [47], or Walden Pond [4],[48] that could also help to explain change
We therefore concur with previous authors that recreational use of the lake was the primary trig
Pond [2],[6],[7], although climatic changes could also be contributing to plankton productivity in

The darkening of sediments in the upper sections of cores WAL-15 and WAL-16 probably reflec
conditions in the hypolimnion within the last century or so because iron compounds in sediment
environments are less likely to produce the pale, rusty coloration that is typical of oxidzed ferric
reflect longer stratification seasons and/or increased phytoplankton productivity. The WAL-15 a
boundary corresponds to the mid-18th century, but in WAL-16 the change occurred only slightly
early 20th century. The lower boundaries of the darkened zones in those cores could reflect dov
conditions in addition to deposition under hypoxia so they do not necessarily indicate precise tir
Nonetheless, they do suggest that cultural eutrophication has likely caused cause dissolved oxy

hypolimnion to decline.

Comparison of A&S percentages in four cores (Fig 7) reveals no consistent, significant trends s interpret this to mean that cultural eutrophication in Walden Pond has more or less stabilized sir the cores also indicate that the phytoplankton community and dissolved oxygen conditions have condition. It is likely that Walden Pond remains in a state of enhanced productivity due to a com to direct anthropogenic nutrient enrichment [3], could also include atmospheric nitrogen deposit [4],[50–53] and internal loading of nutrients from bottom sediments [43] in the deepest portions *Nitella* meadows to oxygenate the surrounding water.

The recent increase in scaled chrysophytes in Walden Pond resembles similar increases in oth been attributed to the competitive advantages that longer summer stratification seasons give to [53],[54]. However, its causes at Walden Pond are difficult to ascertain. Much of the increase in American lakes has been among colonial taxa such as *Synura* [55],[56] rather than the unicellul common in Walden Pond, and multiple local anthropogenic impacts on the lake during the last c identify the cause.

Although the reasons for the recent rise in abundance of chrysophytes remain unclear, the long change is unprecedented during the last 1800 years at Walden Pond. It is not readily related to temperature, or lake ice-cover (Fig 9), and therefore seems likely to be more the result of increa cascades than climatic factors. Regardless, the recent large increase in scaled chrysophytes, a and the decline of *Isoëtes* and *M*. *allorgei*, also means that Walden Pond has not been restored many other lakes around the world [54], Walden Pond has instead moved to a new ecological s years if not the entire post-glacial history of the lake.

Increasing %LOI within the uppermost intervals of WAL-3, WAL-15, and WAL-16 since the 198(inorganic sediment inputs from stabilization of shorelines and foot trails, but it could also reflect declining oxygen concentrations in the hypolimnion. The lack of such an increase of %LOI at th likely reflects the absence of the youngest sediments from that core.

Lake management in a changing future

The widespread occurrence of low lake levels during the MCA has implications for the interpreta that anticipate rising temperatures and heavier precipitation in New England during this century become evident in Massachusetts in recent decades (Fig 9). The warm MCA was not caused b concentrations as much of the warming of the last half-century was [58], but as an imperfect his levels might not rise significantly in a warmer future even if total annual precipitation increases. for example, could reduce spring and summer groundwater supplies, and higher temperatures reducing effective moisture.

Paleolimnological evidence such as that from Crawford Lake, Ontario [43],[59], demonstrates th eutrophication can persist for centuries after the causal nutrient inputs have ceased, and that it eutrophication than to reverse it once it occurs. The sediment darkening and high percentages Walden Pond therefore indicate not only that the lake ecosystem is now quite different from tha also that it may be primed for more severe reductions in water clarity in a warming future. Increa century [57], for example, are likely to encourage heavier summer recreational use of the lake, stratification season through warming of the lake surface could also further enhance internal nu

Major reductions in the extent of *Nitella* meadows due to decreasing water transparency under ecological tipping point that could severely and permanently reduce the clarity of the lake and d

However, the taxonomic composition and ecology of the aquatic macrophyte communities of W characterized. Although the benthic meadows have been described as being composed primari *Fontinalis* moss, not *Nitella*, being dredged from 15.7 m depths, and the decline of *Isoëtes* spor century [6],[7] suggests that *Nitella* might not have been as prevalent in the past as it is now. Co vegetation to the oxygen and nutrient dynamics in Walden Pond, such information could be use lake. For example, different species of *Nitella* and other benthic macrophytes can have different so changes in species composition within the benthic meadows could serve as biotic indicators

