

Report on the Nuisance Sediment Found in Paradise Lake

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Abstract

The Paradise Lake Improvement Board contracted the University of Michigan Biological Station to perform field- and laboratory analyses in the summer of 2017 with the goal of identifying and understanding the appearance of a nuisance sediment in the Southeast Basin of Paradise Lake (Emmet Co., MI). Microscopic examination of the material found that it was comprised primarily of coarse- and fine organic material. Specifically, fragments of *Myriophyllum* sp. (Eurasian Watermilfoil) and filamentous algae known to be epiphytic on *Myriophyllum* sp. (*Mougeotia* sp., *Oedogonium* sp., and *Spirogyra* sp.). A comprehensive suite of trace metal isotopes and organic stable isotopes (92 isotopic ratios in total) were run on samples (32) of sediment and plant material collected from throughout the lake. Hierarchical Cluster Analysis was used to explore cladistic relationships between samples. Modelling found that, among all possible comparisons, the strongest relationship in the entire dataset was exhibited between samples of detached *Myriophyllum* sp. which were taken from the NW basin of the lake and the nuisance sediment collected along the shore of the SE basin. Exploration of these same trace metals as well as nutrient- and other physico-chemical parameters in water samples collected concurrently with sediment- and plant samples suggests that suspended and dissolved material is transported from the NW basin (where parameters are substantially elevated above the relatively undisturbed E basin) and well into the SE basin.

Background.

Paradise Lake is a part of the Carp River watershed. The lake has a surface area of 1,900 acres and is a relatively shallow lake, with the deepest recorded depth at around 5 meters. Paradise Lake has a moderate level of productivity from an abundance of aquatic plants and algae in the water column, which are due to the shallow nature of the lake allowing for light penetration to the benthos. The shore of the lake is inhabited by lake residents on all sides, and Carp Lake Township is located on the Northwestern bay of the lake. The watershed as a whole is predominantly undeveloped forest, wetland, and grassland.

Long-term water chemistry from surveys conducted by Tip of the Mitt Watershed Council (TOMWC; Appendix A1) indicate that the lake is experiencing elevated benthic P loadings compared to historic records. This corresponds to the highest average Chlorophyll-*a* concentration since ca. 2010 when levels were below detection limit (Appendix A2). Chloride levels have remained relatively constant since ca. 2004, indicating that terrestrial inputs from overland flow may have reached some sort of equilibrium since that time. It should be noted, however, that the TOMWC sampling is performed soon after ice-out (April), and so may not be entirely indicative of the trophic status of the lake during algal/diatom blooms (or when the local population has reached its maximum), it is however a conservative indicator of the “background” trophic processes occurring at the ecosystem level. Concurrent observations of Chlorophyll-*a* in Paradise Lake find that, on average, peak productivity in the lake (proxied by Chlorophyll-*a*) is in mid-July. Secchi depth at the established TOMWC sampling point indicates that light readily reaches the benthos in this system (Appendix A3).

In 2010, a Paradise Lake Management Plan was developed by Paul Moore (Bowling Green State University) and some of his undergraduate students from the University of Michigan Biological Station Limnology course. This plan focused on three problems: an invasion of Eurasian milfoil, the presence of invasive zebra mussels, and unusual nutrient levels (Moore et al., 2009). The plan proposed several options for dealing with the three problems found on this lake including a boat washing station to prevent the spread of milfoil and zebra mussels, which was implemented.

The lake has a previous history of an abundance of Eurasian watermilfoil (*Myriophyllum spicatum*), especially in the Northwestern basin of the lake (Moore et al., 2009). The problem stems back to more than 7 years ago. Milfoil is a submersed, perennial aquatic plant that typically grows in water around one to four meters deep, and obtains most of its nutrients through its root system (Smith, C. S., & Barko, J. W., 1990). Dispersal of milfoil occurs primarily via fragmentation when the plant is fragmented by natural disturbances such as water turbulence, and by human-caused disturbances such as boats cutting through the milfoil (Madsen, J. D., & Smith, D. H., 1997).

In an effort to reduce the abundance of the Eurasian milfoil, a laminar flow array was installed in 2010. The main function of this technology is to increase available oxygen (O₂) in an aquatic system through aeration. Low oxygen levels (anoxic conditions) reduce animal life and allow the milfoil to take over all depths in the lake. Aeration systems prevent anoxic conditions from spreading throughout the entire lake by adding oxygen to the water and to keep the organisms

that are dependent on higher oxygen levels (e.g., those that consume milfoil) to survive and inhabit the upper strata of the lake (DeMoyer et. al, 2003).

Riparian residents report that nuisance muck appeared on the Southeast Basin shortly after the bubbler was put in place, and has a habit of appearing on shore every summer following ca. July 4th. Some riparian landowners speculate that the nuisance muck was showing up at the Southeast Basin because of prevailing winds depositing sediment turned up from the bubbler. The composition of the muck was assayed twice by two independent analysts and found to be comprised of degraded and partially-degraded plant material of unknown origin.

The aim of this study is to understand the origin and composition of the nuisance sediment and identify the means by which it is transported or appears in the Southeast Basin of the lake and to develop actionable items in an effort to ameliorate the impact.

Analytical Approach.

Stable isotope analysis is a powerful tool for unraveling the local source of a material in question, particularly in cases of analyzing plant material where the nutrient constituents come approximately from a single location. As a plant grows, it takes on the isotopic signature of its surroundings, effectively becoming “labeled” by the available nutrients, and so forming a unique chemical fingerprint that is indicative of a specific parent location. Simultaneously employing multiple different stable isotope ratios increases statistical resolution between samples that might exhibit similar ratios for one- or two elements.

An increasing number of stable isotopes requires increasingly complex statistical analyses, owing to the inherent multicollinear nature of such datasets. Statistical analyses based on Principal Components Analysis (Bro and Smilde, 2014) actually utilize multicollinearity to group samples based upon their similarity, and provide substantially greater stability when confronted with several multicollinear covariates. Cladistic approaches to classifying plants, animals, and even genetics routinely employ such methods (Durrant et al 2006) and the growing field of chemometrics is in fact based upon this same approach, but with emphasis on applying it toward classification of unknown materials in complex media. As such, PCA-based Hierarchical Cluster Analysis provides an ideal tool for utilizing a multi-isotope approach to discern which locale within the lake a sample of sediment probably originated.

Methods and Materials

In-situ Sampling

Preliminary field scouting was performed on July 6, 2017, and consisted of benthic coring and surface water collection within the South Basin. A sample of the nuisance sediment was collected and subsequently analyzed (Appendix B). Ground water from residential wells was also collected to characterize potential nearshore mixing.

On July 31st, 2017, samples were collected in Paradise Lake at 9 different data collection sites on the lake based on prevailing winds and water flow (sample locations are indicated in Figure 1). Sites 1-6 followed the perceived flow of wind and water from the center of the bubbler array, site 1, to the Southeast basin containing the muck, site 6. Sites 7-9 were located in the Eastern Basin and were used as control sites because they were not downwind from the laminar flow array. Site 10 was selected as the site for the soil core because it was one of the deepest locales on the lake.

Water Chemistry

At each site (1-9), a Eureka Manta 2 multiparameter sonde was used to measure physical characteristics (pH, temperature, dissolved oxygen). Wind directionality and speed was taken with an anemometer and compass. Water samples were obtained using a Horizontal Van Dorn water bottle. Samples were taken near the surface of the lake and just above the lake floor. For each Van Dorn water bottle sample, a syringe and filter were used to transfer water from the Van Dorn sample into a 250 mL acid-washed bottle for chemical analysis.

