Exploring the Factors That Impact Organic Carbon Burial Efficiency in Lacustrine Sediment

BIOS 35502-01: Practicum in Field Biology

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ABSTRACT

Natural carbon sinks are a necessary ecosystem service that fulfill an increasingly important role of mitigating climate change in the global carbon cycle. Marine sediment storage has been acknowledged as a powerful carbon sink for many years, but recent studies have shown that freshwater lakes store a disproportionately high amount of organic carbon within lacustrine sediments. There is a high degree of variability in the overall efficiency of organic carbon burial between freshwater lakes, but the factors that lead to this variability are relatively uninvestigated. This study explores several lacustrine factors and their overall impact on organic carbon burial efficiency using percent organic matter of sediment as an indicator. Three different lakes with a gradient of DOC in UNDERC property in northern Wisconsin were used as study sites. The impact of sediment grain size and regional carbon input due to wind and runoff on percent organic matter were inconclusive. This study found a positive correlation between DOC levels and percent organic matter across lakes, as well as a significant increase in percent organic matter between perimeter samples of lakes and bathymetric centers of lakes. By understanding the factors that cause variation in organic carbon burial efficiency, lakes can be optimally utilized as an important carbon sink on a global scale.

INTRODUCTION AND HYPOTHESIS

Carbon sinks are a natural form of carbon sequestration that can store organic carbon for extended periods of geologic time. The burial of organic carbon in aquatic sediment acts as a crucial carbon sink at a global scale (Cole et al. 2007). Naturally, since oceans cover 71 percent of the earth's surface, marine sediments store large amounts of organic carbon (OC). Oceans accumulate OC at rates of 100 Tg per year (Dean & Gorham 1998). Freshwater lacustrine OC burial has been given very little attention until recently, perhaps because freshwater lakes only cover two percent of the Earth's surface area (Burdige 2007). However, lakes store a disproportionately high rate of OC, equivalent to 42 Tg of carbon per year (Dean & Gorham, 1998). Up to 33 percent of lake OC flux can be attributed to sediment storage (Tranvik et al 2009). Lacustrine OC burial can therefore have a significant impact on the global carbon cycle. Determining the factors that allow for higher carbon burial efficiency may be essential to mitigating climate change due to increasing atmospheric carbon dioxide.

Four distinct processes lead to the long-term storage of OC in lake sediments (Ferland et al. 2013). First, terrestrial OC is loaded into lakes in the form of dissolved OC or particulate OC. Second, that OC is then delivered to sediment through downward particulate flux in a process called sedimentation (Brothers et al. 2008). Third, some carbon is processed and degraded at the sediment/water interface by microbial processes. Finally, OC is gradually removed from deeper sediment layers via sediment bacterial metabolism (Gudasz et al. 2012).

OC burial rates can vary by over two orders of magnitude between lakes (Sobek et al. 2009). This high level of variability indicates that there are multiple external factors that can impact the burial efficiency of a given lake. In marine sediments, the primary mechanisms for this high variability include oxygen exposure time, the surface area of the mineral surface, and the chemical composition of the organic carbon (Sobek et al. 2009). Many of these same factors also impact lacustrine system OC burial. For example, longer oxygen exposure time leads to OC mineralization, which causes lower OC burial rates in many lakes. The overall depth of the lake may also be an important factor in OC burial efficiency, since a longer sinking time could mean longer exposure to the water column and thus a longer period of possible oxidation (Meyers and Ishiwatari 1993). If the carbon oxidizes in the water column, it will not be stored in the sediment.

Marine organic carbon also has been found to adsorb onto the surface of mineral particles. Therefore, a larger particle surface area has been found to have a positive relationship with OC burial due to protective sorption (Mayer 1994). Overall, smaller sediment grains will have a higher surface area-to-volume ratio than larger sediment grains. However, recent lacustrine studies have not found adsorption surface area to be a significant factor on lake OC burial efficiency (Sobek et al. 2009).

Much of the particulate and dissolved OC in aquatic systems are organic plant compounds. These compounds can be either allochthonous or authochthonous and transported throughout the entire aquatic system. In terms of chemical composition, allochthonous (terrestrially derived) compounds are more easily preserved in marine sediments, while autochthonous (internally produced) compounds are far less likely to accumulate in sediments, as heterotrophic microbes more easily decompose them (Sobek et al. 2009). Plant-based organic matter can be divided into two biochemically distinct groups: one from vascular plants with woody, cellulosic tissues, and one from nonvascular plants lacking those tissues, such as algae (Meyers and Ishiwatari 1993). The contributions of these two forms of organic carbon are determined by lake morphology and the abundance of various plants in and around the lake. Directional bearing of wind also factors into lacustrine carbon levels, and additional aeolian deposits of pollen regularly find their way into buried OC in lake sediment (Meyers and Ishiwatari 1993). The overall amount of carbon loaded into a lacustrine system can factor into the total levels of carbon buried within the sediment (Ferland et al. 2013). For this reason, it is worth investigating the differences in sediment burial efficiency in various regions of a given lake, given that some regions are loaded more by aeolian deposits and allochthonous deposits than other regions.

