THESIS

250 YEARS OF CLIMATE-MEDIATED ECOLOGICAL CHANGE IN SANTA FE LAKE, NM

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ABSTRACT

250 YEARS OF CLIMATE-MEDIATED ECOLOGICAL CHANGE IN SANTA FE LAKE, NM

Mountain lakes are sensitive indicators of anthropogenically driven global change. Lake sediment records in the western United States have documented increased percent carbon and nitrogen and heightened primary productivity indicative of eutrophication in mountain lakes. Recent paleolimnological studies suggest atmospheric nutrient deposition and warming underlie these changes. We analyzed a short sediment core from Santa Fe Lake, NM, the southernmost subalpine lake in the Rocky Mountain Range to investigate patterns in lake biogeochemical and algal biomarkers since 1747. Lake sediments were dated using ^{210}Pb activities and analyzed for percent C and N, δ^{13}C, δ^{15}N, and algal pigments representative of total biomass, chlorophytes, cryptophytes, diatoms, and other primary producers from Santa Fe Lake.

Throughout the 250-year sediment record from Santa Fe Lake, we observed changes in algal community composition alongside biogeochemical alterations. During the cold dry conditions of the Little Ice Age, there were greater proportions of cyanobacteria, diatoms, and sulfur bacteria. Total algal biomass increased under increased warming and climate variability with significant increases in chlorophytes and cryptophytes. Significant rates of change occurred concurrently with increases in regional N deposition in the mid-20th century. C, N, δ^{13}C, δ^{15}N remained relatively stable throughout the record, until the mid-20th century when C and N increased exponentially alongside depletions in δ^{13}C, δ^{15}N. Our results suggest climate-driven algal assemblage changes throughout the record with regional N deposition contributing to contemporary productivity increases. The timing and magnitude of these changes differ from other studied lakes. Our findings highlight the heterogeneity of lakes' responses to changing environmental conditions in the Anthropocene and call attention to the role of climate-induced ecological change in the absence of critical N deposition.

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INTRODUCTION

The anthropogenic drivers of global change, such as increased energy and fertilizer use, greater greenhouse gas emissions, and widespread landscape modifications have brought about marked changes to ecosystems worldwide. The exponential increase in both the drivers and responses to global change were termed the “Great Acceleration” by Steffen et al. (2015) due to the unprecedented rates of social and ecological transformation beginning in the mid-20th century. Mountain lakes serve as valuable witnesses to global change because they are often protected from direct watershed modifications such as upstream water management or land use change (Moser et al. 2019).

Mountain lake ecology has been altered by the regional input of limiting nutrients, increasing climatic variability, lengthening of the ice-free season and increased air and water temperatures in the 20th century (Saros et al. 2011, Slemmons and Saros 2012, Jeppesen et al. 2014, Williams et al. 2016). This suite of changes has restructured lake ecosystems, causing shifts in nutrient limitation (Elser et al. 2009) and increased primary productivity in historically oligotrophic lakes (Oleksy et al. 2020). Lake sensitivity to anthropogenic perturbations depends upon complex interactions between external and internal lake processes, which vary in space and time (Schindler 2001). Some systems appear to enter an unprecedented state of productivity (Wolfe et al. 2001, Oleksy et al. 2020) primarily as the result of increased nutrient deposition, climate change, and fish stocking, while other lakes have shown more modest responses to these drivers (Spaulding et al. 2015, Hundey et al. 2014). Not all mountain lakes will respond in the same way or at the same time because signals of global changes will be modified through internal lake processes including; lake morphometry, existing algal community and external features including; catchment characteristics, geographic location, and regional land use (Hood et al. 2003, Adrian et al. 2009, Burpee et al. 2022). Lake sediments serve as archives of ecological changes (Leavitt and Hodgson 2001, Smol 2010). The study of biogeochemical and biological analytes with lake sediments reveal past ecological states and inform trajectories of change in mountain freshwater ecosystems(Catalan et al. 2006, Adrian et al. 2009).

In light of other recent paleolimnological studies of mountain lakes in western North America (Wolfe et al. 2001, Saros et al. 2011, Brahney et al. 2014, Hundey et al. 2014, Spaulding et al. 2015, Williams et al. 2016, Oleksy et al. 2020), we explored biogeochemical and biological signals in Santa Fe Lake, the southernmost alpine lake in the Rocky Mountain Range, over the last 250 years. We expected to see muted changes in biogeochemistry and algae from the end of the Little Ice Age (C.E. 1750 -1880) to the 1950s, and then a strong increase in algal pigments and changing C and N signals coincident with increases in regional and global anthropogenic activities. Unlike lakes in mountain areas proximal to widespread agriculture and urbanization (Sierra Nevada and Rocky Mountain National Park), the Northern New Mexico region has limited agricultural use and urbanization (Dimer et al. 2012). As a result, we expected more muted ecological changes in Santa Fe Lake coincident with the “Great Acceleration” (Steffen et al. 2015), providing a signal more indicative of “background” ecological change within mountain lakes in western North America.

Site Description

Santa Fe Lake (35.7887905N, −105.7780076W) is a small (surface area = 1.9 hectares) and shallow (6.5 m) high elevation subalpine lake (3,530m above sea level) located 28 km northeast of Santa Fe, New Mexico, USA in the Pecos Wilderness. Santa Fe Lake lies at the headwaters of the Santa Fe watershed, which serves as the primary water source for the city of Santa Fe.

Indigenous communities have occupied northern New Mexico since the Late Pleistocene (approximately 12,600 to 12,200 years *ca* BP). The ancestral Puebloans developed agriculture, raised livestock, and controlled fire regimes for thousands of years before the Spanish colonization of the Southwest (Roos et al. 2021). The arrival of the railroad to Santa Fe, NM in the late 1800s facilitated urbanization, the expansion of logging and intensive cattle grazing in the region. From the late 1800s to the mid-1900s there was nearly complete fire suppression in the region (Debuys and Allen 2015). Since the 1970s, large wildfires and annual prescribed burns increased in frequency, including major fires within the Santa Fe National Forest since 1996. Beginning in 2007, there have been annual to bi-annual prescribed burns within the Santa Fe Municipal Watershed (Figure 1).

Santa Fe Lake has a shallow (<1 m deep) and narrow littoral zone (extending 1–5 m from shore) before steep drop-offs into the limnetic zone (Hodgson et al. 2013). Light penetrates to the bottom of the lake during the open water season (Table 1). Precambrian granite underlies the basin, causing Santa Fe lake to have dilute, low ANC waters (Lynch et al. 1988). Water quality assessments conducted in 2007, classified Santa Fe as oligomesotrophic according to Carlson’s (1977) indices for Secchi depth, chlorophyll *a,* total phosphorus, total nitrogen, and algal community composition. Nitrogen was postulated to be the limiting nutrient by Davis and Joseph (2007). There have been several prior studies of Santa Fe Lake. In 1988, Lynch et al. documented trace metal enrichment and diatom species assemblage changes in response to increased sulfate deposition through acid rain precipitation. In 2007, water quality assessments by Davis and Joseph (2007) determined modern water chemistry and algal community composition, including the green algae of the genus *Quadrigula*, which comprised about 57% of the plankton community. More recently, Hodgson et al. (2013), employed diatom assemblages from Santa Fe Lake Sediments to infer solar-modulated millennial scale drought cycles in the region. The study demonstrated changes in diatom species assemblages in Santa Fe Lake during periods of extreme drought (~1000–600 YBP and ~200 YBP) towards more acid-tolerant species and an increase in the acidophilic: alkaliphilic ratio of diatoms. There have also been tree-ring reconstructions of streamflow and fire history within the Santa Fe watershed by Margolis et al. (2007, 2011). The study found increases in the frequency and intensity of drought and deluge events and concluded that the most extreme events in the 700-year tree ring occurred in past ~120 years (Margolis et al. 2011).

Regional Climate

The annual maximum and minimum temperatures for the northern New Mexico Region are 6°C and -8ºC respectively, average annual precipitation is 2.2 cm (1895 – 2020, NOAA, National Centers for Environmental Information (NCEI) northern New Mexico divisional data, https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/divisional). These data are averaged across elevation gradients and likely overestimate temperatures and underestimate precipitation for Santa Fe Lake. Persistent winter snowpack is common in the upper watershed. Precipitation peaks in the summer, with July through September precipitation contributing 43% of the annual total (1895–2007, http://www.prism.oregonstate.edu/). Peak monthly runoff typically occurs in May, resulting from spring snowmelt, but monsoonal moisture can drive a second peak during August (Margolis et al. 2011).

Tree rings and past limnological studies demonstrate variable cycles of drought in the region occurring on millennial scales in relation to changing solar activity (Margolis et al. 2011, Hodgson et al. 2013). The Little Ice Age (C.E. 1300-1850) marked the onset of cold and dry conditions in the region (Petersen 1994). Since the late 19th century, temperatures have increased significantly in the northern New Mexico Mountain region, with an average rate of 0.02ºC in warming since 1895 (NOAA, NCDC). Additionally, precipitation has declined since 1895 with -0.5mm decrease precipitation per decade (NOAA, NCDC). The frequency and intensity of drought events have increased throughout the last 250 years and are expected to continue to increase in the region (Stahle et al. 2000).

METHODS

Field Collection

A 49 cm long sediment core was collected from the deepest part of Santa Fe Lake using a modified gravity corer (Glew 1991) on September 21, 2021. The core was extruded on site in 0.5cm increments from 0 – 40cm and 1cm increments for the bottom 9cm and stored on dried ice during transported to Colorado State University.

Sediment Preparation

Sediments were stored in a freezer at -80ºC prior to analyses at the EcoCore Laboratory at Colorado State University. The sediments were stored in either plastic twist-tie sample bags or 50ml plastic centrifuge tubes. Plastic bags were punctured with numerous small holes and placed inside a second bag for freeze-drying. Falcon tubes were covered with parafilm perforated with small holes. Samples were weighed to acquire their wet mass and then freeze-dried for an initial 24 hours. After 24 hours a subset of samples was weighed, and all samples were freeze-dried for an additional 48 hours. After the initial 72-hour period, the samples were weighed again and dried for an additional 12-24 hours until a constant mass was achieved. All samples were reweighed, and the percent moisture loss was calculated for each sample. Freeze-dried sediments were homogenized and subdivided into portions for stable isotope analyses, the elemental composition of C and N, ^{210}Pb dating, diatom community assemblage, algal pigments, and mass loss on ignition at 500ºC.