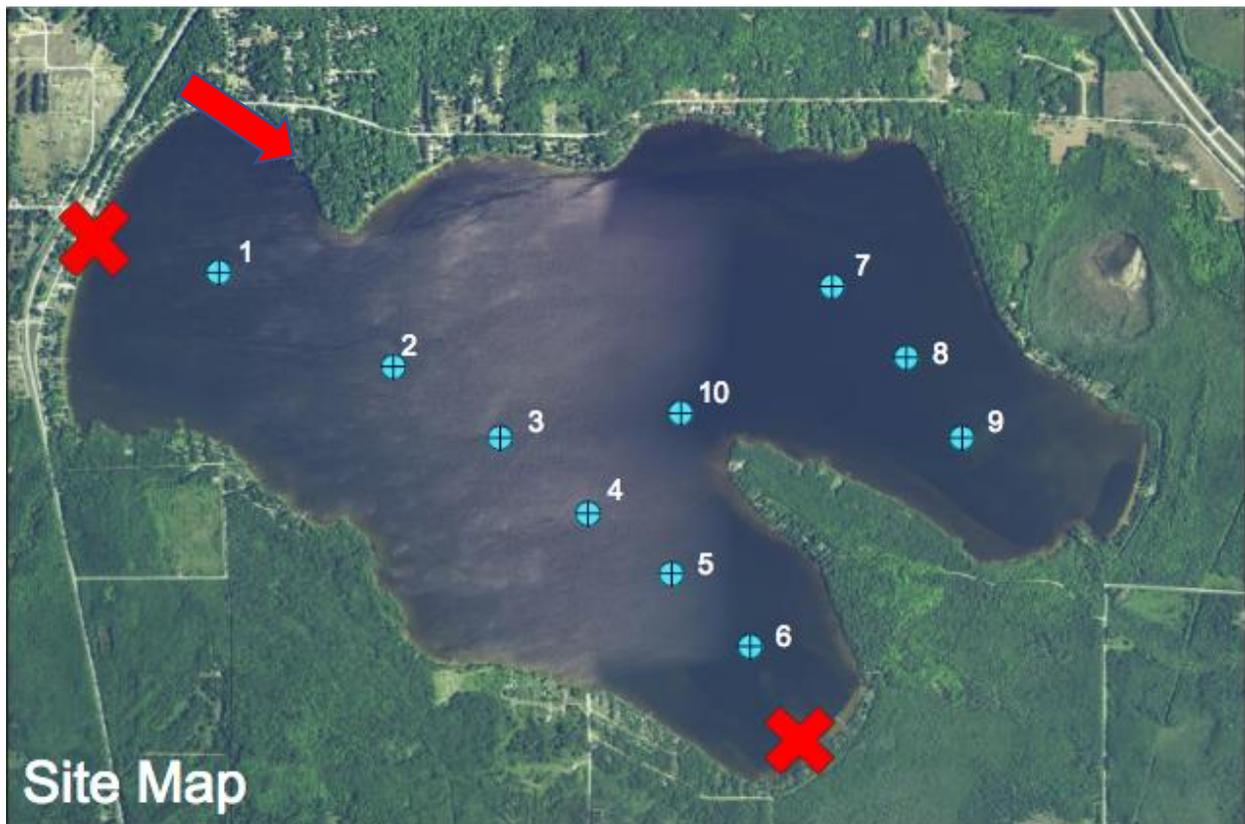


Figure 1. Map of the selected collection sites of Lake Paradise. Sites 1-6 move downwind (prevailing wind indicated by red arrow) from the bubbler to the site of where the nuisance sediment appears. Sites 7-9 were used as control sites. A sediment core was taken at site 10.

Sediment Chemistry

At sites 1-9, an Ekman grab was used to collect sediment of the benthic layer of the lake. From this grab, a sample of the upper benthic sediment was packaged into a Whirl-pak for lab analysis. At site 10, a short gravity corer was used to obtain a sediment core of the lake bottom. The core was obtained at approximately the deepest point in the lake (2.4 meters) in order to minimize the effects of sediment mixing. The core was separated into different cross-sections at each 1 cm interval and separated into individual Whirl-paks. The individual Whirl-paks were used for chemical analysis and a diatom community analysis to reconstruct historical conditions in the lake. Additionally, samples of the nuisance sediment were collected at the Southeastern shore for chemical analysis.

Aquatic Macrophyte Census

At sites 1-9 a plant rake was deployed from four sides of the boat. Plants were separated by plant type (species or common name). Each plant type was given a percentage that expressed the representation each plant provided on the plant community. Samples of each plant were placed into Whirl-paks and brought back to the laboratory for further identification and chemical analysis. Milfoil that was washed up on the northwest shore of Paradise Lake adjacent to the public boat launch (generally upwind of the bubbler array system) was also collected for chemical analysis.

Lab Techniques

Water Chemistry

Water samples were analyzed for major dissolved anions using high-performance ion chromatography (ThermoFisher/Dionex Integrion; EPA M300.0), for ammonium (Seal Analytical AA3; EPA M350.1), total nitrogen (Seal Analytical AA3; EPA M353.2) and total phosphorous (Seal Analytical AA3; EPA M365.3) using automated colorimetry. Trace metals and their isotopic ratios were analyzed by inductively-coupled plasma mass spectrometry (Perkin Elmer ELAN DRC-e; EPA M200.8). These data are presented in **Appendix C**.

Sediment and Macrophyte Chemistry

Abundance and isotope ratios of C, N, O, and H in sediment and macrophyte samples were determined using a continuous-flow elemental analyzer-gas isotope ratio mass spectrometer system (ThermoFisher Scientific Delta V). Following acid digestion, sediment and macrophyte trace metals and their isotopic ratios were analyzed by inductively-coupled plasma mass spectrometry (Perkin Elmer ELAN DRC-e; EPA M200.8) These data are presented in **Appendix C**.

Sediment History

The sediment core taken at site 10 was cross-sectioned into 26 1-inch layers. Each cross-section was analyzed for C, N, O, H and trace metals as above. The topmost and bottommost slides were analyzed for diatom genera presence and relative abundance. Diatoms were identified using compound light microscopes, immersion oil, and naphrax mounting media.

Statistical Analyses

Material Classification

All multivariate analyses were performed using PLS_Toolbox (Eigenvector Research, Inc.) in Matlab (Mathworks, Inc.). Data representing the isotopic signatures of nuisance sediment, aquatic macrophyte and benthic sediment samples were analyzed first using Principal Components Analysis following recommendations in Bro and Smilde (2014) and then further by Ward's Method of Hierarchical Cluster Analysis built from the resulting PCA model. The PCA model consisted of 17 principal components, covering >95% of dataset variance (Q residual = 4.77%).

Dataset Exploration (Water)

Physico-chemical data were imported into ArcGIS (ESRI, Inc.) to explore geospatial dissolved-phase chemistry patterns using Kriged contour maps. Apparent geospatial trends were further investigated for significance using univariate statistics (SPSS).

Results and Discussion

Material Classification

The nuisance sediment collected in the Southeast basin of the lake exhibited the strongest match with detached milfoil collected in the Northwest basin (Fig 2). In fact, the similarity between these two samples was by far the best match of any pairwise comparison in the dataset. The nuisance material did not bear any similarity with sediment samples originating within the

Northwest basin (nor elsewhere). This is in keeping with the light microscopy findings that the nuisance material was comprised of partially-degraded plant and algae tissues. Given the relatively strong isotopic similarity between the milfoil found in the Northwest basin and the nuisance material found along Blake Drive, it is probable that the source of the nuisance material is the milfoil found in the Northwest basin of the lake.

