

University of Nevada, Reno

**ANTHROPOGENIC AND CLIMATIC INFLUENCES ON THE DIATOM FLORA WITHIN THE FALLEN LEAF LAKE
WATERSHED, LAKE TAHOE BASIN, CALIFORNIA**

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Geology

by

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August, 2013

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entitled

**Anthropogenic and Climatic Influences on the Diatom Flora within the Fallen Leaf
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ABSTRACT

Sediment cores and water quality data from the Fallen Leaf Lake (FLL) watershed were analyzed in order to gauge the effects of climate, land use, and atmospheric nitrogen deposition over the past 1200 years. High resolution diatom and geochemical analyses were conducted on core 2E-1G-1 from FLL, a moderately impacted lake that is the lowest catchment in the watershed. The FLL core delineated 3 zones of interest that correspond to the Little Ice Age (LIA), a transitional zone of warming and anthropogenic influence following the LIA, and an upper anthropogenic zone. The LIA is characterized by increased abundances of the diatoms *Stephanodiscus alpinus* and *Aulacoseira subarctica*, and is calibrated with an age model derived from ^{14}C and ^{210}Pb dates to between 1385 and 1807 AD, and indicates a time of cooler, windier conditions. The transitional zone represents a ~140 year period of gradual warming following the LIA, and is characterized by increases in *Cyclotella rossii* and *Discostella stelligera* and decreases in *Pseudostaurosira brevistriata*. The FLL core transitional zone also shows sedimentologic and geochemical changes that include increases in elemental cobalt, zinc, and tin that may be attributed to an increase in coal burning and smelting activities in California and Nevada. Beginning ~1910 AD, increased building, land-use, and recreation around the lake caused an increase in sediment accumulation. The increased sediment accumulation rate can be partly attributed to terrestrial organic input into the lake, as both total organic carbon (TOC) and C:N ratios increase beginning ~1943 AD. Coincident with the sedimentologic shift is the appearance of mesotrophic diatoms responsive to nutrient enrichment, including: the *Fragilaria tenera-nanana* group, *Tabellaria flocculosa* strain IIIp, and *Nitzschia gracilis*. These mesotrophic diatoms characterize the anthropogenic zone, increase rapidly in abundance ~1950 AD, and may be linked to the increased development around FLL. Down core proxies for atmospheric

nitrogen (N) deposition in the FLL watershed are, at best, weakly expressed and appear to be overshadowed by stronger signals. Although the nitrogen responsive diatom species *Asterionella formosa* is a dominant component in FLL today, it is not a newcomer and has been present in similar abundances for at least the last 1200 years. Nitrogen stimulation of *A. formosa* and other N-sensitive phytoplankton in FLL is attributed to the natural process of flushing N-rich water from the upper watershed during spring runoff. A negative shift in $\delta^{15}\text{N}$, another proxy of atmospheric N deposition, is weakly expressed in the FLL core and is overprinted by additional down-core variation. Evidence supporting atmospheric N deposition from Gilmore Lake (GL), a low impact site higher in the watershed, has also proved evasive. In GL, *A. formosa* was found in the water column, but not in surface sediments, indicating that its appearance is very recent, and not synchronous with the anthropogenic zone shift in FLL that commenced in the 1950s. Furthermore, N concentrations in spring runoff into GL were <1 ppb, indicating that, at least for the sampling period, N inputs from wet deposition were negligible. Together, these data show that the FLL record is sensitive to climatic cooling during the LIA and to anthropogenic activities commencing in the 1800s that increased throughout the latter half of the 20th century; however there is no strong coherent signal of anthropogenic N deposition.

DEDICATION

This thesis is dedicated to my friends, family, and amazing husband Wesley Rubio. This work is also dedicated to Nathan Gilmore, because without his foresight Desolation Wilderness may never have come to be.

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1. INTRODUCTION

1.1 Purpose of Study

This project analyzes limnological and paleolimnological data collected from the Fallen Leaf Lake (FLL) watershed in the southern Lake Tahoe Basin to evaluate the effects of human activity and climate variability on the diatom population within FLL over the past 1200 years. Specifically, this study addresses the effects of land use changes on sedimentation and diatom community composition in FLL due to increased recreational activity and urbanization during the 20th century and atmospheric nitrogen deposition during the past 80 years; while attempting to separate these anthropogenic effects from climate forcing. This project is an outgrowth of a monitoring study conducted at FLL (Noble et al., in press) that shows that the modern diatom flora is dominated by several species of araphid phytoplankton (Appendix C, Plate C1, Figures 1-6). Most notably, *Asterionella formosa* (Appendix C, Plate C1, Figures 6A-B), a species that has been attributed to atmospheric nitrogen deposition (N deposition) in an assortment of sub-alpine and alpine lakes in North America (Wolfe et al., 2001; 2003; Saros et al., 2003; 2005; 2009). This project was designed to answer whether the high abundance of *A. formosa* in FLL today is the result of atmospheric deposition, and if not, what other factors, either anthropogenic or climatic, could be used to explain diatom variations throughout the historic period.

One important objective of this study was to accumulate modern limnological and diatom species data for several small lakes in the southern end of the Lake Tahoe Basin to provide some external data with which to test the nitrogen deposition hypothesis in Fallen Leaf Lake. There have been a few scattered studies of water quality and phytoplankton analyses from smaller lakes within the Lake Tahoe Basin, including FLL (Reuter et al., 1996; Lico, 2004).

However, unlike Lake Tahoe, there has been no long-term monitoring program in place, and it is difficult to determine whether reported phytoplankton abundances are specific to FLL or are more widespread. Current monitoring efforts are recent, and there is insufficient data to determine whether the present diatom flora and inter-annual variations represent short term variation or long-term trends. For this reason, a longer record was analyzed through the use of sediment cores.

Limnological data was limited to one season of sampling, and down-core analyses focused largely on the diatoms and sedimentary geochemistry from Fallen Leaf Lake, and to a lesser extent, a sediment core taken from a remote site in the watershed, Gilmore Lake (GL). The data collected was used to determine whether the presence of the N-responsive diatom, *Asterionella formosa*, in FLL is the result of atmospheric nitrogen deposition. Alternative hypotheses to N deposition were explored in the context of the data collected, including whether: (1) increased recreational activity and urbanization around FLL during the mid to late 1900s caused a nutrient-driven response in the diatom flora, and (2) climatic changes in the FLL watershed have had an influence on the diatom community composition.

1.2 Physical Setting of Study Area

This study focuses on Fallen Leaf Lake and Gilmore Lake in the Fallen Leaf Lake watershed, within the southern Lake Tahoe basin (Figure 1). The bulk of the watershed is within Desolation Wilderness and encompasses an area of 44.65 km² (Kleppe et al. 2011). The watershed is steep, relatively narrow and rises from 6380 ft. to 9970 ft. at Dicks Peak (Hanes, 1981). Most of the watershed is composed of alpine tundra that was carved by glaciations during the Pleistocene (Birkeland, 1964; McCaughey, 2005). The watershed surface is composed of thin residual soils, exposed bedrock and talus slopes (Hanes, 1981). The bedrock consists

largely of Cretaceous crystalline basement and Jurassic metamorphic volcanic and metasedimentary rocks of the Tuttle Lake Formation, and glacial deposits of Pleistocene Tioga and Tahoe age (Saucdeo et al., 2005).

The climate within the Fallen Leaf Lake watershed is Sierran montane. Summer temperatures in the watershed are warm during the day and cool at night, while winters are cold. Precipitation in the watershed ranges between 30 inches near the lake and 50 inches near the higher elevations of the watershed (Hanes, 1981). The FLL watershed contains numerous small glacially derived lakes, streams, and wetlands that are active in the late spring following ice melt and persist into the late summer. There is some surface detention storage provided by these waters whose total surface area is roughly 0.5 square miles. Approximately 80% of the precipitation falls as snow in the headwaters of Glen Alpine Creek. Glen Alpine Creek is a semi-ephemeral creek with an annual peak flow usually occurring during the spring as a result of snowmelt runoff. In dry years, Glen Alpine Creek usually does not flow during August and September (Hanes, 1981). Glen Alpine Creek is the main stream in the watershed and drains from Gilmore Lake (2536 m) and Lake Margery (2508 m), as well as from Half Moon Lake (2478 m), Heather Lake (2415 m) and Lost Lake (2484 m) before discharging into its final destination, FLL, via Lily Lake (1996 m).

Fallen Leaf Lake located at 38.883917° N, 120.06592°W and at 1952 m elevation is the lowest lake in the watershed and receives all of its inflow. Fallen Leaf Lake and its surrounding landscape are moderately impacted with homes, a marina, and motorized lake traffic (Oris et al., 2004). In contrast, Gilmore Lake is located in the upper reaches of the FLL watershed in Desolation Wilderness at 38.895843°N, 120.116116°W and at 2536 m in elevation. Gilmore

Lake is minimally impacted, accessible only by hiking, and is used as a low-impact comparative site for distinguishing between natural and anthropogenic impacts recorded in the FLL record.

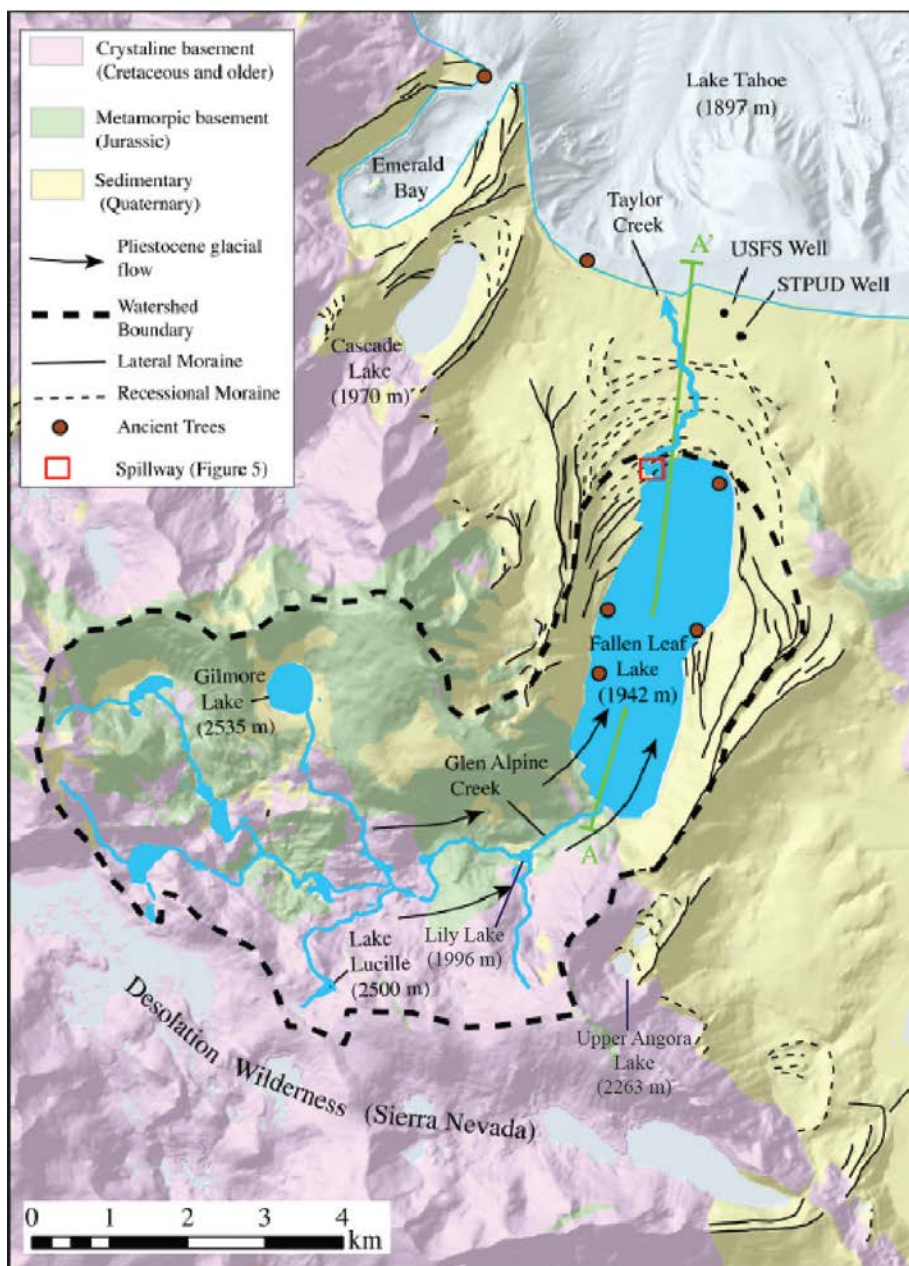


Figure 1: Map showing study lakes in the Lake Tahoe Basin.

2. BACKGROUND & REVIEW OF RELEVANT LITERATURE

2.1 Historical Activities

2.1.1 Lake Tahoe Basin

The history of human occupation in the Tahoe Basin is extensive and varied. Native Americans lived in and around the Tahoe Basin long before migrants and expedition parties arrived in the mid-1800s. Permanent settlement in the basin began in the 1860s (Forney et al., 2001). Over the past 160 years, the Lake Tahoe Basin has experienced significant ecological impacts from human activity. The east-southeastern side of the basin was clear-cut during the Comstock mining era from 1850-1900 to provide timber for the silver mines in Virginia City, NV (Strong, 1981). Tourism in Lake Tahoe began in the 1860s with permanent settlement and the construction of the transcontinental railroad. The tourism industry increased in the 1930s as a result of the legalization of gambling in Nevada. An increase in winter sports activities around the basin further amplified growth and tourism from the 1960s to today (Forney et al., 2001). A significant increase in urbanization of the basin beginning in the 1960s has been associated with increased nutrient loading into Lake Tahoe, which has resulted in increased algal production and decreasing water clarity observed since monitoring commenced in 1968 (Goldman, 1988; TERC, 2011).

2.1.2 Fallen Leaf Lake Watershed

The area directly surrounding Fallen Leaf Lake has seen an increase in land use since the 1860s. Nathan Gilmore brought cattle to FLL in 1861 to graze and subsequently came across Glen Alpine Springs (GAS) in 1863. Gilmore established a cattle and goat ranch on the southern shore of FLL by 1873. Between 1861 and 1873, Gilmore built a wagon road on the southern and

eastern shores of FLL and up to GAS. He built a cabin at GAS along with outbuildings and guest cabins by the end of the 1870s and called the property Glen Alpine Springs Resort (Kaidantzis, 2011). The springs were a resort and tourist destination for those seeking to heal their ailments (James, 1915). The resort was sold numerous times and by the time it closed around 1965 the resort property comprised 80 acres and contained 20 buildings (Kaidantzis, 2011). Fallen Leaf Lake was hardly touched by Comstock logging and only a small piece of land along the eastern side of FLL was logged by Lucky Baldwin in 1878 (Kaidantzis, 2011). A sawmill was built in the northwestern portion of FLL known as Sawmill Cove in the late 1800s and the mill operated for 20-30 years. In 1905, the U.S. Forest Service (USFS) began issuing permits to build cabins around FLL and Lily Lake. The first resort on the shore of FLL, Camp Agassiz, was built in 1906. The western side of FLL was developed first and then Cathedral Road on the western side of FLL was extended ~1910. Between 1923 and 1928, Bill Hildinger built a road to the Angora Lakes on the moraine east of FLL. Although FLL residents cut down trees on their properties to make room for cabins, no significant logging was done until 1924 when Rosebudd Mullender logged some of her 73 acres around the lake. In 1932, Fallen Leaf Lake Road was widened, graded, and oiled to accommodate the increased traffic along the lake (Kaidantzis, 2011). There are a few cabins surrounding Lily Lake and several along Glen Alpine Road, which comprises the first ~1.5 km of the Glen Alpine Trail that begins at Lily Lake. Areas along Glen Alpine Road have been used as trash dumping sites since at least the 1960s (Graham Kent, Personal Communication). There are currently 250 U.S. Forest Service cabins, privately owned homes, and business that follow the road part way around FLL (Todd Gravatt, El Dorado County Assessor Office, Personal Communication). Many of the homes were on septic until the late 1970s when sewer systems were installed that transport waste outside of the Lake Tahoe basin (US EPA, 1978).

2.2 Limnologic Setting

2.2.1 Fallen Leaf Lake

Fallen Leaf Lake is a small, deep lake of glacial origin located near South Lake Tahoe, California. Fallen Leaf Lake is bounded by lateral moraines on the east and west sides, and recessional and terminal moraines at the northern end (Kleppe et al, 2011). The only outflow from the lake is a small dam located at the outlet to Taylor Creek at the northern end of the lake. The dam was built in 1934 by Anita Baldwin to replace the one built further downstream in 1907 (Kaidantzis, 2011) and sits ~1.5 m above the natural sill of FLL (Kleppe et al., 2011).

The major inflow to Fallen Leaf Lake is Glen Alpine Creek, which flows from Lily Lake above (Kleppe et al. 2011). Fallen Leaf Lake is divided into 2 sub-basins; a northern sub-basin and a southern sub-basin. The northern sub-basin is smaller and shallower than the southern (Kleppe et al., 2011; Brothers et al., 2009). Qualitative evaluation of sediment cores taken from FLL in 2006 found that the sediment has a high percentage of biogenic opal and well preserved diatoms (Smith, 2012).

There have been a few scattered studies of water quality and phytoplankton analyses from Fallen Leaf Lake (Reuter et al., 1993; 1996; Lico, 2004, Noble et al., in press); however, there has been no long-term monitoring. The first monitoring efforts began in 1970 and continued intermittently during the 1980s and 1990s (Goldman, 1970; Fuller, 1975, Goldman et al., 1983; Reuter et al., 1990; 1993; 1996). Monitoring efforts resumed in 2009 and continued through 2012 (Noble et al., in press). These intermittent studies characterizing the limnology of FLL over the past 40 years indicate that it has undergone a slight change in trophic status over the past 25 years. Although the lake has not had a significant change in clarity over the historic

period of study on the lake, Reuter et al. (1996) classified FLL as near ultra-oligotrophic, and Allen et al. (2006) classified FLL as meso-oligotrophic. An EPA funded lake assessment study evaluated the physical habitat, observed human influences, chemical and biological characteristics, and molecular biomarkers of contaminant exposure of FLL between 2000 and 2002 and classified FLL as a moderately human impacted lake (Oris et al., 2004). The lake is well oxygenated, monomictic (Allen et al., 2006), thermally stratifies during the summer, and has a low ionic content (Lico, 2004). During stratification a deep chlorophyll maximum develops at a depth of 30-40 m that is dominated by diatoms (Noble et al., 2009; 2011; in press). Chandra and Rost (2008) conducted nutrient bioassays and analyzed the water quality and concluded that the lake is N-limited, which means it should be sensitive to N stimulation, whether through natural or anthropogenic causes.

Samples from Fallen Leaf Lake have shown a significant diatom population that represents approximately 76.9% of the algal biomass of the lake during the spring bloom, and 11.2% during the fall (Reuter et al., 1996). Monitoring between 2009 and 2012 and found that the indigenous FLL diatom population is dominated by phytoplankton, with little to no periphyton present today (Noble et al., in press). Since the early 1990s the dominant phytoplankton species has fluctuated between one of the three or four most abundant taxa in the lake today, namely *Cyclotella rossii*, *Asterionella formosa*, the *Fragilairia tenera-nanana* group, and *Tabellaria flocculosa* strain IIIp (Appendix C, Plates C1-C2) (Noble et al., in press; Reuter et al., 1996). The bulk of the present indigenous diatom assemblage is composed of the centric diatoms *Aulacoseira subarctica*, *Handmannia bodanica*, and the *C. ocellata-rossii* group, and the araphid pennate phytoplankton *T. flocculosa* strain IIIp, *A. formosa*, *Fragilaria gracilis*, and the *F. tenera-nanana* group. *Nitzschia acicularis* and *Nitzschia gracilis* are winter species

also indigenous to FLL that are found entrained in the epilimnion. In addition to the indigenous diatoms, a significant component of dead diatom phytoplankton and periphyton are entrained in the water column and washed in from higher in the watershed. The washed in taxa are particularly abundant during spring runoff and include the centric *Discostella stelligera*, the tychoplanktonic araphid pennate chains *T. flocculosa* strain IV and *Staurosira* spp., and *F. crotonensis* (Noble et al., in press).

2.2.2 Gilmore Lake

Gilmore Lake (GL) is a glacial tarn higher up in the FLL watershed. The lake is located within Desolation Wilderness at an elevation of 2,536 m, and ~3.5 km to the west of Fallen Leaf Lake (Google Earth, 2011). The lake ices over during the winter months (Don Lane (USFS), Personal Communication) and has a maximum depth of 64 m. Access to the lake can only be achieved by hiking. There are no structures surrounding the lake; however, a small dam is located at the southern end of the lake. Limnological information about this lake was not available before this study.

2.2.3 Lily Lake

Glen Alpine Creek passes through Lily Lake, a small, shallow aquatic system located above Fallen Leaf Lake at 38.875707°N, 120.081751°W and an elevation of 1996 m (Figure 1). At the deepest point, the lake is ~9 m deep. In the summer, much of the lake is inhabited by shallow aquatic plants that provide habitat for a variety of lotic and lentic diatom periphyton that may be washed into and preserved in the sediments of FLL. Lily Lake has been observed to freeze over during the winter months (Kaidantzis, 2011). No limnological information was available about this lake before the study period.

2.3 Review of Relevant Literature

2.3.1 Diatoms as Paleoecologic Indicators

Diatoms are a diverse group of unicellular golden algae that inhabit virtually all aquatic ecosystems. Diatom species are sensitive to biological, chemical, and physical changes in their environment, and are known to respond quickly to changes in the characteristics of a water body. This sensitivity is noticeable at the species level, and allows for rapid changes in species abundance and community composition within an ecosystem (Smol et al., 2010). Much work has been done during the past century in determining the optimum lake characteristics that particular diatom species prefer, including: pH, temperature, salinity, available habitat (benthic vs. planktonic), and nutrient concentrations. Their sensitivity to environmental changes has been useful in monitoring a variety of water quality issues, including: eutrophication and lake acidity, as well as climatically induced changes (Smol et al., 2010).

Diatoms have relatively durable siliceous skeletons that are commonly deposited in the sediments. Diatom species composition in sediment cores can allow researchers to understand past lake conditions, water chemistry, water-level, and paleoecology. Sediment cores can also help determine the extent of disturbance, if any, that humans have had on a system (Smol et al., 2010). Lake Washington is a modern example of how diatoms have been used to study cultural eutrophication of lake systems. Diatoms extracted from sediment cores were used to study the cultural eutrophication of Lake Washington between 1941 and 1968 (Edmondson, 1974). The lake was inundated with secondary sewage effluent which contained large concentrations of phosphorous (P). The increase in phosphorus caused an increase in productivity and diatom species abundances. The diatom indicator species for eutrophication: *Fragilaria crotonensis*, *Melosira italica*, *Stephanodiscus niagarae*, and *Asterionella formosa*, became prevalent in the

lake during the inundation. Once the P rich sewage effluent was diverted away from the lake, the eutrophication process began to reverse itself, the water became more clear and the amount of phytoplankton present decreased (Edmondson, 1974; 1991).

2.3.2 Nitrogen Deposition and Climate Variability

Major reorganizations in fossil diatom communities have served as a principal tool in the recognition of anthropogenic influence over the past 60 years in alpine lakes in the western United States. Five alpine lakes of the Colorado Front Range, within Rocky Mountain National Park, were dominated by *Aulacoseira* spp., small colonial *Fragilaria* spp., and several species of *Achnanthes* until ~1950, after which the araphid diatom species *Asterionella formosa* and *F. crotonensis* came to dominate the flora (Wolfe et al., 2003; Wolfe et al., 2001). Similar species turnover patterns were found in oligotrophic alpine lakes in the Beartooth Mountains of Wyoming and Montana (Saros et al., 2005; 2003) and in lakes of the western Sierra Nevada and Greater Yellowstone area (Saros et al., 2010). In the Beartooth Mountains, *A. formosa* and *F. crotonensis* have variably succeeded long established species in these N-limited oligotrophic alpine systems, including: *Staurosirella* spp., *Aulacoseira* spp., and cyclotelloids (Saros et al., 2005; 2003; 2010). These diatom community shifts have been attributed mostly to wet anthropogenic nitrogen deposition of NO_3^- , NH_4^+ , and NH_3 (Wolfe 2001; Saros et al., 2003; 2009; 2010) and suggest that modern day abundances of these araphid species may be an indicator of nitrogen deposition in other regions.

Negative down core shifts in $\delta^{15}\text{N}$ have also been used as a compelling proxy for atmospheric nitrogen deposition in remote lakes of the Northern Hemisphere. A negative 1.5 to 2.5‰ shift in $\delta^{15}\text{N}$ was recognized in the same lakes of the Colorado Front Range and Beartooth Mountains that underwent diatom community shifts (Wolfe et al., 2001; Saros et al., 2003). The

$\delta^{15}\text{N}$ shifts began ~1900, accelerated in the 1950s, and were attributed to increases in agricultural and industrial sources of NO_3 and NH_3 . A comprehensive study of 25 paleolimnological records from pristine oligotrophic lakes in the Northern Hemisphere shows a high level of consistency in the onset of $\delta^{15}\text{N}$ depletion beginning ~1900 and intensifying in the 1950s, which has been attributed to global scale changes in the supply of atmospheric reactive nitrogen through industrialization. Climate, land use, and post-depositional organic matter changes were ruled out as potential drivers based on the vastly different rates of sedimentation, climate histories, and watershed characteristics of the lakes studied (Holtgrieve et al., 2011). The pattern of these 25 lakes is also coincident with a large (>12‰) shift in $\delta^{15}\text{N}$ noted in the Greenland summit ice core (Hastings et al., 2009) that is attributed to atmospheric sources. Collectively, these studies provide compelling evidence that human activities over the past 100 years have dramatically changed nitrogen availability and that these effects have been widely preserved in numerous lake records.