This study utilized the measurement of organic matter(OM) in sediment samples through a loss-on-ignition technique. Since organic carbon is a crucial ingredient in organic carbon, the mass of organic matter in a given sediment sample is a direct function of the mass of organic carbon (Broadbent 1953). The study explored the organic matter levels of three lakes across a gradient of dissolved organic carbon on the UNDERC property in Land O' Lakes, Wisconsin. The primary objectives of this study were (1) to determine how DOC levels impact sediment OM, (2) to determine how sediment OM changes in varying regions of the lake, and (3) to determine if sediment grain size influences sediment OM.

I first hypothesized that lakes on the higher end of the DOC gradient will have more carbon present than can be adsorbed into sediment. As such, sediment OM would also increase with higher DOC. Secondly, I hypothesized that sediment OM would be higher at the perimeter of the lake and lower at the bathymetric centers of the lake, because the deeper water would allow for more carbon oxidation, instead of carbon burial. I also expected that there would be significant differences in percent OM between different directional regions of the lake, due to differing runoff, aeolian deposits, and allocthonous deposits between regions. Finally, I expected that a decreased grain size would allow for higher sediment OM, since a smaller grain size means an increased surface area to volume ratio, and thus a larger surface area for carbon to adsorb onto sediment.

METHODS

Study Sites

This study measured sediment organic matter at three different lakes: Bay Lake, Long Lake, and Hummingbird Lake. Based on past UNDERC studies, these three lakes vary in levels of dissolved OC (Long 2012). Bay Lake has a relatively low DOC level (6.3mg/L; Godwin et al. 2014), while Hummingbird Lake has a relatively high DOC level (20.5mg/L; Godwin et al. 2014). An impermeable curtain runs across Long Lake, separating it into East Long Lake and West Long Lake. These two sides of Long Lake have differing DOC levels: East Long Lake has a medium-high DOC level (10.5mg/L; Godwin et al. 2014) while West Long Lake has a medium-low DOC level (6.5mg/L; Godwin et al. 2014). DOC values for each basin and lake are reported in Table 1.

Sample Collection

Sediment samples were collected around the perimeters of Bay Lake and Hummingbird Lake as well as in the bathymetric center of each lake using an Ekman dredge. A perimeter sample was defined as within 5 meters of the shoreline. Center samples were selected using bathymetric maps and identifying the lakes' deepest points (Figures 1, 2, 3). Bay Lake was separated into three perimeter regions (NW, SE, and SW) in order to compare percent organic matter. An Ekman was also used to collect sediment samples on either side of the curtain at Long Lake. Each surface sediment sample was defined as 0-10 cm below the surface.

Each sediment sample was mixed until it reached a relatively homogenous state before being processed using a loss-on-ignition technique. This loss-on-ignition technique is useful for a low-cost, rapid compositional profile with organic matter results that are accurate to 1-2% with over 10% organic matter (Heiri 2001). A small amount of the sample (1-5 cm^3) was placed into a pre-weighed foil and weighed. Next, the foil was placed in a drying oven at 100°C overnight. The resulting foil weight was recorded as the dry weight. The foil was then placed in a furnace for a 4-hour burn at 550°C, which burned off all organic matter in the sample. The organic matter weight was calculated by subtracting the 550°C final weight from the dry weight. The percent organic matter was calculated by dividing the crucible's organic matter weight by its dry weight.

Four samples from Bay Lake were randomly selected, and the remaining sediment in each sample bag was run through a set of sieves. With this set of sieves, the sediment was sorted into five grain size categories: >2000 µm, 500-2000 µm, 250-500 µm, 125-250 µm, and 0-125 µm. The loss-on-ignition procedure was repeated for all five subsample sediment size categories for each sample.

Statistical Analysis

Before each statistical test, a Shapiro-Wilk test was performed in order to assure normal distribution. If the data was not normally distributed, a transformation was attempted. When variables could not be transformed to reach normality, a non-parametric test was performed. Due to a non-normal distribution, a natural log transformation was used on sieved sediment percent organic matter results.