Characterizing Transport

Water in the Northwest basin exhibits considerably elevated levels of rare trace metals relative to other locales in the lake, possibly as a result of continued sediment disturbance by the laminar flow array. Mapping the concentration of these analytes illustrates a probable correlation with the predominant northwesterly winds present on the lake. An approximately linear decline in concentration, with distance (R^2 0.69-0.97) in 16 metals (Al, As, Ag, Ba, Bi, Ca, Cr, Fe, Ga, Mg, Li, Mn, Ni, Pb, Se, Sr, V, Zn) along the transect spanning from PL1-6 supports the hypothesis of transport following the direction of the prevailing winds. These same 16 metals are significantly (one-tailed T-test $p < 0.05$) elevated above samples taken from the control basin, indicating that transport from the Northwest basin conceivably reaches fully into the Southeast basin.

Characterizing Physico-Chemical Conditions and Plant Communities

On the whole, sampling within Paradise Lake did not indicate an apparent overabundance of dissolved nutrients (Appendix C), though sites PL1 and PL8 exhibited an order of magnitude higher $\text{NH}_4^+\text{-N}$ in samples taken from just above the lake bed. Water temperature sampled just above the benthos at PL1 was the coldest of any sampled (22.86 °C) while PL6 was the warmest (25.57 °C), though the relationship between the sites may be either a function of depth ($R^2 = 0.8195$, $F < 0.01$), or a proximity to the laminar flow array ($R^2 = 0.8478$, $F < 0.01$). Examination of ^{238}U (indicative of groundwater inputs) for a relationship between either covariate did not indicate substantially variable groundwater inputs along the transect. Dissolved oxygen and $\text{NH}_4\text{-N}$ showed a linear relationship ($R^2 = 0.88$, $F < 0.01$), with DO being lowest where $\text{NH}_4\text{-N}$ was highest. In this case, PL1 and PL8 exhibited the lowest benthic DO (3.75 and 6.5 mg/L, respectively), and the highest $\text{NH}_4\text{-N}$ (231.3 and 112.7 $\mu\text{g NH}_4\text{-N/L}$, respectively) whereas the rest of the lake was generally near saturation with DO and below ca. 20 $\mu\text{g NH}_4\text{-N/L}$. Given that $\text{NH}_4\text{-N}$ typically forms in anoxic- or hypoxic conditions during the degradation of organic material, it is not surprising that these phenomena were noted near well-established benthic macrophyte beds. That this phenomenon was observed near the laminar flow array does seem to indicate the potential for anoxic conditions in the event of a sudden massive dieoff of benthic macrophytes (e.g., in the case of herbicide application), particularly if the use of the laminar flow array was ceased concomitantly.

Sediment Record

Chemical analysis of the core taken at Site 10 indicates that metal deposition into the lake exhibits some modality with depth (Fig. 5) Most metals and phosphorous appear to exhibit some nominal background stability from 50-30 cm, then increase sigmoidally from 30 cm to the top of the core, with an asymptote at ca. 10 cm. The Anthropogenic Lead Archeostratigraphy (ALAS) Model (Hurst et al., 1996; Moor et al., 1996) uses the $^{206}\text{Pb}/^{207}\text{Pb}$ ratio, alongside total Pb concentration in sediment cores to infer approximate dates, based upon the deposition of these isotopes from the usage (and cessation) of lead gasoline additives. From this model, we are able to estimate the 30 cm segment to represent deposition during the mid-1960s (where the $^{206}\text{Pb}/^{207}\text{Pb}$ ratio in gasoline was the lowest in North America). The 35-30 cm segments encompass the 1970s where gasoline lead additives became rapidly enriched in ^{206}Pb relative to ^{207}Pb due to rapidly evolving additive manufacturing techniques. The Pb isotopic asymptote from 25-12 cm along with the generally continued increase in overall lead concentration is indicative of the late 1970s through the mid-1980s when manufacturing techniques of lead additives remained relatively constant, and gasoline was still predominantly sold with lead additives. The use of lead additives ceased in the mid-1980s, and so the total lead content of the samples exhibits asymptotic behavior in the top 10 cm of core. The uppermost segments (5 cm to 0 cm) did not yield enough dry material for rigorous chemical analysis and were not included in this modelling effort. The content of Pb in the core from the estimated mid-1960s through ca. early 2000s displays a significant ($R^2 = 0.95$, $F < 0.01$) linear relationship with total sediment P, and most other assayed metals. This trend is in keeping with the period of lakefront real estate development in the region, and indicates that the lake experienced considerable terrestrial inputs that appear to be a deviation from the background concentrations pre-1960s.

Diatom community analysis of the core has to-date been performed on the uppermost and lowest sections. Diatom community compositions were found to be different between the top and bottom of the core (Figure 6), with the genus *Cocconeis* as the third most abundant in the top segment, but absent in the bottom. Since *Cocconeis* is an epiphyte, this contemporary increase in abundance would correspond to an increase in suitable habitat compared to historic conditions. This could perhaps be indicative of *Cocconeis* using the milfoil as a substrate, and suggests that other niche epiphytes that are not preserved in the sediment record (e.g., filamentous algae) may behave similarly. *Cocconeis* was among the organisms in the nuisance sediment in small numbers, though the predominant epiphytic organisms were filamentous algae.

Summary Remarks

The source and identity of the nuisance material was found to be most probably detached milfoil from the Northwest basin of the lake. Isotope tracers demonstrate that this material is transported by prevailing winds to the Southeast basin where it accumulates on the shoreline. The mode by which the milfoil becomes detached could not be determined in this study, though it is likely a combination of management efforts, boat traffic, and natural disturbance by wind and waves.

Efforts to reduce the milfoil density in the Northwest basin will inherently expound the amount of detached milfoil, much of which will be similarly transported to the Southeast. Likewise, allowing the milfoil to grow and proliferate will only increase the amount of biomass that is amenable to detachment by natural means.

In our opinion, further measures may be needed to control the milfoil, which is still considerably dense in the NW basin and has begun to establish elsewhere in the lake. Considerations to ensure aeration of the benthos are critical during processes that would elevate the biochemical oxygen demand in treated areas. As such, the laminar flow array is inherently beneficial to further treatment efforts, while it may not be entirely efficacious on its own. Three options are available for concomitant treatment efforts at present:

- 1.) Treatment with herbivorous weevils
- 2.) Mechanical biomass removal
- 3.) Herbicide treatment

In any case, careful containment and collection of detached detritus will minimize the risk of milfoil re-seeding and should ameliorate the conditions experienced in the Southeast basin.

Weevil treatments have been employed in the past in the lake, with some success. This method is notoriously spurious and requires frequent re-application. The recent shortage of these weevils creates an intrinsic problem for relying upon this treatment effort alone.

Herbicide treatment is both aggressive and efficacious, though concerns exist over the long-term ecological consequences of such applications and the potential for unintentional or unanticipated risks to public health. In the past, stakeholders have nearly unanimously voted against such an approach.

Mechanical harvesting would be the most rapid and aggressive chemical-free means of controlling the milfoil biomass. Such an endeavor requires careful collection of detached biomass to prevent the spread of milfoil to other regions of the lake. There are possible avenues to recoup expenses incurred during such an operation. For example, harvested biomass could be processed into cellulosic ethanol, biodiesel, or natural gas (Reijnders and Huijbregts 2009) or garden fertilizer and sold regionally. This approach, while drastic and potentially expensive most probably offers the best chance for improved biomass control.

In terms of actionable items, a management decision to reduce the extant milfoil standing stock should be selected. Such management should include a means of capturing detached biomass.