As Jeppeson, et al. [63] noted in a review of lake management practices in a changing climate, from precipitation mean that nutrient inputs to many lakes must be reduced if they are to mainta are in today. It will therefore be prudent to further reduce the flow of anthropogenic nutrients to V wetter conditions that most climate models project for New England during the 21st century [57] source of such nutrients now, and demand for the beach facilities is likely to increase in a warm programs or construction of a separate swimming pool facility nearby to relieve pressure on the

Acknowledgments

JCS acknowledges the National Science Foundation (www.nsf.gov) for grant funding (P2C2, AT Department of Conservation and Recreation, Jacqui Kluft, Elliott Lewis, and Rory Fraser for ass analyses for cores WAL-2, WAL-3, and WAL-15 were performed by the National Ocean Service laboratory, Woods Hole, MA (www.whoi.edu/nosams/home). JBH acknowledges contributions b Knudstrup, as well as funding from the National Science Foundation (EAR 126128). The funder data collection and analysis, decision to publish, or preparation of the manuscript.

References

1. Thoreau H D (1854) Walden; or Life in the Woods. Ticknor and Fields, Boston.
2. Maynard WB (2004) Walden Pond: A History. Oxford University Press, New York
3. Colman JA, Friesz PJ (2001) Geohydrology and Limnology of Walden Pond, Concord, Massachusetts. U.S. G Investigations Report 01–4137. Northborough, Massachusetts.
4. Primack RB (2014) Walden Warming: Climate Change Comes to Thoreau's Woods. University of Chicago Pre
5. Deevey ES (1942) A re-examination of Thoreau's "Walden." Q Rev Biol 17: 1–11. View Article • Google Scholar
6. Winkler MG (1993) Changes at Walden Pond during the last 600 years. In: Schofield EA and Baron RC (eds.) North American Press, Golden, CO.
7. Köster D, Pienitz P, Wolfe BB, Barry S, Foster DR, Dixit SS (2005) Paleolimnological assessment of human-ir (Massachusetts, USA) using diatoms and stable isotopes. Aquat Ecosys Health Mgmt 8: 117–131. View Article • Google Scholar
8. Barosh PJ (1993) Bedrock geology of the Walden Woods. pp. 212–259 In: Schofield EA and Baron RC (Eds.) Legacy. North American Press, Golden, CO.
9. Laird KR, Cumming BF (2008) Reconstruction of Holocene lake level from diatoms, chrysophytes and organic

Experimental Lakes Area (northwestern Ontario, Canada). Quat Res 69: 292–305.
View Article • Google Scholar

10. Laird KR, Kingsbury MV, Cumming BF (2010) Diatom habitats, species diversity and water-depth inference m Worth Lake, northwestern Ontario, Canada. J Paleolimnol 44: 1009–1024.
View Article • Google Scholar

11. Laird KR, Kingsbury MV, Lewis CFM, Cumming BF (2011) Diatom-inferred depth models in 8 Canadian borea benthic:planktonic depth boundary and implications for assessment of past droughts. Quat Sci Rev 30: 1201–
View Article • Google Scholar

12. Stager JC, Cumming BF, Laird K, Garrigan-Piela A, Pederson N, Wiltse B, et al. (2016) A 1600 year record of The Holocene https://doi.org/10.1177/0959683616658527

13. Stone JR, Fritz SC (2004) Three-dimensional modeling of lacustrine diatom habitat areas: Improving paleolim ratios. Limnol Oceanogr 49: 1540–1548.
View Article • Google Scholar

14. Schindler DW, Curtis PJ (1997) The role of DOC in protecting freshwaters subjected to climatic warming and 36: 1–8.
View Article • Google Scholar

15. Stuiver M, Reimer PJ (1993) Extended 14C database and revised CALIB radiocarbon calibration program. Ra
View Article • Google Scholar

16. Appleby PG, Oldfield F (1978) The calculation of lead-210 dates assuming a constant rate of supply of unsup 1–8.
View Article • Google Scholar

17. Blaauw M, Christen JA (2011) Flexible paleoclimate age-depth models using an autoregressive gamma proce
View Article • Google Scholar

18. Patrick R, Reimer CW (1966) The diatoms of the United States. Volume 1, Monographs of the Academy of Na Philadelphia, 688 pp.

19. Patrick R, Reimer CW (1975) The diatoms of the United States. Volume 2, Monographs of the Academy of Na Philadelphia, 213 pp.

