Patterns in the sediment organic matter content of arctic lakes

Kenneth Fortino

Department of Environmental Sciences and Engineering

University of North Carolina at Chapel Hill

Present address: Biological and Environmental Sciences, Longwood University

Tel.: (434) 395-2223

Fax.: (434) 395-2652

fortinok@longwood.edu

Stephen C. Whalen Department of Environmental Sciences and Engineering

University of North Carolina at Chapel Hill

Joseph M. Smoak Department of Environmental Science, Policy, and Geography

University of South Florida

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## Abstract

The storage of organic matter in lake sediments is an important component of landscape carbon cycling. Sediment organic matter is derived from both allochthonous and autochthonous sources and removed from the sediment via microbial mineralization. Thus, patterns of sediment organic matter should reflect the relative balance between production and removal processes, as well as the factors that affect these processes. We surveyed the percent sediment organic matter of the top 10 cm of sediment in 22 lakes in the Alaskan Arctic and the rate of organic matter loss with sediment age in 3 lakes in the same region. In general the lakes showed a pattern of organic matter loss with sediment depth, consistent with the biological oxidation of organic matter. Sediment organic matter varied among lakes but not between shallow and deep locations within the same lake, indicating landscape-scale control of patterns in sediment organic matter. In euphotic sediments, percent sediment organic matter was positively correlated with the amount of light reaching the sediments and the concentration of dissolved oxygen in the overlying water, suggesting that differences in organic matter content are driven by differences in benthic photosynthesis rates. The percent organic matter of the aphotic sediments was correlated with the percent organic matter in the euphotic sediments, suggesting that organic matter produced in the shallow, illuminated portions of the lake are transported throughout the lake and that differences in whole-lake sediment organic matter content are determined by differences in benthic primary production. The results suggest that variation in sediment organic matter in this region is the driven by variation in benthic organic matter production and not loss.

**Keywords** light attenuation; Arctic; Alaska; burial efficiency

## Introduction

The anthropogenic alteration of the global carbon cycle through forest clearing and the burning of fossil fuels has highlighted the need to understand the distribution and fate of organic carbon in the world’s ecosystems. Cole et al. (2007) estimate that globally, lakes store between 0.03 and 0.07 Pg of organic carbon per year in their sediments, which is 22% of the total annual carbon burial in all freshwater systems. Just as they are in other regions, lakes are an important component of the ecology and biogeochemistry of Arctic landscapes (Hobbie et al., 1980) and factors affecting the storage of organic matter in arctic lake sediments are likely to alter the response of arctic ecosystems to climate change (Tranvik et al., 2009).

The amount of organic matter present in a lake system results from the balance of organic matter inputs and losses. Gross primary production and detrital import increase the amount of organic matter in the system, while respiration, organic matter export, and non-biological oxidation remove organic matter (Lovett et al., 2006). In lake sediments, the losses due to non-biological oxidation and fluvial export are likely minimal. Thus the organic matter content (i.e., percent organic matter) of lake sediments is determined principally by detrital imports (terrestrial and pelagic) plus benthic gross primary production, minus total sediment respiration.

In oligotrophic lakes typical of those in the Arctic, low water column primary production results in relatively small exports of phytodetritus to the sediments (Wetzel, 2001). In these lakes the sediments receive most of their organic matter inputs from the deposition of organic particles that wash into the lake from the watershed (Molot and Dillon, 1996). The production of sediment organic matter by benthic photosynthesis is limited by light availability (Stanley, 1976a; Bjork-Ramberg, 1983; Hansson, 1992; Vadeboncoeur et al., 2001; Ask et al., 2009; Karlsson et al., 2009). Thus only in lakes with illuminated sediments (e.g., shallow), does benthic primary production make up a large component of whole lake organic matter production (Stanley, 1976b; Vadeboncoeur et al., 2008; Whalen et al., 2008; Ask et al., 2009; Karlsson et al., 2009).

The accumulation of sediment organic matter via the above mechanisms is constantly being countered by heterotrophic respiration of organic substrates, which will deplete sediment organic matter content (Stanley, 1976b; Ask et al., 2009). Over geologic time scales only a very small proportion of the organic matter deposited in sediments will escape mineralization (Burdige, 2007). However the rate of sediment organic matter decomposition is limited by temperature, the availability of electron acceptors (notably oxygen), and lability (Capone and Kiene, 1988; Canfield, 1994; Burdige, 2007). As a result of the sensitivity of mineralization rate to environmental conditions, factors that affect these conditions can affect the loss of organic matter from sediments (den Heyer and Kalff, 1998).