The pronounced lacustrine diatom community shifts that are prevalent throughout the Northern Hemisphere during the last century have also been explained by climate change (Smol et al., 2005; Rühland et al., 2008), or a complex interplay of climate and atmospheric nitrogen deposition (Hobbs et al., 2010). Species turnover observed in Arctic lakes has been attributed to increases in temperature resulting in a longer ice-free season and prolonged periods of summer stratification (Smol et al., 2005). In an expanded study of over 200 Arctic and temperate lakes, small *Discostella* and *Cyclotella* species were shown to replace heavier *Aulacoseira* and *Fragilaria* species (Rühland et al., 2008). These small cyclotelloid taxa are typically successful in lakes that undergo summer stratification with prolonged ice-free seasons. In Arctic lakes, these cyclotelloid species replaced the small benthic littoral zone taxa: *Pseudostaurosira*, *Staurosirella*,

Staurosira, and *Achnanthes* spp., that prefer short growing seasons with low light attenuation (Hobbs et al., 2010). Arctic diatom community changes show community turnover beginning in the late 1800s, significantly earlier than temperate system changes which began in the 1950s (Rühland et al., 2008). In a broad study of 52 Northern Hemisphere lakes, the important consistent factor observed was the rate of species turnover, a feature common to the 52 lakes regardless of the composition of the precursor and replacement assemblages. Throughout a wide array of Arctic and temperate lakes, turnover commenced ~1900 and became more pronounced in the 1950s. Statistical analyses determined that nitrogen deposition is the driver of change in some of the lakes, whereas others show a stronger correlation to temperature, indicating a complex interplay between drivers (Hobbs et al., 2010).

Although some lakes are sensitive to environmental change, other lakes show less sensitivity and lack species turnover. Such was the case with lakes in Glacier National Park (Saros et al., 2010). The lack of sensitivity of the lakes in Glacier National Park requires more study; however it was noted that these lakes are situated in limestone bedrock and buffered to the acidic effects of atmospheric N deposition. The lakes are also P-limited systems, which makes them relatively insensitive to N stimulation (Saros et al., 2010). All things considered, the effects of climate, nitrogen deposition, and local watershed attributes can all be expected to play significant roles in the sensitivity and measured response of diatom communities in alpine lakes.

2.3.3 Nitrogen Deposition in Lake Tahoe

Atmospheric nitrogen deposition in the Lake Tahoe basin has been monitored over the past 30 years and its role may be significant in terms of local diatom community changes. Atmospheric deposition of nitrogen accounts for 55% of the nitrogen introduced into Lake Tahoe (Roberts & Reuter, 2007) and can be attributed to both wet and dry atmospheric

deposition (Jassby et al., 1994; Tarnay, 2001; Dolislager et al., 2006; 2009). Wet atmospheric deposition includes deposition during rain or snow precipitation, whereas dry atmospheric deposition pertains to particulate and gaseous deposition of N without the aid of precipitation (Wetzel, 2001). Jassby et al. (1994) determined that wet deposition comprised a major component of the total atmospheric deposition into Lake Tahoe, yet subsequent studies have shown that dry deposition represents an equally important, if not a larger proportion of the total N load into Lake Tahoe (Tarnay, 2001; Dollislager et al., 2006). Wet deposition is largely comprised of ammonium (NH_4^+) and nitrate (NO_3^-). Ammonia (NH_3) was found to be the largest dry-deposited N component in the Lake Tahoe Basin and together with nitric acid (HNO_3) represents ~75% of total atmospheric nitrogen loading into Lake Tahoe (Dolislager et al., 2009).

Atmospheric modeling indicates that the sources of air pollution into the Lake Tahoe Basin are largely derived from within basin sources (Gertler et al., 2006). The differences in the day and night-time winds coming off of the Sierra Nevada crest on the western slope of the Lake Tahoe Basin cause an atmospheric barrier to form that prevents air masses containing pollution from the Sacramento Valley from being transported into the Basin (Gertler et al., 2006; Bytnerowicz et al., 2004). Although this process prevents the bulk of pollution from entering the Basin from the south and west, some pollution does enter in this manner (Bytnerowicz et al., 2004). Local sources of nitrogen deposition include emissions from motor vehicles and residential fuel combustion.

Variability of topography and meteorological conditions within the Lake Tahoe Basin affect the deposition and the influences of pollutants (Dolislager et al., 2012). Many areas within the Basin are remote and direct measurements of pollutants such as ammonia and nitric acid are difficult to make, thus nitrogen species loads are interpolated (Gertler et al., 2006). Although

spatial characterization of atmospheric nitrogen deposition within the Lake Tahoe Basin has been limited, Dolislager et al. (2012) found that there is a large amount of heterogeneity within the Basin, both spatially and seasonally. The 2003 LTADS by Dolislager et al. (2012) found that particulate NH_4^+ values in the Lake Tahoe Basin are highest during the summer, and the highest concentrations of these reactive nitrogen species occurred in South Lake Tahoe, CA. Given that much of the anthropogenic N deposition in the Lake Tahoe Basin is internally sourced, areas closer to roads and population centers are more heavily influenced than wilderness areas. Monitoring of algal communities that are sensitive to small amounts of nitrogen stimulation (Saros et al., 2010) could be a useful tool in determining the extent of influence within the Fallen Leaf Lake watershed and Desolation Wilderness.

Although the main source of nitrogen to Lake Tahoe is from local dry atmospheric deposition (Dolislager et al., 2012), wet deposition, stream runoff, and excess N from sewage and fertilizers have been contributing factors to limnological changes in Lake Tahoe (Coats & Goldman, 2001). Among the most notable of the changes in the lake occurred during the 1980s. It was at this time the lake shifted from co-limitation by N and P, to a system limited by P, presumably the result of increased N loading to the lake (Goldman, 1988; Jassby et al., 1994). In N-limited lake systems, the growth-limiting nutrient is nitrogen and the algal flora responds rapidly to any introduction of nitrogen, causing algal blooms, decreases in clarity, and trophic cascades (Wetzel, 2001). Yearly measurements have shown that primary productivity in Lake Tahoe has increased steadily since 1968, as the water clarity has decreased significantly. Recent studies of algal communities in Lake Tahoe indicate that the amount of shoreline algae has increased, although the phytoplankton concentrations have not changed significantly since the

mid-1990s (TERC, 2011). Atmospheric nitrogen deposition continues to be an area of critical concern and study in the Tahoe Basin.

The diatoms in Lake Tahoe have undergone two recent community reorganizations in the past 23 years, one related to nutrients, and more recently, changes in temperature controlling lake stratification (Winder & Hunter, 2008). Since 1950, there has been an increase in the ratio of araphid pennate to centric diatoms with the increase of the eutrophication-indicator species *Fragilaria crotonensis* (Byron & Eloranta, 1984). Saros (2005) showed that the araphid pennates *Asterionella formosa* and *F. crotonensis* are abundant in alpine lakes of the Beartooth Mountains when N is moderate to high in concentration. Lake Tahoe has undergone increased stratification over the past few decades as a result of warming lake temperatures. This has caused the diatom populations to undergo a second shift in 2000 towards smaller celled species with a slower sinking velocity so that they can stay higher in the water column and take up incoming nutrients (Winder et al., 2009). The trend towards increasing *Cyclotella* dominance has continued since 2008 and was even more pronounced in the 2010-2011 monitoring data (Hackley et al., 2011). Although warming temperatures have caused recent changes in the diatom flora, the large amounts of N deposited into the Lake Tahoe Basin have the potential to cause significant changes to smaller lakes in the Basin. It is important to understand how nitrogen enters N-limited lake systems like Fallen Leaf Lake so that one can determine whether the lake is being fertilized year-round from atmospheric nitrogen deposition or internal watershed processes. It is crucial to understand the cycling of N in the Lake Tahoe Basin to better manage pollution that may cause algal stimulation and trophic status changes in area lakes. Although this project was designed to determine whether the current presence of *Asterionella formosa* in smaller lakes of the Lake Tahoe Basin, specifically FLL, is the result of

atmospheric nitrogen deposition, diatom species shifts are also used to infer changes due to urbanization and recreational activity over the past 150 years and climatic changes over the past 1200 years.

3. METHODS

Fallen Leaf Lake was chosen as a principal study area because the previous monitoring efforts indicated that the nitrogen responsive diatom *Asterionella formosa* was a dominant component of the modern flora. Based on the amount of recreational activity and land development, FLL is considered a moderately impacted lake (Oris et al., 2004). One lake with a low human impact was added to this study to provide a basis for separating any historical atmospheric changes in FLL from land use changes. For example, similar shifts in phytoplankton composition between FLL and the low impact lake, Gilmore Lake, may indicate that extrabasinal atmospheric nitrogen deposition is more of a contributing factor to the diatom floral shifts than localized lake front development.

3.1 Limnological Sampling

Limnological measurements and diatom species data were collected for the three lakes studied within the Fallen Leaf Lake watershed to provide modern baseline data that could be used to compare and potentially calibrate with down-core diatom analyses. Limnological monitoring was conducted at the study lakes twice in 2011, once during the spring bloom and again during the fall turnover. Gilmore Lake was sampled 8/7/2011 and 10/15/2011. In 2011, GL was ice covered and surrounded by snow until the beginning of August, so sampling the spring bloom during August was equivalent to June in lower elevation lakes. Fallen Leaf Lake was sampled on 6/21/2011 and 9/2/2011, and Lily Lake on 6/27/2011 and 10/1/2011. Limnological sampling was also conducted at Upper Angora Lake on 6/27/2011 and 10/1/2011; however due to the scarcity of diatoms in the phytoplankton population, this lake was eliminated from further analysis.

3.1.1 Lake Measurements and Water Sampling

Temperature, specific conductance (temperature compensated conductivity), and dissolved oxygen were measured with a YSI 85 at each lake. Secchi depth readings for water clarity were also observed. From the information collected, a depth gradient of lake condition was formulated for each sampling period (Figures 2-4). A 2-liter Van Dorn Sampler was used to take water samples from discrete depths in each lake. The water samples were subdivided for chlorophyll *a* (chl *a*), geochemical, and future diatom analyses. The chl *a* analysis was used to determine the phytoplankton biomass present during each sampling. The Trophic State Index (TSI) of each lake was calculated with the surface chlorophyll values and Secchi depth readings for each sample period using the equations presented in Carlson (1977):

$$TSI(\text{Secchi Depth}) = 10 \left(6 - \frac{\ln(\text{Secchi Depth})}{\ln 2} \right)$$

$$TSI(\text{Chl } a) = 10 \left(6 - \frac{2.04 - 0.68 \ln(\text{Chl } a)}{\ln 2} \right)$$

The TSI's calculated for each lake were compared to the Trophic Status Index charts in Carlson & Simpson (1996) and the Tahoe: State of the Lake Report (TERC, 2011) to determine the trophic status of each lake. Geochemical and diatom analyses of the water samples were done to determine the conditions and species present at specific depths in each lake during a particular time.

3.1.2 Chlorophyll *a* Analysis

Chl *a* analyses followed standard operating procedures used in the Aquatic Ecosystems Laboratory at the University of Nevada, Reno. 100 ml of sample water from each lake depth was filtered with a Whatman GF/C (1.2 μm) glass microfiber filter, placed in aluminum foil to keep

light out, and placed in the freezer. The chl *a* coated filters were then placed in a film canister with 100% methanol for 24 hours and then the methanol/chlorophyll mixture was placed in a Turner Designs 10-AU fluorometer for analysis. Each sample was acidified to determine the pheophytin concentrations, and the chl *a* values reported here are corrected for pheophytin. Chl *a* data was used to determine the Trophic State Index (TSI) for each lake using the methodology presented in Carlson (1977).

3.1.3 Geochemical Analyses

Water samples were collected from six Gilmore Lake depths on 8/7/2011 and one from Lily Lake on 6/27/2011. Sample aliquots were filtered with a Whatman GF/C (1.2 μm) glass microfiber filter. The filtered water was sent to the High Sierra Water Lab in Truckee, California for $\text{NH}_4\text{-N}$ (ammonium), $\text{NO}_3/\text{NO}_2\text{-N}$ (nitrate/nitrite), and DP-P (dissolved phosphorous) analysis. The US Environmental Protection Agency methods used for analysis include: ($\text{NH}_4\text{-N}$) EPA 350.1 modified, ($\text{NO}_3/\text{NO}_2\text{-N}$) EPA 353.1 modified, and (DP-P) EPA 365.3. Results can be found in Table 1.

Water sampled from 3 discrete depths (3, 20, 50 m) of Gilmore Lake on 8/7/2011 were filtered and acidified for cation analysis on a Varian VistaAX-ICP-OES at the Nevada Bureau of Mines and Geology, Nevada Analytical Laboratory at the University of Nevada, Reno. Results can be found in Table 2.

3.1.4 Phytoplankton Tows

Both surface and vertical plankton tows were taken from the lakes studied during 2011. Surface phytoplankton tow samples were taken from the upper 20-30 cm of the water column by dragging an 8 inch diameter 20 μm mesh plankton net for 50 to 100 m. Permanent slides

were made for taxonomic identification and to determine the relative abundance of diatom species in each lake.

Vertical phytoplankton tow samples were taken by attaching a small weight to the same 20 μm mesh plankton net, lowering down the water column to a specified depth and dragging it to the surface. The Fallen Leaf Lake and Gilmore Lake vertical plankton tows were taken starting at 50 m, while the Lily Lake vertical tow was taken starting at 8 m. The vertical plankton tows serve as a useful composite of the phytoplankton found throughout the water column. Permanent slides were made from each vertical tow to determine the relative abundance of diatoms and compare the relative abundances to those found in sediment samples.

3.2 Lake Sediment Coring and Processing

The data presented come from Fallen Leaf Lake and Gilmore Lake gravity cores. The 43-cm core, 2E-1G-1 (2E), and 41-cm core, 3B-1G-1 (3B), were taken from FLL in November 2010 with the assistance of the Limnological Research Center (LRC) at the University of Minnesota and their Kullenberg coring platform. Core 2E was taken from the deepest part of FLL at a water depth of 111 m, near the center of the southern sub-basin. Core 3B was taken from the northern sub-basin of the lake at a water depth of 94.9 m, within a thin pocket of sediment found between two recessional moraines. The 19-cm GL core, GL-2012-1, was taken from the deepest part of the lake at a water depth of 64 m, using a MUCK gravity corer that was deployed from a raft in the August 2012. The GL core was sectioned in 1-cm intervals in the field using an extruding rod and placing the sediment samples into pre-weighed Ziploc bags. Field sectioning was deemed appropriate for the GL core because of the remoteness of the lake, whereas the FLL gravity cores were shipped to the National Lacustrine Core Facility (LacCore) at the University of Minnesota for processing and analysis.

At LacCore, the Fallen Leaf Lake cores were split, photographed, and high resolution magnetic susceptibility was measured using a GEOTEK multi-sensor core logger every 5 mm. Working halves of each core were sectioned for loss-on-ignition and ^{210}Pb analysis. Loss-on-ignition (LOI) was performed to determine the H_2O and carbonate content of the cores using the LacCore methodology modified from that presented by Heiri et al. (2001). The cores were sent to the Harmon Research Center at the St. Croix Watershed Research Station for ^{210}Pb dating by Dan Engstrom. ^{210}Pb geochronology is generally applicable for the dating of sediments younger than ~150 years old (Noller, 2000) and the ^{210}Pb analysis of the two FLL cores was necessary to demonstrate that the sediment stratigraphy was largely intact and encompassed a reliable limnologic record of FLL. Protocols for ^{210}Pb analysis required that a higher resolution sectioning interval of 0.5-cm be used in the upper section of the core, representing the last 150 years, and that a lower resolution 1 cm interval could be used for the older portion of the core to provide background radiation counts. Based on an initial sedimentation rate estimate of $\leq 2\text{-mm year}$, the top 35-cm of core 2E and the top 27-cm of core 3B were sectioned at 0.5 cm intervals and the remainder was sectioned every 1-cm thereafter. Core 2E, with its higher sedimentation rate, was chosen as the master core on which X-ray fluorescence, stable isotope, and diatom analyses were conducted. All core depths are reported in centimeters below lake floor (cmblf).

3.2.1 Diatom processing

The 54 sediment samples from core 2E were processed using a modification of the method outlined in Battarbee et al. (1986). Roughly 10 mg of sediment was boiled in 20 ml 30% H_2O_2 for 1 hour, after which a several drops of HCl were added. Distilled water was added, left to settle for 24 hours, and decanted 6 times to remove all reagents (Stoermer, 1995). Microscope slides were made for diatom analysis by placing a diluted portion of each processed

sediment sample onto cover slips in order to attain a random and even scattering of diatoms. Cover slips were allowed to dry and then attached to microscope slides with the mounting medium Zrax.

Permanent slides of plankton tow samples were made as boil mounts; sample water was dried on a cover slip and mounted to a microscope slide using Zrax. Boil mounts preserve both the chlorophyll and lipid droplets of live diatoms and are useful in discriminating the live cells from any dead cells that may be washed in or re-suspended in the water column.

3.3 Diatom Species Identification and Analysis

The top 10-cm of Fallen Leaf Lake core 2E were analyzed at 0.5 cm intervals and the bottom 32 cm in 1-cm intervals for diatom species abundance and diversity. The diatom species present were identified and 500 valves per slide were counted by transmitted light microscope using methods outlined by Winder and Hunter (2008). The diatoms were identified to the species level in order to get a comprehensive species list. Diatom species identifications were made using up to date Internet literature, common diatom identification literature, and species-specific papers. Most of the species identifications were made using webpages on the Diatoms of the United States website created by Spaulding et al. (2010), Patrick & Reimer (1966; 1975), and the Krammer & Lange-Bertalot series (1986, 1988, 1991a, 1991b). Other identifications were based on: Antoniadou et al. (2008), Bahls (2005), Bloom (2001), Camburn & Charles (2000), Cremer & Wagner (2001), Cumming et al. (1995), Foged (1981), Hakansson (2002; 1990; 1986), Hamilton & Siver (2008), Hickel & Hakansson (1993), Houk & Klee (2004), Kelly et al. (2005), Kociolek & Stoermer (1987), Koppen (1975), Krammer (2000; 2002; 2003), Lange-Bertalot (2001), Morales & Manilov (2006), Peterson (1938), Round (1990), Siver & Kling (1997), Sovereign (1958), Tuji & Houki (2004), Tuji & Williams (2006; 2008), and Williams & Round

(1987). A taxonomic list that includes the sources for each species can be found in Appendix A and diatom photo plates with the most important species in Appendix C. The timing of diatom shifts down core was compared with a chronology of human activity around the Lake Tahoe Basin to distinguish climatic signals from those induced by humans. Confidence limits were calculated using the program MOSLIMIT (Mosimann, 1965) to determine whether diatom shifts seen down core were outside the counting error.

3.3.1 Multivariate Analyses

Since ordinations are often used to visualize and describe ecological patterns, multivariate analyses were run on the Fallen Leaf Lake core 2E species data. Using PC-ORD (McCune & Mefford, 2011) and the methodologies described in Borcard et al. (2011), multivariate ordination techniques were employed to evaluate the observed taxonomic shifts in the FLL sediment core. A detrended correspondence analysis (DCA) was employed along with a nonmetric multidimensional scaling (NMS) analysis (McCune et al., 2002) to find underlying patterns in the species distribution. Additionally, a stratigraphically constrained hierarchical clustering analysis and DCA were performed to determine distinct species zones and gradients throughout the past 1200 years.

A species-site matrix was loaded into PC-ORD (McCune & Mefford, 2011) containing all species present at any one depth in abundances $\geq 1\%$. Of the 161 species counted in the Fallen Leaf Lake sediment core, only 34 were input into the ordination analyses. The data was analyzed for outliers and *Melosira varians* was found to be the only possible outlier. The DCA and NMS were run with and without this possible outlier, and there appeared to be no reason to exclude the species. Since several of the ordination techniques assume normality, the species matrix was analyzed for skewness. The species data was found to be slightly, positively skewed (1.459) and

no transformations were implemented. The DCA was run using the Relative Euclidean Distance. The NMS was run on Autopilot mode, and the Sorensen (Bray-Curtis) distance measure was used for 500 runs and 51 iterations. To determine whether the NMS was extracting stronger axes than expected by chance, a Monte Carlo test was performed.

3.4 Elemental, Carbon and Nitrogen and Stable Isotope Geochemistry

3.4.1 Scanning XRF Analysis

The archived half of the Fallen Leaf Lake gravity core 2E was sent to the Large Lakes Observatory in Duluth, Minnesota for X-ray fluorescence (XRF) elemental analysis. The analysis was performed on a Cox Analytical Systems ITRAX scanner at a 2mm resolution with both a Mo X-ray source and a Cr X-ray source. To determine whether the data needed to be normalized, the raw scanning XRF elemental data was normalized with the kilocounts per second (kcps) and incoherent scattering (inc). The Si/kcps and Si/inc data were plotted and compared to the raw Si data down core. The patterns were similar in all 3 cases, and it was determined that the data did not need to be normalized. The scanning XRF data in this paper are presented as raw counts. Several elemental proxies have been found to be useful in lakes with similar sedimentological characteristics to FLL and are presented herein. The XRF elemental ratio of Si:Ti is used as a proxy for down-core fluctuations in biogenic silica in systems with high percentages of biogenic opal, such as FLL (Johnson et al., 2011; Kylander et al., 2011; Brown et al., 2007). The Ba:Ti ratio is used as a proxy of productivity (Croudace et al., 2006). The incoherent to coherent X-ray scattering ratio (Inc/Coh) is used as a proxy for organic matter content (Guyard et al., 2007). Lastly, ratios of Fe and Mn to Ti were used to determine the depth of redox diagenesis in the core (Croudace et al., 2006).

3.4.2 Carbon and Nitrogen Analyses

Following the method of Yamamuro & Kayanne (1995), thirty-eight sediment samples from core 2E were placed into an HCl fumigation desiccator for 1 month to remove carbonates. After the removal of carbonate, carbon and nitrogen concentrations, and carbon and nitrogen isotope analyses were performed using a Eurovector EA 3000 elemental analyzer interfaced to a Micromass IsoPrime stable isotope ratio mass spectrometer equipped with a helium diluter to allow for carbon and nitrogen analyses of each sample run, using the method described by Werner et al. (1999). $\delta^{13}\text{C}$ results are reported in units of ‰ vs. VPDB, with a recommended uncertainty of $\pm 0.1\%$. $\delta^{15}\text{N}$ results are reported in units of ‰ vs. air, with a recommended uncertainty of $\pm 0.2\%$. The samples were run with duplicates and acetanilide standards for $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$, and error bars for reproducibility of analyses were determined by calculating the standard deviation for each duplicated sample. The average isotopic and elemental concentrations and corresponding standard deviations for the 12 acetanilide standards are: ($\delta^{15}\text{N}$) -1.26 ± 0.10 , ($\delta^{13}\text{C}$) -33.66 ± 0.02 , (weight % C) 71.09 ± 0.96 , and (weight % N) 10.36 ± 0.15 . Isotopic and elemental C and N results are presented in Figure 11.

4. RESULTS

This section includes an overview of the modern limnological monitoring data, as well as the Fallen Leaf Lake sediment core data. The modern monitoring data will be discussed first to set the stage for determining differences between the modern system and the historical systems. The watershed nutrient data is presented afterward. The second half of the results section encompasses the results of the Fallen Leaf Lake sediment core chronology, lithology, geochemical and diatom stratigraphy, and multivariate analyses.

4.1 Limnological Monitoring

4.1.1 Lily Lake

The first sampling of Lily Lake in 2011 was taken from the outlet to Glen Alpine Falls in June during the spring runoff. The corrected chl *a* value at the outlet of Lily Lake during the first sampling was 0.15 µg/L (Figure 7). Reflecting this low chl *a* value, a plankton tow at the outlet found few diatoms, including: *Tabellaria fenestrata*, *Aulacoseira lirata*, *Aulacoseira pusilla*, *Eunotia* spp., *Aulacoseira subarctica*, and several small araphids. The diatoms found during this period were empty frustules entangled in decaying organic material originating from higher up in the watershed and were not living in the lake at that time (Noble et al., in press). During the second sampling of Lily Lake in October 2011, a full profile was taken at the deepest part of the lake. This second sampling indicates that the lake was well-mixed to a depth of 7 m and became anoxic near the bottom (Figure 4). At that time, the corrected chl *a* values ranged from 2.2-52.9 µg/L (Figure 7), with the highest levels at a depth of 6 m. Plankton tows taken during this sampling were similar to the one taken in June 2011. Coincident with an increase in chl *a*, the average Secchi clarity reading of Lily Lake decreased to 3.5 m (Table 3). The TSI values from the

deepest part of Lily Lake in 2011 range between 38.4 and 41.9 (Table 3) and indicate that the Lily Lake trophic status is mesotrophic. Previous data regarding Lily Lake is not available and thus no comparisons could be made with the data collected in 2011.

4.1.2 Gilmore Lake

The first sampling of Gilmore Lake (8/7/2011) occurred approximately 2 weeks after ice-out and established that the lake had stratified by early August, with a shallow epilimnion comprising the top 4 m of the water column (Figure 3). Water from this sampling was also analyzed for cation abundances (Table 2) and silica was found to be highest in the shallow epilimnion along with K, Al, Na, and Mg. At this time, the corrected chl *a* values ranged from 0.08-8.35 $\mu\text{g/L}$ and the lake had developed a deep chlorophyll maximum (DCM) at 26 m (Figure 6). Interestingly, the vertical plankton tows from this sampling indicate that few diatom phytoplankton were present in the water column and the bulk of the phytoplankton consisted of soft algae. The lake was clearest during this time with an average Secchi reading of 13 m (Table 3). By mid-October, stratification had progressed and the epilimnion deepened to include the top 15 m of the lake (Figure 3). At this time, the corrected chl *a* values ranged from below detection to 5.74 $\mu\text{g/L}$ (Figure 6). GL had a DCM at 30 m (Figure 6) and the plankton tows were composed almost entirely of *Asterionella formosa*. Coincident with an increase in phytoplankton, the average Secchi clarity reading of GL decreased to 11.4 m (Table 3). TSI values from the 2011 GL samplings range between 8.5 and 24.9 (Table 3) and indicate that the GL trophic status is ultra-oligotrophic to oligotrophic. Previous data regarding GL is not available and thus no other comparisons could be made.