In order to compare mean percent organic matter between lakes with varying DOC levels, a Kruskal-Wallis test was performed, along with multiple Mann-Whitney U-tests as post-hoc tests. A linear regression was also used to analyze the relationship between specific pre-recorded DOC levels of the lakes and their mean organic matter percent. To compare the mean percent OM of bathymetric center samples and perimeter samples, a Mann-Whitney U test was performed. To compare sediment OM in various directional regions of lakes, a one-way ANOVA was conducted. A one-way ANOVA was run to analyze sediment OM between each sieve size category. All statistical analyses were run in R 3.2.0 for MAC OS X, using the package R Commander version 2.1-7. All graphs were created using Microsoft Excel 2011 for Mac 2011 14.1.0.

The linear regression displayed a positive correlation between DOC levels in a lake and percent OM of samples from the lake ($R^2=0.3164$, $p<0.0001$; Figure 4). The results of the Kruskal-Wallis test were significant ($p<0.05$), which led to the performance of several Mann-Whitney U tests as post-hoc. These post-hoc tests found that Hummingbird Lake had significantly higher OC than Bay Lake ($p<0.001$; Figure 5) and that East Long also had significantly higher sediment OC than Bay Lake ($p<0.05$; Figure 5). There was a general upward trend in percent OM as DOC increased by lake.

The average percent OM found in center samples was significantly higher than the perimeter sample percent OM mean ($p<0.01$; Figure 6). There was no significant difference between directional regions of Bay Lake ($p>0.05$; Figure 7). Although the differences were not significant, it is interesting to note the high degree of variability between sample means in differing regions of the same lake.

Finally, there was no significant difference between sediment grain sizes and percent OM means ($p>0.05$; Figure 8), but there appears to be a general upward trend between sediment size and percent OM means.

DISCUSSION

DOC Gradient and Percent Organic Matter

The positive correlation between DOC levels and sediment percent organic matter give support to the hypothesis that the amount of carbon loading in a lake determines the efficiency of carbon burial in sediment (Ferland et al. 2013). It would follow that a lake more saturated with carbon via DOC would in turn also be more saturated with organic matter in its sediment.

In addition, a DOC gradient also signifies a gradient in nutrient levels (dystrophic versus oligotrophic) and types of carbon present (allochthonous versus autochthonous) (Riera et al. 1999). Dystrophic lakes, such as Hummingbird Lake, are often supersaturated with allochthonous carbon, more so than oligotrophic lakes such as Bay Lake (Jonsson 2001). This allochthonous carbon makes for more efficient carbon burial than autochthonous sources of carbon, primarily because heterotrophic microbes more readily digest autochthonous forms of carbon before the carbon is able to be buried in the sediment (Sobek et al. 2009). The high saturation of DOC in Hummingbird Lake, as well as the high ratio of allochthonous-to-autochthonous carbon in dystrophic lakes such as Hummingbird help to explain the significantly higher levels of percent organic matter in the sediment. Furthermore, the low saturation of DOC in eutrophic Bay Lake and the relatively low ratio of allochthonous-to-autochthonous carbon both justify the lowered percent OM found in the sediment of Bay Lake.

There was no statistically significant difference between percent OM levels in East Long and West Long, but it is important to note the large variability in mean percent OM between the two sides of the lake (Figure 5). Although there is only a curtain separating these halves of Long Lake, sediment percent OM has quite high variability between these two sides, in comparison to the variability of samples within Bay Lake or Hummingbird Lake. Because the DOC has shifted dramatically across sides in only a few years since the installation of the impermeable curtain, we see an interesting shift in sediment OM burial (Godwin et al. 2014). In the future, exploration of the timescale at which sediment OM burial occurs would help explain this large variability between the two sides of Long Lake.

Lake Regions and Percent Organic Matter

Bathymetric center point samples had a significantly higher percent mean organic matter than perimeter samples across lakes. These findings are counterintuitive to this study's hypothesis. Because the bathymetric center points of the lakes are also the deepest points with the longest sinking time, I anticipated that much of the carbon would be oxidated in the water column before it was given the opportunity to bury in the sediment (Meyers and Ishiwatari 1993). Given these findings, depth may not be a truly significant inhibitor to carbon burial. In fact, conflicting studies have shown that small, deep lakes are more efficient carbon sinks than large, shallow lakes (Ferland et al. 2013). Although oxygen exposure time has been found to have a negative relationship with organic carbon burial efficiency, a deeper lake does not always mean an increased oxygen exposure time (Ferland et al. 2013). In fact, a deeper lake may allow for a wider range of oxygen penetration depths in comparison to a shallow lake. This actually means that the carbon would be exposed to a shorter oxygen exposure time in a deeper lake, and oxidation would thus be less likely, leading to higher carbon burial efficiency (Sobek et al. 2009). Lake bathymetry is a primary determinant in overall carbon burial efficiency, and must be regarded as one of the more important factors in lacustrine carbon storage.