Lake Core Chronology

Freeze-dried and homogenized sediment samples were dated using ^{210}Pb alpha spectroscopy at the U.S. Geological Survey St. Petersburg Coastal and Marine Science Center

(USGS SPCMSC). The core's chronologies were determined using 15, 250mg sediment samples dispersed throughout the core, with groupings in the first and final 2 cm of the core. Sediments were dated by analysis of ^{210}Pb activities and application of the constant rate of supply (CRS) model developed by Appleby and Oldfield (1978). The CRS model assumes a constant fallout ^{210}Pb from the atmosphere to the sediment, irrespective of sediment accumulation rates as described. The unsupported ^{210}Pb concentration in each sediment layer will decline over time due to the radioactive decay law. This law is used to calculate the age of the sediment, and depends upon an initial estimate ^{210}Pb concentration in the lake bed (Appleby and Oldfield 1978). The tidypaleo package developed by Dunnington et al. (2022) was used to approximate dates for each section of the lake sediment core. This tool allows interpolation between known values and extrapolation using average sedimentation rates based on established ^{10}Pb dated from the application of the CRS at discrete points in the Santa Fe Lake core (Dunnington et al. 2022).

Elemental Analysis

Carbon and nitrogen isotope ratios and elemental composition were analyzed at the Institute of Environmental Change and Society (IECS), University of Regina, Saskatchewan, Canada. Approximately 30 mg sediment was analyzed using a ThermoQuest DeltaPLUS XL isotope ratio mass spectrometer equipped with a continuous flow unit (Con Flo II), an automated Carlo Erba elemental analyzer as an inlet device, and following standard procedures (Leavitt and Hodgson 2006). Stable N (δ^{15}N) and C (δ^{13}C) isotopic compositions were expressed in the conventional notation: units of per mil (‰) deviation from atmospheric N2 and an organic C standard calibrated against Vienna Pee Dee Belemnite. Sample reproducibility was < 0.25‰ and < 0.10‰ for δ^{15}N and δ^{13}C determinations.

Algal Pigments

Carotenoids, chlorophylls, and their derivatives were quantified as metrics of past algal and cyanobacterial abundance following standard procedures (Leavitt and Hodgson 2001) at IECS. Approximately 50 mg of sediment was extracted in an 80:15:5 (% by volume) mixture of acetone, methanol, and water at -12ºC. After 24 hours, pigments were filtered through a 0.2-µm pore membrane filter and dried under inert N_2 gas. After drying, pigment residues were reconstituted in a known volume of standard injection solution and analyzed on an Agilent 1100 High-Performance Liquid Chromatography (HPLC) system equipped with a photodiode array detector. Individual pigments were distinguished on the basis of chromatographic position and light absorbance characteristics and compared with authentic standards of common algal and cyanobacterial pigments from DHI (Hoslholm, Denmark) and local isolates (Leavitt and Hodgson 2001). All pigment concentrations are presented as nmol pigment per g^{-1} organic carbon, a metric that is linearly correlated to annual phototroph standing stock in whole lake calibrations (Leavitt and Findlay 1994).

A total of 13 pigments were identified in the sediment core. Pheophytin *a*, a derivative of unstable chl *a*, was used as a proxy for total primary production in lakes. Labile fucoxanthin and diadinoxanthin from diatoms were not used for the analysis because of obvious post-depositional degradation, (Leavitt and Hodgson 2001). β-carotene, a pigment typically used as a proxy for total algal biomass was excluded from analysis due to irregular preservation in the core. The ratio of labile chlorophyll *a* : stable pheophytin *a* (preservation index) was used as a proxy for changes in down-core pigment preservation (Table 2).

Loss on Ignition

Mass loss on ignition (LOI) at 500ºC was used to establish total organic content of each sediment section (Heiri et al. 2001). Ceramic crucibles were heated to heated to 500ºC for 4 hours to remove any organic materials, then cooled completely. Thirty milligrams of sediment were added to tared and cleaned crucibles. Samples were transported in a desiccator to a muffle furnace (make and model) at EcoCore, Colorado State University. Samples were ignited in the furnace at 550ºC for approximately 8 hours, after which they were allowed to cool for 12-24 hours and reweighed. The total weight of the samples was determined emptying the crucible content onto a tared weight paper in a microbalance scale.

Statistical Analyses

All statistical analyses were performed in RStudio 2022.07.1. The Santa Fe Core did not have annual laminations and the compression of sediments can lead to uneven sampling intervals through time. As a result, we did not use simple linear regression or non-parametric approaches to assess trends in our data due to the violations of the model's assumptions (Birks and others 2012). Instead, we used generalized additive models (Hastie and Tibshirani 1987; Wood 2017) to estimate trends in our response variables. Generalized additive models (GAMs) have the advantage of estimating complex, non-linear, and non-monotonic trends in time series, allowing better identification of significant change while accounting for the lack of independence, a common issue in paleolimnological time series (Simpson 2018). Generalized additive models (Hastie and Tibshirani 1987; Wood 2017) were employed to estimate trends in our response variables (Figure 3). All models were fit using the *gamm()* function (Wood 2004) in the *mgcv* package (Wood 2017) and were parameterized following the technical recommendations of Simpson and Anderson (2009). The tidypaleo package developed by

Dunnington et al. (2022) was used to plot stratigraphic diagrams of the sediment core density and sedimentation rate (Figure 7). Supplementary PCA analyses were completed using JMP software (Figure 9,10).

RESULTS

Chronology, Mass Loss on Ignition and PCA's

The analyses of ^{10}Pb activities provided a reliable sediment chronology for Santa Fe Lake (Figure 2). The core was dated to 1805 and extrapolated to 1747 using linear age accumulation relations observed in the early 20th century using the tidypaleo package**.**

Loss on ignition data revealed significant increases in organic matter (OM) in the core over time from an average of 28.1 ± 3.6 %OM organic matter from *ca* 1749-1800 to 40.4 ± 21.7 %OM from *ca* 1970 – 2020 (Figure 3). The extreme variability observed in the LOI data post. 1970 indicated a failure in the method, as a result, we did not use LOI to estimate organic matter (OM) trends and instead C and N (%dry mass).

PCA analyses were conducted for algal and biogeochemical data. The first two axes of the PCA of algal pigments from Santa Fe Lake explained 69.7% of the total variance. Pheophytin *a,* diatoxanthin, alloxanthin, pheophytin *b* and lutein- zeaxanthin (chlorophyte, cryptophyte, and diatom biomarkers) were well represented by PC1. Echinenone, canthaxanthin (cyanobacteria biomarkers), and okenone (anoxic sulfur-reducing bacteria) were well represented by PC2 (Figure 10). In a PCA of the algal pigments and biogeochemical data from Santa Fe lake 70.4% of the total variance was explained by the first two axes. PC1 was correlated δ^{13}C (% dry mass), N (% dry mass), chlorophyte, cryptophyte, and diatom pigment biomarkers. PC2 represented δ^{15}N, and cyanobacteria pigment biomarkers (Figure 11). The PCAs informed the presentation of algal pigment results below but were excluded from the discussion because they did not provide novel information about processes within the lake.

Biogeochemistry

Throughout the core $\delta^{15}N$, $\delta^{13}C$, C, and N were relatively stable over time until the mid-20th century (Figure 4). Bulk sediment $\delta^{15}N$ values ranged from 1.98‰ at the beginning of the core chronology (*ca* 1747) to -0.41‰ in the uppermost section of the core (*ca* 2019) and experienced significant depletion from *ca* 1945 - 2020 (Table 2, Figure 4). Bulk sediment $\delta^{13}C$ remained between -26‰ to -25‰ from *ca* 1747-1910. From *ca* 1961 – 2020, $\delta^{13}C$ became progressively depleted from -25‰ to -28‰ (Figure 4). Percent dry mass of C and N were relatively stable from *ca* 1747 - 1975 with values of ~14% C and ~1.2% N, respectively (Figure 4). There was a significant increase in % dry mass of C from *ca* 1818 – 1840 (Figure 4, Table 2). Carbon (% dry mass) increased from 13.79% – 15.04% during this period (Figure 4). Then C declined from *ca* 1865 -1913 from 12.17% – 11.39% (Figure 4, Table 2). Nitrogen (% dry mass) declined significantly from ~1.11 % - 1.05% between *ca* 1897 – 1942 then significantly increased between *ca* 1958 – 2020, from 1.34% – 2.93%. Between *ca* 1975 – 2020 C increased from 13.44 - 23.63% (Figure 4). The C:N ratio remained stable throughout the record until *ca* 1957 – 2020 when the C:N ratio in Santa Fe Lake decreased from 12 to 9 (Table 2, Figure 4).

Algal Pigments

Total Algal Biomass

Total algal biomass, represented as pheophytin *a,* was present in the record at concentrations of 96.4 ± 8.6 nmol g^{-1} organic carbon from *ca* 1750 – 1800. Total algal biomass significantly declined from *ca* 1803 – 1852 and reached its lowest value of ~25 nmol g^{-1} organic carbon in *ca* 1921 (Table 2, Figure 5) Beginning in *ca* 1956, total algal biomass significantly increased, resulting in an average concentration of ~100 nmol g^{-1} (SE) organic carbon in modern sediments (*ca* 2007-2020) exceeding historic concentrations (Figure 5).

Chlorophytes and Cryptophytes

Increased concentrations of algal biomass from *ca* 1965 - 2020 were largely due to increases in chlorophytes as represented by lutein-zeaxanthin and pheophytin *b,* as well as increases in cryptophytes represented by alloxanthin (Figure 5, 6). Chlorophytes, as represented by pheophytin *b* averaged 161.6 ± *51.3* nmol g^{-1} organic carbon as represented by pheophytin *b* were roughly stable in concentration until *ca* 1958 (Table 2). Pheophytin *b* pigments significantly increased from the *ca* 1952 - 2019 averaging 182 ± 63.4 nmol g^{-1} organic carbon (Table 2, Figure 5). Chlorophytes as lutein-zeaxanthin increased linearly from oldest to youngest sediments, although variability in concentrations was notably greater after *ca* 1850 (Figure 5). Values ranged from 60.10 - 184.19 nmol g^{-1} organic carbon. Cryptophytes, a typical planktonic alga represented by alloxanthin, significantly declined from *ca* 1881 - 1915 (Table 2, Figure 5). Alloxanthin significantly increased from 11.76 - 31.78 nmol g^{-1} organic carbon from *ca* 1965 - 2020 (Table 2, Figure 5). Increases within chlorophytes and cryptophytes are commensurate with the changes observed in C and N content (Table 2, Figure 4, 5).

Diatoms

Diatoms, as represented by diatoxanthin, were variable throughout the record (Table 2, Figure 5). The greatest concentrations of diatoxanthin (99.49 nmol g^{-1} organic carbon in *ca* 1749; Table 2, Figure 5), occurred in the deepest and oldest layer of the sediment core. Concentrations declined rapidly from 1749 – 1797 from 99.49 - 47.88 nmol g^{-1} organic carbon and 1889 – 1892 to a minimum of 19.37 in *ca* 1920 nmol g^{-1} organic carbon and increased linearly until *ca* 1995 (Table 2, Figure 5). Diatoms decreased since *ca* 1995 resulting in a historically low proportion of the total algal biomass in most recent decades (as pheophytin *a* to diatoxanthin, Figure 6. Fucoxanthin and diadinoxanthin, representative of diatoms, were excluded from analyses due to obvious post-depositional degradation, but were present in surface sediments, implying a benthic biofilm within the lake.