4.1.3 Fallen Leaf Lake

The first sampling of Fallen Leaf Lake in 2011 established that the lake had not become fully stratified by late June (Figure 2). At this time, the corrected chl *a* values ranged from 0.22-1.04 µg/L and the lake had developed a deep chlorophyll maximum at 30 m (Figure 5). The 2011 plankton tows from FLL are summarized in Noble et al. (in press). During the first sampling, the dominant phytoplankton were the *Fragilaria tenera-nanana* group, *Asterionella formosa*, *Tabellaria flocculosa* strain IIIp, and *Aulacoseira subarctica*. At this time, the average Secchi clarity reading of FLL was 8.1 m (Table 3). By early September, FLL was completely stratified with the epilimnion comprising the top 10 m of the water column (Figure 2). At this time, the corrected chl *a* values ranged from 0.14-0.48 µg/L and the lake had developed a deep chlorophyll maximum between 25 and 30 m (Figure 5). During this second 2011 sampling, the dominant species present in the plankton tow were similar. Coincident with a decrease in the chl *a* values, the average Secchi clarity reading of FLL increased to 11.9 m (Table 3). The 2011 FLL TSI values range between 13.9 and 29.8 (Table 3), which indicates that the FLL trophic status is ultra-oligotrophic to oligotrophic.

4.1.4 Nutrient Analyses

Macronutrients from Gilmore and Lily Lakes are reported in Table 1 and the cations from GL in Table 2. The first suite of GL samples were taken about 2 weeks after ice out in 2011 to get an idea of the amount of nitrogen entering the lake as wet deposition from the snowpack, while Lily Lake was sampled during the height of the spring runoff to determine how much nitrogen was being flushed through the Fallen Leaf Lake watershed. Water samples from GL and Lily Lake were analyzed for DP-P, NH₄-N, and NO₃/NO₂-N (Table 1). The value of DP-P is higher for GL than Lily Lake, 7 ppb and 3 ppb respectively. The levels of NO₃/NO₂-N are higher in the

surface water of Lily Lake, 21 ppb, than in the bulk of the GL water column which is at ~ 1 ppb. Near the lake bottom of GL; however the $\text{NO}_3/\text{NO}_2\text{-N}$ values reach 35 ppb. The $\text{NH}_4\text{-N}$ values are higher in GL surface waters at 5 ppb. Lily Lake surface water $\text{NH}_4\text{-N}$ values are 3 ppb. The cation analyses from GL indicate that the Mg, Si, and K are high during the spring runoff, while Fe and Na are low in comparison to 2009 data from FLL (Noble et al., in press). The two lakes are similar in Li, Mo, and Ba concentrations. In general, the 2009 FLL Al concentration is higher than that seen in the 2011 GL sample (Noble et al., in press).

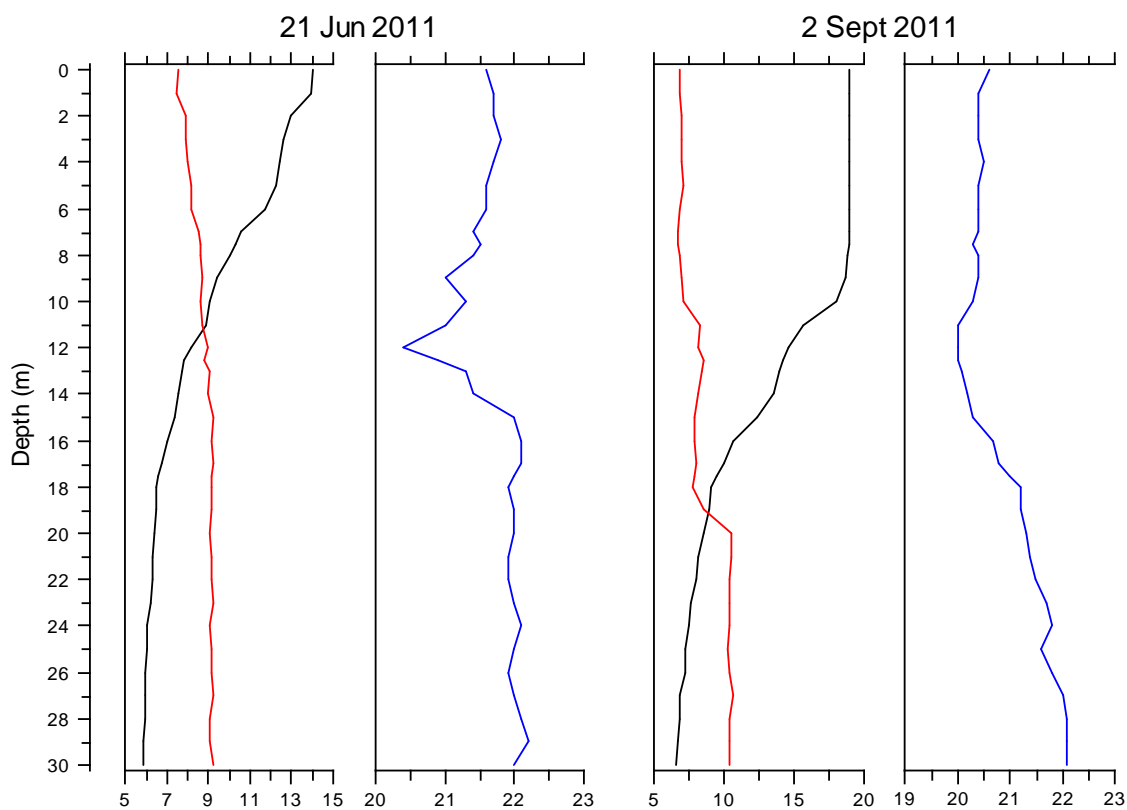


Figure 2: 2011 Fallen Leaf Lake water column profiles for dissolved oxygen, temperature, and specific conductance. Stratification was not fully developed during the early summer sampling and was developed by early fall. The dissolved oxygen follows the stratification structure. Red – Dissolved Oxygen (mg/L). Black – Temperature ($^{\circ}\text{C}$). Blue - Specific Conductance ($\mu\text{S}/\text{cm}$).

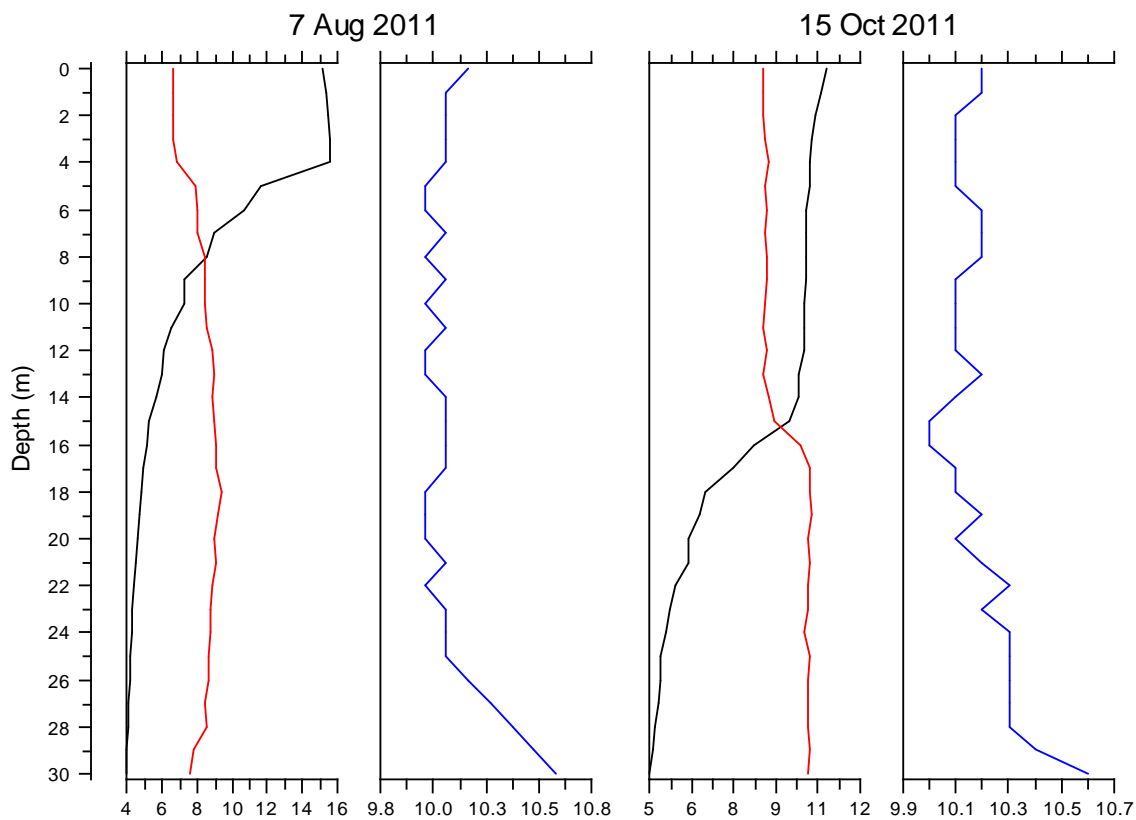


Figure 3: 2011 Gilmore Lake water column profiles for dissolved oxygen, temperature, and specific conductance. August epilimnion was shallow and the lake fully stratified in October. The dissolved oxygen follows the stratification structure. Red – Dissolved Oxygen (mg/L). Black – Temperature (°C). Blue - Specific Conductance (µS/cm).

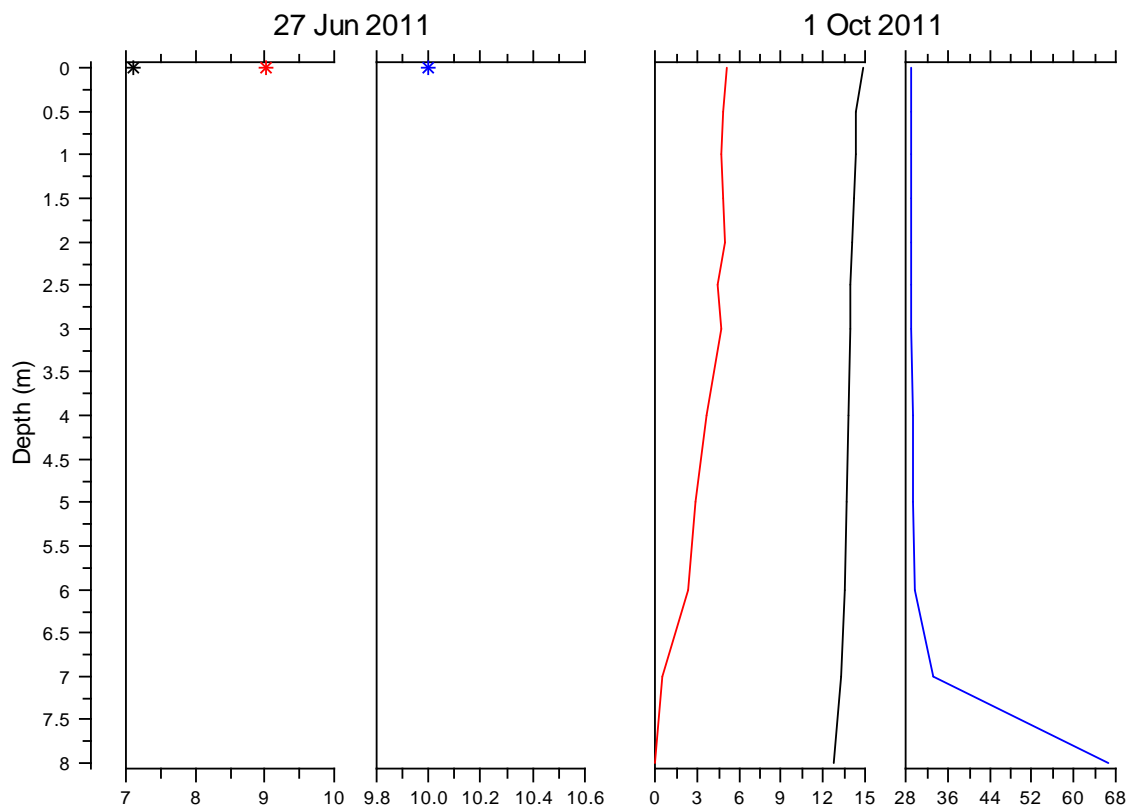


Figure 4: 2011 Lily Lake water column profiles for dissolved oxygen, temperature, and specific conductance. The lake was well mixed during the October sampling. Red – Dissolved Oxygen (mg/L). Black – Temperature (°C). Blue- Specific Conductance ($\mu\text{S}/\text{cm}$). Note: 27 Jun 2011 sample was taken at the outlet of Lily Lake. 1 Oct 2011 sample was taken at the deepest part of the lake.

Lake	Sample Date	Water Depth (m)	NH ₄ -N (ppb)	NO ₃ /NO ₂ ⁻ N (ppb)	DP-P (ppb)
Gilmore Lake	7-Aug-11	0	5	1	7
		10	2	1	3
		20	1	1	3
		30	1	1	5
		40	1	1	4
		50	1	35	4
Lily Lake (outlet)	27-Jun-11	0	3	21	3
Analyses run at High Sierra Water Lab					

Table 1: 2011 Gilmore Lake and Lily Lake water quality data

Water Depth (m)	Fe	Li	Na	Mg	Al	Si	K	Sr	Mo	Ba
3	<1.00	<1.00	809	371	13.2	2265	608	11.1	<1.00	1.78
20	<1.00	<1.00	764	328	4.25	1621	488	10.5	<1.00	1.72
50	1.39	<1.00	685	331	8.28	1883	515	11.6	<1.00	2.00

***All cation values are in ($\mu\text{g/L}$)

Table 2: Gilmore Lake water cation analyses from samples taken August 7, 2011

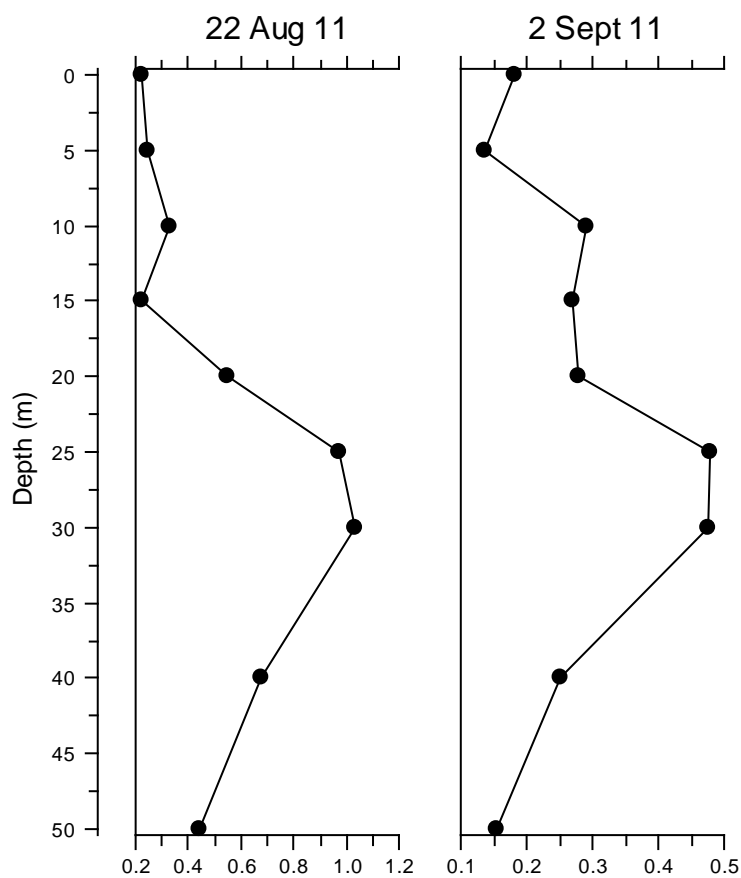


Figure 5: 2011 chlorophyll *a* profiles for Fallen Leaf Lake. Deep chlorophyll maximum present at 30 m. Chlorophyll *a* values presented in $\mu\text{g/L}$.

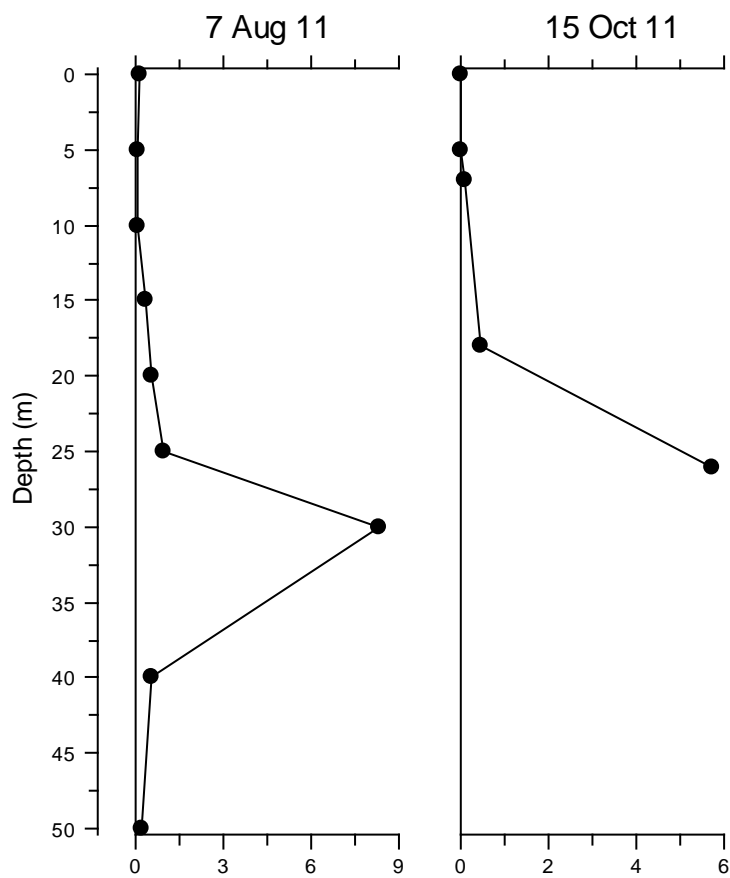


Figure 6: 2011 chlorophyll *a* profiles for Gilmore Lake. August deep chlorophyll maximum present at 30 m and 27 m in October. Chlorophyll *a* values presented in $\mu\text{g/L}$.

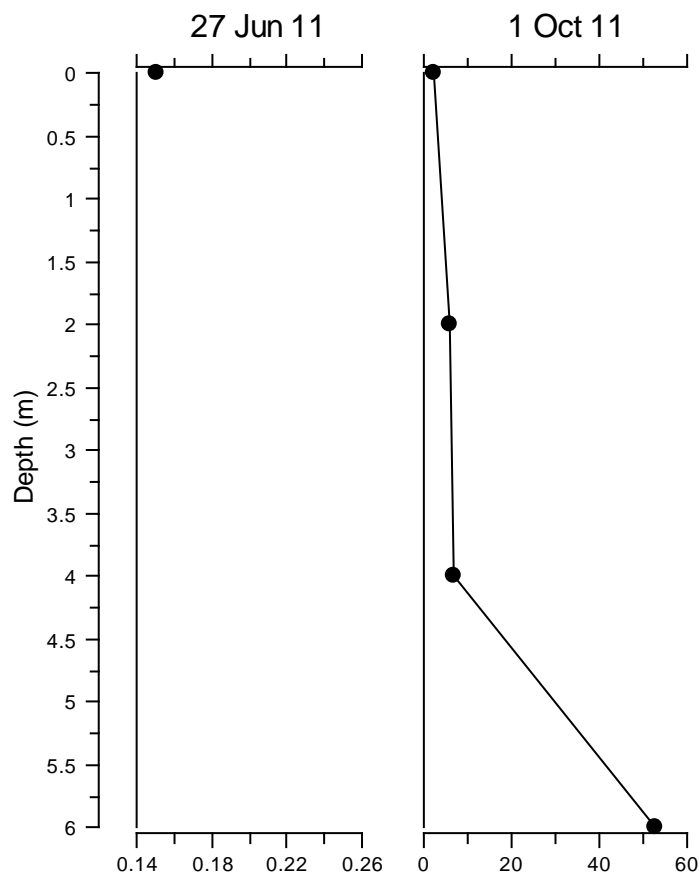


Figure 7: 2011 chlorophyll *a* profiles for Lily Lake. Chlorophyll *a* values presented in µg/L. Chlorophyll maximum present at 6 m during the fall sampling. Note: 27 Jun 2011 sample was taken at the outlet of Lily Lake. 1 Oct 2011 sample was taken at the deepest part of Lily Lake.

Lake	Sample Date	Average Secchi Disk (m)	Secchi Disk Trophic State Index	Surface chl a ($\mu\text{g/L}$)	Chl a Trophic State Index
Fallen Leaf Lake	22-Jun-11	8.1	29.8	0.2207	15.7
	2-Sep-11	11.9	24.3	0.1828	13.9
Gilmore Lake	7-Aug-11	13.0	23.0	0.1053	8.5
	15-Oct-11	11.4	24.9	0.1132	9.2
Lily Lake	27-Jun-11	--	--	0.1511	12
	1-Oct-11	3.5	41.9	2.217	38.4
Trophic State Index (TSI) calculations run using methodology presented in Carlson (1977)					

Table 3: Average Secchi, surface chl a , and Trophic State Index values for Fallen Leaf Lake, Gilmore Lake, and Lily Lake. Note: June 27, 2011 Lily Lake sample was taken from the outlet to Glen Alpine Creek.

4.2 Fallen Leaf Lake Sediment Cores

4.2.1 Fallen Leaf Lake Core Chronology

The dates for the top 3.5-cm of core 3B were established with ^{210}Pb and go back to 1818 AD indicating a low sediment accumulation rate. The dates for the top 10-cm of core 2E were established with ^{210}Pb and a ^{14}C date at 34-cm to provide a constraint on the lower part of the core (Figure 8). The ^{210}Pb provides a robust chronology for the upper 10 cm, going back to 1812 AD and indicates the core has stratigraphic integrity. The chronology for the lower and middle parts of the core is the weakest and is based on extrapolation between the ^{210}Pb and ^{14}C dates. The age of the base of the core is dated at 837 ± 90 AD, extrapolated from the ^{210}Pb at the top of the core and a single ^{14}C date at 34 cm below the lake floor which is calibrated as 1102 ± 60 AD, using OxCal v. 4.0.5 (Bronk Ramsey et al., 2001) and calibrated using the IntCal 04 curve (Reimer et al., 2004). The sediment accumulation rate was determined from the ^{210}Pb chronology for the

top 10-cm of the core (Figure 9). The sediment accumulation rate increased rapidly starting in 1952 AD continuing to the present. Another small increase in the sediment accumulation rate occurred between 1902 and 1943 AD. The smallest increase in the sediment accumulation rate occurred between 1812 and 1860 AD. A sharp peak in the sediment accumulation rate occurred between 1812 and 1860 AD. A sharp peak in the sediment accumulation rate occurs ~1943 AD and is associated with a silty layer at 4-5cm. Core 3B from the northern Fallen Leaf Lake sub-basin shows the same sediment accumulation patterns, with the exception that it lacks the sharp peak ~1943 AD. The 1943 AD sediment accumulation spike is discussed further in the next section.

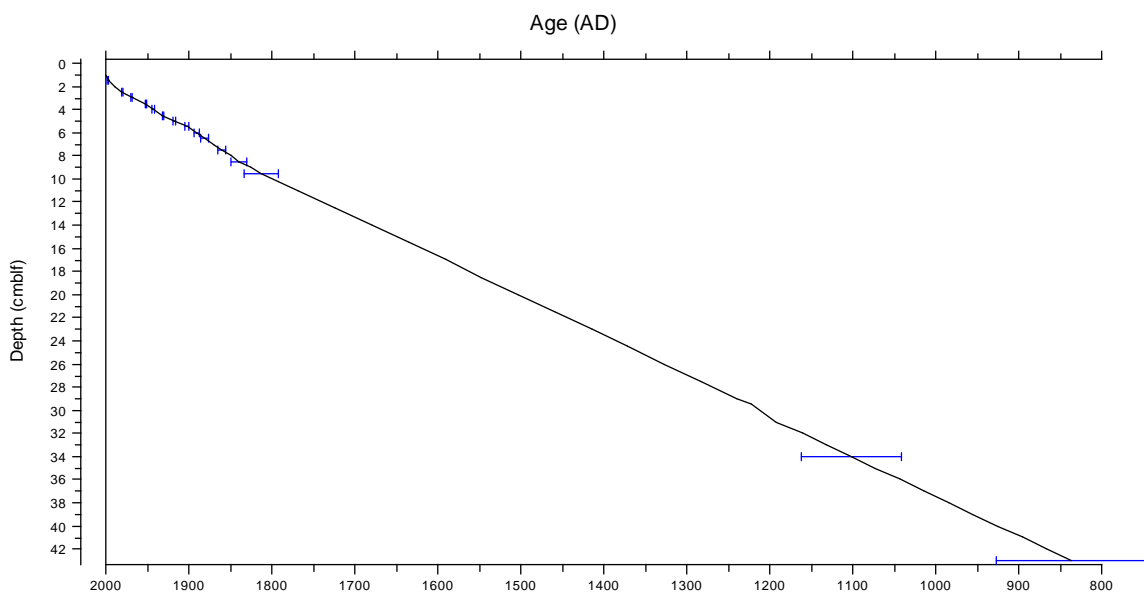


Figure 8: ^{210}Pb and ^{14}C age-depth model for the Fallen Leaf Lake gravity core. The blue horizontal lines going through the age model represent the standard deviation from the mean.