The organic matter content of a sediment sample will reflect the integrated effects of organic matter production, deposition and mineralization history, all of which are affected by the environmental conditions of the lake sediments. In this paper we report the results of a survey of sediment organic matter from 22 lakes in the Alaskan Arctic. We evaluate the effect of select environmental variables (e.g., depth of the overlying water, water temperature, irradiance reaching the sediments, dissolved oxygen in the overlying water) on the distribution of sediment organic matter both within and among lakes. Furthermore we estimate the loss of sediment organic matter with sediment depth (i.e., age) in 3 lakes to evaluate the heterotrophic removal of organic matter from sediments.

## Materials and Methods

### Study Site

We sampled 22 small lakes (0.3 – 8.5 ha, surface area) near Toolik Lake in the Alaskan Arctic (Fig. 1). The Toolik Lake region is characteristic of the Alaskan Arctic Foothills, which is dominated by tundra vegetation and underlain by continuous permafrost (Ping et al., 1998). The annual mean air temperature is between -10o and -8o C and annual precipitation ranges 140 to 270 mm, of which 40% is snow (Ping et al., 1998). During the summer, air temperatures moderate to an average of 11o C and the region experiences 24–h daylight (Oechel et al., 2000).

The glacial geology of each lake in the survey was determined from the map in Hamilton (2002). Lakes were assigned to either the Itkillik glacial drift (id) or the Sagavanirktok glacial drift (sd). All of the lakes in the Itkillik drift except E–2 and E–pond are on the phase II drift which occurred between 25 and 11.5 ka (ka: thousand years before present). Lakes E–2 and E–pond are on the phase I drift which has an age of 120 to 55 ka. The older Sagavanirktok surface is between 780 and 125 ka (Hamilton, 2002). Two lakes could not be clearly assigned to one of the above categories. Hamilton (2002) shows lake S–3 on subglacial meltwater deposits associated with the Itkillik drift so this lake was included with the younger id lakes. Finally lake GTH 110 occurs partially on the sd surface and partially on solifluction deposits (Hamilton, 2002) but was grouped with the sd lakes.

### Core Sampling and Sediment Collection

Sediments were collected during the summer (June - August) using a K-B style gravity corer (Wildlife Supply Company, Yulee, FL). In 2007, all cores were sectioned into 10, 1 cm increments in the field. Each sediment section was homogenized and transferred to a preweighed 20 ml plastic scintillation vial. Two cores each were collected from a single “shallow” and “deep” location in each lake. The relative designations of “shallow” and “deep” refer to samples collected at the shallowest depth with sufficient sediments for coring and the deepest location in the lake. If the shallowest depth suitable for coring and the maximum depth of the lake were similar, only a single sample was collected and was designated “shallow” or “deep” based on the sample depth relative to the depth of the other lakes in the survey.

In 2008, lakes E-4, S-3 and GTH 91 were sampled in the same manner as the lakes surveyed in 2007 except that the sediments were collected into a 15 ml glass centrifuge tube following sectioning. The porewater was extracted from these sediments via centrifugation (1000 or 2000 rpm for 30 min) and the sediments were transferred to glass 20 ml scintillation vials. All sediments were dried at 40 - 60o C for at least 48 h or 105o C for 12 h. The percent organic matter in the sediments was determined via loss on ignition (LOI) where the the mass lost from the dried sediments after combustion for 4 h at 550o C divided by the total dry mass times 100 (Wetzel and Likens, 2000). Dry bulk density was determined as the dry mass the sediment of each core slice, multiplied by the volume of the core slice.

### Environmental and Spatial Variables

On the same day the sediments were sampled from a lake we measured select environmental variables. We collected depth profiles of temperature and dissolved oxygen using either a YSI Model 85 multiparameter water quality meter (YSI Incorporated, Yellow Springs, OH) or Hydrolab, Data Sonde 5 (Hach Hydromet, Loveland, CO). All profiles began just below the air-water interface and measurements were collected in 0.5 m intervals to the deepest point in the lake. Photosynthetic photon flux density (PPFD) was similarly measured in 0.5 m intervals using a LI-192SA underwater 2π quantum sensor with a Li–Cor LI-250 quantum meter (Li-Cor, Lincoln, NE). The percent of the surface PPFD reaching the sediments at each depth (hereafter, percent surface irradiance) was estimated using the light attenuation coefficient calculated as the slope of the natural log of PPFD versus depth. Dissolved organic carbon (DOC) was measured from a water sample taken at the same depth as the cores using a Van Dorn sampler (Wildlife Supply Company, Yulee. FL). Samples were filtered through a 0.45 μm polypropylene (PP) filter, acidified with 500 μl of 1N HCl and stored at 4o C until analyzed for DOC on a Shimadzu TOC–V Total Carbon Analyzer (Shimadzu Scientific Instruments Columbia, MD).