20. Krammer K, Lange-Bertalot H (1991) Süßwasserflora von Mitteleuropa, 3 Teil: Cantrales, Fragilariaceae, Eun 576 pp.

21. Siver PA (1991) The Biology of Mallomonas: Morphology, Taxonomy, and Ecology. Springer-Science+Busines

22. Burge D, Edlund M (2017) Lindavia bodanica. In Diatoms of the United States. Retrieved January 02, 2018, fr /taxa/species/lindavia_bodanica.

23. Sutherland RA (1998) Loss-on-ignition estimates of organic matter and relationships to organic carbon in fluvi 153–167.
View Article • Google Scholar

24. Heiri O, Lotter AF, Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate conte comparability of results. J Paleolimnol 25: 101–110.
View Article • Google Scholar

25. Jaakkola T, Tolonen K, Huttunen P, Leskinen S (1983) The use of fallout ^{137}Cs and ^{239,240}Pu for dating of lak
View Article • Google Scholar

26. Davis RB, Hess TC, Norton SA, Hanson DW, Hoagland KD, Anderson DS (1984) ^{137}Cs and ^{210}Pb dating of s England (U.S.A.) and Scandinavia, a failure of ^{137}Cs dating. Chem Geol 44: 151–185
View Article • Google Scholar

27. Mann ME, Zhang Z, Rutherford S, Hughes MK, Shindell D, Amman C, et al. (2009) Global signatures and dyr Medieval Climate Anomaly. Science 326: 1256–1259. pmid:19965474
View Article • PubMed/NCBI • Google Scholar

28. Marlon JR, Pederson N, Nolan C, Goring S, Shuman B, Robertson A, et al. (2017) Climatic history of the nort years. Clim Past 13: 1355–1379.
View Article • Google Scholar

29. Pederson D, Peteet D, Kurdyla D, Guilderson T (2005) Medieval Warming, Little Ice Age, and European impa millennium in the lower Hudson Valley, New York, USA. Quat Res 63: 238–249.
View Article • Google Scholar

30. Clifford MJ, Booth RK (2015) Late-Holocene drought and fire drove a widespread change in forest community Holocene 25: 1102–1110.
View Article • Google Scholar

31. Laird KR, Haig HA, Kingsbury MV, Brown TA, Lewis CFM, Oglesby RJ, Cumming BF (2012) Expanded spatia revealed in lake-sediment records across the boreal region in northwest Ontario. Glob Change Biol 18: 2869–
View Article • Google Scholar

32. Booth RK, Notaro N, Jackson ST, Kutzbach JE (2006) Widespread drought episodes in the western Great Lal Geographic extent and potential mechanisms. Earth Planet Sci Lett 242: 415–427.
View Article • Google Scholar

33. Woodhouse CA, Meko DM, MacDonald GM, Stahle DW, Cook ER (2010) A 1200-year perspective on 21st ce America. Proc Nat Acad Sci 107: 21283–21288. pmid:21149683
View Article • PubMed/NCBI • Google Scholar

34. Cook BI, Smerdon JE, Seager R, Cook ER (2014) Pan-continental droughts in North America over the last mi

View Article • Google Scholar

35. Newby PE, Shuman BN, Donnelly JP, Karnauskas KB, Marsicek J (2014) Centennial-to-millennial hydrologic
coast, USA, during the Holocene. Geophys Res Lett 41: 4300–4307.
View Article • Google Scholar

36. Oswald WW, Foster DR (2011) A record of late-Holocene environmental change from southern New England,
View Article • Google Scholar

37. Cook ER, Seagar R, Heim Jr., Vose RS, Herwijer C, Woodhouse C (2010) Megadroughts in North America: P
change in a long-term palaeoclimatic context. J Quat Sci 25: 48–61.
View Article • Google Scholar

38. Hubeny JB, King JW, Reddin M (2011) Northeast US precipitation variability and North American climate telec
varved sediments. Proc Nat Acad Sci 108: 17895–17900. pmid:22011576
View Article • PubMed/NCBI • Google Scholar

39. Reavie ED, Smol JP, Carmichael NB (1995) Post-settlement eutrophication histories of six British Columbia (C
2388–2401.
View Article • Google Scholar

40. Dixit SS, Smol JP, Charles DF, Hughes RM, Paulsen SG, Collins GB (1999) Assessing water quality changes
States using sediment diatoms. Can J Fish Aquat Sci 56: 131–152.
View Article • Google Scholar

41. Hall RI, Smol JP (1999) Diatoms as indicators of lake eutrophication. In Stoermer EF and Smol JP (Eds), The
and Earth Sciences, pp. 128–168. Cambridge University Press, Cambridge.