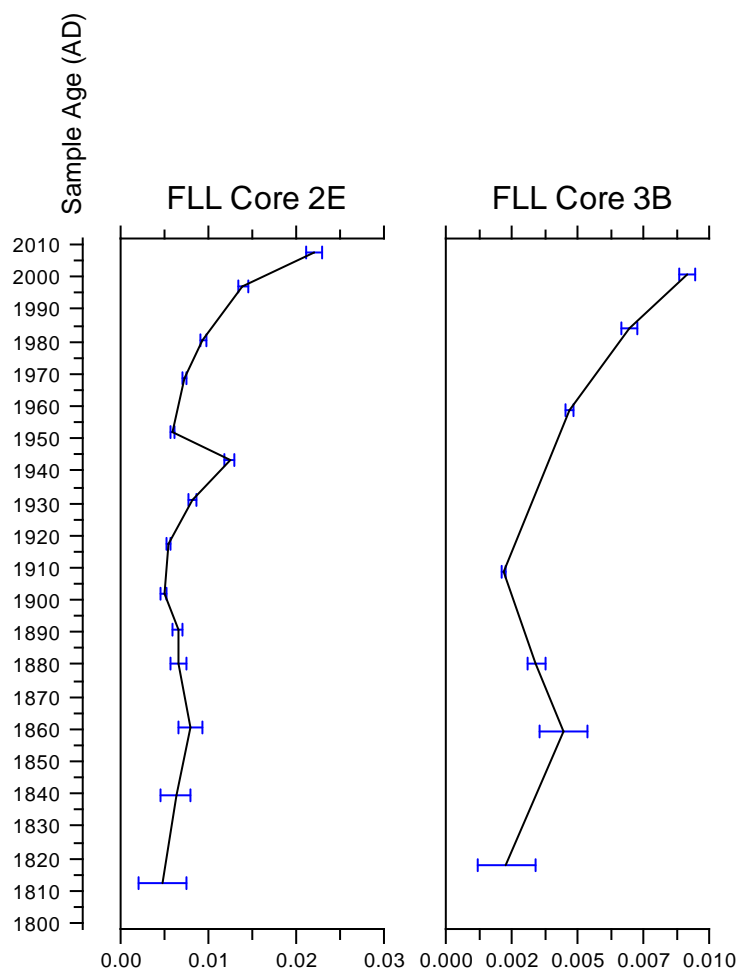


Figure 9: The sediment accumulation rates for the Fallen Leaf Lake gravity cores. Sediment accumulation is given in units of $\text{g}/\text{cm}^2 \text{ yr}$. The horizontal error bars represent the standard deviation from the mean.

4.2.2 Fallen Leaf Lake Core Lithology

The Fallen Leaf Lake core is a homogeneous olive-gray opal-rich clay with few notable structures. A dark redox layer is present in the upper 6-cm, which has an increased magnetic susceptibility (Figure 10). Near the base of the redox layer, is a darker silty band between 4 and 5 cm. This silty layer centers ~ 1940 AD and is associated with both a high magnetic susceptibility peak and a spike in sediment accumulation rates (Figure 10). The band also coincides with a small increase in the % inorganic carbon and the lowest % CaCO_3 . At 21 cm, there is a subtle

change in sediment color to a lighter color below that corresponds with a small magnetic susceptibility peak. This is manifested best in the % CaCO₃ which shows a ~1.5 % baseline shift at 21 cm (~1473 AD) that persists until 12 cm (~1738 AD). After 1943 AD, the CaCO₃ content increased ~1 %. The percent organic and inorganic content has been relatively stable over the past ~1100 years, changing ~3 % over that period of time.

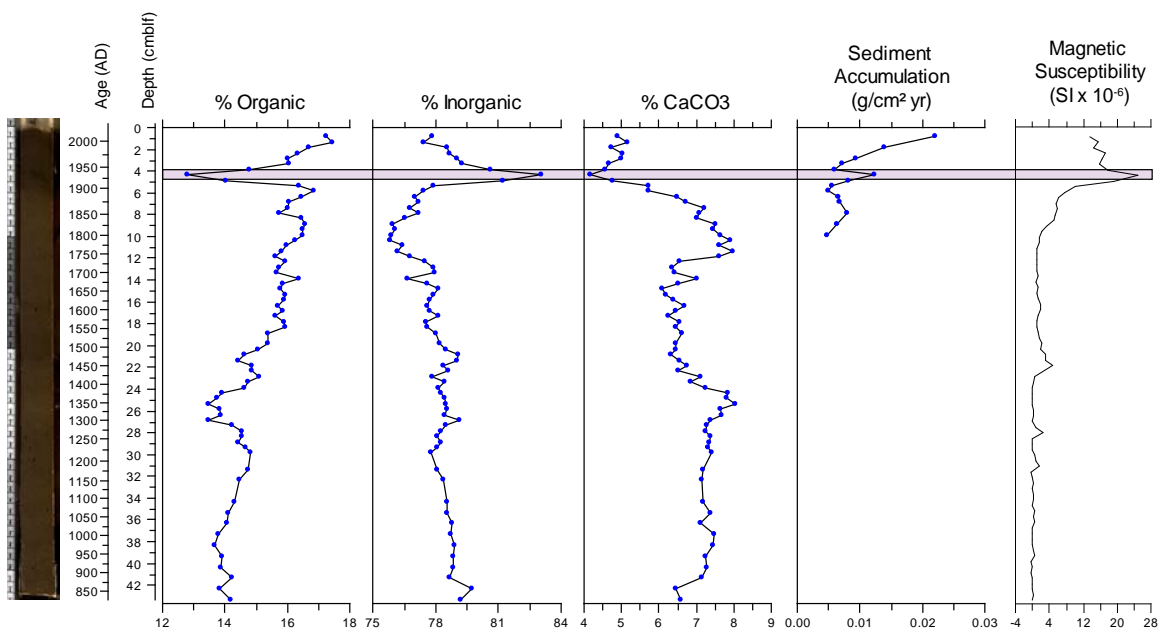


Figure 10: Loss-on-ignition and magnetic susceptibility data for Fallen Leaf Lake core 2E. From left to right: core photo, % organic content, % inorganic content, % CaCO₃, sediment accumulation, magnetic susceptibility. Blue circles indicate sample data points. Purple box indicates the sandy layer between 4 and 5 cm.

4.2.3 Fallen Leaf Lake Core Elemental and Isotopic Carbon and Nitrogen Stratigraphy

Carbon and nitrogen have often been studied in sediment cores to look at changes in nutrient and organic input into lacustrine systems (Talbot, 2002). The silty band ~1943 AD (4 cm) coincides with a sharp decrease in the weight % of both C and N (Figure 11). The C:N ratio and weight % C exhibit a negative spike centering around 896 AD while the $\delta^{13}\text{C}$ exhibits a positive

spike. The $\delta^{13}\text{C}$ values increase $\sim 4\text{‰}$, the C:N ratio decreases by 2, and the weight % C decreases by 1%. This spike does not appear to be associated with a sedimentologic change. The C:N ratio dropped after 1931 AD and bottomed out in 1981 AD after which there is a sharp increase. The ratio appears to correspond with fluctuations in $\delta^{15}\text{N}$. There has been a slight increasing trend in the C:N ratio, $\delta^{13}\text{C}$, and weight % C from 39-0 cm (955-2007 AD). The C:N ratio decreased nearly 2%, the $\delta^{13}\text{C}$ increased 2‰ , and the weight % C increased $\sim 1\%$. The weight % N has remained relatively stable throughout the core while the $\delta^{15}\text{N}$ values have shown a small degree of variability. The change in $\delta^{15}\text{N}$, although small and within $\sim 0.5\text{‰}$, it exceeds the error calculated. There is a positive spike excursion associated with the silty layer followed by a slight negative trend in the latter half of the 20th century that ends with the isotopically most negative $\delta^{15}\text{N}$ values in the surface sample. This ~ 50 year negative trend results in a 0.5‰ $\delta^{15}\text{N}$ depletion that is overprinted by a positive excursion in the late 1990s.

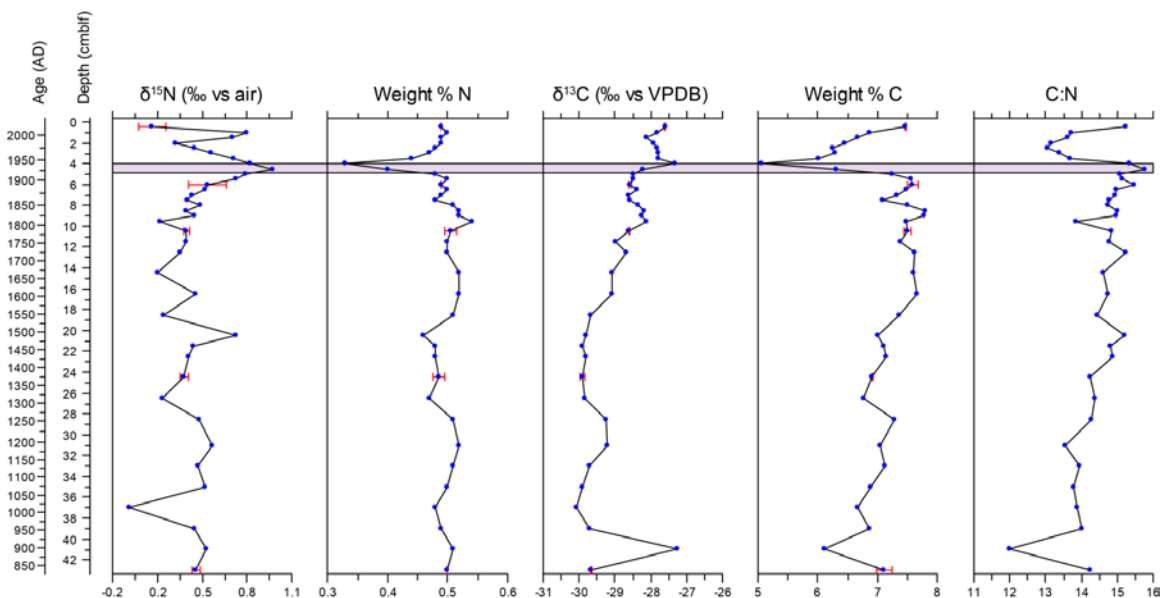


Figure 11: Carbon and nitrogen stable isotope and concentration results for the FLL gravity core 2E. From left to right: $\delta^{15}\text{N}$, weight % N, $\delta^{13}\text{C}$, weight % C, and C:N. Blue circles indicate sample data points. The red horizontal error bars represent the standard deviation from the mean for samples where replicate analyses have been run. Purple box indicates the sandy layer between 4 and 5 cm.

4.2.4 Fallen Leaf Lake Scanning XRF Stratigraphy

Most of the elements evaluated with the scanning XRF exhibit relatively stable patterns throughout the core. Some of the elements exhibit decreasing values over the past 200 years, but only three elements show rapidly increasing trends over the same time frame: cobalt (Co), zinc (Zn), and tin (Sn) (Figure 12). Before the rapid increases, 837-1800 AD, these trace metals are found in low abundances. The elements cobalt and zinc show similar trends throughout the core, while the tin trend is unique within the core. The amount of tin in the Fallen Leaf Lake sediment core increased rapidly after ~1850 AD. Although the amount of tin increased to the top of the sediment core, 2010 AD, the rate of increase slowed beginning in the 1930s. Both the Co and Zn began to increase in the FLL sediment core ~1800 AD and have continued to increase to the present 2010 AD.

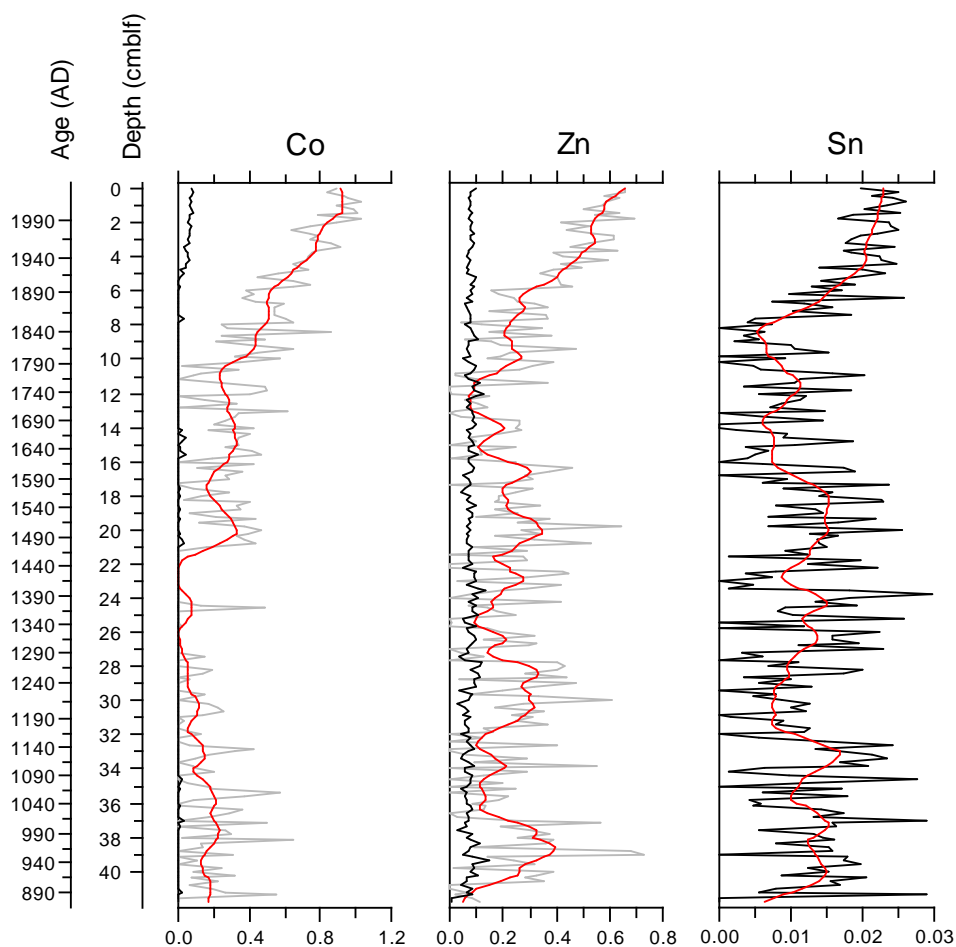


Figure 12: Fallen Leaf Lake down core scanning XRF plots for cobalt, zinc, and tin in kilocounts per second (kcps). From left to right: Co (cobalt), Zn (zinc), Sn (tin). The graphs in gray are from the Mo source and the black from the Cr source. A loess smooth is represented by a red line on each plot.

Several elemental ratios, namely Si:Ti, Ba:Ti, and Inc:Coh (incoherent:coherent X-ray scattering), Fe:Ti, and Mn:Ti are of interest because they can be used as proxies for paleoproductivity, diatom content, and diagenetic overprints. The scanning XRF proxy for biogenic silica, which is largely diatoms, is Si:Ti (Brown et al., 2007; Johnson et al., 2011; Kylander et al., 2011). In the Fallen Leaf Lake core the Si:Ti has remained constant from 0-4 cm (2007-1943 AD) (Figure 13). The proxy Ba:Ti, reported as a primary productivity indicator

(Croudace et al., 2006), has remained steady over the top 4.5 cm of the core (Figure 13). The Ba:Ti pattern generally follows that of Si:Ti throughout the core. The ratio of incoherent (Compton) to coherent (Rayleigh) scattering, Inc:Coh, decreases at 4 cm and has since remained stable (Figure 13). Higher Inc:Coh ratios have been attributed to higher abundances of elements with low atomic mass, and may be attributed to an increase in either porosity or organic matter content (Guyard et al., 2007). In the case of the FLL core, it is likely the porosity decrease is due to compaction. The indicators of redox diagenesis, Fe:Ti and Mn:Ti (Figure 13), increase between 0 and 4 cm. These elevated levels of Fe and Mn at the top of the core suggest that the top 4 cm is a redox layer (Croudace et al., 2006).

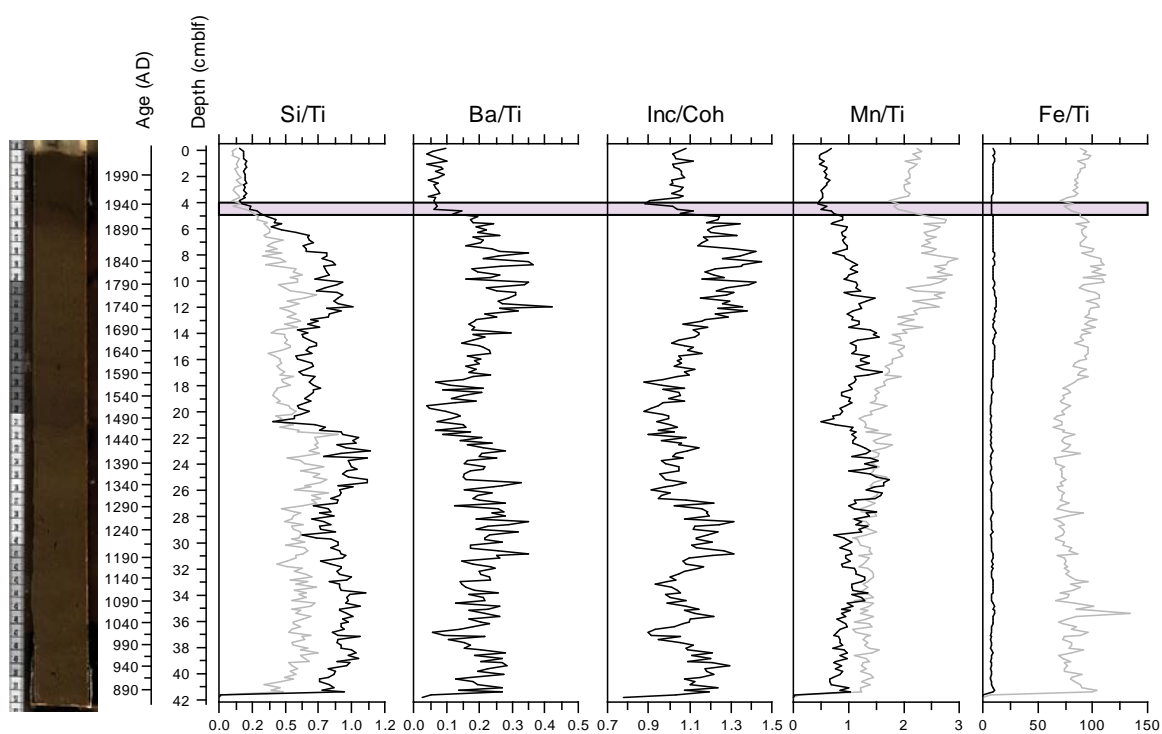


Figure 13: Fallen Leaf Lake scanning XRF ratios. From left to right: Si/Ti, Ba/Ti, Inc/Coh, Mn/Ti, and Fe/Ti. Values are relative elemental ratios. The graphs in gray are from the Mo source and the black from the Cr source. Purple box indicates the sandy layer between 4 and 5 cm.

4.2.5 Fallen Leaf Lake Core Diatom Analyses

The Fallen Leaf Lake core diatom population is diverse with 161 diatom species identified. The diatom population over the past 1200 years has been centric dominated with a sizable araphid component. At their highest abundances the centric species *Aulacoseira subarctica*, the *Cyclotella rossii-ocellata* group, *Discostella stelligera*, and the araphid *Pseudostaurosira brevistriata* each compose up to 20-30% of the FLL core diatom population. Between 55% and 74% of the diatom population in the FLL core is composed of phytoplankton native to the lake today and the remaining percentages are composed of taxa that are washed into the lake via Glen Alpine Creek (Noble et al., in press). The centric species that dominate the lake today also dominate the core population, with the exception of *Handmannia bodanica*, with abundances of only up to ~3% in the core. *Asterionella formosa* is present throughout the core in abundances up to ~14%. There have been recent increases in both the *Fragilaria tenera-nanana* group and *Tabellaria flocculosa* strain IIIp. About 20 years ago, the *F. tenera-nanana* group spiked to 15% and *T. flocculosa* strain IIIp increased to 5%.

4.3 Data Analysis

4.3.1 Diatom Multivariate Analyses

Analysis of the diatom data results in a gradient from colder, species associated with enhanced mixing to species that are associated with anthropogenic influences. Axis 1 shows a principal gradient with *Stephanodiscus alpinus* and *Cyclotella ocellata* on one end and the *Fragilaria tenera-nanana* group, *Fragilaria crotonensis*, *Nitzschia gracilis*, and *Tabellaria flocculosa* strain IIIp on the other (Figures 14 A-B). *Asterionella formosa* plots in the middle of this axis. The proportion of variance represented by the DCA Axis 1 is 0.600. The DCA axis 2 shows a weak gradient with *S. alpinus* on one side and *Cyclotella rossii* on the other (Figure 14

A). The proportion of variance represented by DCA Axis 2 is 0.063. There is not a clear species gradient displayed by DCA axis 3 (Figure 14 B); nevertheless the proportion of variance described by the axis is 0.030.

The NMS results are similar to those of the DCA (Figure 14). NMS was run on Autopilot mode, and the Sorenson (Bray-Curtis) distance measure was used for 500 runs and 51 iterations. The NMS best solution was 3-D and had a stress value of 11.28. Following Clarke's rules of thumb for final stress values, the solution is a relatively good ordination (McCune et al., 2002). To determine whether NMS was extracting stronger axes than expected by chance, a Monte Carlo test was performed. From more than 250 randomized runs, the Monte Carlo test computed a probability of 0.0040 that a similar final stress could have been obtained by chance. Axis 1 of the NMS shows the same gradient as the DCA axis 1 (Figure 14) and the NMS axis 2 is mirrored by the DCA axis 2 (Figure 14).

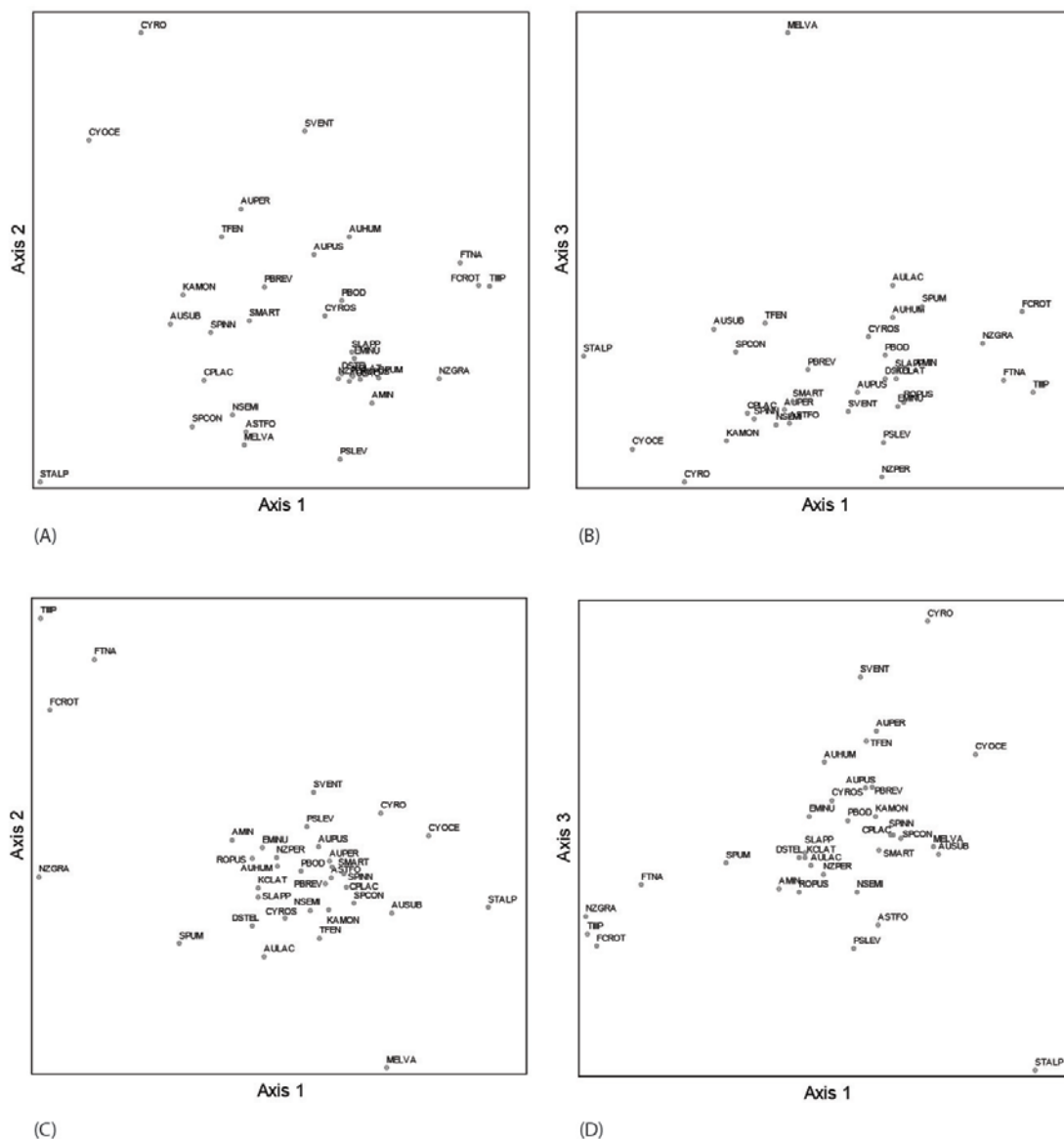


Figure 14: DCA and NMS ordinations for the Fallen Leaf Lake core species. (A) DCA showing Axis 1 vs. Axis 2, (B) DCA showing Axis 1 vs. Axis 3, (C) NMS showing Axis 1 vs. Axis 2, (D) NMS showing Axis 1 vs. Axis 3 for the Fallen Leaf Lake core species.

4.3.2 Diatom Biostratigraphy

A stratigraphically constrained cluster analysis of the down core diatom stratigraphy was performed in R using the Rioja package (Juggins, 2011; R Development Core Team, 2011) and

indicates that there are four diatom zones over the past 1200 years (Figure 15). Axis 1 of a DCA is plotted on the far right of Figure 15, showing species gradient relationships along this principal axis.

Diatom Zone 1: 837 ± 90 - 1385 ± 45 AD (43-24 cm)

Zone 1 spans from the base of the core (837 ± 90 AD) to a major inflection point at 24 cm (1385 ± 45 AD) where the DCA Axis 1 drops from a stable baseline to its minimum value of -0.4 (Figure 15). *Tabellaria fenestrata* exhibits a 4% decline in species abundance from the middle of zone 1 beginning ~ 1175 AD to the top of the zone. The top of zone 1 and bottom half of zone 2 represents a major break marked by the lowest abundances of *T. fenestrata*. *Stephanodiscus alpinus* makes its first appearance at the top of zone 1 ~ 1300 AD.