Cyanobacteria and Sulfur Bacteria

Total cyanobacteria as represented by echinenone linearly declined throughout the record from *ca* 1749 - 2020 (Table 2, Figure 5). Values ranged from 1.8 - 18.64 nmol g^{-1} organic carbon. Canthaxanthin, a nostocales cyanobacteria-associated pigment, experienced modest increases from *ca* 1975 -1995 (Table 2). Modern increases in canthaxanthin were below historic maxima and averaged 6.79 ± 2.85 g^{-1} organic carbon (Table 2, Figure 5). Concentrations of echinenone and canthaxanthin were an order of magnitude lower than chlorophyte biomarkers (lutein-zeaxanthin and pheophytin *b*, Figure 5, 6).

Okenone is a pigment representative of purple photosynthetic sulfur-reducing bacteria whose presence indicates benthic anoxia and high UVR penetration. This pigment was most abundant early in the record from *ca* 1747 - 1802 averaging 13.06 (± 2.77) nmol g^{-1} organic carbon (Figure 5, 6). The pigment significantly declined from *ca* 1878 - 1937 reaching a low in *ca* 1950 at 0.42 nmol g^{-1} organic carbon (Table 2). From 1966 – 2020, concentrations have significantly increased to an average of ~ 6.15 nmol g^{-1} organic carbon (Table 2, Figure 5).

DISCUSSION

Trends In Santa Fe Lake

Over the 250-year lake sediment record, we observed distinct ecological states within the lake. At the beginning of the record *ca* 1747, the Little Ice Age created a stable, cold and dry climate. During this period cyanobacteria, okenone, and diatoms composed a greater proportion of the community (Figure 6). At the end of the LIA (*ca* 1880), air temperatures increased alongside more frequent and intense periods of drought and precipitation (NOAA NCEI 2022, Margolis et al. 2011; Figure 8). Initially, this dramatic shift in climate appeared to drive declines in nearly all algal groups within the lake. In the mid-1900s, alongside increasing regional temperatures, the algal biomass increased, and community composition shifted to favor more chlorophytes and cryptophytes. Post-1950, we began to see significant increases in total algal biomass and significant rates of change in chlorophytes and cryptophytes. These groups benefit from warming and increased inputs of organic matter (OM). From the mid-20th century to present, exponential increases in C and N alongside depletions in $\delta^{13}C$ and $\delta^{15}N$, and a decline in the C:N (Figure 4), suggest a shift in the source and quantity of organic matter in the lake more terrestrially derived nutrients to those of aquatic origin. Lake productivity is mediated by a suite of external and internal processes. During the past 250 years, the external environment surrounding Santa Fe has experienced widespread transformation. Considering these changes, we explore some hypotheses below.

Changes Driven by Direct Human Impacts

Despite their relatively remote locations, mountain lakes can be modified by direct human impacts including livestock grazing, timber harvest, frequent human visitation, and fish stocking. After the Mexican-American war in 1848, Euro-Americans expanded timber harvest and commercial grazing operations in the Southwest (Raish and McSweeny 2001). These activities mobilize sediment and release organic matter, which negatively impacts water quality and can result in increased algal productivity in mountain lakes (Derlet et al. 2012). In the lower Santa Fe Watershed, extreme sediment erosion from cattle grazing led to the watershed's closure in 1932 to public visitation, and grazing (Margolis; personal communication, Figure 1). There is no evidence of timber harvests or grazing impacts directly within the Santa Fe Lake basin during the past 250 years and the sedimentation rate in the lake does not suggest events causing increased sediment inputs (Figure 7). Human visitation, like livestock grazing, can alter lake ecosystems through direct soil erosion and increased N and P inputs via biological waste. Human visitation is low and infrequent surrounding Santa Fe Lake,

Fish have been introduced to many historically fishless mountain lakes in western North America, altering food-web dynamics and ecosystem function in these systems (Finlay and Vredenburg 2007). Fish increase nutrient recycling through the consumption of zooplankton and macroinvertebrates, which alter the food-wed structure and increase standing algal biomass (Leavitt and Findlay 1994). They also increase nutrient availability through waste and decomposition after death (Schindler et al. 1993). Santa Fe Lake has no history of fish and currently remains fishless. There is a population of Western Tiger salamanders (*Ambystoma mavortium*) within the lake.

Changes Driven by Atmospheric Deposition

Inputs of atmospherically deposited limiting nutrients, trace elements, and other contaminants are known to alter the biology and biogeochemistry of remote mountain ecosystems. High-elevation lakes are particularly sensitive to atmospheric deposition due to their relatively high precipitation inputs compared to low-elevation regions, and from cold condensation - the process by which compounds volatilize in a warm location and condense in cooler environments, leading to greater deposition inputs at high elevations (Blais et al. 1998, Moser et al. 2019). In the northern New Mexico region, likely deposition inputs include nitrogen, phosphorus, ash from regional fires, and sulfates.

Nitrogen Deposition

Increased atmospheric N deposition since the mid-20th century is considered a primary driver of change in mountain lake ecosystems worldwide (Catalan et al. 2013). Similar paleolimnological studies of mountain lakes in the Sierra Nevada Mountains, CA, Greater Yellowstone Ecosystem (Saros et al. 2012), Teton Range, WY (Spaulding et al. 2015), Rocky Mountain National Park (Wolfe et al. 2001, 2003), and Uinta Mountains, UT (Hundey et al. 2014) have documented N enrichment and related biological changes beginning in the mid-20th century. Across these systems, algal species assemblages have shifted to favor more pelagic and nitrophilic taxa, but overall algal biomass increases to N deposition are variable. Some systems have experienced exponential increases in algal biomass, such as lakes within Rocky Mountain National Park, CO, where Oleksy et al. (2020) determined a200-300% increases in chlorophytes and double the total algal biomass in response to increased nitrogen deposition and warming post-1950. In contrast, lakes studied in the Uinta and Teton Ranges have experienced more muted responses like the trends observed in Santa Fe lake.

One explanation for this variability could be the quantity of atmospheric N deposition. The critical load for N deposition in Rocky Mountain National Park lakes was proposed by Baron (2006) to be 1.5 $kg \cdot ha^{-1} \cdot yr^{-1}$. The critical load is defined as the input of atmospheric deposition below which there are no measurable impacts (Nilsson and Grennfelt 1988). Studies in the Greater Yellowstone Ecosystem and Central Rocky Mountains agreed with this value (Saros et al. 2011, Nanus et al. 2017), while others have postulated an even lower critical load of 1.0 kg N ha^{-1} $year^{-1}$ for lakes of the Sierra Nevada and Cascades (Baron et al. 2011, Sheibley et al. 2014). In the western United States, the estimate for pre-industrial, or background inorganic-N deposition is between 0.4 and 0.7 $kg\cdot ha^{-1}\cdot yr^{-1}$ (Holland et al. 1999). Data from the National Atmospheric Deposition Program, National Trends Network (NADP, NTN) site at Bandelier National Monument, NM, reports total N deposition between 0.7 and 1.9 $kg\cdot ha^{-1}\cdot yr^{-1}$ since 1989 with an average of 1.27 $kg\cdot ha^{-1}\cdot yr^{-1}$ (Figure 9).In comparison, total N deposition in the Rocky Mountain Front Range averaged 3 $kg\cdot ha^{-1}\cdot yr^{-1}$ during this same period, (NADP, NTN, Rocky Mountain National Park). Average regional deposition falls below the critical load for the Central Rocky Mountains, and it is possible that the critical load for the northern New Mexico region is lower. Therefore, we cannot rule this out as a potential driver of ecological change. Biogeochemical data from the Santa Fe lake core suggests that N enrichment occurred in Santa Fe lake. For example, there was an increase in N (%dry mass) within the lake sediments since the mid-20th century and depletion of $\delta^{15}N$ that aligns with global trends of depletion in temperate and arctic lakes due to atmospheric N deposition (Holtgrieve et al. 2011, Figure 4). Throughout the record, $\delta^{15}N$ declined from 1.98‰ in the deepest sediments to 0.62‰ mid-20th century and depleted to -0.4‰ in surface sediments (Figure 4). Atmospheric $\delta^{15}N$ values range between 5‰ t0 -5‰ in temperate lakes (Botrel et al. 2014), while terrestrial N inputs average 3.7‰ and internal aquatic sources average 4.95‰ (Meyers and Ishiwatari 1993). The depletion of $\delta^{15}N$ could also occur from terrestrial changes within the watershed that promote alternative N cycling pathways (Baron 2006). The Santa Fe Lake basin is dominated by spruce forest and rocky talus. There is no evidence of forest-type conversion or other major landscape changes within the lake basin throughout the past 250 years. As a result, we conclude that N enrichment in Santa Fe Lake's sediments is primarily due to atmospheric deposition.

Phosphorus Enrichment

Phosphorus enrichment causes similar biological impacts as N deposition, resulting in algal community composition changes and productivity increases (Brahney et al. 2014b). Phosphorus is mobile within lake sediments and migrates into upper sediments, which makes historical P-loading difficult to determine. (Carignan and Flett 1981) As a result, we did not measure P in the Santa Fe Lake core. In remote mountain lakes, phosphorus enrichment primarily occurs through dust deposition (Ballantyne et al. 2011). Beginning in the 1800s, land use associated with Euro-American colonization of Western North America including cattle grazing, expansion of agriculture, and river system modification led to significant dust mobilization (Neff et al. 2008, Kemp et al. 2020). Increased sedimentation rates within lake cores can be used to reveal dust deposition (Ballantyne et al. 2011). The sedimentation rates within the Santa Fe core remained relatively stable over time and declined throughout the 20th century when dust deposition increased regionally (Figure 7). However, even small additions of phosphorus rich dust on the 1g/m2/yr scale, which would not noticeably influence the sedimentation rate, have nutrient and water column implications (Brahney et al. 2014). Santa Fe lake is positioned on the leeward side of the Southern Rocky Mountain Range, the lake could be topographically buffered from regional dust mobilization, despite significant regional increases in dust emissions during the last century. The lake's topographic position may also inhibit atmospheric N deposition, creating a "deposition shadow" effect, for atmospherically derived nutrients.