In contrast, directional region within a lake was found to have no significance on overall percent organic matter in sediments. These results do not support this study's hypothesis of a significant difference between regions because of heterogeneity in carbon input due to runoff and wind. These findings do not necessarily mean that aeolian deposits and runoff do not significantly impact the total carbon load of a lake (Meyers and Ishiwatari 1993). However, it does lead to the implication that even if the input of allochthonous carbon deposits through wind or runoff across regions of a lake is heterogeneous, it is homogenized by the time it reaches the point of sediment burial. The idea of heterogeneity of carbon input due to current and wind factors can be better explored in the future by increasing sample size and dividing up regions into smaller directional areas for a more detailed profile of the lake.

Sediment Grain Size and Percent Organic Matter

This study's findings for sediment grain size versus percent organic matter were inconclusive, with no significant differences between grain sizes. However, there was a general upward trend in percent organic matter as grain size increased (Figure 8). These results conflict with this study's hypothesis of smaller grain size allowing for higher percent organic matter due to a higher surface-area-to-volume ratio (Mayer 1994). One explanation for these unforeseen results may be the unanticipated factor of leaf litter or woody debris accumulating in a layer on top of the surface sediment during sampling and then being filtered out by the 2000 μm sieve. This would falsely increase percent organic matter and skew results, since this study uses percent organic matter as an indicator of organic carbon sediment burial. In addition, during the sieving process, the overall mass of each grain size sample generally decreased as grain size decreased, due to the filtering of the sediment. The scale that was used throughout the study measured in grams, and was limited in accuracy to four decimal points. As the mass of samples decreased, the overall error of percent organic matter may have increased. These experimental issues led to inconclusive results for grain size and organic carbon burial efficiency.

The importance of grain size in lacustrine sediment burial is currently disputed (Sobek et al. 2009). For a future experiment to explore grain size, larger sediment sample masses, a higher accuracy scale, and a limited amount of leaf litter in surface sediment samples are necessary.

Conclusions

This study proposes that two effective determining factors of organic carbon burial efficiency are DOC levels across lakes and lake bathymetry. DOC levels may have a significant effect on carbon efficiency because of the amount of carbon loaded into a lake system. Bathymetry is of surprisingly high importance to the determination of carbon burial efficiency in sediments because of its effect on overall oxygen exposure time. Results for regional differences in percent organic matter, as well as sediment grain size, were inconclusive.

By researching the factors that affect inland lacustrine ecosystem efficiency in carbon burial, we can gain useful insight of the mechanisms that allow for terrestrial carbon transport, oxidation, and storage (Cole et al. 2007). Further research is necessary in order to obtain a greater overall understanding of the global carbon cycle and to capitalize upon the factors that allow for maximal carbon burial efficiency. Through additional investigation, we can uphold lake systems as a crucial element of the Earth's carbon budget.

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TABLES

Lake	DOC (mg/L)
Hummingbird	20.5
East Long	10.5
West Long	6.5
Bay	6.3

Table 1. DOC measures (mg/L) per lake. Data is from a previous study (Godwin et al, 2014).