Diatom Zone 2: 1385 ± 45 - 1807 ± 21 AD (24-9.75 cm) Little Ice Age

The base of this zone is marked by a rapid increase in the abundance of *Stephanodiscus alpinus*, which increases rapidly to 8% after 1400 AD and then steadily decreases to $\sim 2\%$ ~ 1600 AD where it remains for the duration of the zone. *Asterionella formosa* is highest in abundance during this period at 14%, along with *Aulacoseira subarctica* at 28%. *Tabellaria fenestrata* exhibits a 3.5% decline in species abundance between 1694 AD and 1807 AD. *Discostella stelligera* abundances remain low ($<0.5\%$) throughout zone 2. The top of the zone shows the first appearance of *Fragilaria crotonensis*. The bottom of zone 2 represents the lowest stratigraphically constrained DCA value, and there is a strong positive gradient in the DCA 1 axis throughout the zone. *S. alpinus* represents one end member of the DCA axis 1 and *F. crotonensis* is one of the species on the opposite end of the axis (Figures 14-15).

Diatom Zone 3: 1807-1948 AD (9.75-3.75 cm) Transitional Zone

The base of this zone is marked by a sharp increase in *Discostella stelligera* (15%) and rapid decrease in *Aulacoseira subarctica* (17%). The abundance of *A. subarctica* remains low through present day. The increase in *D. stelligera* continues until 1900 AD (30%) and then decreases to 20% at the top of the zone from 1900-1948 AD. *Cyclotella rossii* was present at its highest abundance (23%) during this period and *Asterionella formosa* reaches its lowest abundance (2%) in 1943 AD. *Pseudostaurosira brevistriata* decreased 12% rapidly after 1850 AD and began to increase again after 1931 AD. Several groups become more prominent or make their first appearance in the upper part of this zone during the late 1800s. The *Fragilaria tenera-nanana* group increases steadily beginning at the bottom of this zone while *Fragilaria crotonensis* reappears and becomes persistent beginning in 1891 AD. *Tabellaria flocculosa* strain IIIp makes its first appearance in 1870 AD and begins to increase rapidly ~1931 AD. *Nitzschia gracilis* makes its first appearance at the bottom of zone 3 (1807 AD) and becomes a persistent component (0.5-1-5%) in the late 1870s.

Diatom Zone 4: 1948-2010 AD (3.75-0 cm) Anthropogenic Zone

The base of this zone is marked by rapid increases in several araphid phytoplankton, including the *Fragilaria tenera-nanana* group, *Tabellaria flocculosa* strain IIIp, and *Fragilaria crotonensis*. The araphid species appear to peak in the middle of the zone and show a decline starting ~1989 AD. Throughout the zone, centric phytoplankton remain stable and are lower in abundance compared to zone 3 below. *Asterionella formosa* remains at about 6% throughout the zone, which is a lower mean abundance than the three zones below.

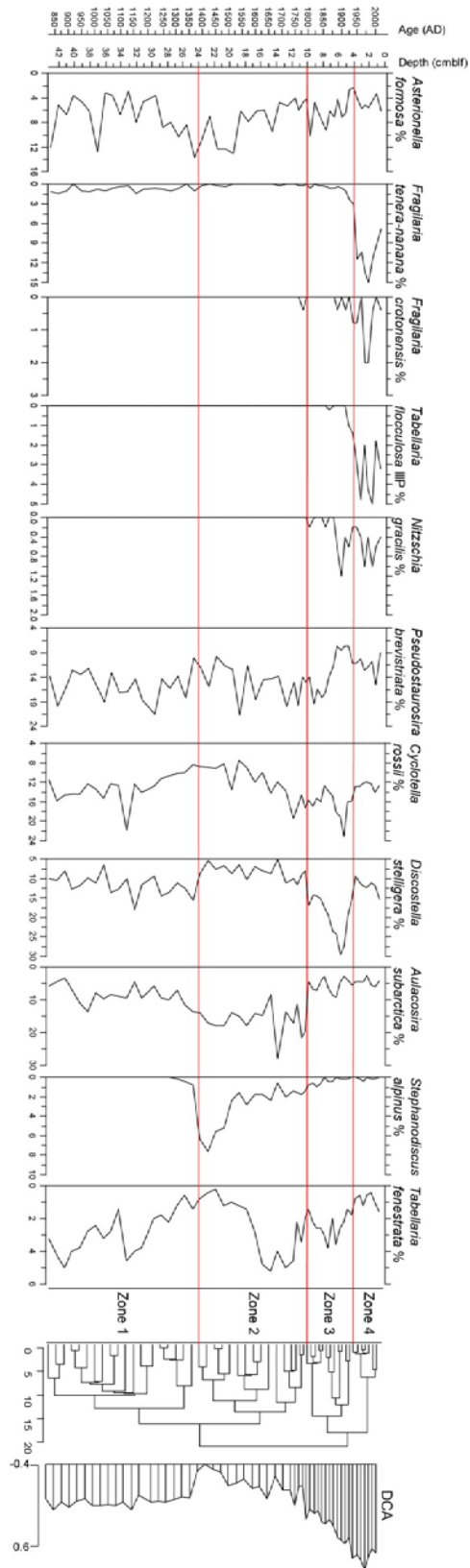


Figure 15: Diatom stratigraphy of Fallen Leaf Lake with four diatom species zones, cluster dendrogram, and stratigraphically constrained DCA. The diatom species values are represented in relative abundance (%).

4.4 Gilmore Lake Sediment Core

In both the surface and vertical tows, *Asterionella formosa* was found to comprise most of the diatom phytoplankton population in Gilmore Lake during the October 2011 water sampling. Interestingly, only one *A. formosa* valve was found in the top most sample of the Gilmore Lake core, and was not present below this. To make sure that the top of the GL core was not lost or compromised, the top of a second short core plus several surface samples taken from shallower water were examined, and *A. formosa* was also absent. The near absence of *A. formosa* in these cores suggests that the presence of *A. formosa* is a relatively recent phenomenon. The preliminary examination of diatoms throughout the core suggests that the centric diatom population has decreased towards the top in favor of littoral zone diatom periphyton, while the size of the *Aulacoseira* species valves increased. A full list of the diatom taxa present in the GL core are presented in Appendix D.

5. DISCUSSION

5.1 Limnology and Watershed Dynamics

5.1.1 Limnological Comparison of Lakes in Fallen Leaf Lake Watershed

Gilmore Lake is an ultra-oligotrophic to oligotrophic lake high in the Fallen Leaf Lake watershed. In general, the lake is shallow with a deep area at the northern end. Although GL is much shallower than FLL and has higher chl *a* values, it is clearer than FLL. During spring runoff, GL was cold with a shallow epilimnion and was the clearer of the two samplings. By the fall, the lake was fully stratified with a thicker epilimnion. The deep chlorophyll maximum was at a comparable depth 25-30 m during both the summer and fall samplings. The 50 m vertical plankton tow indicated that few phytoplankton were in the water column during the spring runoff, yet the highest 2011 chl *a* values were at 30 m at that time. Perhaps the phytoplankton present in the lake at that time were picoplankton that passed through the 20 μm mesh openings of plankton net, and thus not present in the plankton tow. Although the 2011 fall plankton tow indicated that the phytoplankton population at GL is dominated by *Asterionella formosa*, the lake sediment indicates contributions of large centric diatoms and araphid periphyton diatoms from the shallow littoral zone. GL is higher in the watershed and diatom species from GL may be traveling to Lily Lake via Glen Alpine Creek throughout the year, contributing to the higher species diversity seen in Lily Lake.

Lily Lake is a small, shallow mesotrophic lake that is well-mixed and generally has the highest chl *a* values of the three lakes sampled during this study. No other water quality data exists for Lily Lake, so few seasonal comparisons can be made. However, the chl *a* values of Lily Lake were low during the 2011 spring runoff and higher during the fall. The surface water

temperature during the first sampling was cold ($\sim 7^{\circ}\text{C}$), thus it is no surprise that the spring flora was not established at that time. The 2011 plankton tows of Lily Lake indicate that the species present are similar during both summer and fall and support the interpretation that many of the araphid and centric diatom species found in Lily Lake are subsequently washed into Fallen Leaf Lake throughout the year.

Fallen Leaf Lake is the largest and deepest of the three lakes in this study and has the lowest chl *a* values. The lake was not quite stratified during the spring runoff, but was fully stratified by the fall sampling. The deep chlorophyll maximum in FLL was at 30 m during both sample periods and the plankton tows showed that the summer and fall diatom species were similar. The diatom species present in FLL today are primarily centrics and araphid pennates; and many species found in the lake sediments today are washed in from higher in the watershed (Noble et al., in press). Fallen Leaf Lake and Gilmore Lake are similar in their seasonal water column structure and both have a deep chlorophyll maximum. Although these two lakes are similar in several features, FLL is not as clear, perhaps due to diverse recreational activities and residential uses around the lake.

5.1.2 Fallen Leaf Lake Watershed Nutrient Dynamics

Recognizing how nutrients are transported to and throughout the Fallen Leaf Lake watershed is important in understanding nutrient enrichment in these systems. Gilmore Lake was sampled about 2 weeks after ice out in 2011 to get an idea of the amount of nitrogen entering the lake as wet deposition from the snowpack, while Lily Lake was sampled during the height of the spring runoff to determine how much nitrogen is being flushed through the FLL watershed. Results from nutrient analyses for DP-P, $\text{NH}_4\text{-N}$, and $\text{NO}_3/\text{NO}_2\text{-N}$ at GL and Lily Lake are shown in Table 1. The data from GL indicates that little nitrogen in the form of nitrate, but a

larger amount of $\text{NH}_4\text{-N}$ is entering the lake with snowmelt. Gilmore Lake had no detectable phytoplankton present in the water column during this time, thus the low values of $\text{NO}_3/\text{NO}_2\text{-N}$ cannot be attributed to phytoplankton uptake. Lily Lake was sampled at the outlet and shows high $\text{NO}_3/\text{NO}_2\text{-N}$ values, suggesting internal nitrogen loading processes are occurring in the watershed and this N is being flushed through the system during spring runoff (Noble et al., in press). The higher $\text{NH}_4\text{-N}$ and DP-P values in the surface waters of GL during the spring indicate that ammonium and phosphorous are entering the watershed via snowmelt during the spring runoff.

5.2 Fallen Leaf Lake Watershed Climate Reconstruction

From an understanding of the modern limnological system, the significance of past diatom communities and species changes can be evaluated. This section of the discussion is focused on the reconstruction of climate within the Fallen Leaf Lake watershed with the use of diatom species and geochemical proxies of a FLL sediment core.

Diatom zone 1 (837 ± 90 to 1385 ± 45 AD) is somewhat ambiguous to interpret because the base of the zone is artificially defined by the lowest sample. The top of the zone however represents a significant break and is discussed below in zone 2. The lower part of zone 1 spans the time encompassing the end of the Medieval Climate Anomaly (MCA), $\sim 800\text{-}1300$ AD, which in Fallen Leaf Lake is represented by the end of an extended drought and a lake highstand (Kleppe et al., 2011). The MCA is being examined more fully in a companion project on a piston core from the same site as 2E (Stratton, 2013).

Diatom zone 2 (1385 ± 45 to 1807 ± 21 AD) is defined with the sharp increase of *Stephanodiscus alpinus* and the highest abundances of *Aulacoseira subarctica*, which coincide

with a subtle change in sediment color at 24 cm. From a temporal standpoint, this zone encompasses the Little Ice Age (LIA), 1250-1900 AD, in the Sierra Nevada as defined in Bowerman & Clark (2011). These two species have an affinity for cold, windy environments (Gibson et al., 2003; Stoermer & Ladewski, 1976). *Aulacoseira subarctica* is a meroplanktonic species that flourishes in turbid waters due to its high density (Gibson et al., 2003). The species was found to increase with glaciations in Ribains Crater Lake in France (Rioual et al., 1998). *Stephanodiscus alpinus* is a euplanktonic species that has been found in disturbed areas of large lakes and is a common winter/spring species of the Great Lakes (Stoermer and Ladewski, 1976; Stoermer & Yang, 1970; Theriot & Stoermer, 1982). The ecology of these two species supports interpretation that diatom zone 2 encompasses the Little Ice Age.

Diatom zone 3 (1807-1948 AD) is a transitional zone between the end of the LIA and the start of apparent anthropogenic changes in diatom zone 4 (1948-2010 AD). Zone 3 shows increases in *Cyclotella rossii* and *Discostella stelligera* along with a decrease in *Pseudostaurosira brevistriata*. *Discostella* spp. and *Cyclotella* spp. are typically successful in lakes with water columns that become stratified during the summer months, and exhibit a prolonged ice-free season (Hobbs et al., 2011). The small benthic littoral zone taxa *Pseudostaurosira* spp. prefers short growing seasons with low light attenuation (Hobbs et al., 2010). The appearance of *C. rossii* and *D. stelligera* and the decline of *P. brevistriata* was seen by Hobbs et al. (2010) in Arctic lakes as a response to warming and climate change. *Pseudostaurosira brevistrata* is currently being found in Fallen Leaf Lake, entangled in organic debris that is washed in from small, shallow lakes higher in the watershed that are sensitive to warming temperatures (Noble et al., in press). The decrease of this species in zone 3 may reflect warmer conditions in the Tahoe Basin over the past 150 years.

5.3 Land Use in the Fallen Leaf Lake Watershed

Land use changes as a result of anthropogenic activities are one of many influences that have affected lakes around the world, including those in the Fallen Leaf Lake watershed. For example, increased land use around Walden Pond in Massachusetts caused increased sedimentation into the lake, diatom population changes, and eutrophication due to increased nutrient inputs into the system (Köster et al., 2005). Land use changes within the FLL watershed could have caused similar changes to the system over the past 150 years. Significant changes in land use within the FLL watershed began in the early 1900s and are one possible cause of increases in sediment accumulation and changes in diatom community composition beginning in zone 3 (3.75-9.75 cm) and continuing through zone 4. The watershed was probably influenced by human activities as early as the late 1800s. Nathan Gilmore brought cattle to FLL in 1861 and established a cattle and goat ranch on the southern shore of FLL by 1873. By 1873, Gilmore had built a wagon road on the southern and eastern shores of FLL and along Glen Alpine Creek up to Glen Alpine Springs Resort (Kaidantzis, 2011). Glen Alpine Creek flows into the southern end of FLL and is the source of much of the sediment input into the lake. Interestingly, the addition of cattle and goats to the FLL watershed and the construction of Glen Alpine Springs Resort may have caused a slight increase in the sedimentation rate of the FLL cores between 1861 and 1873.

Around the same time, a sawmill was built in the northwestern portion of Fallen Leaf Lake known as Sawmill Cove. The sawmill operated for 20-30 years and no increases in the sedimentation rate were seen in the northern sub-basin core 3B as a result of this operation. Around 1905, the U.S. Forest Service (USFS) began issuing permits to build cabins around FLL and Lily Lake. The gravity core shows the sedimentation beginning to increase in FLL ~1910 AD, along with increasing land-use around the lake. While more cabins were being built around FLL,

fishing clubs and private enterprises were altering the upper watershed. Starting in 1925, the Mt. Ralston Fish Planting Club built dams throughout Desolation Wilderness to improve stream habitat. At the same time, the Price Family constructed a hydro-electric plant on Glen Alpine Creek below Glen Alpine Falls, and John Steinbeck and Toby Street built a reservoir below Lily Lake to regulate the water flow into the hydro-electric plant (Kaidantzis, 2011). Both the clastic bed centered around 1937 AD (Figure 9) and the large peak in sediment accumulation occur during the period, 1925-1955, when the Glen Alpine Creek Dam was built (Kaidantzis, 2011), and may be the result of altered sediment inputs or disturbances following its construction. Another significant event during this time was the big storm of 1938. Before the storm Glen Alpine Creek was split into two streams with an island in between before the water entered the lake. After the storm, the course of Glen Alpine Creek near the outlet at FLL had changed to one stream. The sharp peak in the sediment accumulation of core 2E is associated with a silty layer at 4-5 cm. Core 3B from the northern FLL sub-basin shows the same sedimentation patterns, with the exception of the sharp peak ~1937 AD (Figure 9). Comparison of the two cores shows that the southern sub-basin has a higher sediment accumulation rate and is more sensitive to changes higher up in the watershed; and that Glen Alpine Creek carries more sediment into FLL than what is washed in from around the lake and from in-lake production.

Fallen Leaf Lake has undergone a period of increased land use over the past 150 years which has resulted in a large amount of organic and inorganic nutrient inputs into the lake. Along with the increased terrestrial organic matter and sediment into FLL, the clarity decreased 12 m between 1991 and 2011 AD (Reuter et al., 1990; 1993; Noble et al., in press). Comparison of monitoring data from 1989, 1991, and 1994 (Reuter et al., 1990; 1993; 1996) with 2009-2011 data shows comparable chl *a* values in FLL (Noble et al., in press), indicating no significant or

discernible increases in primary productivity. Although chl *a* values show no discernible trend, the clarity of FLL, as measured by Secchi disc (Table 3), has decreased when compared to the 14.5-23.8 m reported by Reuter et al. (1993). With no discernible increases in primary productivity, the loss of clarity in FLL may be partially attributed to increases in the amount of terrestrial organic matter and sediment into the lake. In lacustrine systems, elemental ratios, isotopic concentrations, and diatom species are useful in determining changes in organic and inorganic material to a lake system. The uppermost part of diatom zone 3 (~1900 AD) marks the appearance of several mesotrophic diatom species responsive to nutrient enrichment caused by land use change or disturbance: *Fragilaria tenera-nanana* group, *Tabellaria flocculosa* strain IIIp, and *Nitzschia gracilis* (Koster et al., 2005; Kawecka et al., 1998). Conversely, *Aulacoseira subarctica* abundances decrease with sustained eutrophication as described in Gibson et al. (2003). The scanning XRF elemental ratios suggest that after 1950 AD the diatom population and productivity stabilized, while the organic matter increased slightly. The rate of sediment accumulation has steadily increased since about 1950 AD with an increase in building around the lake. Interestingly, the percent inorganic proxy decreases beginning ~1943 AD and continues to decrease until 2002 AD. This suggests that the amount of organic matter in the lake increased faster than the terrestrial sedimentation into the lake. The stable Si:Ti ratio values in the top 4-cm of the core (1943-2010 AD) imply that the increased organic matter is not the result of an increasing diatom population in the lake.

Elemental ratios of C:N in sediments can be a useful proxy in recording changes of organic source material. The C:N values of lake sediments dominated by phytoplankton remains are between 6 and 7 (sometimes slightly higher), whereas the ratio is 20 or greater for terrestrially derived plant material (Talbot, 2002). When an oligotrophic alpine lake receives a

large proportion of terrestrial organic matter from local human disturbance, increases in the C:N ratio can be seen in sediments (Guilizzoni et al., 1996). The C:N ratio in Fallen Leaf Lake is between 12 and 15 and reached the highest values in 1931 AD suggesting more terrestrially derived plant material in the lake at that time. After this time, the C:N ratio decreased significantly and subsequently increased rapidly again after 1981 AD suggesting an increased input of terrestrial organic matter into the lake. The stable Si:Ti values in the top 4-cm of the core (1943-2010 AD) and recent increases in C:N imply that any increases in organic matter in FLL are not the result of an increasing diatom population, but rather the result of increases in terrestrial organic matter. Together, the sediment core proxies and monitoring data are suggesting that FLL has showed an increase in sediment accumulation since 1943 AD that is partly derived by an increase in terrestrial organic matter that might be related to particulate matter input and has resulted in a decrease in clarity. The increased presence of diatoms responsive to land disturbance along with increases in the sedimentation rate and organic matter suggests that land use changes have affected FLL over the last 70 years.

5.4 Atmospheric Deposition of Metals and Nutrients

5.4.1 The California Gold Rush and Coal Combustion

California was settled by few non-Native American people before the California Gold Rush. The non-Indian population of California was 2,000 in 1810 and increased to 6,000 by 1840. The California Gold Rush caused a mass migration of people to northern California beginning with the discovery of gold in Coloma in 1848. With the promise of gold, the population of California increased 2,500% between 1848 and 1852. The California census in 1860 totaled 380,000 people, and 560,000 people in 1870 (Holliday & Swain, 2002). The large population in California during the latter half of the 1800s had high energy needs. Coal had been used to

produce power and electricity in the United States since 1816 (U.S. Department of Energy, 2013) and many miners burned coal for use on mining claims throughout the Mother Lode of northern California during the California Gold Rush (St. Clair, 1998/1999). The first practical coal-fired electric generating station was built in the eastern United States by Thomas Edison in 1882 (U.S. Department of Energy, 2013) and around the same time, northern California became home to several hydroelectric dams and coal processing facilities. One of these coal processing facilities was present in Marysville, CA, approximately 140 km west of Fallen Leaf Lake (Hopkins & Delamere, 2007). In 1830, the first practical American-built locomotive that burned coal was manufactured (U.S. Department of Energy, 2013). The Transcontinental Railroad was completed in the 1860s and allowed coal-powered locomotives to penetrate the area (Kaidantzis, 2011).

Most of the trace element input into the atmosphere is from human energy production, and historically coal combustion has been a large source of energy. Combustion of coal produces light particulate matter known as fly ash which contains metals like tin (Sn) (Demir et al., 1998), and 5-20% of the global emissions of Sn are thought to come from coal combustion (Sloss, 1995). The Fallen Leaf Lake sediment core exhibits increasing levels of Sn after 1850 AD during a time of increased population and mining in the area. A study looking at Lake Michigan found that Sn enters the lake only through air pollution caused by the burning of coal and automotive fuels (Winchester & Nifong, 1971). The increase in coal combustion for power and electricity in California from the Gold Rush to the present coincides with the rapid increase of Sn in the FLL sediment core after ~1850 AD and may be associated with increased populations in the Lake Tahoe Basin at that time.

5.4.2 Atmospheric Cobalt and Zinc

Atmospheric emissions of zinc (Zn) are largely the product of metal ore smelting (Dudka & Adriano, 1997). Sediment cores from the Harz mountains of Germany revealed elevated levels of Zn as a result of 4 phases of mining and smelting activities in the area (Matschullat et al., 1997). A study of the particulate material emitted from copper smelters in southeastern Arizona found large enrichments in Zn (Germani et al., 1981). Hutchinson & Whitby (1974; 1977) found that in the Sudbury region of Ontario, Canada, large scale nickel and copper smelting operations were emitting 4.44 tons of particulate cobalt (Co) and 11.81 tons of particulate Zn into the atmosphere every 28 days. Cobalt is associated with larger particles and is released during copper smelting. Before modern electrostatic precipitators (ESPs) were involved in the smelting process, Co was released into the atmosphere along with Zn (Germani et al., 1981). The Fallen Leaf Lake scanning XRF Co values level off around 1990 AD, the same year that the 1990 Clean Air Act was implemented to reduce air pollution and the number of toxic contaminants in the atmosphere (Clean Air Act Amendments of 1990). Cobalt is an extremely toxic element and its decline suggests that more efficient ESPs installed at smelting facilities in the 1990s reduced particle output into the atmosphere.

Smelting facilities have been operating in the United States since the early 1800s (Sloto & Reif, 2011). Two major smelting centers were located within 400 km of the Lake Tahoe Basin in the late 1800s: Eureka, Nevada and Shasta County, CA. Eureka is a mining town in central Nevada, approximately 350 km to the east of Fallen Leaf Lake, is considered the birthplace of silver-lead smelting in the United States (Nolan, 1962). Mining and smelting operations in Eureka were at their highest levels between 1870 and 1890 (Vanderburg, 1938). In 1873 the town contained 17 furnaces and 8 smelting sites with furnace capacities of 20-90 tons per day

(Ingalls, 1907). By 1876, there were 19 furnaces in Eureka (Vanderburg, 1938). In the 1880s, copper mining was the major industry in Shasta County, CA, which is located ~275 km northwest from FLL. The first copper smelter in the county was built in 1896 and at least 5 more were built before all of the smelters were shut down in 1919. The copper in the Shasta Mining District had a high zinc component and due to toxic smoke and the associated environmental disaster, the smelters were shut down (Lydon, 1974; Kristofers, 1973). Hutchinson & Whitby (1974; 1977) found that the concentration of cobalt declines significantly with distance away from the smelters, whereas the Zn concentration does not significantly decline with an increase in distance from the smelters. The prevailing winds from Eureka, NV are often from the south (Wind Information, 2013) and thus the Eureka smelting facility is not the most likely source of the trace metals. Although there were no commercial mining and/or smelting facilities in the Lake Tahoe Basin, those facilities previously described as well as other California and Nevada smelting activities may have impacted the air quality in the Lake Tahoe Basin during the late 1800s. The initial increase in Co and Zn around 1800 AD and after 1919 AD may be due to smelting in the eastern U.S. and Europe, with aerosol particles being transported around the world. However, due to the lack of nearby smelting facilities today and the fact that Co concentrations decline with increased distance from smelting facilities, this explanation does not fully explain the high concentrations of Co seen into the present.

5.4.3 Atmospheric Nitrogen Deposition

As discussed earlier, nutrient loading through atmospheric nitrogen deposition has been an important concern in the Lake Tahoe Basin, and many of the atmospheric pollutants are derived from intrabasinal sources. Nitrogen deposition data reported by Fenn et al. (2003) from the El Dorado National Forest and Tahoe National Forest indicate that 2.1-3.9 kg/ha per year of

NO₃-N and 2.1-2.5 kg/ha per year of NH₄-N were deposited between 2000 and 2001. Total nitrogen values of 1.5 kg/ha have been found to be sufficient to alter diatom assemblages in the Sierra Nevada (Baron, 2006; Saros et al., 2010; Baron et al., 2011). Both the National Atmospheric Deposition maps (NDAP, 2010) and the Fenn et al., (2003) study of nitrate and ammonium ion wet deposition show that the Lake Tahoe Basin has exceeded this value.

As previously discussed, the paleolimnological records of remote N-limited, Northern Hemisphere lakes have shown the influence of anthropogenic nitrogen deposition through negative shifts in $\delta^{15}\text{N}$ that are coupled with a rapid turnover in the algal population (Wolf et al., 2001; Holtgrieve et al., 2011). In Fallen Leaf Lake, the N-sensitive species *Asterionella formosa* has been present for the last 1200 years with no appreciable increases during the last 50 years. Its presence can be best explained by N-stimulation during spring flushing events, rather than atmospheric nitrogen deposition. The values of NO₃⁻ and NH₄⁺ entering FLL during the spring runoff are on the order of 12-15 ppb (Noble et al., in press) and the combined measurements of NO₃⁻ and NH₄⁺ in Lily Lake were 24 ppb (Table 1). The values in both FLL and Lily Lake are well above the spring runoff values measured in Gilmore Lake, which were exceedingly low (Table 1). The 1950s coincide with a marked turnover where *Aulacoseira subarctica* was replaced with *Nitzschia* and several other araphid species, including: *Tabellaria flocculosa* strain IIIp and the *Fragilaria tenera-nanana* group. The rapid increase and abundance of these species may be attributed to the global trend described by Holtgrieve et al. (2011). The $\delta^{15}\text{N}$ record of FLL is somewhat equivocal and at best shows a weak negative trend that may be attributed to anthropogenic nitrogen deposition. Beginning in the 1950s, a negative 0.5‰ shift can be discerned, but is confounded by a positive excursion occurring from 1997-2002 AD (Figure 11). Although this 50 year negative $\delta^{15}\text{N}$ trend may be related to the hemispheric scale phenomenon

discussed by Holtgrieve et al. (2011), the overall magnitude of the shift is much smaller than what is seen in the 25 lakes they report.