Inputs from Fires

Fires have the potential to increase organic matter inputs through ash deposition and increased soil erosion (Fitch and Meyer 2016). Increased organic matter input will primarily alter light penetration which can change water temperature, lake water column stratification, and mixing regimes. Dissolved organic matter is an important energetic input into the lake food web and increases can alter algal communities (Solomon et al. 2015). In the past 250 years, regional fire patterns have transitioned from complete suppression at the beginning of the sediment record to semi-annual prescribed burns beginning in the mid-1970s (Covington and Moore 1994, Anderson et al. 2008, Margolis and Balmat 2009). Within the Santa Fe Lake core, biogeochemical data revealed increased organic content in the core throughout the entire record (Figure 3). These results align with observed productivity increases in biogeochemical and algal data, but %C and %N did not reveal spikes in the organic matter within the lake during or after known local fire events (Figure 4). Additionally, the declining C:N ratio as well as the $\delta^{13}C$ data imply the lake's increased OM is largely due to internal sources (Figure 4). Lake sediment analyses best demonstrate overall trends and can mute singular events such as a local fire. Although alterations in in the regional fire regime have significantly impacted local forest structure, the biogeochemistry and algal pigment data from Santa Fe Lake do not correlate to these changes.

Sulfate Deposition

The atmospheric deposition of sulfates can drive acidification resulting in increased water clarity, and biological impacts (Schindler et al. 1980, Stokes 1986). Santa Fe lake, like many alpine lakes, is situated on crystalline granitic bedrock with a low buffering capacity, making it especially sensitive to acidification (Catalan et al. 2013). In the northern New Mexico region, copper smelter activity and coal-burning power plants led Lynch et al. (1988) to assess New Mexican high-elevation lakes' sensitivity to acid rain and trace metal contamination. In this survey Santa Fe's sediments were found to be enriched Hg, Mn, Pb and Zn beginning in 1920. Furthermore, Santa Fe was one of the more acidic lakes sampled with lake pH ranging from 5.7. - 7.2 during the summer season. The lake experienced a strong acid pulse during peak snowmelt, which likely influenced the shift from alkaliphilic species to more acid-tolerant diatoms documented in the study. We do not have detailed diatom species data from the Santa Fe Lake core and can only speculate what affects, if any, increased acidity had on the algal community and biogeochemical data post-1987. Increased lake acidity reduces dissolved organic carbon inputs in lakes resulting in greater water transparency and increased UVR penetration (Schindler 2001). High UVR can limit phytoplankton production, and increase pigment production from benthic taxa (Leavitt et al. 1997). Furthermore, algal community assemblage changes and increases in chlorophytes resulting from post-industrial lake acidity were documented in large, deep, low-elevation lakes on the Canadian Shield by Vinebrooke et al. (2002). Santa Fe's chlorophyte community did increase post-1960. However, given the brevity of the acid pulse from snowmelt it is unlikely that these periods of acidity drove long-term algal assemblage change. Further, a study in the Loch Vale watershed, Rocky Mountain National Park, CO of daily spring water chemistry found the acid pulse from snowmelt was mitigated by a flush of water from forest soils preventing surface water acidification (Denning et al. 1991). A similar pattern may have occurred at Santa Fe Lake since the acidity of the lake neutralized within the same open water season (Lynch et al. 1988). Since 1988, sulfate deposition has declined regionally (Figure 9; NADP, NTN 2022) due to the closure of regional smelters and power plants, while chlorophyte concentrations have continued to increase (Figure 4). A study of Sierra Nevada Lakes (Heard et al. 2014) found that acidified lakes had recovered alkalinity following emissions regulations under the Clean Air Act Amendments. Modern water quality assessments by (Davis and Joseph 2007) recorded a pH of 7.7 during the summer season in Santa Fe Lake suggesting that Santa Fe has entered a more alkaline state in recent decades. Although, acidic inputs into Santa Fe lake, were likely brief, however past research has demonstrated even with chemical recovery, acidic inputs may drive novel lake biological and chemical states, which will be reinforced by climate change (Smol 2010).

Changes Modulated by Lake Morphometry

Other explanations for limited algal response to N enrichment include lake depth and dominance of benthic algae. Productivity in shallow lakes, like Santa Fe Lake, is primarily limited by ultraviolet radiation (UVR). Shallow lakes are also susceptible to frequent mixing via wind and ice scouring events during winter months (Kosten et al. 2009). These disturbances interact to limit overall algal biomass and favor benthic algal taxa, which are more resilient to water column disturbances and less responsive to nutrient enrichment than planktonic algae (Gettel et al. 2013). Shallow lakes within the Teton Range, WY, experienced N enrichment and changes in algal community changes to favor more pelagic and nitrophilic taxa. However, total algal biomass was not shown to increase due to the lake's shallow depth and dominant benthos (Spaulding et al. 2015). Santa Fe's modest increases in algal biomass may be due to muted response from benthic taxa. The ratio of typically planktonic cryptophytes (alloxanthin) to benthic associated diatoms (diatoxanthin) increased post-1950, but the dominant algal group chlorophytes consist of both benthic and pelagic species.

Climate-Mediated Algal Assemblage and Biogeochemical Change

In the absence of significant atmospheric deposition, the biogeochemical and algal assemblage trends in Santa Fe Lake are likely being driven by climate. During the past 250 years, the frequency and intensity of drought and extreme precipitation events increased in northern New Mexico (Figure 8). A study by Margolis et al. (2011) employing tree-ring data to reconstruct Santa Fe River flow found that within the past 700 years determined some of the most extreme single-year, 3-year, and 7-year average low flow events occurred within the last 60 years (e.g., the 1950s and 2000s droughts). At the same time, 81% of the wettest reconstructed 40-year and 7-year high flow periods also occurred between 1914 - 2007, with extremely wet periods in 1920 and 1980.

Drought will reduce water influx, resulting in decreases in terrestrial dissolved organic matter inputs to lakes while increasing in water transparency, UVR penetration, salinity, and acidity (Hodgson et al. 2013, Williamson et al. 2016). In contrast, extreme precipitation events reduce transparency and limit UVR penetration. Lakes with frequent or intense precipitation events are known to have warmer mixed surface water, reduced chlorophyll maxima, and greater oxygen depletion in deeper waters (Williamson et al. 2016). This can result in whole lake ecosystem metabolism shifts, as observed by Sadro and Melack (2012) during an extreme deluge event in Emerald Lake, CA.

At the local scale, the water quality effects of drought and precipitation are complex and dependent on the biophysical characteristics of water bodies and their catchments (Mosley 2015). Sediment records best demonstrate overall trends, not singular events, but we did see a decline in all algal pigments at the end of the LIA (late 1880s) through 1930 (Figure 5,6). This period began with a relatively large drought in the early 1900s followed by a period of extreme precipitation in the 1920s (Figure 8). Okenone, a sulfur-reducing photosynthetic bacteria, relies on anoxic conditions in the sediment surface or at the sediment-water interface, high light penetration, and organic matter. Okenone declined significantly from *ca* 1882 – 1930 and remained low in concentration until the 1960s (Figure 5). The decline in okenone could be linked to less light penetration to the benthos as the result of alterations in mixing regimes and stratification due to increases in drought and deluge events.

Climate change can increase the occurrence of extreme drought and precipitation events and has driven warmer air temperatures. In mountain lake ecosystems, warming can enhance production by lengthening the ice-free while increasing nutrient cycling, nutrient concentrations, and lake water residence time (Rühland et al. 2008). Alongside warmer air temperatures, we noted increases in chlorophytes, cryptophytes, and overall algal biomass within Santa Fe Lake (Figure 6,8). Chlorophytes have been shown to respond positively to warming in both paleolimnology studies and field experiments (Kuefner et al. 2021, Oleksy et al. 2021). Alloxanthin, a pigment associated with the planktonic algal group cryptophytes, is demonstrated to increase from a combination of warming and dissolved organic matter (Lami et al. 2000, Buchaca and Catalan 2007). This pigment increased alongside increases in C and N post-1960, suggesting higher OM in the lake during this period (Figure 4,5). C and N increased exponentially post ca 1975 in combination with a decline in the C:N (Figure 4) implying a shift from more terrestrially derived OM to that of aquatic origin. This decline occurs because phytoplankton contains little or no carbon-rich cellulose or lignin (Meyers and Ishiwatari 1993), which reduces carbon in the lake.

The depletion of $\delta^{13}C$ (-25‰ to -28‰, Figure 4) provided further evidence of a transition throughout the record from more enriched terrestrially derived OM to algal or respiratory OM sources that are depleted in $\delta^{13}C$ (Finlay and Kendall 2007). Declines in $\delta^{13}C$ could also be the result of greater proportions of planktonic algal taxa. This trend was observed in lakes in Rocky Mountain National Park, by Oleksy et al. (2020) as the result of N enrichment and warming. The depletion of $\delta^{13}C$ in Santa Fe Lake from -25‰ to -28‰ suggests that a similar shift from benthic (26 ‰ ± 3) to more planktonic algae (32‰ ± 6) occurred over time. The depletion of $\delta^{13}C$ could also be attributed to background global $\delta^{13}C$ depletion known as the "Suess Effect", in which increases in atmospheric CO2 from the burning of $\delta^{13}C$ depleted fossil fuels has caused a global decline in $\delta^{13}C$ values (Verburg 2007). However, exponential increases in C and N (% dry mass) since *ca* 1950, support internal lake productivity increases.

Cyanobacteria concentrations are thought to increase in warmer conditions (Anneville et al. 2015), but pigments associated with cyanobacteria (echinenone and canthaxanthin), declined or remained at low concentrations in modern sediments despite ongoing increases in regional temperature (Figure 5,6). In a survey of 308 lakes across Europe, Lami et al. (2009) found declines in cyanobacteria and okenone in lakes with limited N enrichment in favor of fucoxanthin and diadinoxanthin. Santa Fe's limited regional N deposition could have driven declines in cyanobacteria in combination with low concentrations of okenone in sediments post-1960. We excluded fucoxanthin and diadinoxanthin from our analyses due to poor preservation, but both pigments were found in the surface sediments. A similar substitution may be occurring in Santa Fe Lake, but we currently do not have adequate data to support this trend. Declines in cyanobacteria could also be attributed to a competitive disadvantage to chlorophytes, which have a greater mean average growth rate at optimal temperatures (Lürling et al. 2013). Furthermore, Gallina et al. (2011) that even under extreme climate variability, if a critical climate threshold was not breached, dominance in algal communities will not change from historical norms despite conditions facilitating growth across algal groups. The dominance of chlorophytes throughout the record in combination with their faster growth rates under warming may underlie the overall declines in cyanobacteria in Santa Fe Lake.

CONCLUSIONS

The trends observed in Santa Fe Lake over the past 250 years align with a growing body of research demonstrating increased productivity in historically oligotrophic lakes driven by global change. Recent productivity changes observed in Santa Fe Lake are the result of multifaceted relationships between internal and external features. The evidence suggests changes in climate have served as the primary regulator of biogeochemical and biological changes in Santa Fe Lake over the past 250 years. Increased air temperatures alongside more frequent periods of extreme drought and precipitation beginning in the early 1900's favored chlorophyte and cryptophyte communities, which benefit from warming and organic matter inputs. Modest regional N deposition has likely supported productivity increases in the lake and enhanced nutrient cycling post 1960. Furthermore, the lake's morphometry, alongside minor inputs of atmospherically deposited dust, ash, and sulfates, likely influenced algal assemblage changes over time. Our findings provide evidence of heterogeneity in the magnitude, timing, and influence of external stressors in facilitating productivity increases in mountain lakes. Under increasing climate warming the algal community shifts observed in Santa Fe Lake may lead to novel ecological states within the lake.