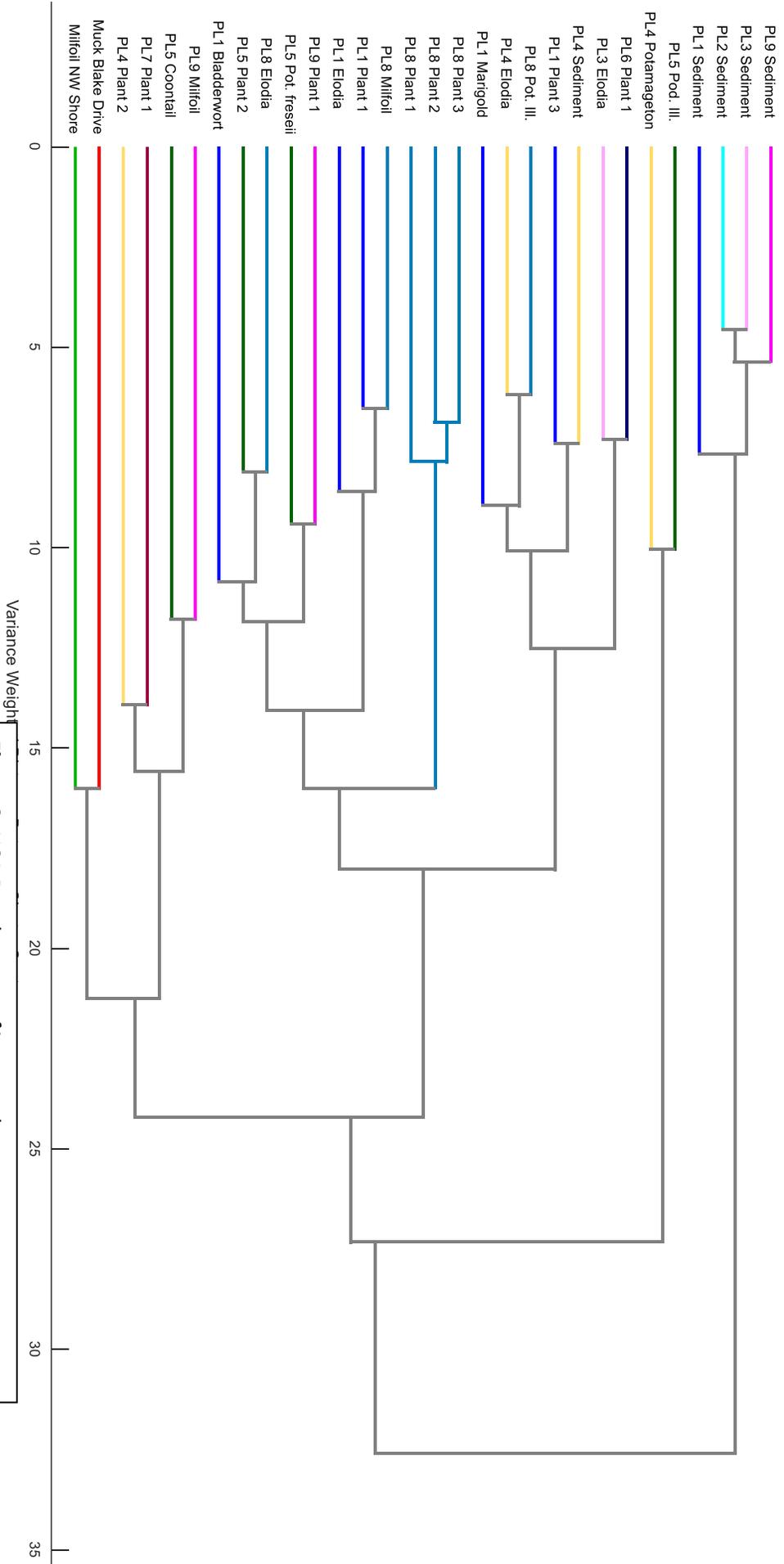


Figure 2. HCA Dendrogram of isotope data.

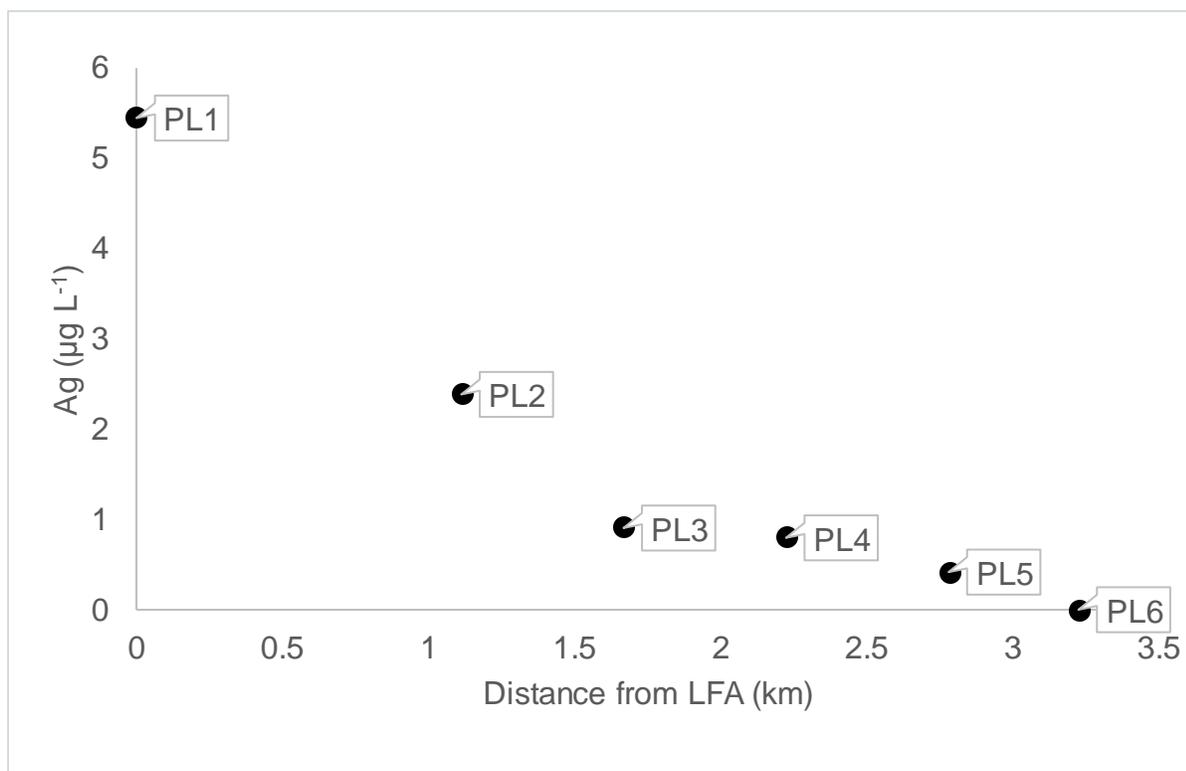
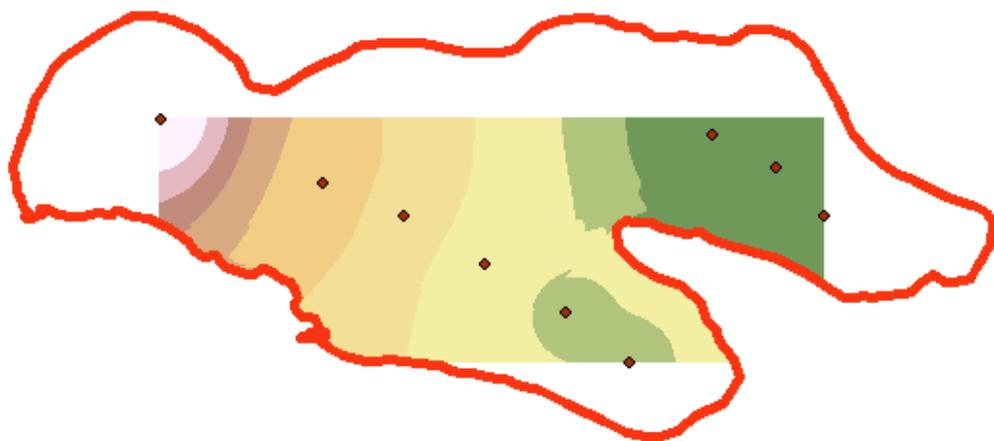


Figure 3: Example Kriged contour map (top) and graphical representation of dissolved metal data. Regression line significance $R^2 = 0.88$; $F < 0.01$.