Another disconcerting aspect of attributing changes within the Fallen Leaf Lake anthropogenic diatom zone to atmospheric nitrogen deposition is the lack of synchronicity with Gilmore Lake. The absence of *Asterionella formosa* valves in the GL surface sediment indicates that its presence in the upper FLL watershed is very recent. If hemispheric-scale changes in atmospheric nitrogen deposition have affected the FLL watershed for the last ~50 years, GL (low-impact site) should show the same species patterns with *A. formosa* and *Fragilaria crotonensis*, because air with extrabasinal pollutants from the Sacramento Valley cross the western crest of the Sierra Nevada and move into the Lake Tahoe Basin, passing over or near GL. One might argue that the hydraulic residence time of GL is possibly much shorter than that at FLL, and that dry and wet sourced nitrogen entering the system may be flushed through the lake at a faster rate. If this is the case, high flushing would have a more significant impact on wet deposited N, and less of an effect on dry deposited N, which is at its seasonal high during the summer (Dolislager et al. 2012). Direct dry deposition of N may possibly be more impacted by ice-out dates; shorter ice years might experience greater dry deposition than years with later ice-out dates. Despite differences in the mechanisms that might account for the lack of synchronicity between FLL and GL, it appears that the algal response to atmospheric nitrogen deposition in the upper FLL watershed is at best a very recent phenomenon, and may possibly be due to dry N deposition.

One significant difference between Fallen Leaf Lake and the 25 remote lakes chosen in the Holtgrieve et al. (2011) study is the level of direct human influence in the form of land use and ecosystem manipulations. In addition to the land use changes discussed previously, non-

native fish have been stocked in FLL since the 1950s, non-native crayfish were introduced in the early 1900s, and mysid shrimp were introduced in the mid-1960s (Allen et al., 2006). These introductions have been shown to play a major role in altering the trophic structure in other lakes (e.g. Ellis et al., 2011), and may have impacted both the algal populations and the nitrogen budget. Both increased land development and ecosystem manipulations are plausible drivers for explaining the observed algal shifts in FLL and should be investigated further.

6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The paleolimnological record of the last 1,200 years in Fallen Leaf Lake shows that the lake has been responsive to both localized anthropogenic activities and climate change. The strongest climate signal is manifested by increased abundances of the diatoms *Stephanodiscus alpinus* and *Aulacoseira subarctica*, which define the period between 1385 and 1807 AD that corresponds to the Little Ice Age and the neoglacial advances observed in the southern Sierra Nevada. This LIA interval represents conditions that were cooler and windier than during the past 200 years. For the ~140 years after the LIA, FLL experienced a period of warming, and both the sedimentologic and diatom records were influenced by anthropogenic factors. Increased coal burning in northern California beginning with the California Gold Rush ~1850 AD caused more tin to be released into the atmosphere, and evidence of this is seen in the FLL core after ~1850 AD. Similarly, smelting facilities in California and Nevada were in operation since the late 1800s and may have contributed to higher levels of cobalt and zinc in the FLL core. The diatoms show a large anthropogenic related species shift starting ~1917 AD that accelerates after 1948 AD, which may be related to land use changes in the FLL watershed. The anthropogenic shift is marked by increases in the *Fragilaria tenera-nanana* group, *Tabellaria flocculosa* strain IIIp, and *Nitzschia gracilis*, and may in part be driven by eutrophication. A DCA ordination shows a diatom species gradient from the base of the LIA zone through the anthropogenic zone. The anthropogenic indicator species appear on the DCA axis 1 gradient opposite the cold climate indicator species, *S. alpinus*, which is indicative of the onset of the LIA. Sediment accumulation rates increased most dramatically during the anthropogenic zone, starting ~1950 AD with increased building, land-use, and recreation around the lake. Organic matter accumulation also

increased during this time and shifts in the C:N ratios indicate some perturbations in the carbon source. A decreasing C:N ratio between 1943 and 1981 AD may be the result of increased soft algae in the lake, while increases from 1918 AD to the present may indicate increased terrestrial organic matter inputs.

The effects of atmospheric nitrogen deposition on the lakes within the Fallen Leaf Lake watershed are inconclusive and do not show a coherent pattern between the low and high impact sites examined. Isotopic nitrogen values throughout the upper 60 years of the FLL sediment core show a slight negative trend that is overprinted by a positive excursion between 1997 and 2002 AD. The negative trend is much smaller in magnitude than what has been observed in other Northern Hemisphere lakes affected by atmospheric nitrogen deposition. Furthermore, the nitrogen-responsive diatom species *Asterionella formosa*, an indicator species for nitrogen deposition in N-sensitive oligotrophic lakes, has been a significant component of FLL going back 1200 years and has not recently increased in abundance. *Asterionella formosa* in FLL is likely stimulated by the flushing of nitrogen from higher in the watershed during spring runoff rather than from atmospheric sources. *Asterionella formosa* is also present in the 2011 Gilmore Lake water column samples, and its presence may be related to the very recent effects of dry atmospheric deposition. However, *A. formosa* is absent in the GL surface sediment and sediment core. In contrast, other studies have shown that a significant part of the nitrogen load entering Lake Tahoe is from both wet and dry atmospheric sources, most of which is derived from within the Lake Tahoe Basin. This study suggests that the effects of atmospheric nitrogen deposition on lakes in the Tahoe Basin may be spatially heterogeneous and just beginning to manifest themselves in the upper FLL watershed.

6.2 Future Work

Additional work in the Fallen Leaf Lake watershed and the Lake Tahoe Basin will be necessary to more fully evaluate the anthropogenic effects observed in the FLL core, especially the effects of anthropogenic nitrogen deposition on local algal communities. Measurements of wet and dry ammonia, ammonium, nitric acid, nitrogen oxides, and nitrate taken from within the FLL watershed would be helpful in determining how much of each N component is entering the watershed. Additionally, isotope analyses from the lake water, rain and snow would be useful in determining the $\delta^{15}\text{N}$ values of the N entering the watershed. An analysis of $\delta^{15}\text{N}$ should be completed for sediment cores from low impact sites in the FLL watershed and Lake Tahoe Basin, including the Gilmore Lake core collected in this study, in order to gauge the synchronicity of negative isotope shifts. Comparisons could then be made with the FLL core and would provide a better understanding of the isotopic ($\delta^{15}\text{N}$) values seen in the core. Nutrient stimulation experiments in GL would be useful in determining whether the lake is N-limited or co-limited. Additional experiments to help determine the physiochemical requirements of other anthropogenic species, including: *Tabellaira flocculosa* strain IIIp and the *Fragilaria teneranana* group, would also be useful in determining the drivers for the dramatic species shifts in FLL over the past 50 years. An additional core from GL and other low impact sites in relatively undisturbed watersheds of the Lake Tahoe Basin and the Sierra Nevada would be useful in determining the timing and extent of anthropogenic changes to the diatom communities. Monitoring and water quality analysis for all of the lakes and streams within the FLL watershed would be useful in determining the habitats of all of the species found in the FLL core and help with down-core interpretations.

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8. APPENDIX

Appendix A: Upper Angora Lake Limnological Research

A1. Study Area

Upper Angora Lake (UAL) is a moderately impacted ecosystem (Oris et al., 2004) located at 38.862361° N, 120.06867°W. The lake lies at an elevation of 2263 m and has a maximum depth of 13 m (Oris et al. 2004). The lake is located ~1.75 km to the south of Fallen Leaf Lake (Google Earth, 2011), and is located just outside of the Fallen Leaf Lake watershed. The lake appears to be a tarn that resulted from the formation of a cirque by a glacier. UAL ices over during the winter months. Chandra and Rost (2006) found that the lake is N-limited. The lake has been home to the Angora Lakes Resort since the 1920s with 9 rustic cabins that have limited facilities. Motorized watercrafts are not allowed on the lake (Angora Lakes Resort, 2012). It is unclear whether the area immediately surrounding the lake was spared from logging during the Comstock era.

A2. Limnological Monitoring Results

The first sampling of Upper Angora Lake in 2011, approximately 2 weeks after ice-out and a mass wasting event into the lake that caused the lake to be mixed. The sampling established that the lake had begun to stratify by late June (Figure A1). Upper Angora Lake was analyzed for DP-P, NH₄-N, and NO₃/NO₂-N (Table A1) and the high NO₃/NO₂-N values indicate that the lake sediments are enriched in these ions. At this time, the corrected chl *a* values ranged from 0.13-0.94 µg/L and the lake had developed a chlorophyll maximum at 5 m (Figure A2). By early October, the lake was fully stratified and the water column became anoxic near the bottom (Figure A1). At this time, the corrected chl *a* values ranged from 0.74-4.66 µg/L and the

lake had developed a chlorophyll maximum at 8 m (Figure A2). The 2011 plankton tows indicate that the lake is not diatom dominated and few diatoms were present. The lake clarity did not change significantly between the early summer and fall samplings. The 2011 UAL TSI values range between 10.8 and 33.6 (Table A2), which indicates that the UAL trophic status is oligotrophic to meso-oligotrophic. Previous data regarding UAL is not available and thus no comparisons could be made with the data collected in 2011.

Lake	Sample Date	Water Depth (m)	NH ₄ -N (ppb)	NO ₃ /NO ₂ -N (ppb)	DP-P (ppb)
Upper Angora Lake	27-Jun-11	0	2	21	3
		5	2	22	3
		8	9	23	2
		10	24	24	3
Analyses run at High Sierra Water Lab					

Table A-1: Water Quality data for Upper Angora Lake in 2011.

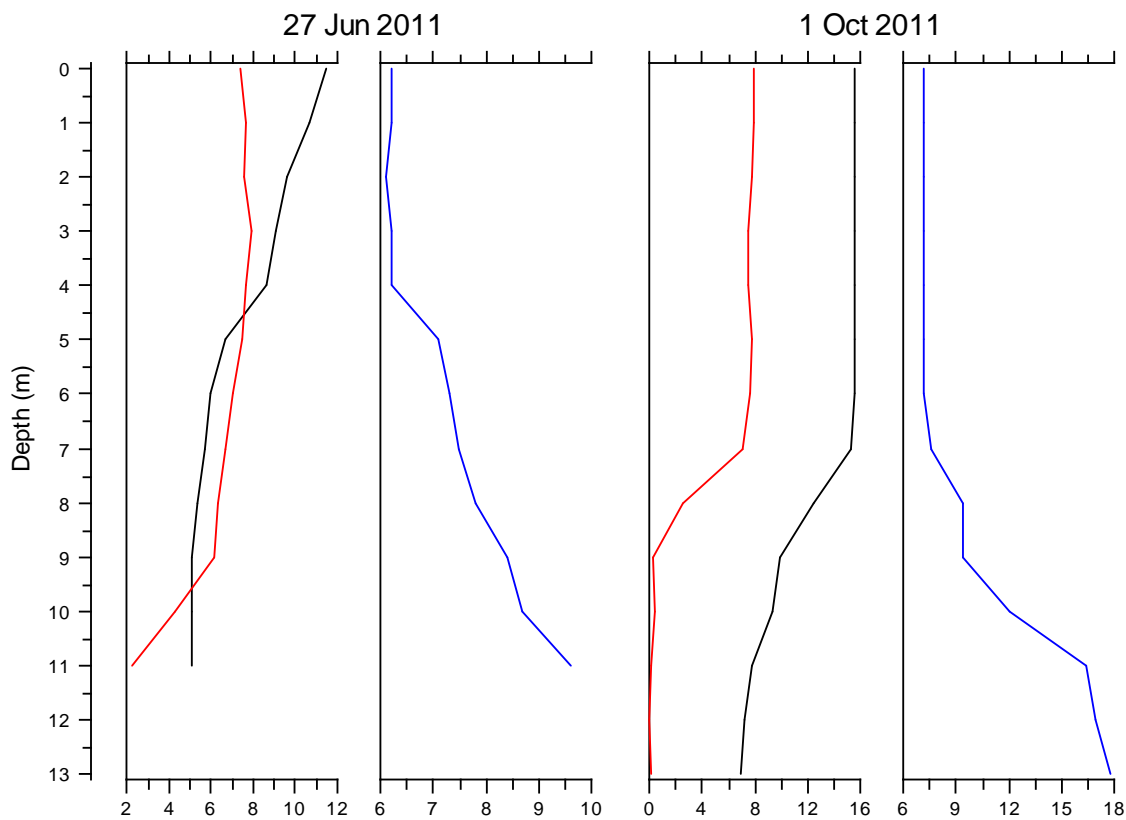


Figure A1: 2011 Upper Angora Lake water column profiles. Red – Dissolved Oxygen (mg/L). Black – Temperature (°C). Blue - Specific Conductance (µS/cm).

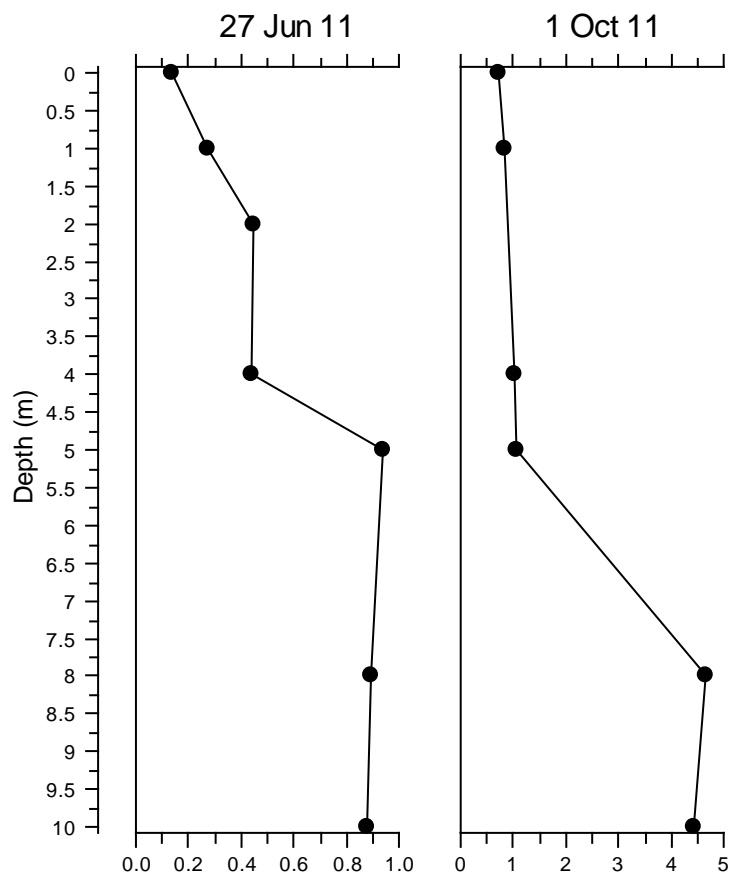


Figure A2: 2011 Upper Angora Lake chlorophyll *a* profiles. Chlorophyll *a* values presented in µg/L.

Lake	Sample Date	Average Secchi Disk (m)	Secchi Disk Trophic State Index	Surface Chl <i>a</i> (µg/L)	Chl <i>a</i> Trophic State Index
Upper Angora Lake	27-Jun-11	6.4	33.3	0.1335	10.8
	1-Oct-11	6.3	33.6	0.7357	27.6
Trophic State Index (TSI) calculations run using methodology presented in Carlson (1977)					

Table A-2: Upper Angora Lake average Secchi, surface chl *a*, and Trophic State Index values.

Appendix B: Scanning XRF Data

Scanning XRF elemental values are relative proportions and not absolute concentrations. Löwemark et al. (2011) suggests that Al should be used to normalize scanning XRF data of lakes that have a large component of clay. The Al contained too much noise, was low in abundance, and the sediment of is largely composed of opaline silica, so the data was normalized with Ti. The Mo XRF source values are in grey and the Cr source in black. Red lines on some of the graphs are Loess Smoothing Lines that were placed on the graphs using C2 (Juggins, 2007).

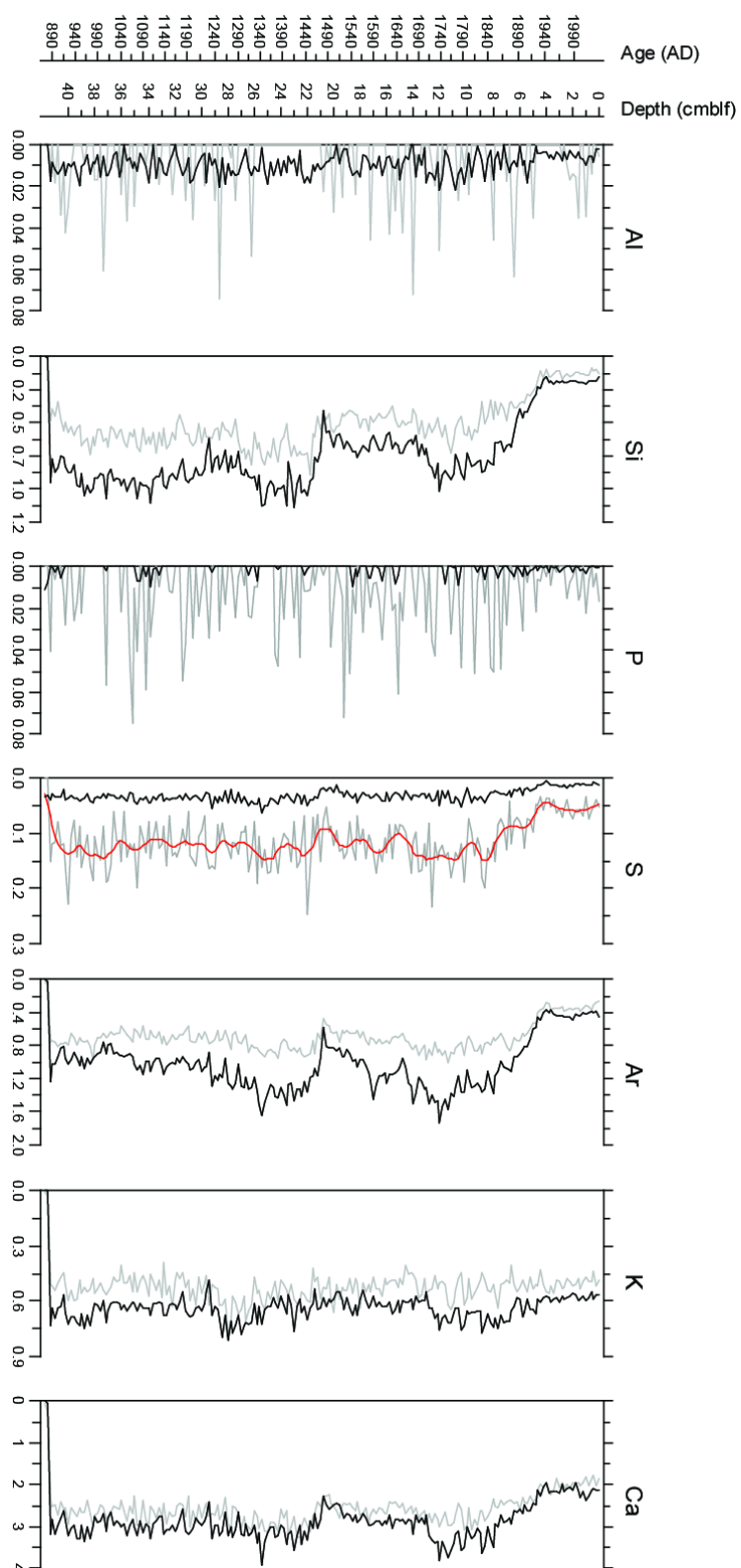


Figure B1: Fallen Leaf Lake core 2E scanning XRF analysis results for: Al, Si, P, S, Ar, K, and Ca.

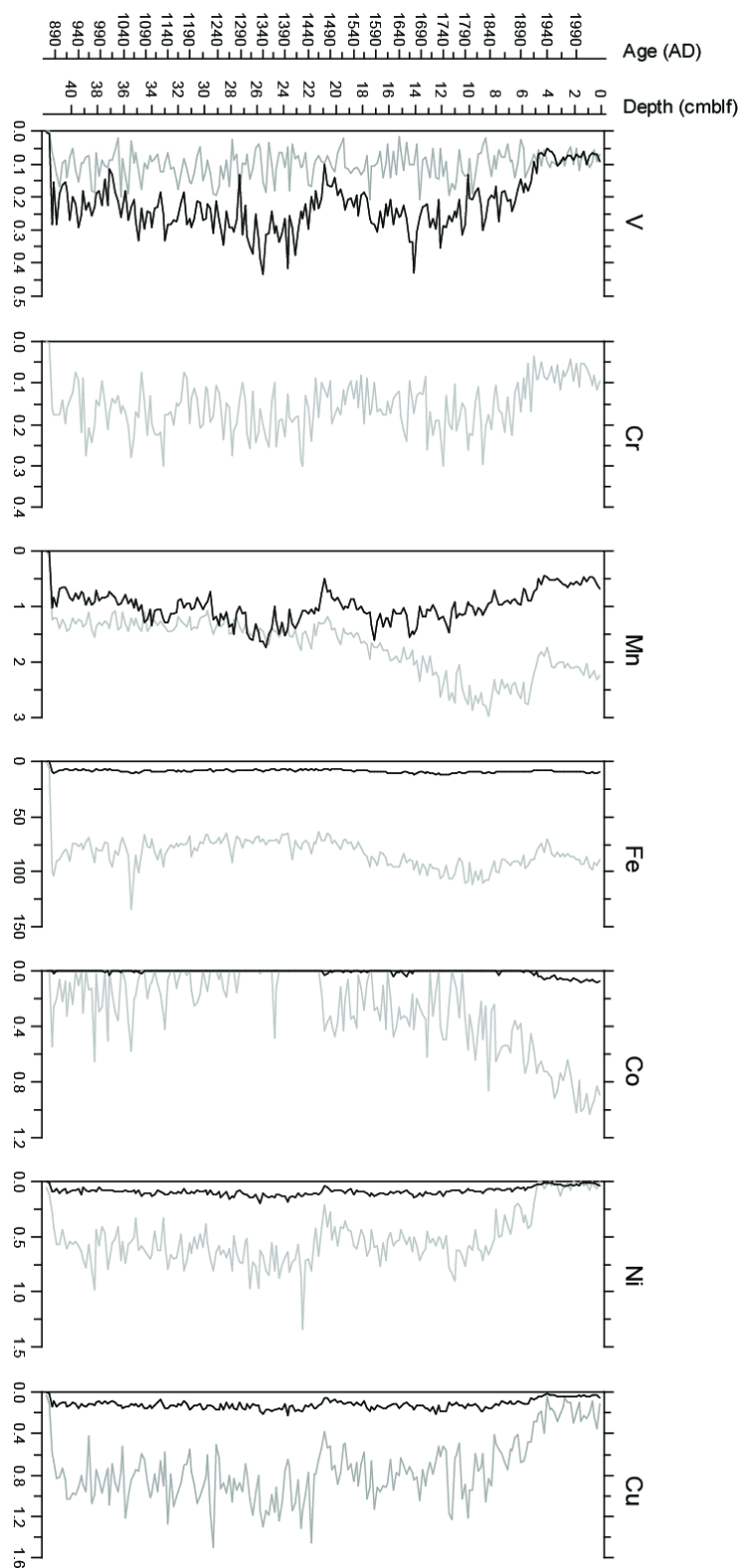


Figure B2: Fallen Leaf Lake core 2E scanning XRF analysis results for: V, Cr, Mn, Fe, Co, Ni, and Cu.

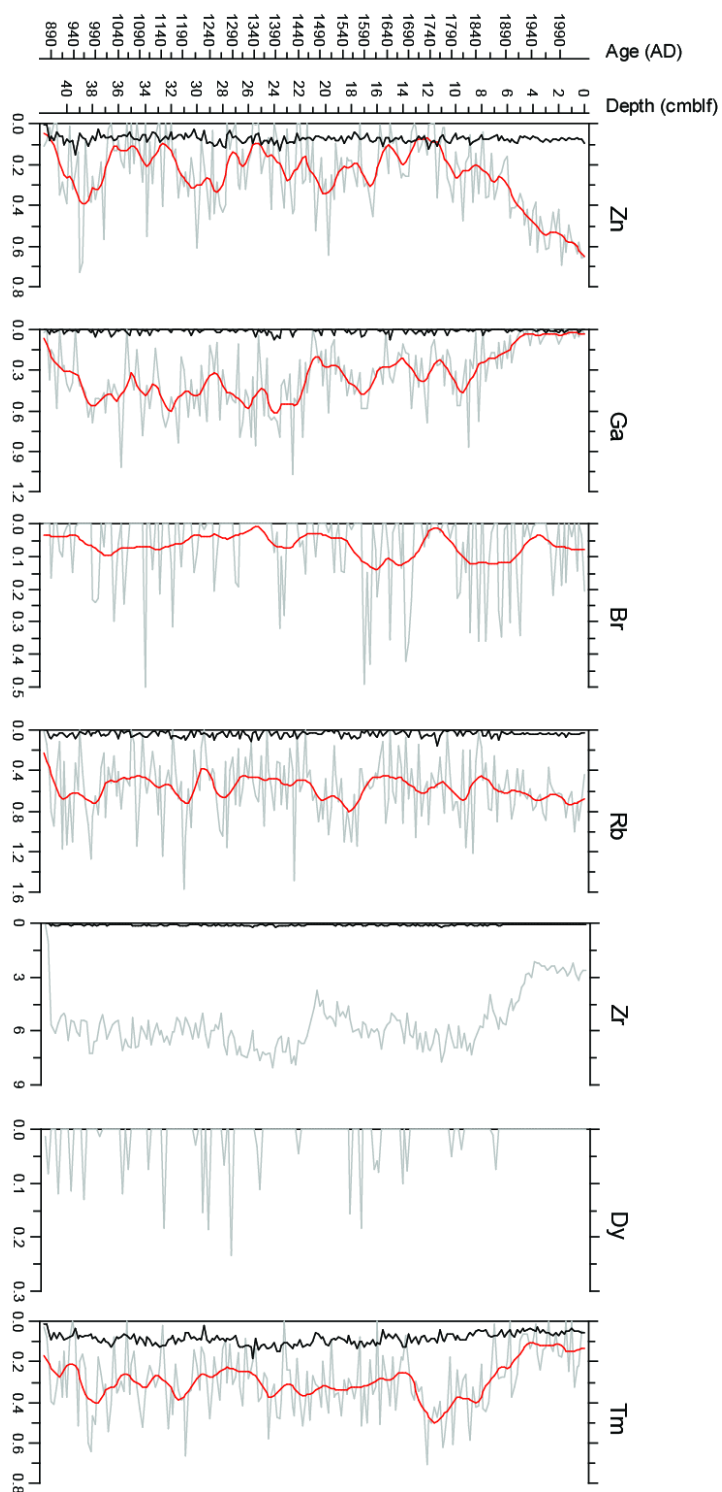


Figure B3: Fallen Leaf Lake core 2E scanning XRF analysis results for: Zn, Ga, Br, Rb, Zr, Dy, and Tm.