FIGURES

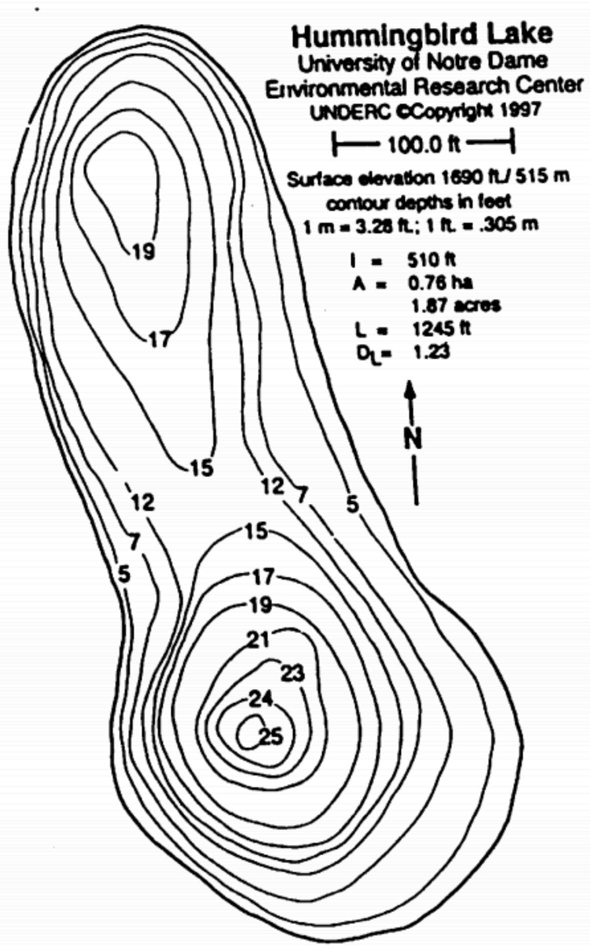

Figure 1. Bathymetric map of Hummingbird Lake. Center points were collected at the deepest bathymetric points, while perimeter points were collected <5m from the shoreline (Aquatic Habitat Descriptions, UNDERC).

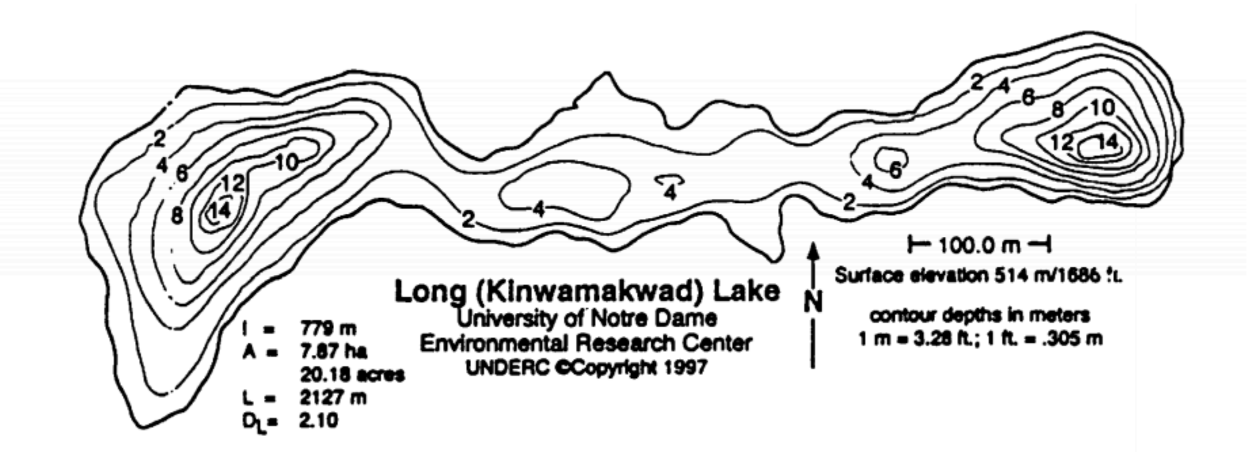

Figure 2. Bathymetric map of Long Lake. Center points were collected at the deepest bathymetric points, while perimeter points were collected <5m from the shoreline (Aquatic Habitat Descriptions, UNDERC).