Table 1. Santa Fe Lake site information.

Water chemistry data was collected by Davis et al. 2007, during the open water season.
** Dissolved oxygen and temperature are mean values (from the epilimnion (upper 1/3 of water column)

Santa Fe Lake Location	35.78884, -105.77804
Elevation (m)	3530
Max Depth (m)	6.5
Surface Area (ha)	2.4
Basin Area (ha)	15.9
Secchi disk depth (m)	6.5
Dissolved oxygen ** (mg/L)	7.3
Dissolved oxygen - Bottom (mg/L)	1.2
pH	7.7
Conductivity (µS/cm)	22
Turbidity (NTUs)	0.62
Chlorophyll *a* (µg/L)	3.26
Total phosphorus (mg/L)	<0.01
Total nitrogen (mg/L)	0.35
Limiting Nutrient	Nitrogen
Stratified (Y/N)	N

Table 2. Model summary of GAMs for all geochemical and pigment biomarkers.

We used generalized additive models for the detection of trends on all sedimentary pigments and elemental biomarkers. For each predictor, effective degrees of freedom (EDF), F-statistic, p-value, and adjusted R2, and periods of significant change are shown.

Analyte	EDF	F	p-value	adj. R2	Period of Change (-)	Period of Change (+)
δ15N	2.36	7.36	<2e-16 ***	0.69	1945 - 2020 (-)	
δ13C	3.3	3.3	<2e-16 ***	0.95	1961 - 2020 (-)	
%C	6.74	88.61	<2e-16 ***	0.91	1865 - 1913 (-)	1818 - 1844 (+), 1975 - 2020 (+)
%N	4.79	57.99	<2e-16 ***	0.84	1897- 1942(-)	1958 - 2020 (+)
C:N	5.14	35.22	<2e-16 ***	0.89	1957 - 2020 (-)	
Pheophytin a	2.67	6.06	<2e-16 ***	0.38	1803 - 1852 (-)	1956 - 2020 (+)
Pheophytin b	3.51	7.65	<2e-16 ***	0.24		1952 - 2020 (+)
Lutein /Zeaxanthin	1	42.34	<2e-16 ***	0.38		1749 - 2020 (+)
Alloxanthin	5.64	13.38	<2e-16 ***	0.7	1881 - 1915 (-)	1965 - 2020 (+)
Echinenone	1	26.94	<2e-16 ***	0.3	1749 - 2020 (-)	
Canthaxanthin	3.84	13.98	<2e-16 ***	0.51	1845 - 1931 (-)	1975-1995 (+)
Diatoxanthin	6.06	30.56	<2e-16 ***	0.63	1749 -1797 (-) , 1828 - 1892 (-), 1995 - 2020 (-)	1915 - 1983 (+)
Okenone	5.6	28	0.05 *	0.7	1878- 1937 (-)	1966- 2020 (+)

Legend	
⬜	Biogeochemical
🟩	Total Algal Biomass
🟩	Chlorophytes
🟧	Cryptophytes
🟦	Cyanobacteria
🟨	Diatoms
🟪	Okenone

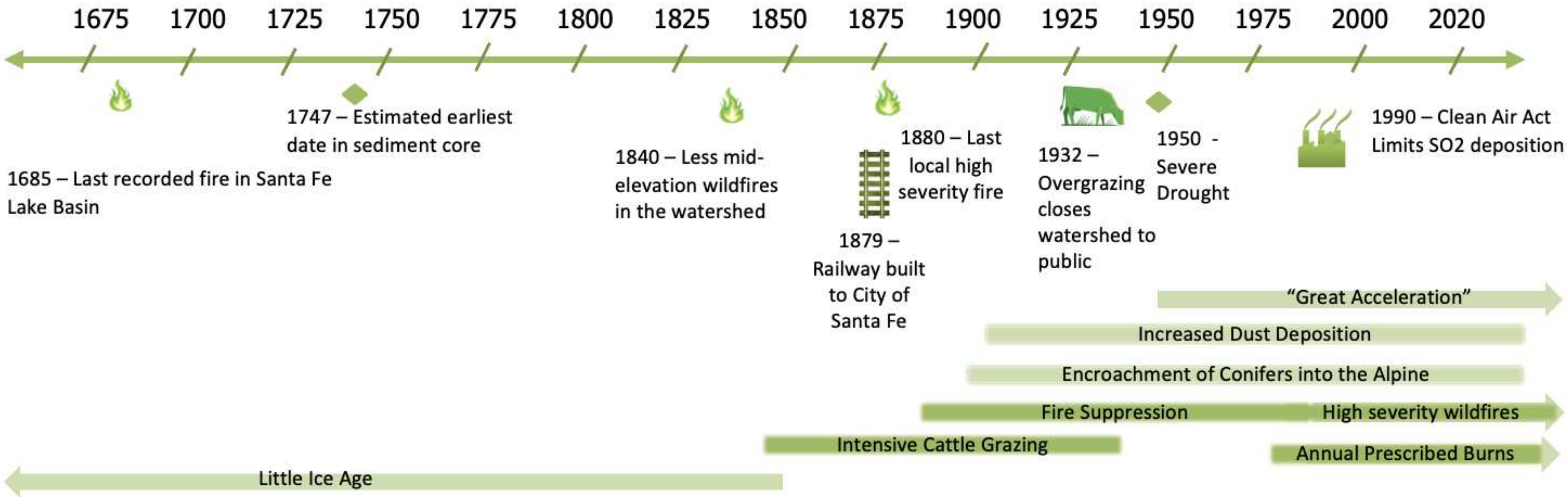


Figure 1. Regional and global drivers of change in Santa Fe Lake's history.

The timeline includes singular events such as completion of the Santa Fe Railway (1879), which marked the beginning of increased regional settlement and industrialization. Periods of change (green bars) include the "Little Ice Age", a period of climatic cooling from approximately 1200 A.D to 1850 (Petersen 1984). Other periods include, the "Great Acceleration", defined by Steffen et. al 2015, as the exponential impacts of post-industrial anthropogenic actives on earth's systems.

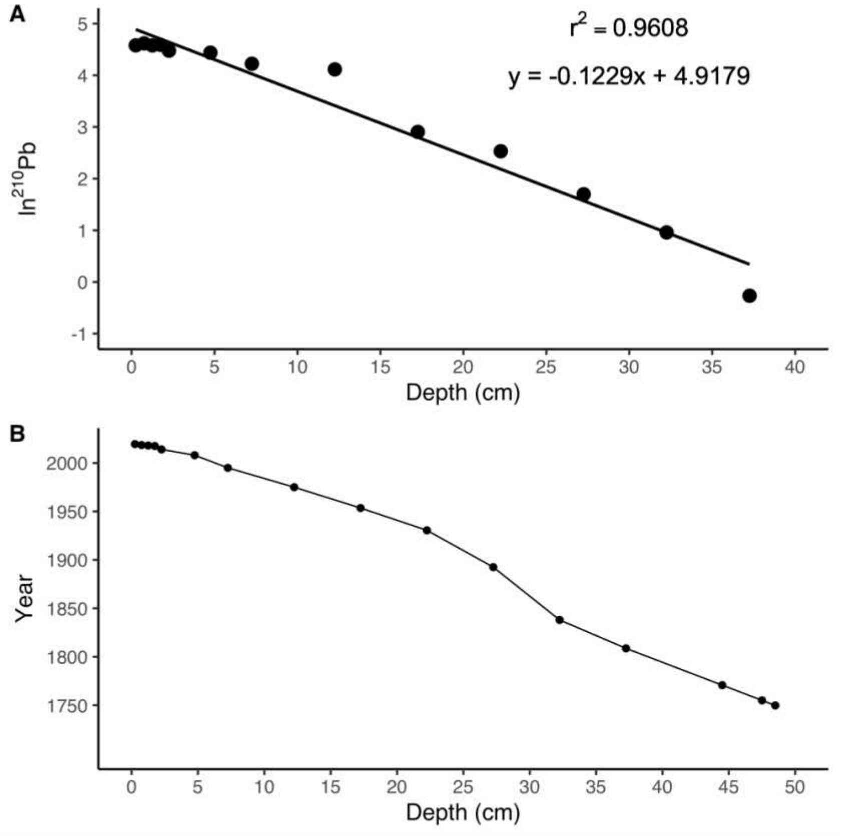


Figure 2. Chronology for the Santa Fe Lake sediment core.

(A) Natural log 210Pb, (B) Estimated age by depth for Santa Fe Lake sediments.

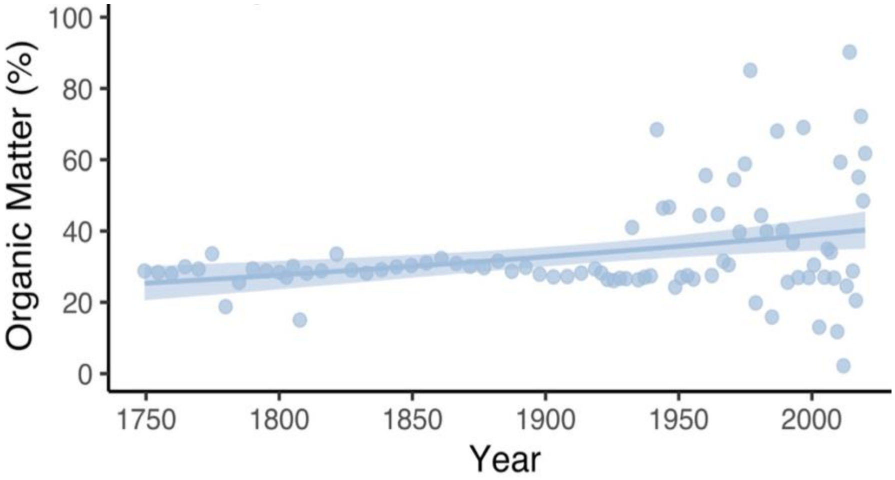


Figure 3. Loss on ignition from the Santa Fe Lake core.

Percent Organic Matter determined with mass loss on ignition data from the lake sediments is plotted over time.