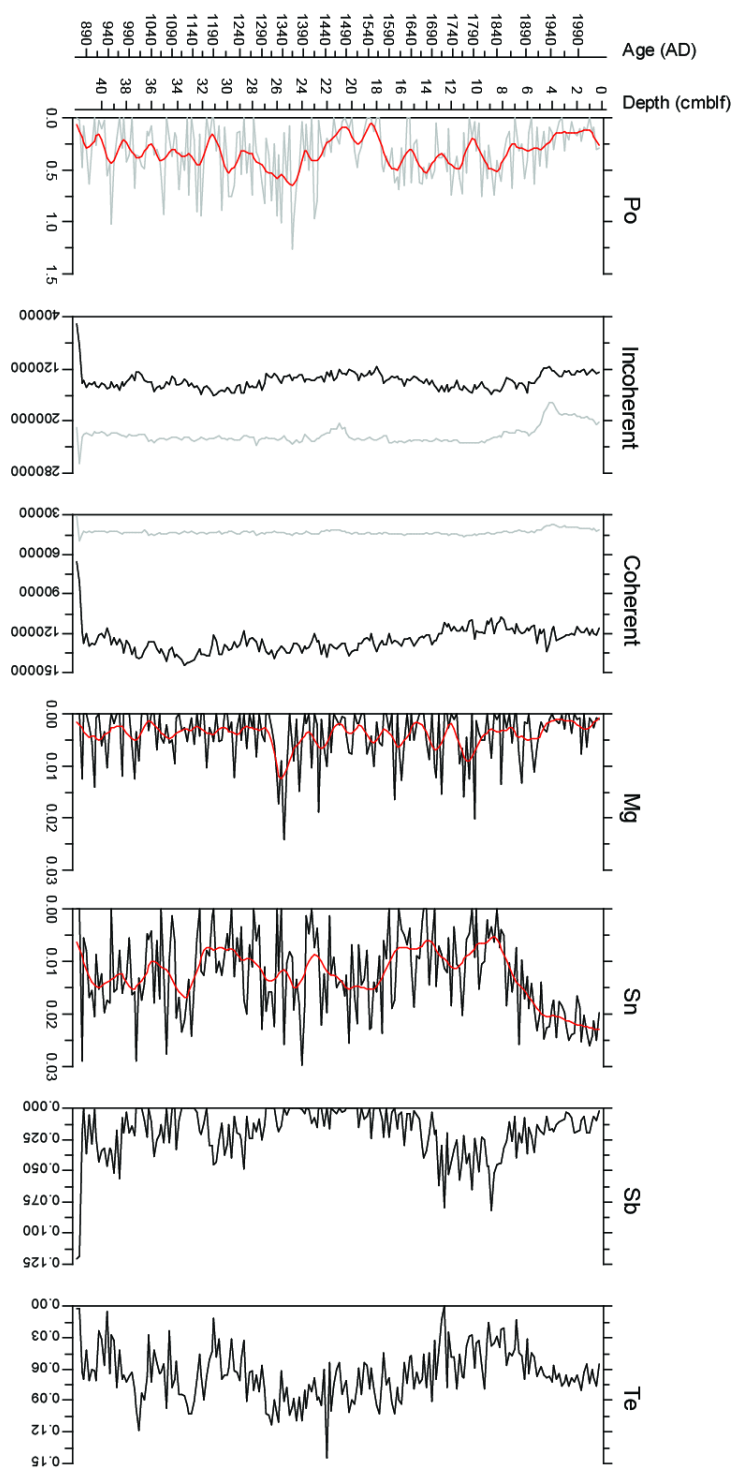


Figure B4: Fallen Leaf Lake core 2E scanning XRF analysis results for: Po, Incoherent scattering, Coherent scattering, Mg, Sn, Sb, and Te.

Appendix C: Fallen Leaf Lake Diatom Photographs

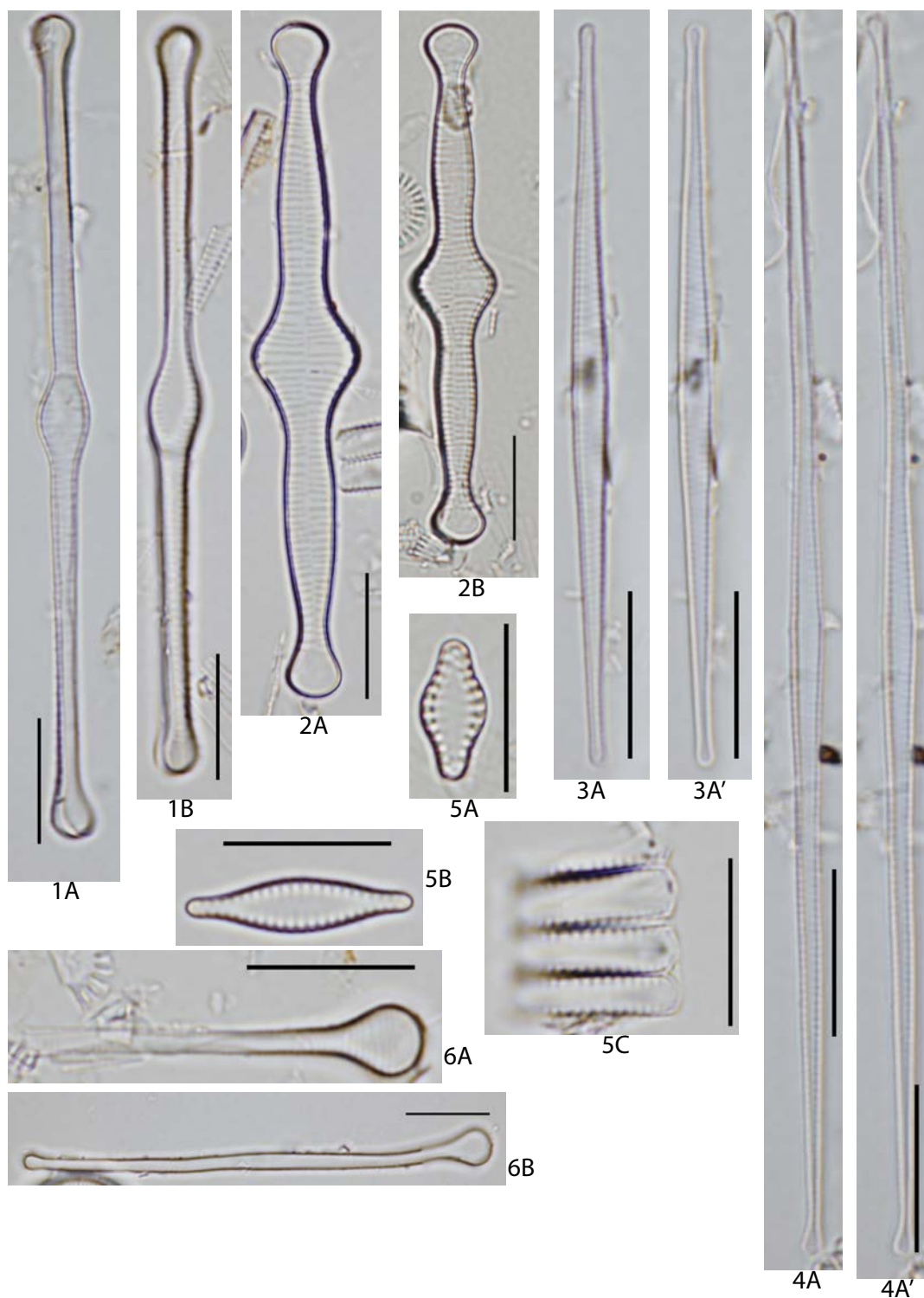


Plate C1: Important araphid diatom species of Fallen Leaf Lake, CA. *Tabellaria flocculosa* strain Illp (1A-B), *Tabellaria fenestrata* (2A-B), *Fragilaria crotonensis* (3A-A'), *Fragilaria tenera-nanana* group (4A-A'), *Pseudostaurosira brevistriata* (5A-C), *Asterionella formosa* (6A-B).

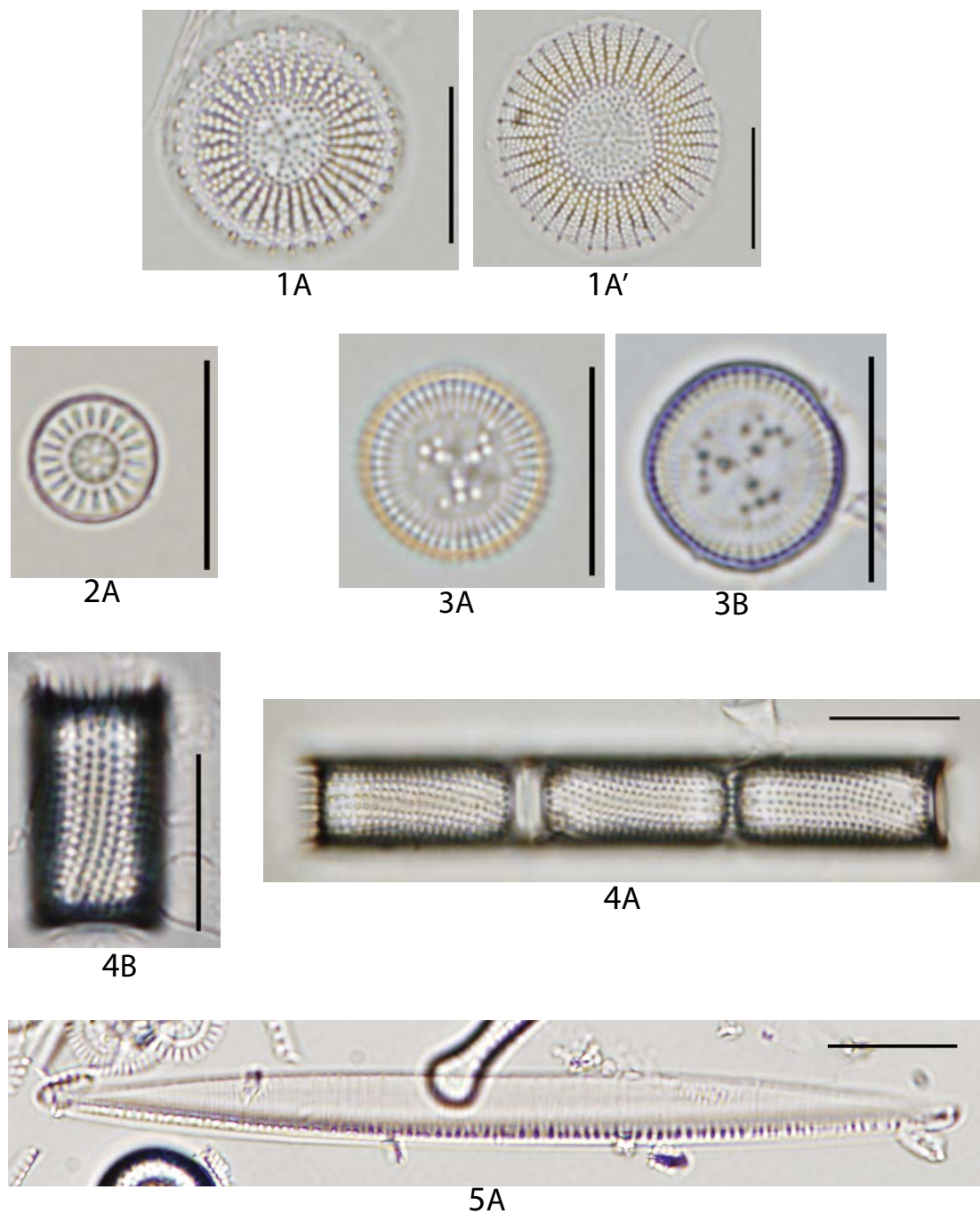


Plate C2: Important centric and nitzschioid diatom species of Fallen Leaf Lake, CA. *Stephanodiscus alpinus* (1A-A'), *Discostella stelligera* (2A), *Cyclotella rossii* (3A-B), *Aulacoseira subarctica* (4A-B), *Nitzschia gracilis* (5A).

Appendix D: Diatom Species of Fallen Leaf Lake and Gilmore Lake

Araphids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Asterionella formosa</i>	Hassall 1850	<i>Asterionella formosa</i> Hassall 1850	Patrick & Reimer (1966); Camburn & Charles (2000)	✓	✓
<i>Diatoma anceps</i>	(Ehrenberg) Kirchner 1878	<i>Fragilaria anceps</i> Ehrenberg	Camburn & Charles (2000); Patrick & Reimer (1966)	✓	✓
<i>Diatoma mesodon</i>	Kutzing 1844	<i>Diatoma mesodon</i> Kutzing 1844	Patrick & Reimer (1966); Potapova (2009a)	✓	✓
<i>Fragilaria crotonensis</i>	Kitton 1869	<i>Fragilaria crotonensis</i> Kitton 1869	Patrick & Reimer (1966)	✓	
<i>Fragilaria gracilis</i>	Ostrup 1910	<i>Fragilaria gracilis</i> Ostrup 1910	Bloom (2001)	✓	
<i>Fragilaria mesolepta</i>	<i>Fragilaria mesolepta</i> Rabenhorst 1861	<i>Fragilaria mesolepta</i> Rabenhorst 1861	Patrick & Reimer (1966); Bloom (2001); Tuji & Williams (2008)	✓	
<i>Fragilaria nanana</i>	Lange-Bertalot 1991	<i>Synedra nana</i> Meister 1912	Krammer and Lange- Bertalot (1991a); Cumming et al. (1995)	✓	
<i>Fragilaria perminuta</i>	(Grunow) Lange- Bertalot 2000	<i>Synedra capucina</i> var. <i>perminuta</i> Grunow in Van Heurck 1881	Krammer & Lange-Bertalot (1991a)	✓	✓
<i>Fragilaria tenera</i>	(W. Smith) Lange- Bertalot 1980	<i>Synedra tenera</i> W. Smith 1856	Patrick & Reimer (1966)	✓	✓

Araphids Continued					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Fragilaria vaucheriae</i>	<i>Fragilaria vaucheriae</i> (Kutzing) Petersen 1938	<i>Exilaria vaucheriae</i> Kutzing 1833	Morales (2010a); Petersen (1938)	✓	
<i>Fragilariaforma viriscens</i>	(Ralfs) Williams & Round 1988	<i>Fragilaria virescens</i> Ralfs 1843	Morales & Spaulding (2011); Patrick & Reimer (1966)	✓	✓
<i>Hannea arcus</i>	(Ehrenberg) Patrick 1961	<i>Navicula arcus</i> Ehrenberg 1836	Patrick & Reimer (1966)	✓	
<i>Meridion circulare</i>	(Greville) Agardh 1831	<i>Echinella circularis</i> Greville 1823	Patrick & Reimer (1966)	✓	✓
<i>Meridion circulare</i> var. <i>constrictum</i>	(Ralfs) Van Heurck 1880	<i>Meridion constrictum</i> Ralfs	Camburn & Charles (2000); Patrick & Reimer (1966)	✓	✓
<i>Pseudostaurosira brevistriata</i>	(Grunow) Williams et Round 1987	<i>Fragilaria brevistriata</i> Grunow in Van Heurck 1885	Spaulding et al. (2010b); Camburn & Charles (2000); Patrick & Reimer (1966)	✓	
<i>Pseudostaurosira parasitica</i>	(W. Smith) E. A. Morales 2003	<i>Odontidium parasiticum</i> W. Smith 1856	Morales (2010c); Patrick & Reimer (1966)	✓	
<i>Pseudostaurosira</i> sp. FLL 1	--	--	Mark Edlund (personal communication)	✓	
<i>Punctastriata lancettula</i> f. <i>subcapitata</i>	(Schumann) P.B. Hamilton & P.A. Siver 2008	<i>Fragilaria lancettula</i> Schumann 1867	Hamilton & Siver (2008); Camburn & Charles (2000)	✓	

Araphids Continued					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Staurosira construens</i> cf. var. <i>pumila</i>	(Grunow) J. C. Kingston 2000	<i>Fragilaria construens</i> var. <i>pumila</i> Grunow	Patrick & Reimer (1966); Camburn & Charles (2000)	✓	
<i>Staurosira construens</i> var. <i>venter</i>	(Ehrenberg) Hamilton 1992	<i>Fragilaria venter</i> Ehrenberg 1854	Patrick & Reimer (1966); Morales (2010d); Camburn & Charles (2000)	✓	✓
<i>Staurosira</i> <i>psuedoconstruens</i>	(Marciniak) Williams & Round 1987	<i>Fragilaria</i> <i>psuedoconstruens</i> Marciniak 1982	Bloom (2001); Krammer & Lange-Bertalot (1991a)	✓	
<i>Staurosirella</i> <i>lapponica</i>	(Grunow in Van Heurck) Williams & Round 1987	<i>Fragilaria lapponica</i> Grunow in Van Heurck 1881	Williams & Round (1987); Patrick & Reimer (1966)	✓	
<i>Staurosirella martyi</i>	(Héribaud) E.A. Morales & K.M. Manoylov 2006	<i>Opephora martyi</i> Héribaud 1902	Patrick & Reimer (1966); Morales & Manilov (2006)	✓	✓
<i>Staurosirella pinnata</i>	(Ehrenberg) Williams and Round 1987	<i>Fragilaria pinnata</i> Ehrenberg 1843	Camburn & Charles (2000); Morales (2010e)	✓	✓
<i>Synedra ulna</i>	(Nitzsch) Ehrenberg 1832	<i>Bacillaria ulna</i> Nitzsch 1817	Patrick & Reimer (1966); Bloom (2001)	✓	
<i>Tabellaria fenestrata</i>	(Longbye) Kutzing var. fenestrata Koppen 1975	<i>Diatoma fenestratum</i> Lyngbye 1819	Koppen (1975)	✓	✓

Araphids Continued					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Tabellaria flocculosa</i> var. (<i>strain IIIp</i>) sensu Koppen	sensu Koppen (Roth) Kutzing	<i>Conferva flocculosa</i> Roth 1797	Koppen (1975)	✓	
<i>Tabellaria flocculosa</i> var. (<i>strain IV</i>) sensu Koppen	sensu Koppen (Roth) Kutzing	<i>Conferva flocculosa</i> Roth 1797	Koppen (1975)	✓	

Asymmetrical Biraphids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Amphora ovalis</i> var. <i>affinis</i>	(Kützing) V. H. ex DeT.1891	<i>Amphora affinis</i> Kützing 1844	Patrick & Reimer (1975); Camburn & Charles (2000)	✓	✓
<i>Amphora</i> <i>pediculus</i>	(Kützing) Grunow in Schmidt 1875	<i>Cymbella pediculus</i> Kützing 1844	Spaulding et al. (2010); Cumming et al. (1995)	✓	
<i>Cymbella janischii</i>	(A. Schmidt) De Toni 1891	<i>Coconema janischii</i> A. Schmidt 1881	Krammer (2002); Patrick & Reimer (1975)	✓	
<i>Encyonema</i> <i>lunatum</i>	<i>Encyonema</i> <i>lunatum</i> (Smith) Van Heurck	<i>Cymbella lunata</i> W. smith 1855	Patrick & Reimer (1975); Camburn & Charles (2000)	✓	
<i>Cymbella</i> <i>neocistula</i>	Krammer 2002	<i>Cymbella neocistula</i> Krammer 2002	Krammer (2002)	✓	
<i>Cymbopleura</i> <i>cuspidata</i>	(Kützing) K. Krammer 2003	<i>Cymbella cuspidata</i> Kützing 1844	Patrick & Reimer (1975); Camburn & Charles (2000)	✓	✓
<i>Cymbopleura</i> <i>naviculiformis</i>	(Auerswald) Krammer 2003	<i>Cymbella naviculiformis</i> Auerswald ex Heiberg 1863	Bahls (2012b); Patrick & Reimer (1975); Krammer & Lange- Bertalot (1986)	✓	✓
<i>Encyonema</i> <i>elginense</i>	(Krammer) Mann in Round, Crawford & Mann 1990	<i>Cymbella elginensis</i> Krammer	Antoniades et al. (2008)	✓	

Asymmetrical Biraphids Continued					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Encyonema lunatum</i>	(W.Smith) Van Heurck 1896	<i>Cymbella lunata</i> W. Smith	Krammer & Lange-Bertalot (1986); Patrick & Reimer (1975)	✓	✓
<i>Encyonema minutum</i>	Hilse in Ravenhorst) Mann in Round, Crawford & Mann 1990	<i>Cymbella minuta</i> Hilse in Rabenhorst 1862	Antoniades et al. (2008)	✓	✓
<i>Encyonema reimeri</i>	Spaulding, Pool, et. Castro 2010	<i>Cymbella muelleri</i> Hustedt 1938	Spaulding et al. (2010); Patrick & Reimer (1975)	✓	✓
<i>Encyonema silesiacum</i>	(Bleisch in Rabenhorst) Mann in Round, Crawford & Mann 1990	<i>Cymbella silesiaca</i> Bleisch in Rabenhorst 1861-1882	Antoniades et al. (2008)	✓	
<i>Gomphoneis herculeana</i> var. <i>abundans</i>	Kociolek & Stoermer 1988	<i>Gomphoneis herculeana</i> var. <i>abundans</i> Kociolek & Stoermer 1988	Kociolek & Stoermer (1988)	✓	
<i>Gomphonema acuminatum</i>	Ehrenberg 1831	<i>Gomphonema acuminatum</i> Ehrenberg 1831	Patrick & Reimer (1975)	✓	
<i>Gomphonema angustatum</i>	(Kutzing) Rabhenhorst 1864	<i>Gomphonema angustatum</i> (Kutzing) Rabhenhorst 1864	Patrick & Reimer (1975); Krammer & Lange-Bertalot (1986)	✓	✓

Asymmetrical Biraphids Continued					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Gomphonema camburnni</i>	Metzeltin et Lange-Bertalot 1998	<i>Gomphonema camburnii</i> Metzeltin et Lange-Bertalot 1998	Camburn & Charles (2000)	✓	✓
<i>Gomphonema helveticum</i>	Brun 1895	<i>Gomphonema helveticum</i> Brun 1895	Krammer & Lange-Bertalot (1986)	✓	
<i>Gomphonema clavatum</i>	Ehrenberg 1832	<i>Gomphonema clavatum</i> Ehrenberg 1832	Patrick & Reimer (1975) (as subclavatum); Krammer & Lange-Bertalot (1986)	✓	
<i>Gomphonema gracile</i>	Ehrenberg 1838	<i>Gomphonema gracile</i> Ehrenberg 1838	Patrick & Reimer (1975); Krammer & Lange-Bertalot (1986)	✓	
<i>Gomphonema truncatum</i>	Ehrenberg 1832	<i>Gomphonema truncatum</i> Ehrenberg 1832	Krammer & Lange-Bertalot (1986)	✓	
<i>Gomphonema subtile</i>	Ehrenberg 1843	<i>Gomphonema subtile</i> Ehrenberg 1843	Patrick & Reimer (1975); Krammer & Lange-Bertalot (1986)	✓	
<i>Reimeria</i> c.f. <i>sinuata</i>	(Gregory) Kociolek & Stoermer 1987	<i>Cymbella sinuata</i> Gregory 1856	Kociolek & Stoermer (1987); Patrick & Reimer (1975)	✓	
<i>Rhoicosphenia abbreviata</i>	(Agardh) Lange-Bertalot 1980	<i>Gomphonema abbreviatum</i> Agardh 1831	Krammer & Lange-Bertalot (1986)	✓	

Centrics					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Aulacoseira alpigena</i>	(Grunow) Krammer 1991	<i>Melosira distans</i> var. <i>alpigena</i> Grunow in Van Heurck 1882	Potapova (2009e); Krammer & Lange-Bertalot (1991a)		✓
<i>Aulacoseira pusilla</i>	(Meister) Tuji and Houki 2004	<i>Melosira pusilla</i> Meister 1913	Tuji & Houki (2004); Tuji & Williams (2007); Potapova (2010a)	✓	
<i>Aulacoseira humilis</i>	(Cleve-Euler) Genkal & Trifonova in Trifonova & Genkal 2001	<i>Melosira distans</i> var. <i>humilis</i> Cleve-Euler 1939	English & Potapova (2010); Siver & Kling (1997)	✓	
<i>Aulacoseira lacustris</i>	(Grunow in Van Heurck) Krammer 1991	<i>Melosira lyrata</i> var. <i>lacustris</i> Grunow in Van Heurck	Siver & Kling (1997); Camburn & Charles (2000)	✓	
<i>Aulacoseira lirata</i>	(Ehrenberg) R. Ross in Hartley 1986	<i>Gaillonella lirata</i> Ehrenberg 1843	Siver & Kling (1997); Camburn & Charles (2000)	✓	✓
<i>Aulacoseira perglabra</i>	(Oestrup) Haworth 1988	<i>Melosira perglabra</i> Ostrup	Siver & Kling (1997); Camburn & Charles (2000)	✓	
<i>Aulacoseira subarctica</i>	(Muller) Haworth 1988	<i>Melosira italica</i> subsp. <i>subarctica</i> f. <i>recta</i> Muller 1906	Tuji & Houki (2004); Potapova & English (2010)	✓	
<i>Aulacoseira valida</i>	(Grunow in Van Heurck) Krammer 1991	<i>Melosira crenulata</i> var. <i>valida</i> Grunow in Van Heurck 1882	Camburn & Charles (2000)	✓	