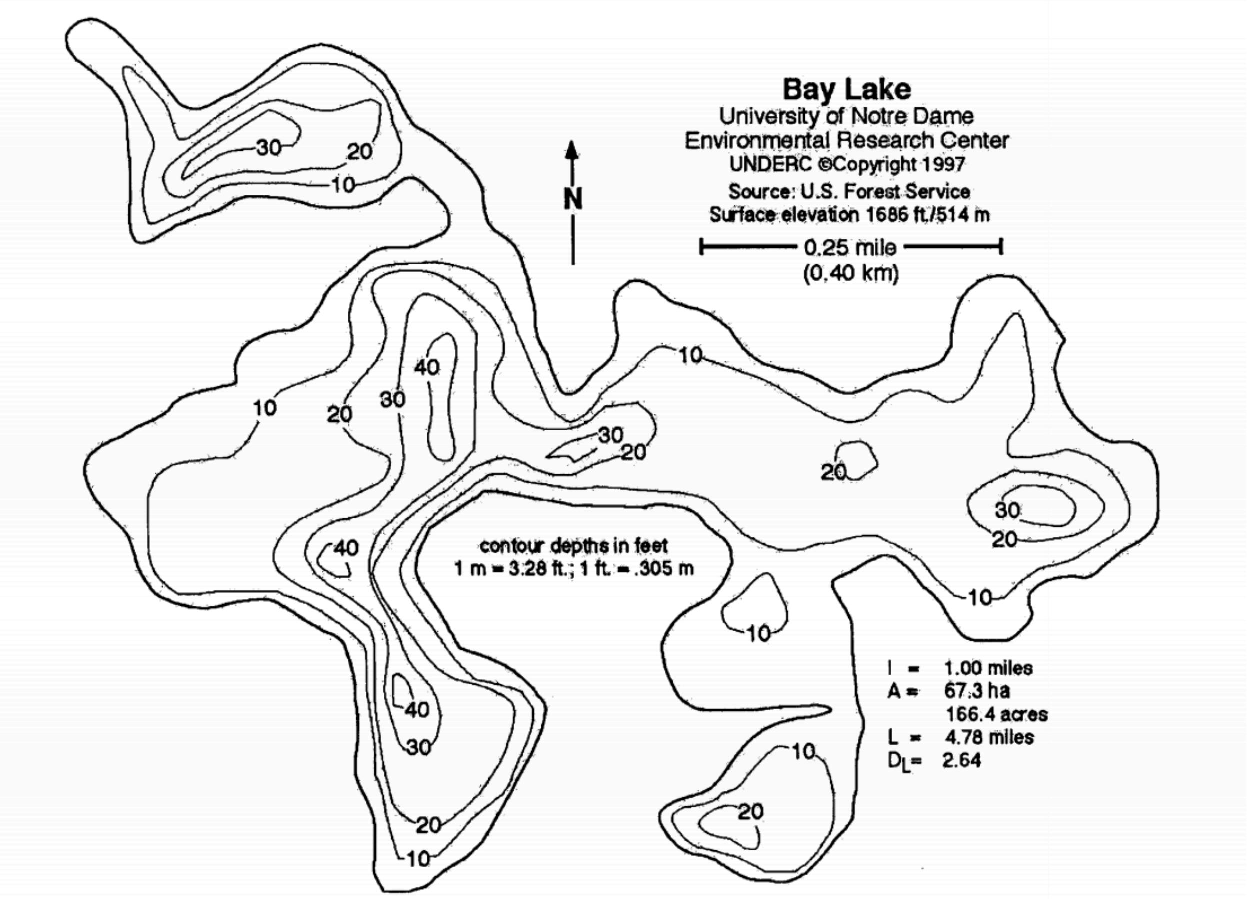

Figure 3. Bathymetric map of Bay Lake. Center points were collected at the deepest bathymetric points, while perimeter points were collected <5m from the shoreline (Aquatic Habitat Descriptions, UNDERC).

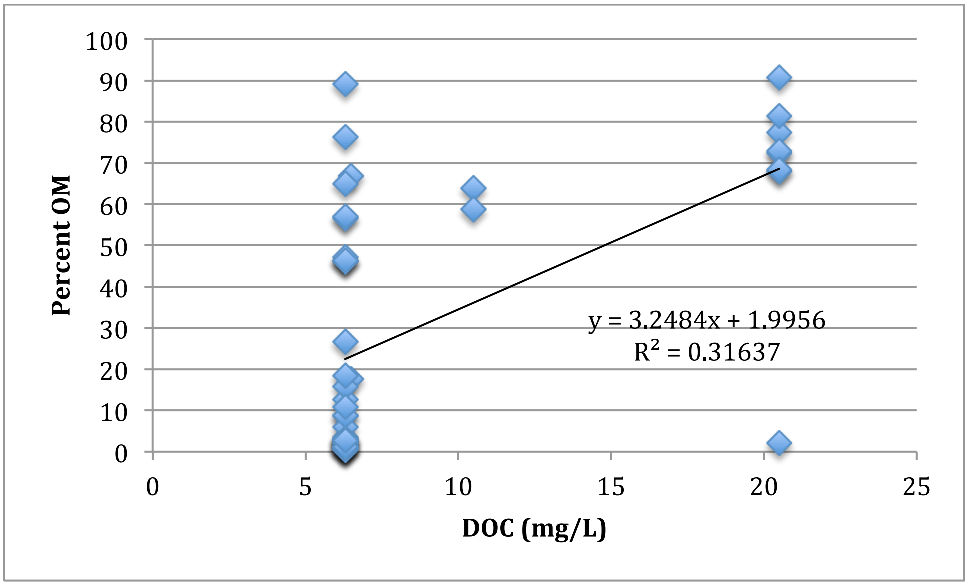

Figure 4. Sediment OM as a function of DOC (mg/L) at Hummingbird, East Long, West Long, and Bay Lake (R^2=0.3164, dF=43, $p<0.0001$).