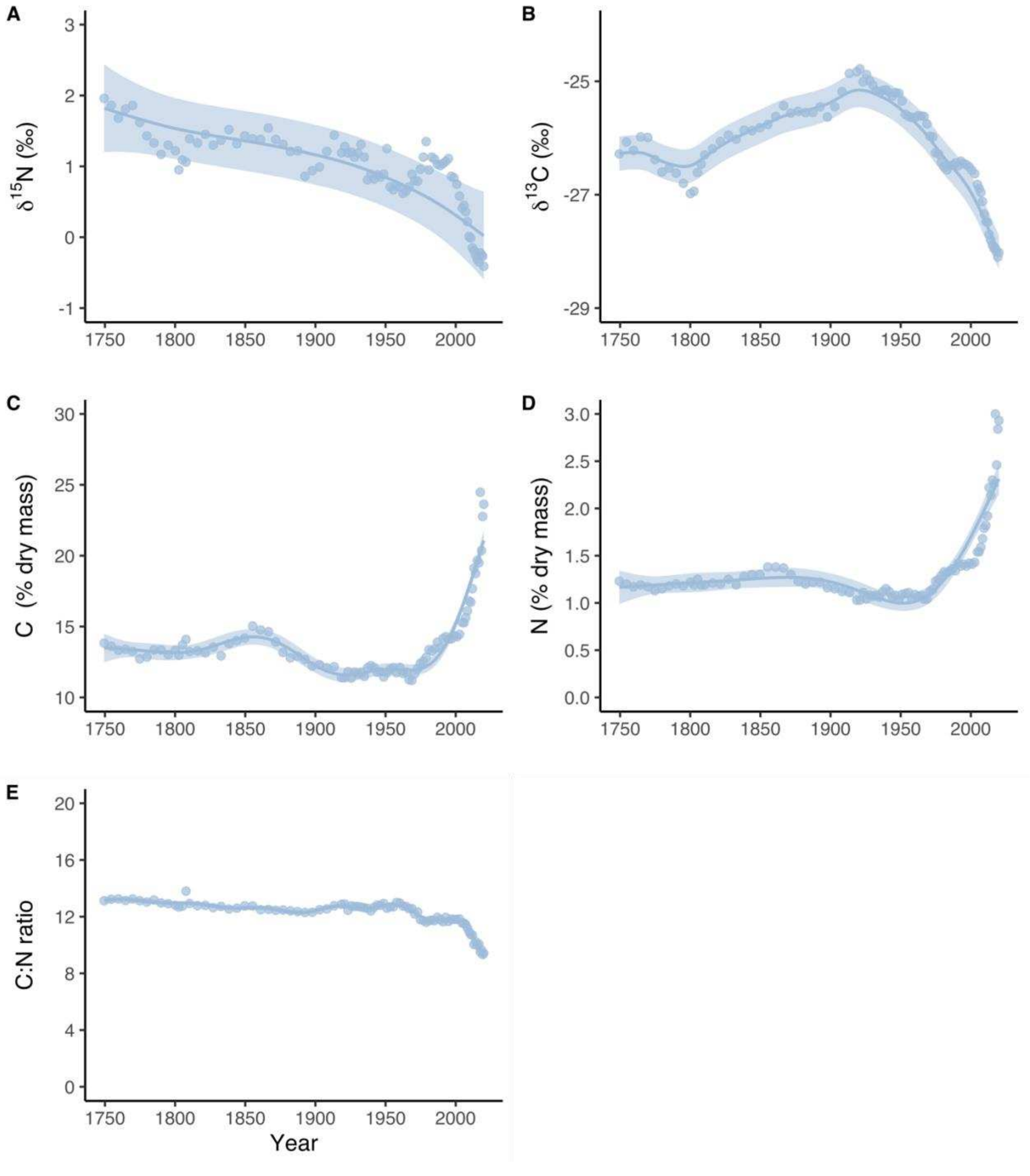
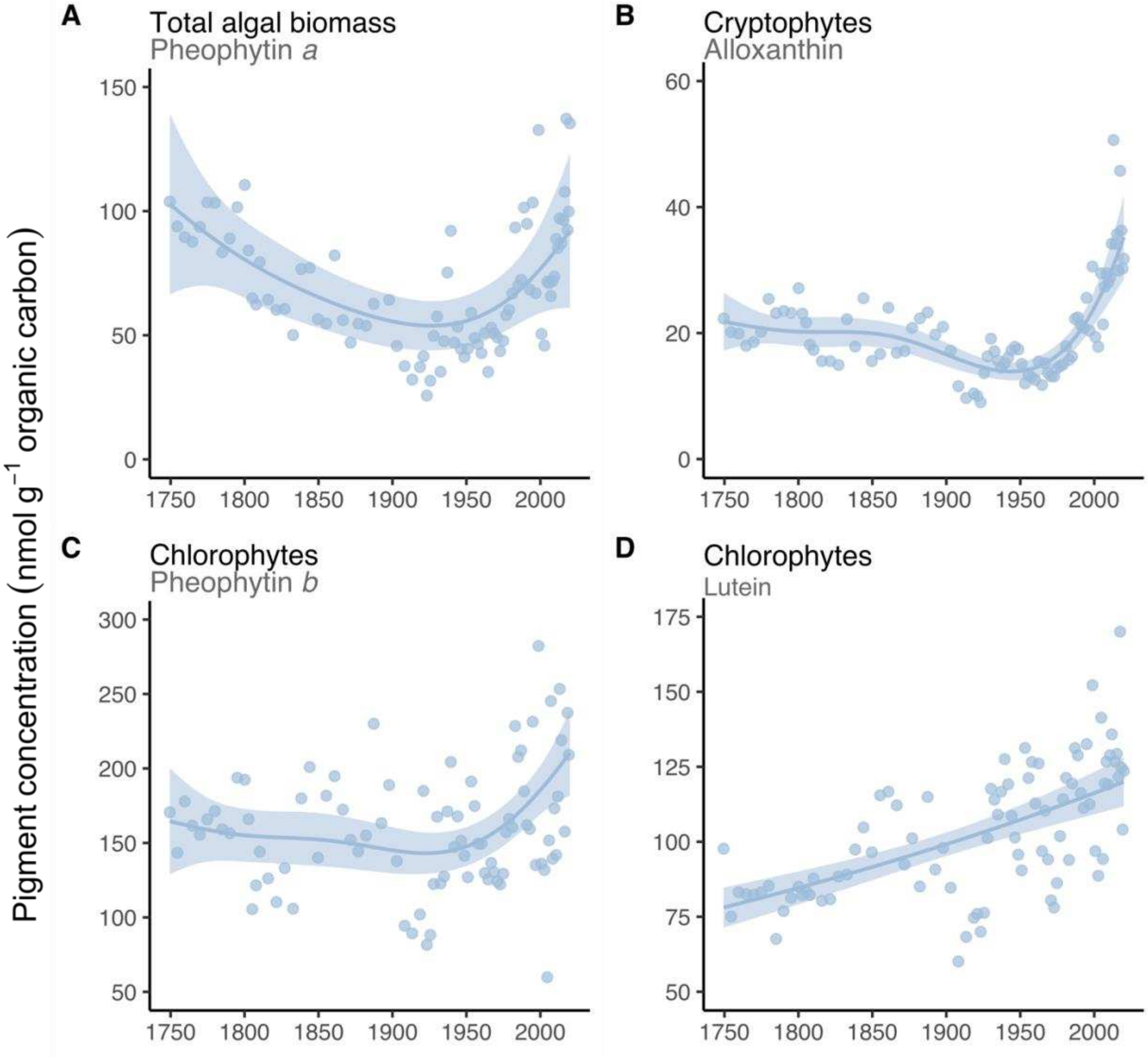


Figure 4. Summary of temporal trends in biogeochemical signals from Santa Fe Lake.

The $\delta^{13}C$, $\delta^{15}N$, C (% dry mass), N (% dry mass), and C:N plotted against year. Values were fitted with a GAM-Smoothing trend and 95% confidence interval. (a) $\delta^{13}C$ of bulk sediments; (b) $\delta^{15}N$ of bulk sediments; (c) carbon content as a percentage of dry mass; (d) nitrogen content as a percentage of dry mass; and (e) C:N ratio.


A
Total algal biomass
Pheophytin a
B
Cryptophytes
Alloxanthin
C
Chlorophytes
Pheophytin b
D
Chlorophytes
Lutein
Pigment concentration (nmol g−1 organic carbon)
0
50
100
150
0
20
40
60
50
100
150
200
250
300
50
75
100
125
150
175
1750
1800
1850
1900
1950
2000

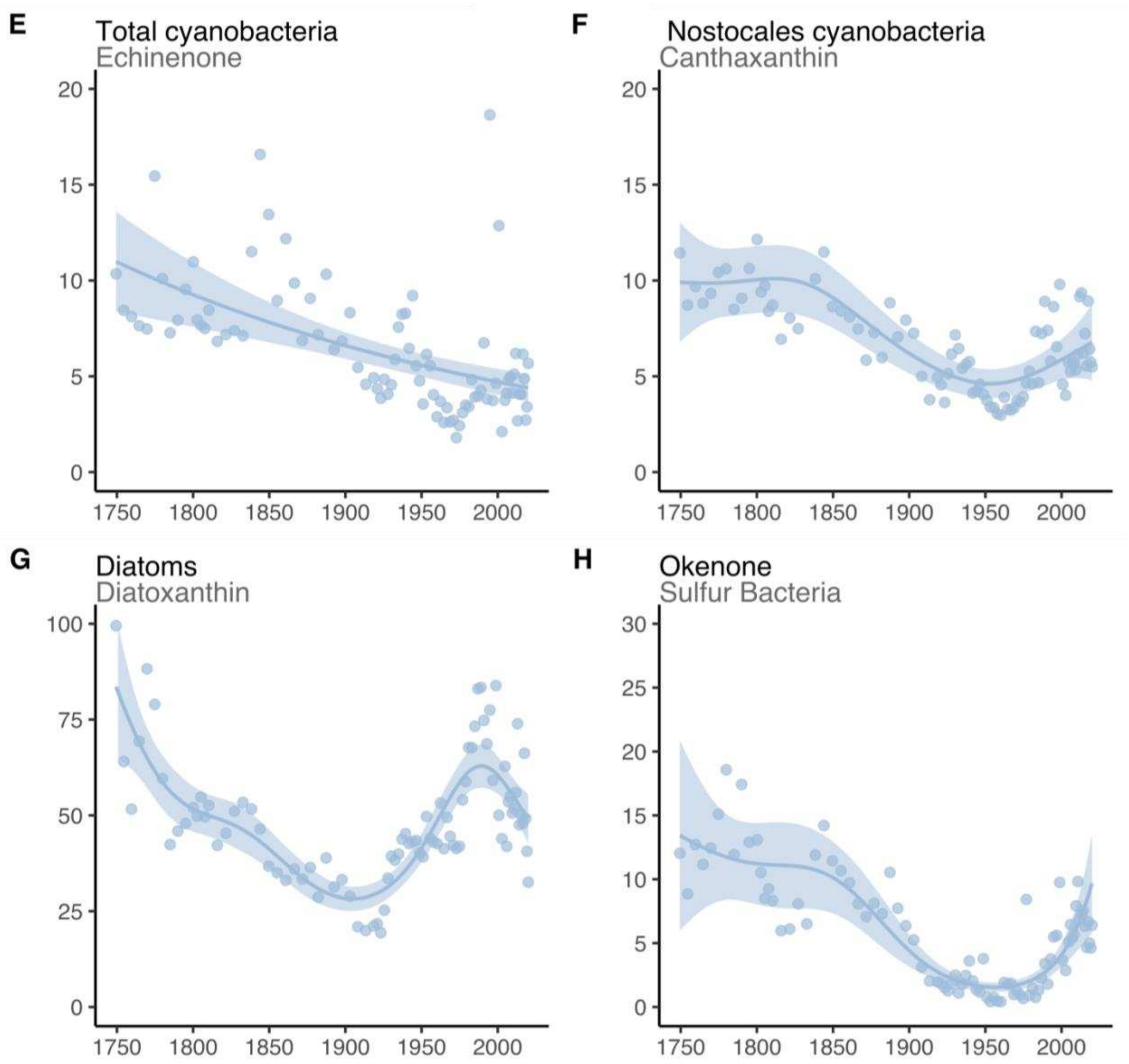


Figure 5. Temporal trends in major algal functional groups inferred by pigment analyses.