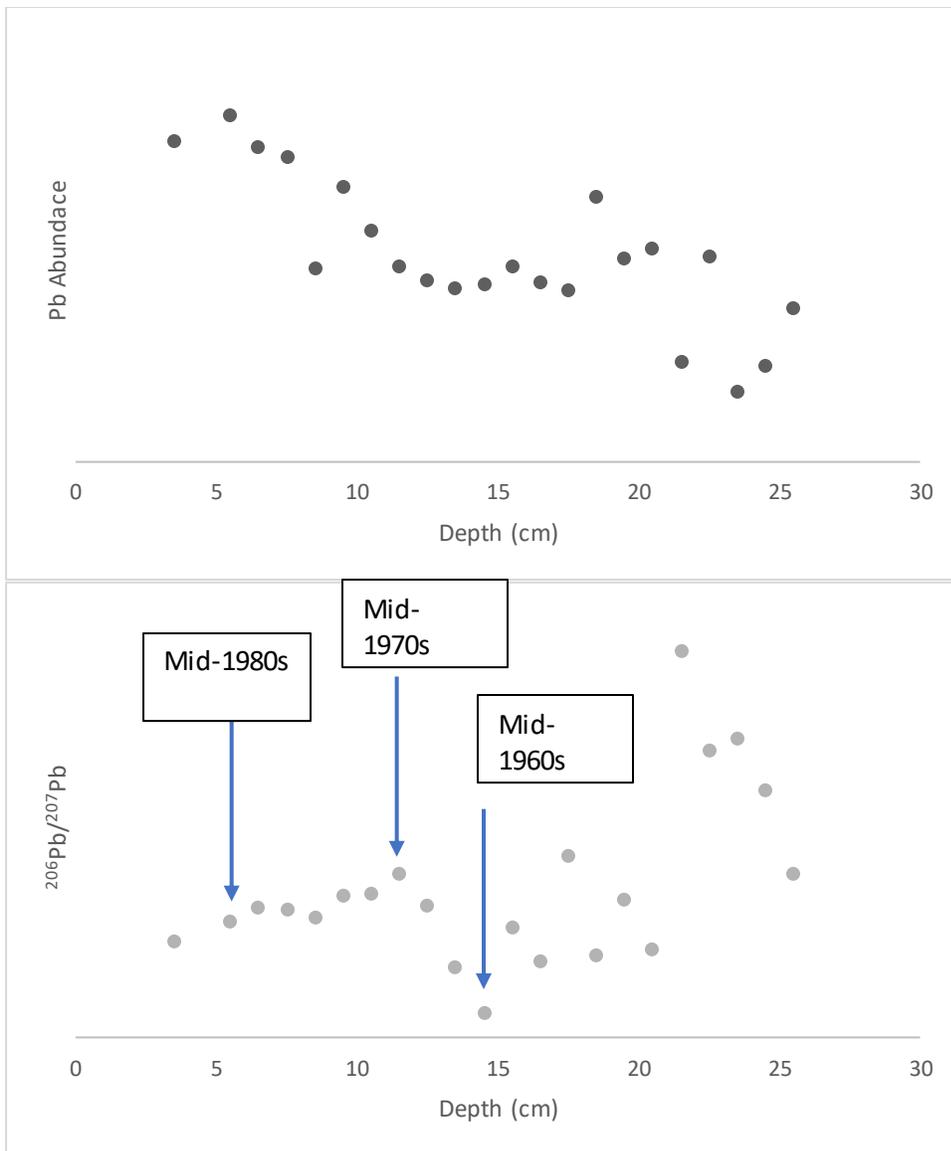


Figure 4: Pb date estimates using the ALAS.

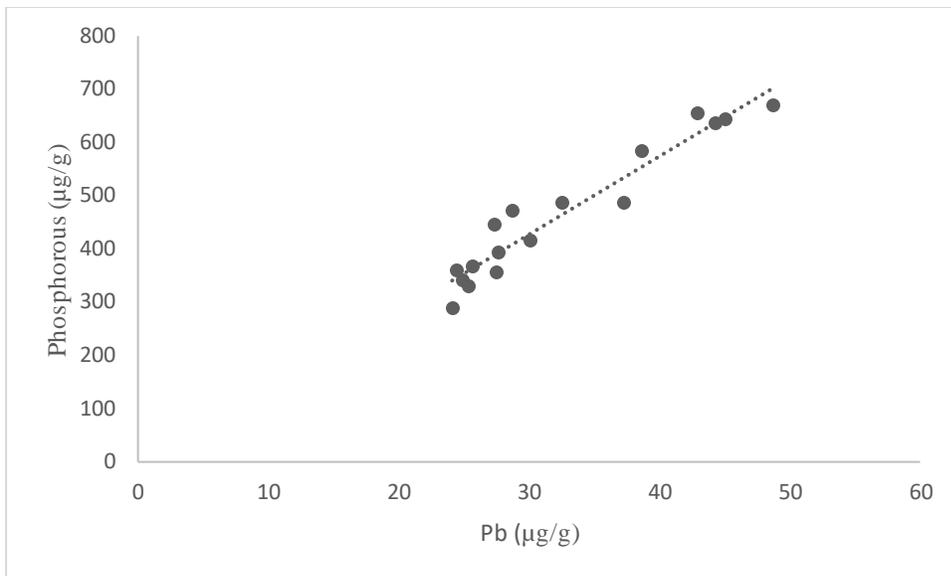


Figure 5: Comparison of anthropogenic activity proxied by lead and phosphorous accrual in sediment from mid-1960s to current