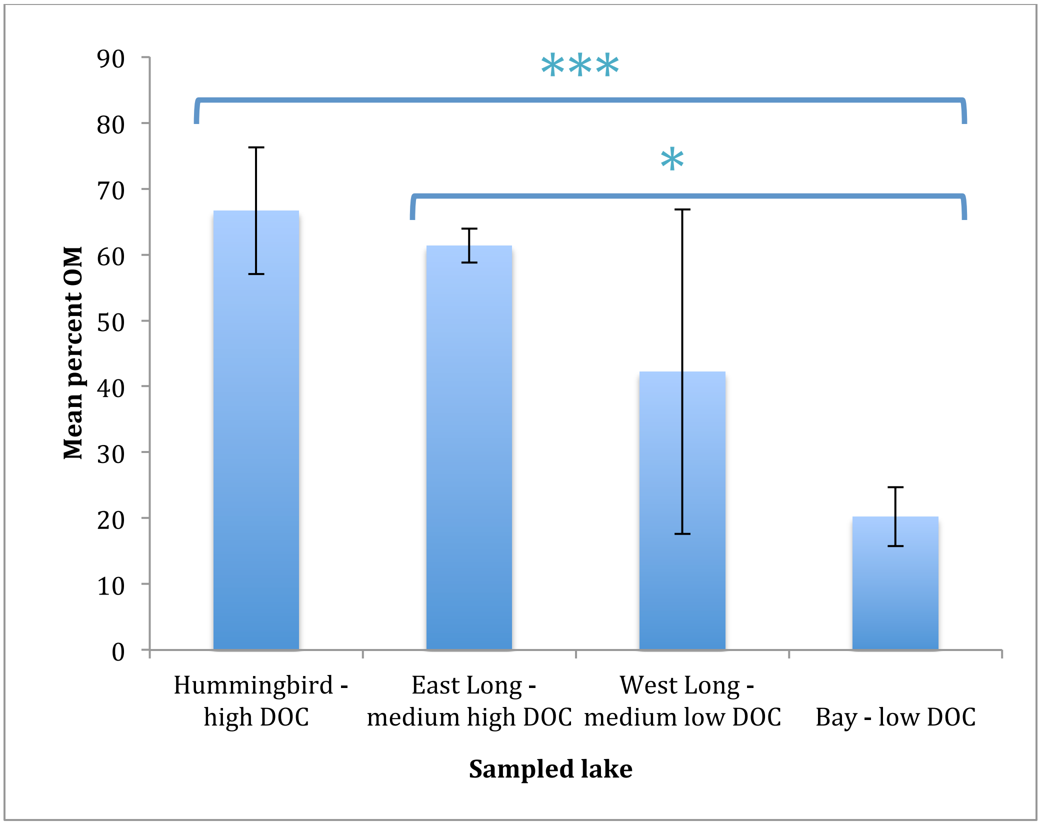

Figure 5. Average percent sediment OM according to lake. There is a significant difference between Hummingbird and Bay percent OM levels ($p<0.001$), as well as a significant difference between East Long and Bay percent OM levels ($p<0.05$). Error bars represent standard error.

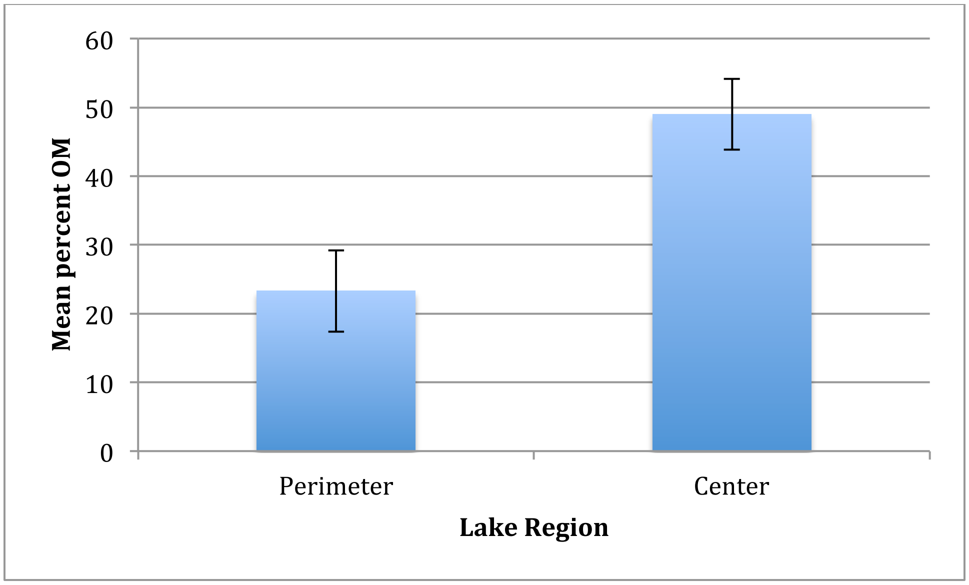

Figure 6. Average sediment OM in perimeter lake samples versus center lake samples. Center samples have a significantly higher mean percent OM than perimeter samples ($p<0.01$). Error bars represent standard error.