GAM-smoothing trends fitted are depicted with 95% confidence intervals for all major algal pigments in Santa Fe Lake time series. Pheophytin *a* (a) is a proxy for total algal biomass. Alloxanthin (b) is proxy for total cryptophytes. Pheophytin *b* (c) and Lutein-zeaxanthin (d) are proxies for total chlorophyte biomass. Echinenone (e) and canthaxanthin (f), and are proxies for cyanobacteria (total, and nostocales, respectively). Okenone (g) is a proxy for a purple sulfur-reducing photosynthetic bacterium. Diatoxanthin (H) is a proxy for total diatom biomass.

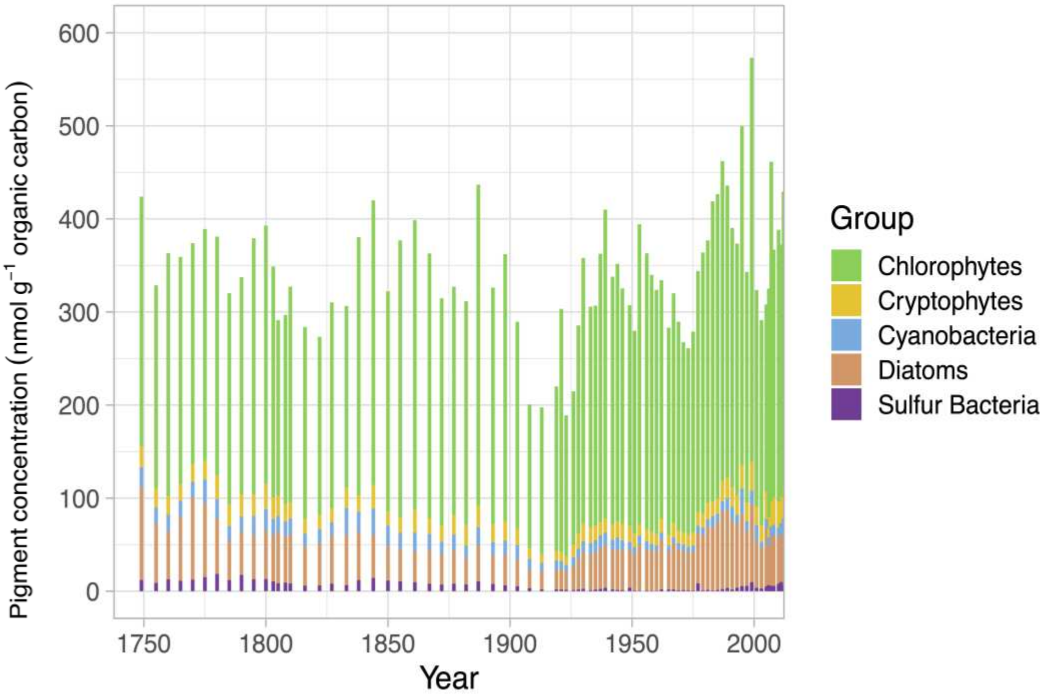


Figure 6. Proportions of major algal groups throughout the Santa Fe Lake core.

Diatoms, cyanobacteria and sulfur bacteria composed a greater proportion of the community at the beginning of the record. Almost all pigments declined in the middle of the record ca 1900-1930. Increases in algal biomass post. 1960 are due to increases in chlorophytes and cryptophytes.

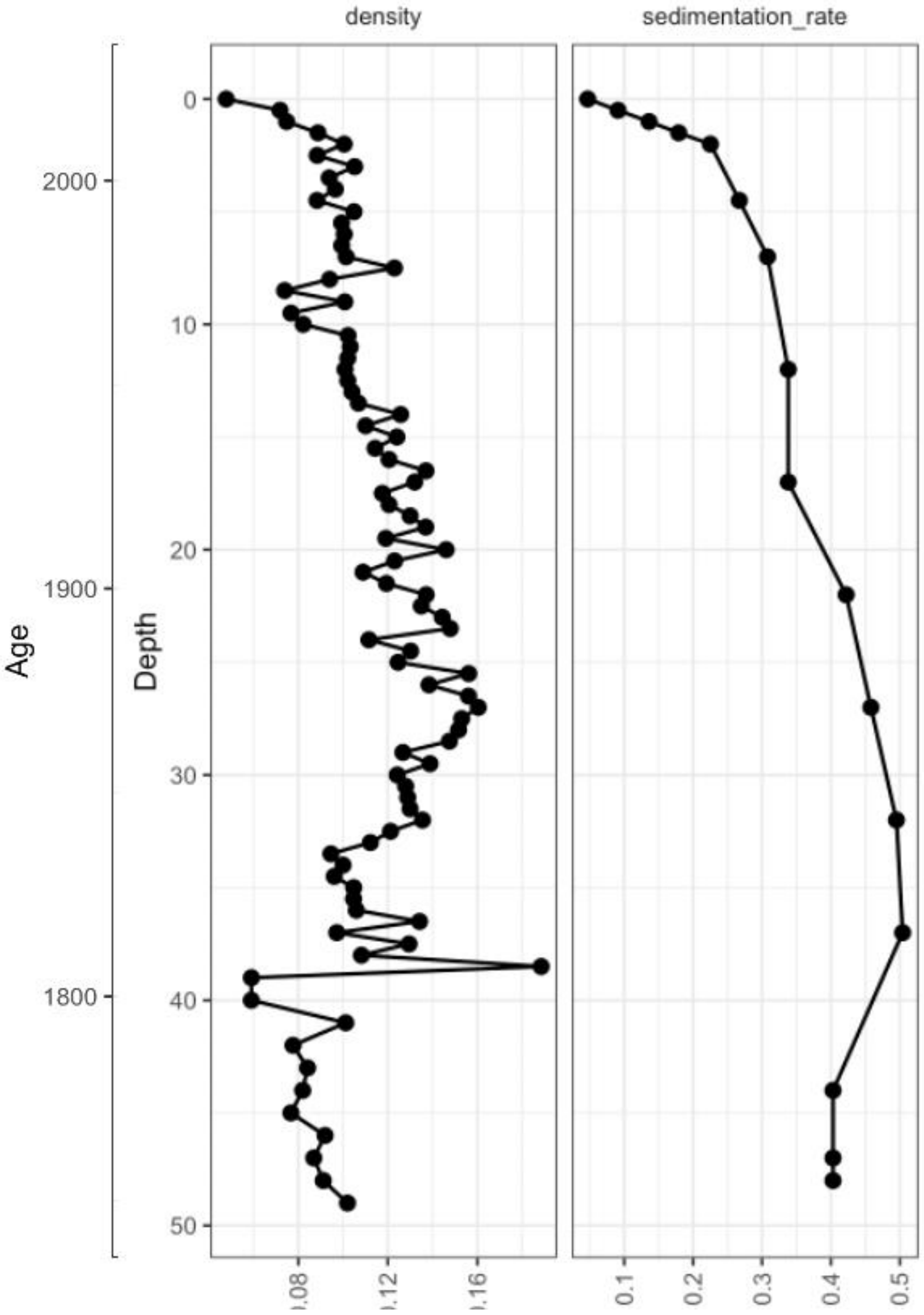


Figure 7. Santa Fe Lake Core Sediment Density and Sedimentation Rate.

Sediment density was calculated using the dry mass of the Santa Fe Lake core sediments (left). Sedimentation rate was calculated using the CRS model (right). The Y-axis includes core depth (cm) and estimated ages. Plots were created using the tidypaleo package (Dunnington et al. 2022).