42. Bennion H, Monteith D, Appleby P (2000) Temporal and geographical variation in lake trophic status in the En
diatoms and aquatic macrophytes. Freshw Biol 45: 394–412.
View Article • Google Scholar

43. Ekdahl EJ, Teranes JL, Wittkop CA, Stoermer EF, Reavie ED, Smol JP (2007) Diatom assemblage response
eutrophication of Crawford Lake, Ontario, Canada. J Paleolimnol 37: 233–246
View Article • Google Scholar

44. Järnefelt H (1952) Plankton als Indikator der Trophiengruppen der Seen. Ann Acad Sci.Fenn Ser A IV 18: 1–2
View Article • Google Scholar

45. Nürnberg GK (2009) Assessing internal phosphorus load—Problems to be solved. Lake Res Mgmt 25: 419–4
View Article • Google Scholar

46. Fraser AI, Harrod TR, Haygarth PM (1999) The effect of rainfall intensity on soil erosion and particulate phosp
Tech 39: 41–45.

View Article • Google Scholar

47. Hodgkins GA, James IC, Huntington TG (2002) Historical changes in lake ice-out dates as indicators of climat Climatol 22: 1819–1827.
View Article • Google Scholar

48. Thoreau HD (2009) The journal of Henry David Thoreau, 1837–1861. Searls D (Ed.) New York Review Books

49. Holtgrieve GW, et al. (2011) A coherent signature of anthropogenic nitrogen deposition to remote watersheds 1545–1505. pmid:22174250
View Article • PubMed/NCBI • Google Scholar

50. Saros J, Andersen N (2014) The ecology of the planktonic diatom *Cyclotella* and its implications for global en 522–541. pmid:24917134
View Article • PubMed/NCBI • Google Scholar

51. Rühland K, Paterson AM, Smol JP (2015) Lake diatom responses to warming: Reviewing the evidence. J Pal
View Article • Google Scholar

52. Sivarajah B, Rühland KM, Labaj AL, Paterson AM, Smol JP (2016) Why is the relative abundance of Asterion lake as nutrient levels decline? J Paleolimnol 55: 357–367.
View Article • Google Scholar

53. Sivarajah B, Ruhland KM, Smol JP (2017) Are diatoms recovering to pre-acidification assemblages in a warm Park lakes (Ontario, Canada). Fund Appl Limnol 190: 13–28.
View Article • Google Scholar

54. Winder M, Sommer U (2012) Phytoplankton response to a changing climate. Hydrobiologia 698: 5–16.
View Article • Google Scholar

55. Paterson AM, Cumming BF, Smol JP, Hall RI (2004) Marked recent increases of colonial scaled chrysophytes management of taste and odour events. Freshw Biol 49: 199–207.
View Article • Google Scholar

56. Paterson AM, Winter JG, Nicholls KH, Clark BJ, Ramcharan CW, Yan ND, Somers KM (2008) Long-term cha Canadian Shied lakes in response to multiple anthropogenic stressors. Can J Fish Aquat Sci 65: 846–861.
View Article • Google Scholar

57. United States Global Change Research Program (USGCRP; 2017) Third National Climate Assessment. Acce http://nca2014.globalchange.gov/report.

58. IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Panel on Climate Change [Pachauri RK, Meyer LA (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

59. Ekdahl EJ, Teranes JL, Guilderson TP, Turton CL, McAndrews JH, Wittkop CA, Stoermer EF (2004) Prehistor

Crawford Lake, Canada. Geology 32: 745–748.
View Article • Google Scholar

60. Sinha E, Michalak AM, Balaji V (2017) Eutrophication will increase during the 21st century as a result of preci pmid:28751610
View Article • PubMed/NCBI • Google Scholar

61. Swarz AM, de Winton M, Hawes I (2002) Species-specific depth zonation in New Zealand charophytes as a fu 209–217.
View Article • Google Scholar

62. Wang H, Liu C, Yu D (2015) Morphological and reproductive differences among three charophyte species in r Biol 24: 91–100.
View Article • Google Scholar

63. Jeppesen E., Søndergaard M, Zhengwen L (2017) Lake restoration and management in a climate change pe
View Article • Google Scholar