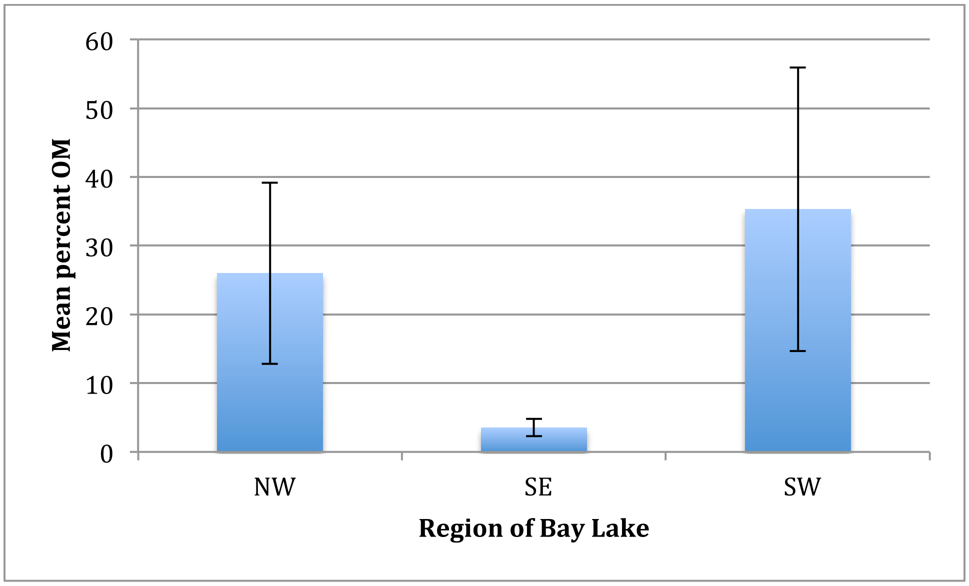

Figure 7. Average percent OM of various sampled regions of Bay Lake: northwest, southeast, and southwest. There is no significant difference between the percent OM of differing regions (p>0.05). Error bars represent standard error.

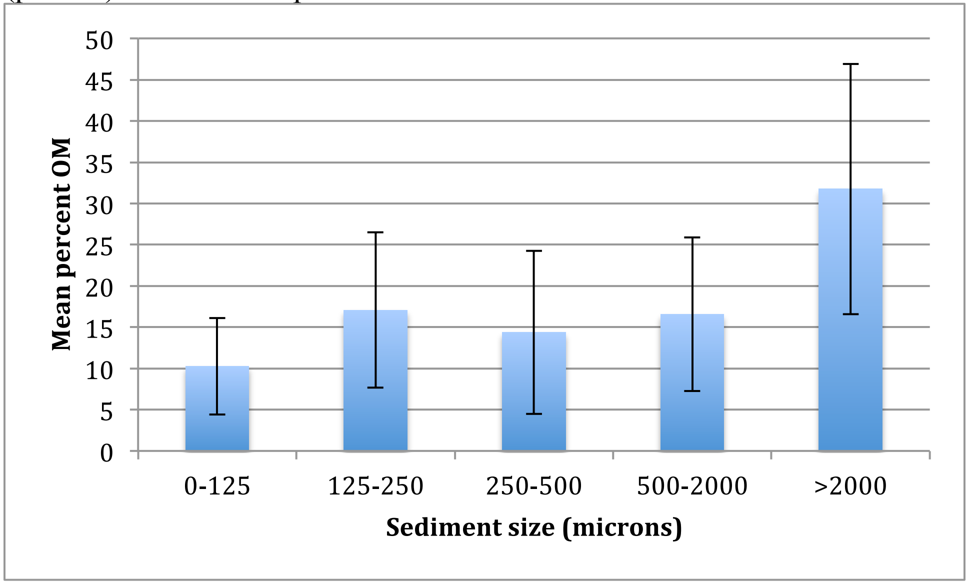

Figure 8. Average percent sediment OM according to sediment size (microns). There is no significant difference between the percent OM of differing sediment sizes(p>0.05). Error bars represent standard error.