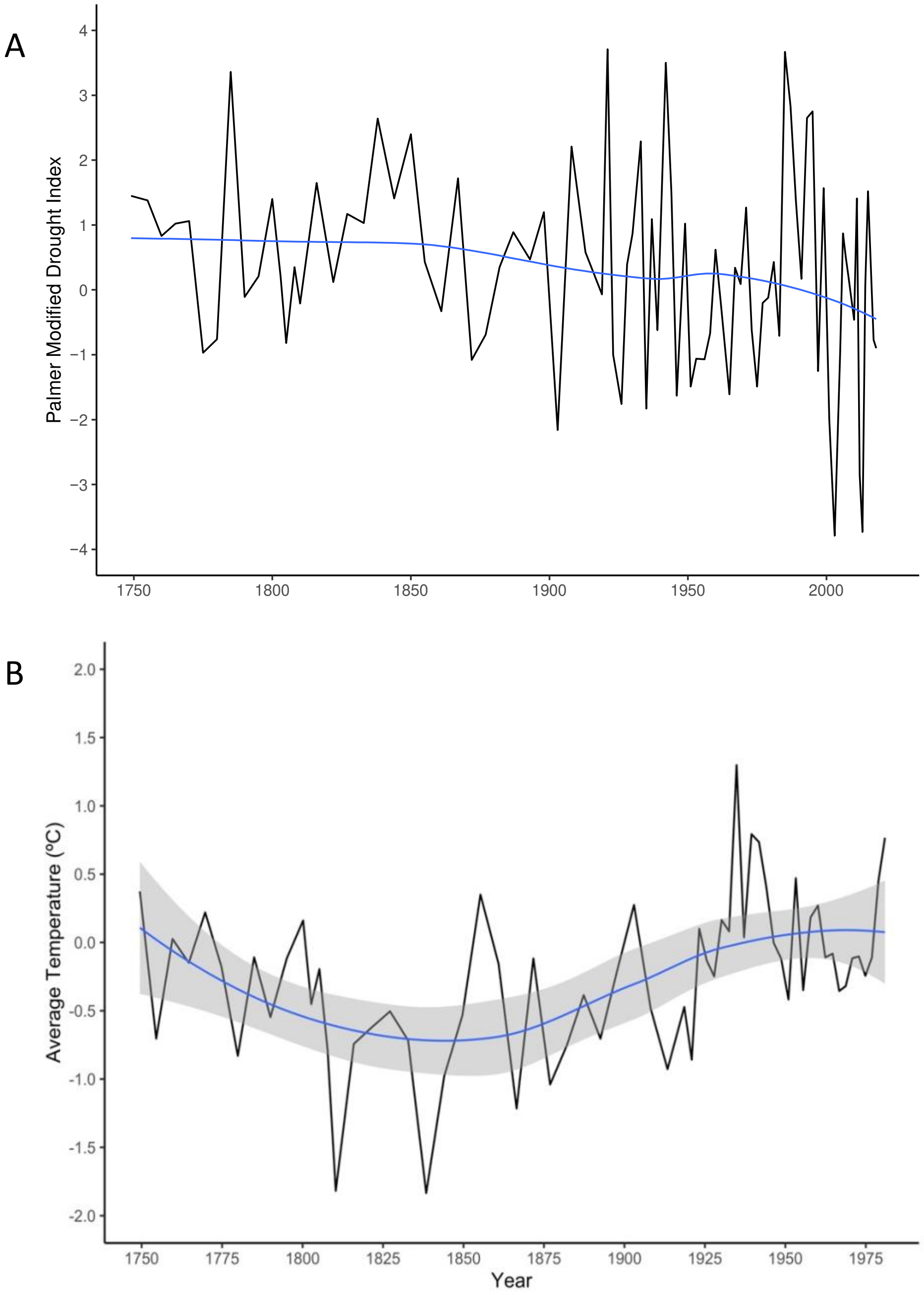


Figure 8. Regional drought and temperature reconstructions.

(A) Palmer Modified Drought Index (PMDI) and (B) Average North America air temperatures (ºC). Temperature reconstructions plotted from the 'The Western North America 500 Year Annual Temperature Reconstruction' by Wahl and Smerdon. (2012). Palmer Modified Drought reconstructions are a product of the Living Blended Drought Atlas Version 2 (Cook et al. 2010) https://www1.ncdc.noaa.gov/pub/data/paleo/drought/LBDP-v2/lbda-v2_pmdi_kddm_template.txt.

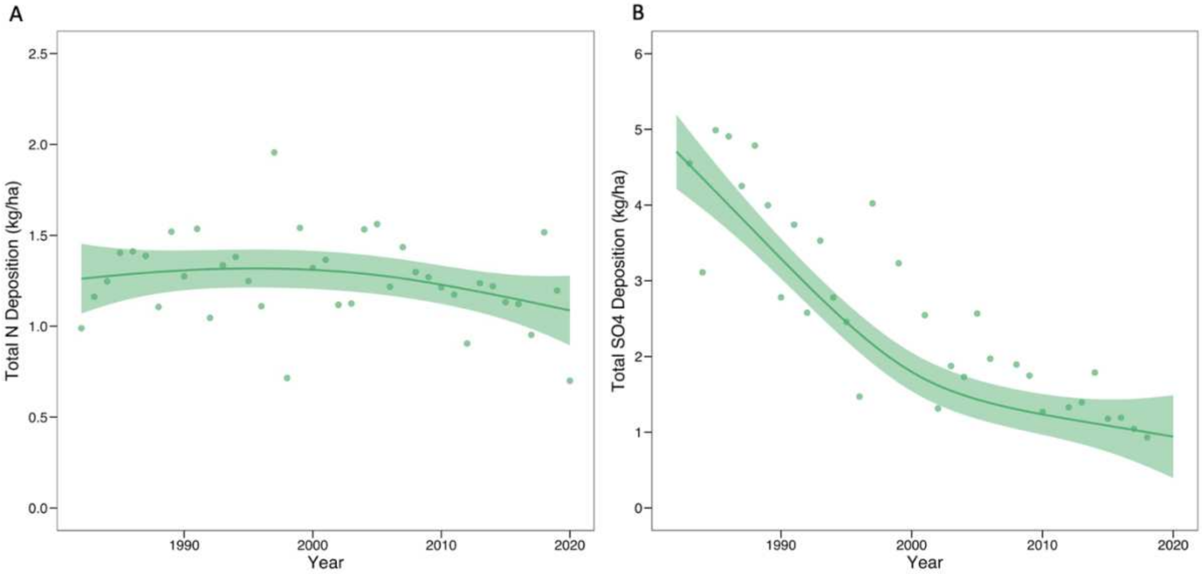


Figure 9. Regional total N and SO4 deposition

Data is from the National Trends Network, Bandelier National Monument location (site NM07) maintained by the National Park Service and the National Atmospheric Deposition Program. No significant change in N deposition (A) occurred in northern New Mexico region from 1983-2020.SO4 (B) deposition significantly declined from 1989 – 1997.

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APPENDIX

Supplemental Materials

Principle Component Analyses

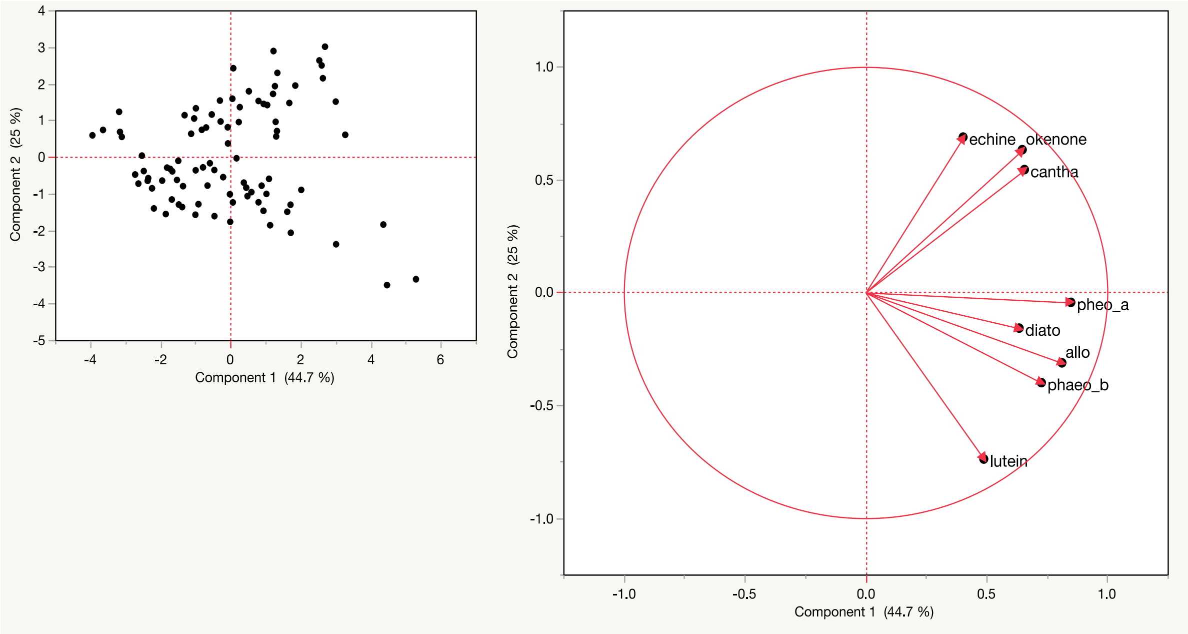

Figure 10. PCA of Algal Pigments in Santa Fe Lake

PCA of pigments from Santa Fe lake (left) and pigment axes (right). The first two axes of the PCA of algal pigments from Santa Fe lake explained 69.7% of the total variance. Pheophytin a, diatoxanthin, alloxanthin, pheophytin b and lutein (chlorophyte, cryptophyte, and diatom biomarkers) were well represented by PC1. Echinenone, canthaxanthin (cyanobacteria biomarkers), and okenone (anoxic sulfur reducing bacteria) were well represented by PC2. Principle component analyses (PCA) were completed using JMP Pro vs. 16.

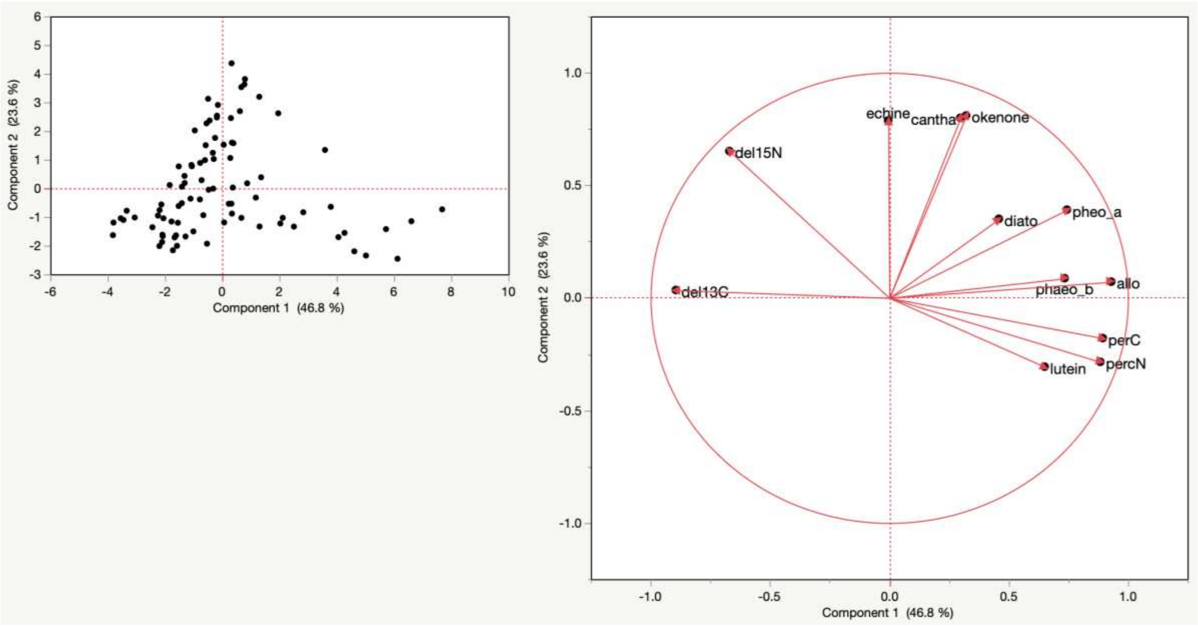

Figure 11. PCA of Algal Pigments and Biogeochemistry in Santa Fe Lake

PCA of algal pigments and biogeochemical data (left) and PCA axes (right). 70.4% of the total variance was explained by the first two axes. PC1 was correlated δ^{13}C, C (% dry mass), N (% dry mass), chlorophyte, cryptophyte and diatom pigment biomarkers. PC2 represented δ^{15}N, and cyanobacteria pigment biomarkers. Principle component analyses (PCA) were completed using JMP Pro vs. 16.