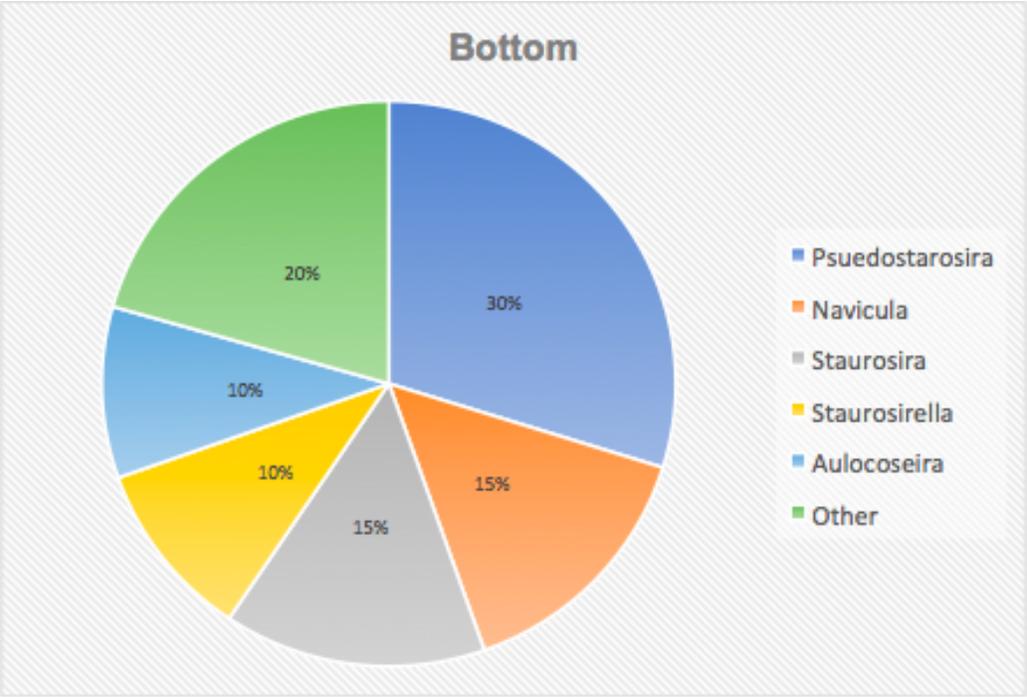
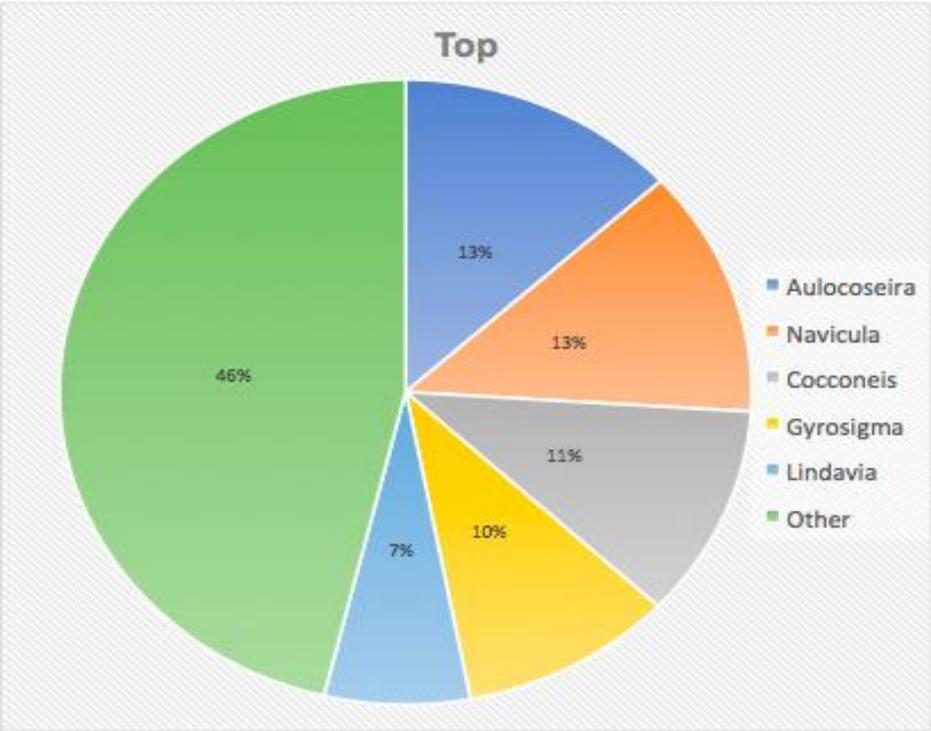
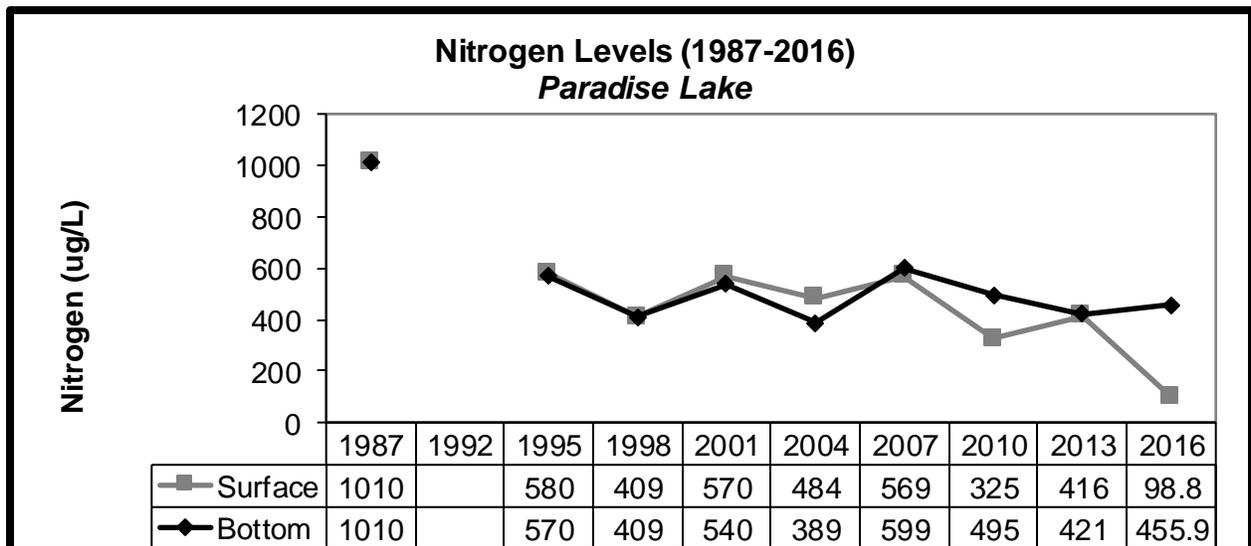
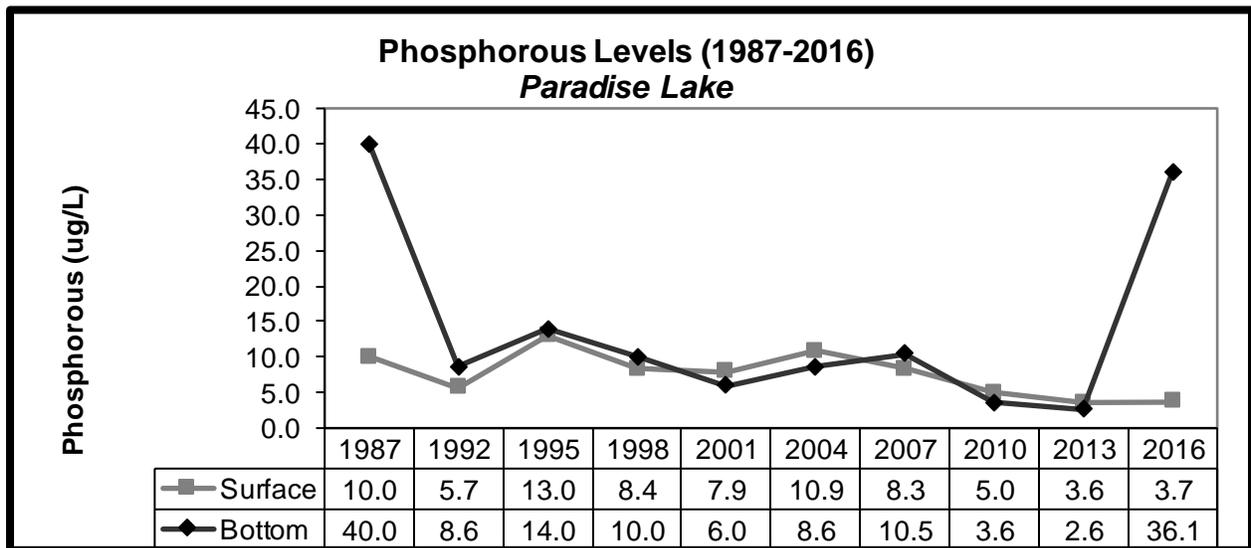
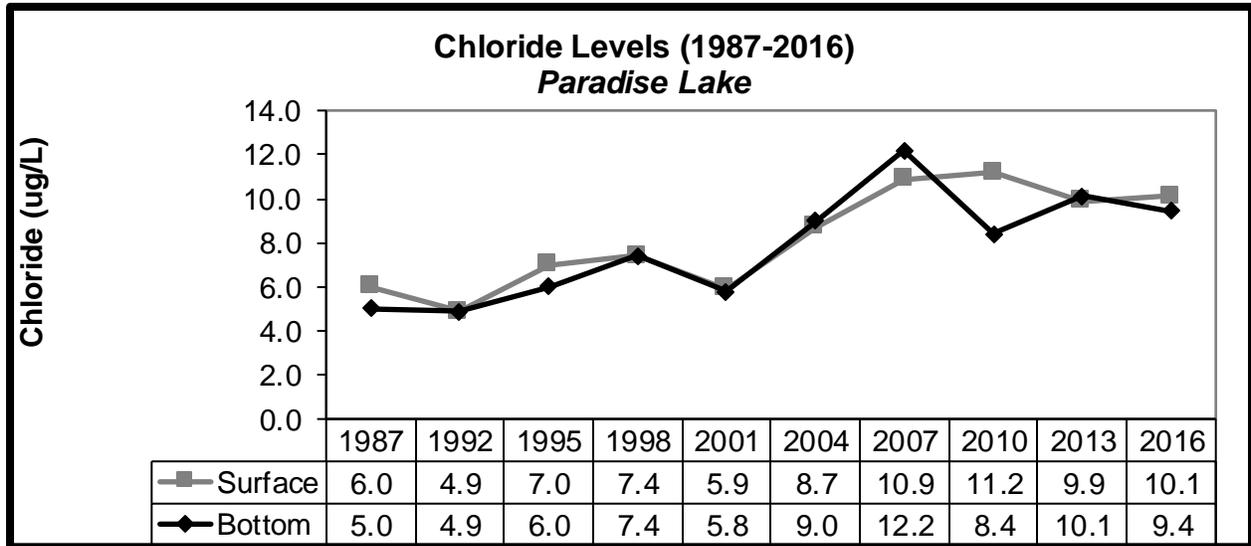
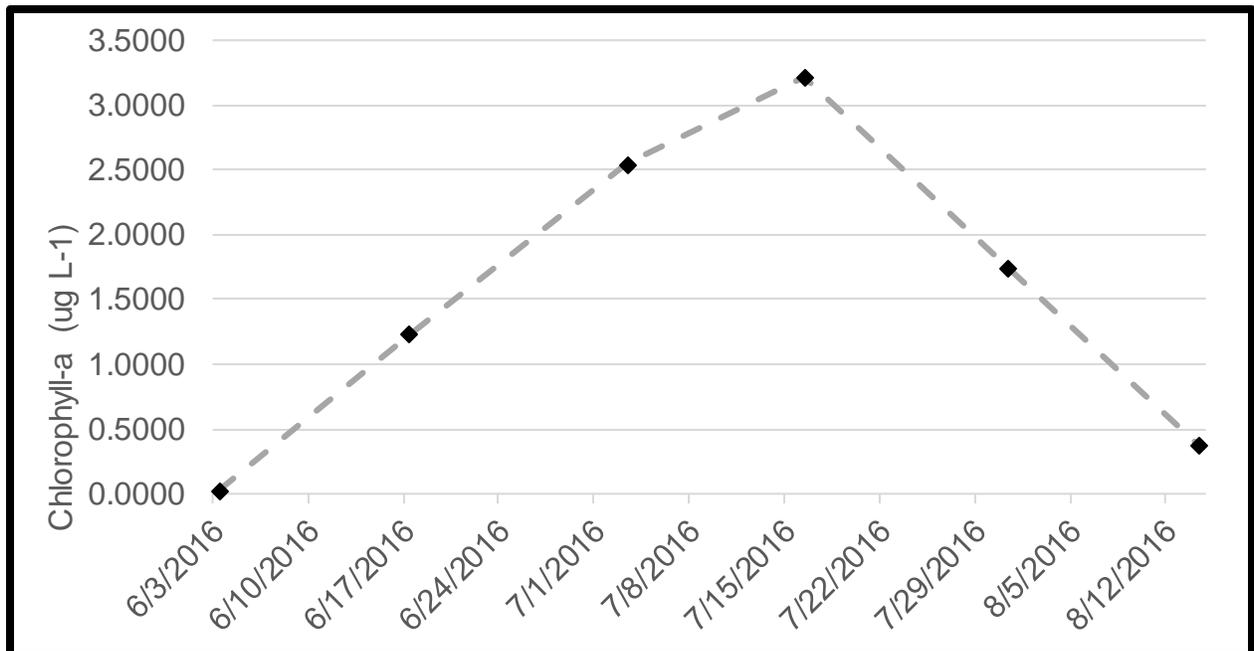
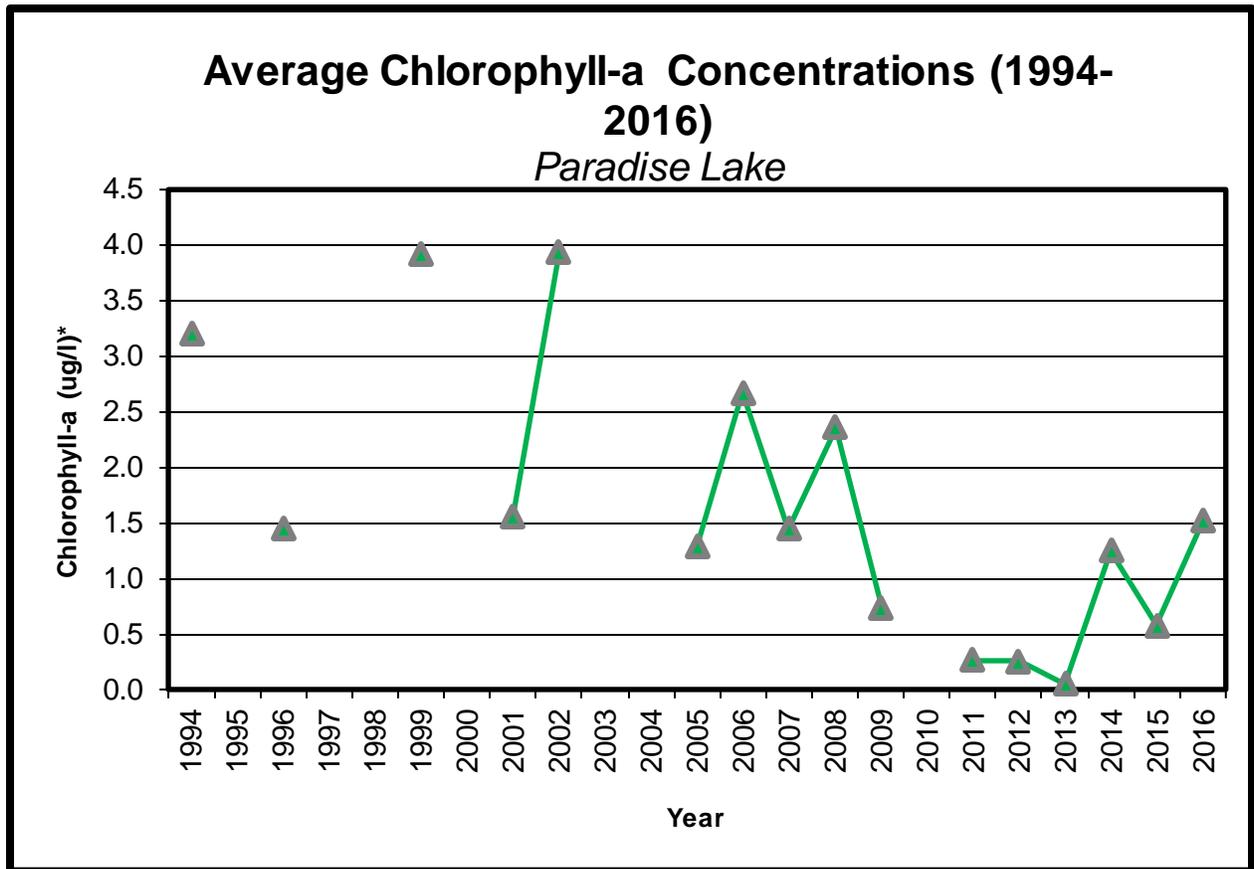