Centrics Continued					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Cyclotella antiqua</i>	W. Smith 1853	<i>Cyclotella antiqua</i> W. Smith 1853	Camburn & Charles (2000)	✓	
<i>Cyclotella fottii</i>	Hustedt in Huber-Pestalozzi 1942	<i>Cyclotella fottii</i> Hustedt in Huber-Pestalozzi 1942	Krammer & Lange-Bertalot (1991a)	✓	
<i>Cyclotella</i> indeterminate cf. <i>rossii-ocellata</i>	--	--	--	✓	
<i>Cyclotella ocellata</i>	Pantocsek 1902	<i>Cyclotella ocellata</i> Pantocsek 1902	Cremer & Wagner (2001); Camburn & Charles (2000)	✓	
<i>Cyclotella rossii</i>	Hakansson 1990	<i>Cyclotella rossii</i> Hakansson 1990	Hakansson (1990); Cremer & Wagner (2001); Camburn & Charles (2000)	✓	
<i>Discostella stelligera</i>	(Cleve & Grunow) Houk & Klee 2004	<i>Cyclotella meneghiniana</i> v. <i>stelligera</i> Cleve & Grunow 1881	Houk & Klee (2004); Camburn & Charles (2000)	✓	✓
<i>Ellerbeckia aerenaria</i>	(Moore ex Ralfs) Crawford 1988	<i>Melosira aerenaria</i> Moore ex Ralfs 1843	Bahls (2012a); Krammer & Lange-Bertalot (1991a)	✓	

Centrics Continued					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Handmannia bodanica</i>	(Eulenstein ex Grunow) Kociolek & Khursevich	<i>Cyclotella bodanica</i> Grunow in Schneider	Khursevich & Kociolek 2012	✓	
<i>Melosira varians</i>	Agardh 1827	<i>Meloseira varians</i> Agardh 1827	Potapova (2009b); Krammer & Lange-Bertalot (1991a)	✓	
<i>Stephanodiscus alpinus</i>	Hustedt 1942	<i>Stephanodiscus alpinus</i> 1942	Hickel & Hakansson (1993)	✓	

Epithemioids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Epithemia adnata</i>	(Kutzing) Brebisson 1838	<i>Frustulia adnata</i> Kutzing 1838	Lowe (2010); Patrick & Reimer 1975	✓	
<i>Epithemia sores</i>	Kutzing 1844	<i>Epithemia sores</i> Kutzing 1844	Patrick & Reimer (1975)	✓	
<i>Epithemia turgida</i> var. <i>westermanni</i>	(Ehrenberg) Grunow 1862	<i>Navicula westermanni</i> Ehrenberg 1835	Patrick & Reimer (1975); Krammer & Lange-Bertalot (1988)	✓	
<i>Rhopalodia gibba</i>	(Ehrenberg) Otto Müller 1895	<i>Navicula gibba</i> Ehrenberg 1830	Patrick & Reimer (1975)	✓	

Eunotioids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Eunotia curvata</i>	(Grunow) Woodhead & Tweed 1954	<i>Synedra lunaris</i> var. <i>capitata</i> Crunow 1862	Patrick & Reimer (1966); Camburn & Charles (2000)	✓	✓
<i>Eunotia diadema</i>	Ehrenberg 1837	<i>Eunotia diadema</i> Ehrenberg 1837	Patrick & Reimer (1966); Camburn & Charles (2000)	✓	✓
<i>Eunotia flexuosa</i>	(Brebisson in Kützing) Kützing 1849	<i>Synedra flexuosa</i> Brébisson ex Kützing 1846	Patrick & Reimer (1966); Camburn & Charles (2000)	✓	✓
<i>Eunotia formica</i>	Ehrenberg 1843	<i>Eunotia formica</i> Ehrenberg 1843	Patrick & Reimer (1966); Camburn & Charles (2000)	✓	
<i>Eunotia incisa</i>	W. Smith ex Gregory 1854	<i>Eunotia incisa</i> W. Smith ex Gregory 1854	Patrick & Reimer (1966); Camburn & Charles (2000)	✓	
<i>Eunotia naegelii</i>	Migula 1907	<i>Eunotia naegelii</i> Migula 1907	Patrick & Reimer (1966); Camburn & Charles (2000)	✓	✓
<i>Eunotia pectinalis</i>	(Kützing) Rabenhorst 1864	<i>Himantidium pectinale</i> Kützing 1844	Patrick & Reimer (1966); Camburn & Charles (2000)	✓	
<i>Eunotia praerupta</i>	Ehrenberg 1843	<i>Eunotia praeruptamonos</i> var. <i>praeruptamonos</i> f. <i>polaris</i> A. Berg	Patrick & Reimer (1966); Camburn & Charles (2000)	✓	✓

Eunotioids Continued					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Eunotia praerupta</i> var. <i>monodon</i> f. <i>polaris</i>	(A. Berg) Symoens 1960	--	Camburn & Charles (2000)	✓	✓
<i>Eunotia tenella</i>	(Grunow in Van Heurck) Hustedt in Schmidt et al. 1913	<i>Eunotia arcus</i> var. <i>tenella</i> Grunow in Van Heurck 1881	Patrick & Reimer (1966)	✓	

Monoraphids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Achanthes obliqua</i>	(Gregory) Hustedt 1924	<i>Stauroneis obliqua</i> Gregory 1856	Krammer & Lange-Bertalot (1991b)	✓	✓
<i>Achnanthes stolidia</i>	(Krasske) Krasske 1949	<i>Navicula stolidia</i> Krasske 1939	Krammer & Lange-Bertalot (1991b); Bloom (2001)	✓	✓
<i>Achnantheidium exiguum</i>	(Grunow) Czarnecki 1994	<i>Achnanthes exigua</i> Grunow in Cleve & Grunow 1880	Potapova (2010b); Bloom (2001); Patrick and Reimer (1966)	✓	
<i>Achnantheidium gracillimum</i>	(Meister) Lange-Bertalot in Krammer & Lange-Bertalot 2004	<i>Microneis gracillima</i> Meister 1912	Potapova (2010c)	✓	
<i>Achnantheidium minutissimum</i>	(Kützing) Czarnecki 1994	<i>Achnanthes minutissima</i> Kützing 1833	Potapova (2009c)	✓	✓
<i>Cocconeis placentula</i>	Ehrenberg 1838	<i>Cocconeis placentula</i> Ehrenberg 1838	Patrick & Reimer (1966)	✓	
<i>Cocconeis placentula</i> var. <i>euglypta</i>	(Ehrenburg) Cleve 1895	<i>Cocconeis euglypta</i> Ehrenberg 1854	Patrick & Reimer (1966)	✓	
<i>Cocconeis rugosa</i>	Sovereign 1958	<i>Cocconeis rugosa</i> Sovereign 1958	Sovereign (1958); Patrick & Reimer (1966)	✓	
<i>Eucoocconeis alpestris</i>	(Brun) Lange-Bertalot in Lange-Bertalot & Genkal 1999	<i>Achnanthes flexella</i> var. <i>alpestris</i> Brun 1880	Potapova (2010d); Patrick & Reimer (1966)	✓	

Monoraphids Continued					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Karayevia amoena</i>	(Hustedt) Bukhtiyarova 2006	<i>Achnanthes amoena</i> Hustedt 1952	Potapova (2010e); Krammer & Lange-Bertalot (1991b)	✓	✓
<i>Karayevia clevei</i>	(Grunow) Bukhtiyarova 1999	<i>Achnanthes clevei</i> Grunow in Cleve & Grunow 1880.	Potapova (2010f); Patrick & Reimer (1966)	✓	
<i>Karayevia laterostrata</i>	(Hustedt) Bukhtiyarova 1999	<i>Achnanthes laterostrata</i> Hustedt 1933	Potapova (2010g); Krammer & Lange-Bertalot 1991	✓	
<i>Karayevia suchlandtii</i>	(Hustedt) Bukhtiyarova	<i>Achnanthes suchlandtii</i> Hustedt 1933	Potapova (2010h); Patrick & Reimer (1966)	✓	
<i>Planothidium apiculatum</i>	(Patrick) Lange-Bertalot 1999	<i>Achnanthes lanceolata</i> var. <i>apiculata</i> Patrick 1945	Patrick & Reimer (1966); Potapova (2010i)	✓	
<i>Planothidium calcar</i>	(Cleve) M.B. Edlund in M.B. Edlund, N. Soninkhishig, R.M. Williams, & E.F. Stoermer 2001	<i>Achnanthes calcar</i> Cleve 1891	Bahls (2005); Krammer & Lange-Bertalot (1991b)	✓	
<i>Planothidium frequentissimum</i>	(Lange-Bertalot in Krammer & Lange-Bertalot) Lange-Bertalot 1999	<i>Achnanthes lanceolata</i> subsp. <i>frequentissima</i> Lange-Bertalot 1993	Potapova (2010j); Patrick & Reimer (1966)	✓	

Monoraphids Continued					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Planothidium haynaldii</i>	(Schaarschmidt) Lange-Bertalot 1999	<i>Achnanthes haynaldii</i> Schaarschmidt 1881	Potapova (2011a)	✓	
<i>Planothidium oestrupii</i>	(Cleve-Euler) M.B. Edlund 2001	<i>Achnanthes lanceolata</i> var. <i>oestrupii</i> Cleve-Euler	Krammer & Lange-Bertalot (1991b)	✓	
<i>Planothidium peragallii</i>	(Brun & Héribaud) Round et Bukhtiyarova 1996	<i>Achnanthes peragallii</i> Brun & Héribaud	Patrick & Reimer (1966); Krammer & Lange Bertalot (1991b)	✓	
<i>Planothidium</i> sp. 1	--	--	--	✓	
<i>Platessa hustedtii</i>	(Krasske) Lange-Bertalot in Krammer & Lange-Bertalot 2004	<i>Cocconeis hustedtii</i> Krasske 1923	Potapova (2011b)	✓	
<i>Platessa stewartii</i>	(Patrick) Potapova 2004	<i>Achnanthes stewartii</i> Patrick 1945	Potapova (2010k)	✓	
<i>Psammothidium curtissimum</i>	(Carter) Aboal in Aboal, Alvarez-Cobelas, Cambra & Ector 2003	<i>Achnanthes curtissima</i> Carter 1963	Potapova (2010l); Bloom (2001)	✓	✓
<i>Psammothidium didymum</i>	(Hustedt) Bukhtiyarova et Round 1996	<i>Achnanthes didyma</i> Hustedt 1933	Potapova (2010m); Bloom (2001)	✓	✓

Monoraphids Continued					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Psammothidium levanderi</i>	(Hustedt) Bukhtiyarova & Round 1996	<i>Achnanthes levanderi</i> Hustedt 1933	Potapova (2010n); Camburn & Charles 2000; Bloom (2001)	✓	✓
<i>Psammothidium marginulatum</i>	(Grunow) Bukhtiyarove et Round 1996	<i>Achnanthes marginulata</i> Grunow in Cleve & Grunow 1880	Potapova (2010o); Krammer & Lange-Bertalot (1991b)	✓	✓
<i>Psammothidium ventralis</i>	(Krasske) Bukhtiyarova et Round 1996	<i>Navicula ventralis</i> Krasske	Krammer & Lange-Bertalot (1986); Camburn & Charles (2000)	✓	
<i>Rossithidium pusillum</i>	(Grunow) Round et Bukhtiyarova 1996	<i>Achnanthes pusilla</i> Grunow 1880	Potapova (2009d); Bloom (2001); Camburn & Charles (2000)	✓	✓

Nitzschioids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Nitzschia acicularis</i>	(Kützing) W. Smith 1853	<i>Synedra acicularis</i> Kützing 1844	Kociolek (2011a)	✓	
<i>Nitzschia bacillum</i>	Hustedet 1922	<i>Nitzschia bacillum</i> Hustedt 1922	Krammer and Lange-Bertalot (1988)	✓	✓
<i>Nitzschia dissipata</i>	(Kützing) Grunow 1862	<i>Synedra dissipata</i> Kützing 1844	Manoylov (2010); Krammer and Lange-Bertalot (1988)	✓	✓
<i>Nitzschia fonticola</i>	(Grunow) Grunow in Van Heurck 1881	<i>Nitzschia palea</i> var. <i>fonticola</i> Grunow 1880	Krammer and Lange-Bertalot (1988)	✓	
<i>Nitzschia gracilis</i>	Hantzsch 1860	<i>Nitzschia gracilis</i> <i>Hantzsch 1860</i>	Krammer and Lange-Bertalot (1988)	✓	
<i>Nitzschia hantzschiana</i>	Rabenhorst 1860	<i>Nitzschia hantzschiana</i> Rabenhorst 1860	Krammer and Lange-Bertalot (1988)	✓	
<i>Nitzschia innominata</i>	Sovereign 1958	<i>Nitzschia innominata</i> Sovereign 1958	Sovereign (1958)	✓	
<i>Nitzschia intermedia</i>	Hantzsch ex Cleve and Grunow 1880	<i>Nitzschia intermedia</i> Hantzsch ex Cleve and Grunow 1880	Krammer and Lange-Bertalot (1988)	✓	
<i>Nitzschia liebetruthii</i>	Rabenhorst 1864	--	Krammer and Lange-Bertalot (1988)	✓	
<i>Nitzschia paleacea</i>	Grunow in Van Heurck 1881	<i>Nitzschia paleacea</i> Grunow in Van Heurck 1881	Kociolek (2011b); Krammer and Lange-Bertalot (1988)	✓	✓

Nitzschioids Continued					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Nitzschia perminuta</i>	(Grunow in Van Heurck) Peragallo 1903	<i>Nitzschia frustulum</i> var. <i>perminuta</i> Grunow in Van Heurck 1881	Krammer and Lange-Bertalot (1988)	✓	✓
<i>Nitzschia tubicola</i>	Grunow in Cleve & Grunow 1880	<i>Nitzschia tubicola</i> Grunow in Cleve & Grunow 1880	Krammer and Lange-Bertalot (1988)	✓	✓

Symmetrical Biraphids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Amphipleura pellucida</i>	Kützing 1844	<i>Frustulia pellucida</i> Kützing 1833	Patrick & Reimer (1966)	✓	
<i>Brachysira brebissonii</i>	Ross in Hartley 1986	<i>Navicula aponica</i> var. <i>brachysira</i> Breb. Ex. Kützing 1849	Hamilton (2010)	✓	✓
<i>Caloneis hyalina</i>	Hustedt 1937	<i>Caloneis hyalina</i> Hustedt 1937	Patrick & Reimer (1966)	✓	
<i>Caloneis</i> (cf. <i>fasciata</i>)	(Lagerstedt) Cleve 1894	<i>Navicula fasciata</i> Lagerstedt 1873	Antoniades et al. (2008)	✓	
<i>Caloneis undosa</i>	(Gregory) Krammer 1985	<i>Pinnularia undulata</i> Gregory 1854	Camburn & Charles (2000)	✓	✓
<i>Cavinula cocconeiformis</i>	(Gregory ex Greville) Mann & Stickle in Round, Crawford & Mann 1990	<i>Navicula cocconeiformis</i> Gregory ex Greville 1855	Patrick and Reimer (1966); Camburn & Charles (2000); Otu & Spaulding (2011a)	✓	
<i>Cavinula jaernefeltii</i>	(Hustedt) D.G. Mann & A.J. Stickle 1990	<i>Navicula jaernefeltii</i> Hustedt 1942	Antoniades et al. (2008)	✓	
<i>Cavinula pseudoscutiformis</i>	(Hustedt) Mann & Stickle in Round, Crawford & Mann 1990	<i>Navicula pseudoscutiformis</i> Hustedt in Pasch. 1939	Patrick and Reimer (1966); Antoniades et al. (2008); Otu & Spaulding (2011b)	✓	

Symmetrical Biraphids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Cavinula scutiformis</i>	(Grunow ex A. Schmidt) Mann & Stickle in Round, Crawford & Mann 1990	<i>Navicula scutiformis</i> Grunow in Schmidt et al. 1881	Patrick & Reimer (1966), Round et al. (1990)	✓	
<i>Cymbella amphioxys</i>	(Kützing) Cleve 1894	<i>Navicula amphioxys</i> Kützing 1844	Krammer & Lange-Bertalot (1986); Camburn & Charles (2000)	✓	
<i>Diploneis elliptica</i>	(Kützing) Cleve 1891	<i>Navicula elliptica</i> Kützing 1844	Patrick & Reimer (1966)	✓	
<i>Diploneis marginestriata</i>	Hustedt 1922	<i>Diploneis marginestriata</i> Hustedt 1922	Camburn and Charles (2000); Patrick and Reimer (1966)	✓	✓
<i>Frustulia amphipleuroides</i>	(Grunow) Cleve-Euler 1934	<i>Navicula rhomboides</i> var. <i>amphipleuroides</i> Grunow 1880	Kociolek & Graeff (2011a)	✓	✓
<i>Frustulia quadrisinuata</i>	Lange-Bertalot 1996	<i>Frustulia quadrisinuata</i> Lange-Bertalot 1996	Graeff (2012); Lange-Bertalot (2001)	✓	✓
<i>Frustulia rexii</i>	Graeff & Kociolek in Graeff et al. 2012	<i>Frustulia rexii</i> Graeff & Kociolek in Graeff et al. 2012	Graeff (2011)	✓	✓

Symmetrical Biraphids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Frustulia rhomboides amphipleuroides</i>	(Grunow in Cleve & Grunow) De Toni 1891	<i>Navicula rhomboides</i> var. <i>amphipleuroides</i> Grunow in Cleve & Grunow 1880	Patrick & Reimer (1966)	✓	
<i>Frustulia saxonica</i>	Rabenhorst 1850	<i>Frustulia saxonica</i> Rabenhorst 1853	Kociolek & Graeff (2011b)	✓	✓
<i>Geissleria kreigeri</i>	(Kraske) Lange-Bertalot in Lange-Bertalot & Metzeltin 1996	<i>Navicula kriegeri</i> Kraske 1943	Potapova (2010p)	✓	
<i>Navicula</i> spp.	--	--	--	✓	✓
<i>Navicula absoluta</i>	Hustedt 1950	<i>Navicula absoluta</i> Hustedt 1950	Krammer & Lange-Bertalot (1986); Camburn & Charles (2000)	✓	
<i>Navicula</i> c.f. <i>arctotenelloides</i>	Lange-Bertalot & Metzeltin in Lange-Bertalot et al. 1996	Lange-Bertalot & Metzeltin in Lange-Bertalot et al. 1996	Lange-Bertalot (2001)	✓	
<i>Navicula aurora</i>	Sovereign 1958	<i>Navicula aurora</i> Sovereign 1958	Patrick & Reimer (1966); Sovereign (1958)	✓	
<i>Navicula</i> cf. <i>leptostriata</i>	Jørgensen 1948	<i>Navicula leptostriata</i> Jørgensen 1948	Lange-Bertalot (2001)	✓	✓
<i>Navicula costulata</i>	Grunow in Cleve & Grunow 1880	<i>Navicula costulata</i> Grunow 1880	Patrick & Reimer (1966); Krammer 2001	✓	

Symmetrical Biraphids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Navicula cryptotenella</i>	Lange-Bertalot in Krammer & Lange-Bertalot 1985	<i>Navicula cryptotenella</i> Lange-Bertalot in Krammer & Lange-Bertalot 1985	Krammer & Lange-Bertalot (1986)	✓	✓
<i>Navicula detenta</i>	Hustedt 1943	<i>Navicula detenta</i> Hustedt 1943	Krammer & Lange-Bertalot (1986)	✓	
<i>Navicula minima</i> (<i>Eolimnia minima</i>)	Grunow in Van Heurck 1880	<i>Navicula minima</i> Grunow 1880	Camburn & Charles (2000); Krammer & Lange-Bertalot (1986)	✓	
<i>Navicula pseudolanceolata</i>	Lange-Bertalot 1980	<i>Navicula pseudolanceolata</i> Lange-Bertalot 1980	Lange-Bertalot (2001)	✓	
<i>Navicula pseudoventralis</i>	Hustedt in Schmidt et al. 1936	<i>Navicula pseudoventralis</i> Hustedt in Schmidt et al. 1936	Cumming et al. (1995); Krammer & Lange-Bertalot (1986)	✓	
<i>Navicula radiosa</i>	Kützing 1844	<i>Navicula radiosa</i> Kützing 1844	Bahls (2005); Patrick & Reimer (1966)	✓	✓
<i>Navicula rhynchocephala</i>	Kützing 1844	<i>Navicula rhynchocephala</i> Kützing 1844	Krammer & Lange-Bertalot (1986)	✓	✓
<i>Navicula seminuloides</i>	Hustedt 1937	<i>Navicula seminuloides</i> Hustedt 1937	Camburn & Charles (2000)	✓	
<i>Sellaphora seminulum</i>	(Grunow) D.G. Mann 1989	<i>Navicula seminulum</i> Grunow 1860	Patrick & Reimer (1966); Camburn & Charles (2000)	✓	

Symmetrical Biraphids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Neidium bisulcatum</i> var. <i>subundulatum</i>	(Grunow) Reimer comb. nov.	<i>Navicula firma</i> var. <i>subundulata</i> Grunow ex A. Schmidt et al. 1877	Patrick & Reimer (1966)	✓	✓
<i>Neidium iridis</i>	(Ehrenberg) Cleve 1894	<i>Neidium iridis</i> Ehrenberg	Patrick & Reimer (1966)	✓	✓
<i>Neidium iridis</i> var. <i>ampliatum</i>	(Ehrenberg; Ehrenberg) Cleve 1894	<i>Navicula ampliata</i> Ehrenberg 1854	Patrick & Reimer (1966)	✓	
<i>Nupela carolina</i>	Potapova & Clason in Potapova et al. 2003	<i>Nupela carolina</i> Potapova and Clason 2003	Potapova (2010q); Potapova et al. (2003)	✓	
<i>Nupela neogracillima</i>	M. Kulikovskiy, H. Lange-Bertalot & A. Witkowski 2009	<i>Achnanthes gracillima</i> Hustedt 1927	Foged (1981)	✓	
<i>Nupela</i> spp.	--	--	--	✓	✓
<i>Nupela</i> sp. FLL 1	--	--	--	✓	
<i>Nupela</i> sp. FLL 2	--	--	--	✓	
<i>Navicula farta</i>	Hustedt in Schmidt et al. 1934	<i>Navicula farta</i> Hustedt in Schmidt et al. 1934	Foged (1981)	✓	
<i>Pinnularia abaujensis</i> var. <i>linearis</i>	(Hustedt) Patrick 1966	<i>Pinnularia gibba</i> var. <i>linearis</i> Hustedt 1930	Patrick & Reimer (1966)	✓	
<i>Pinnularia neomajor</i> var. <i>inflata</i>	K. Krammer 2000	<i>Pinnularia neomajor</i> var. <i>inflata</i> K. Krammer 2000	Krammer (2000)	✓	

Symmetrical Biraphids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Pinnularia nodosa</i> var. <i>percapitata</i>	<i>Pinnularia nodosa</i> var. <i>percapitata</i> Krammer 2000	--	Krammer (2000)	✓	✓
<i>Pinnularia termitina</i>	(Ehrenberg) Patrick 1966	<i>Pinnularia termitina</i> Ehrenberg 1854	Patrick & Reimer (1966); Camburn & Charles (2000)	✓	✓
<i>Placoneis porifera</i>	(Hustedt) E.J. Cox 2003	<i>Navicula porifera</i> Hustedt 1944	Krammer & Lange-Bertalot (1986)	✓	
<i>Sellaphora bacillum</i>	(Ehrenberg) D.G. Mann 1989	<i>Navicula bacillum</i> Ehrenberg	Patrick & Reimer (1966)	✓	
<i>Sellaphora pupula</i>	(Kützing) Mereschkowsky 1902	<i>Navicula pupula</i> Kützing 1844	Lange-Bertalot (2001); Patrick & Reimer (1966)	✓	✓
<i>Sellaphora seminulum</i>	(Grunow) D.G. Mann 1989	<i>Navicula seminulum</i> Grunow 1860	Patrick & Reimer (1966); Krammer & Lange-Bertalot (1986)	✓	✓
<i>Sellaphora vitabunda</i>	<i>Navicula vitabunda</i> Hustedt 1930 (Hustedt) D.G. Mann 1989	<i>Navicula vitabunda</i> Hustedt 1930	Krammer & Lange-Bertalot (1986)	✓	
<i>Stauroneis anceps</i> f. <i>gracilis</i>	Rabhenhorst 1864	<i>Stauroneis anceps</i> f. <i>gracilis</i> Rabenhorst 1864	Cumming et al. (1995)	✓	✓
<i>Stauroneis anceps</i>	Ehrenberg 1843	<i>Stauroneis anceps</i> Ehrenberg 1843	Patrick & Reimer (1966); Bahls (2011)	✓	

Symmetrical Biraphids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Stauroneis smithii</i>	Grunow 1860	<i>Stauroneis smithii</i> Grunow 1860	Foged (1981); Kelly et al. (2005)	✓	

Surirelloids					
Species	Attribution	Basionym	Identifying Reference	Present in Fallen Leaf Lake	Present in Gilmore Lake
<i>Stenopterobia curvula</i>	(W. Smith) Krammer ex Krammer & Lange-Bertalot 1987	<i>Nitzschia curvula</i> W. Smith 1856	Camburn & Charles (2000)	✓	
<i>Stenopterobia</i> spp.	--	--	--	✓	✓
<i>Surirellaspp.</i>	--	--	--	✓	✓
<i>Surirella linearis</i>	W. Smith 1853	<i>Surirella linearis</i> W. Smith 1853	Foged (1981)	✓	✓
<i>Surirella linearis</i> var. <i>lacus-karluki</i>	Manguin ex Kociolek & Reviers 1996	<i>Surirella linearis</i> var. <i>lacuskarluki</i> Manguin 1961	Foged (1981)	✓	