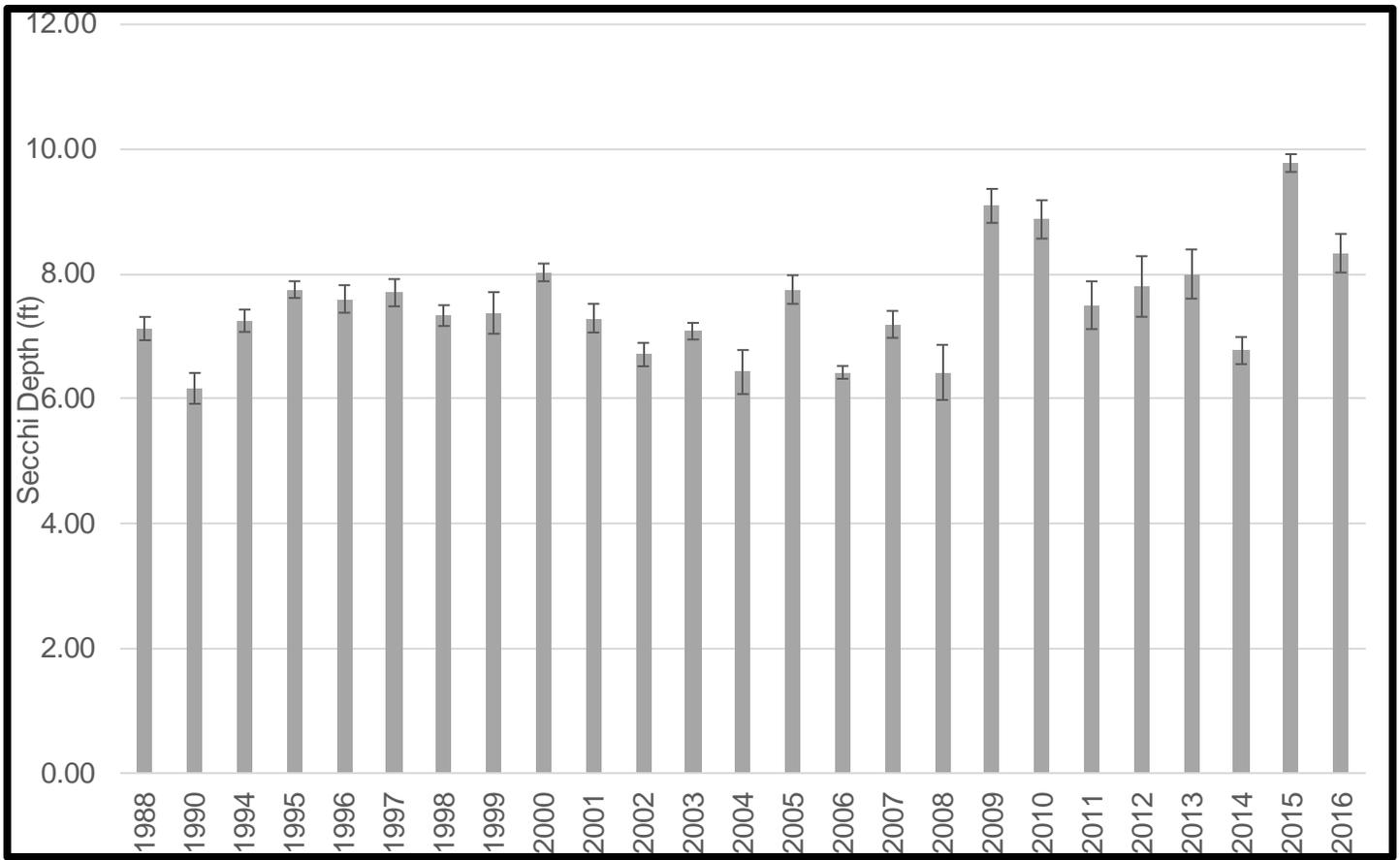
Figure 6: Diatom compositions found at the top and bottom of the Site 10 sediment core.



A1: Long-term nutrient and Cl loadings in Paradise Lake (Courtesy of TOMWC)



A2: Chlorophyll-a dynamics in Paradise Lake (Courtesy of TOMWC).



A3: Annual mean summer Secchi depth +/- SE (Courtesy of TOMWC).

Appendix B

Paradise Lake: Preliminary report on the microscope examination of the black sludge

July 25 2017.

Dr. Robert W. Pillsbury

On July 6th we visited the shores of Paradise Lake and spoke with some residents. They pointed out to me some of the sludge washing up on shore that has become a nuisance to those living on that side of the lake. I collected a sample of the material in question and examined it under a microscope (400x) to try and determine its origin.

With this preliminary examination, I determined that the bulk of material was composed of both coarse (>2mm) and fine particulates (<1mm). The coarse particulates were mainly milfoil (*Myriophyllum* sp.) stems and leaflets in various stages of decay. The finer particulates were mainly pieces of filamentous green algae (Chlorophyta) from several genera (*Mougeotia* sp., *Oedogonium* sp., and *Spirogyra* sp.). Similar to the Milfoil, these filaments were in various stages of decay. I also noted that the Diatom *Rhopalodia* sp. was very common in the sample. Many other diatoms were also present.

Speculation: This speculation is very preliminary. The sample of sludge collected may not be representative of the sludge in other areas of the lake or at other times. More work needs to be done to characterize this material. But if our sample is representative, it seems obvious that the material is organic in nature (derived from plants and algae). Since I did not see large masses of milfoil or filamentous green algae near the shore, it also seems obvious that this material was generated elsewhere in the lake and when it started to die back it became detached from where it was growing and was brought in by currents. Filamentous green algae in general tend to grow in large masses where there is a lot of light. It might be that zebra mussels (or the aeration system in the lake if it has cleared up the water) have caused the lake to be less turbid. This allowed more light to reach the bottom which would allow for filamentous green algae to increase. Another scenario would be for the milfoil growing in some areas of the lake to act as a substrate for the filamentous green algae to grow on, allowing the algae to be closer to the surface and receive more light. This too could cause large masses of algae that could eventually turn into sludge. The *Rhopalodia* in the samples suggest that the lake may be Nitrogen limited since this alga can fix its own Nitrogen.

Next steps?:

-Collect and examine more samples of the sludge to make sure we understand what it is composed of most of the time.

-Look for the source of the sludge-Where is this material growing in the lake before it is washed up and decaying? We could possibly collect samples around the lake looking for masses of developing filamentous green algae (along the bottom? Draped over milfoil beds?). If we find a suspected source, we could examine the associated diatoms in the sample and compare it to the

diatoms found in the sludge as a sort of ecological finger-print to try and identify the true original location of the sludge.

-we can take a sediment core from the lake to try and determine when major changes in the lake occurred that may have led to the increase of the sludge.

Appendix C is a Separate Excel Spreadsheet.

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