**Pb Analysis**

Sediment accumulation rates were determined for lakes E-4, S-3, and GTH 91 using the distribution of 210Pb. These lakes were chosen for sediment accumulation analysis because they have been studied much more extensively than most of the other lakes in the survey and thus, these additional data would be more valuable overall. To perform the analysis, two sediment cores were collected from the deepest location in each lake using a K-B style sediment corer. The upper 10 cm of the cores were sectioned in 1 cm intervals and dried as described above. The 210Pb and 226Ra measurements were made using an intrinsic germanium detector coupled to a multi-channel analyzer (Princeton Gamma-Tech HPGe, Princeton, NJ). Dried sediments were packed and sealed in gamma tubes and activities were calculated by multiplying the counts per minute by a factor (determined from standard calibrations) that includes the gamma-ray intensity and detector efficiency. Identical geometry was used for all samples. The 210Pb activity was determined by the direct measurement of the 46.5 KeV gamma peak. The 226Ra activity was determined following a 21 d ingrowth period via 214Pb granddaughter measurement at 351.9 KeV. Accumulation rates were calculated using the constant initial concentration (CIC) model (Appleby and Oldfield, 1992).

### Statistics and Calculations

The mean percent organic matter content of the sediments (hereafter, mean percent organic matter) was calculated by averaging the percent organic matter in each sediment slice across the entire 10 cm core. The percent organic matter of the sediments near the sediment-water interface (hereafter, surface percent organic matter) is the average of the replicate measures of percent organic matter in the 0 - 1 cm core slice. The degree of correlation between mean and surface percent organic matter was assessed with Pearson’s correlation. We tested whether surface percent organic matter was greater than mean percent organic matter in each lake using a paired t-test.

In the 3 lakes with dated sediments (i.e., E-4, S-3, and GTH 91), the rate of sediment organic matter loss with sediment depth was estimated in the deep cores by fitting a linear model (least squares) to the change in percent sediment organic matter with depth below the sediment mixing depth identified by the 210Pb profile. The slope of this relationship (percent organic matter cm-1) was scaled to the age of the sediments by multiplying the slope of the loss of percent organic matter with depth times the depth-based sediment accumulation rate (cm y-1). Sediment age at the base of the core was determined as the mean cumulative dry mass of sediment in the core (mg cm-2) divided by the mass-based sediment accumulation rate (mg cm-2 y-1) calculated using the 210Pb analysis.

Mean percent organic matter and surface percent organic matter were highly correlated (see Results) so only mean percent organic matter was used in the analysis. Comparisons between the distribution of sediment or lake factors on different glacial surfaces (i.e., the old (sd) and young (id) landscapes) and between the shallow and deep samples was evaluated with Wilcoxon Rank Sum tests. The relationship between mean percent organic matter and environmental variables (i.e., the lake depth from where the core was collected, percent surface irradiance, water column dissolved oxygen concentration, DOC, and temperature) were explored using pairwise Pearson’s correlations. Any comparisons with a correlation coefficient greater than 0.3 were tested for significance. All analyses were performed in R (R Development Core Team, 2009)

## Results

Shallow samples were collected from 20 lakes and deep samples were collected from 13 lakes (Tables 1 and 2). The mean ( 1 standard deviation) depths of the shallow and deep samples were 2.4 ( 0.7) and 6.7 ( 2.9) m respectively (Tables 1 and 2). The surface percent organic matter and the mean percent organic matter of the same core were highly correlated (r = 0.86, df = 31, p < 0.001). Surface percent organic matter exceeded mean percent organic matter by an average of 5.4% in a given lake and this difference occurred significantly greater than would be expected by chance (t = 3.95, df = 32, p = 0.0004; Fig. 2). The only lakes that did not fit this pattern were lakes S–11 and GTH 98, which had much higher percent organic matter in the sediments near the sediment-water interface than in the sediments overall (Fig. 2).

The distribution of mean percent organic matter did not differ significantly between the shallow and deep samples (W = 144, Nshallow = 20, Ndeep = 13, p = 0.624). Due to the lack of suitable conditions to collect samples at both shallow and deep locations in all lakes, samples from both depths were collected in only 11 lakes (42% of the total). Variation in the mean percent organic matter of the deep samples was significantly and positively correlated with variation in the mean percent organic matter of the shallow samples from the same lake (r = 0.70, df = 10, p = 0.016; Fig. 3). This pattern was not true for lakes N-1 and S-3 in which the mean percent organic matter of the shallow sample was much greater than that of the deep sample (Fig. 3). The bulk density of the sediments overall ranged from 0.008 g cm-3 to 0.416 g cm-3 with a median of 0.068 g cm-3.

Due to missing data not all lakes had data for all of the environmental variables (Tables 1 and 2). There was significantly greater mean percent organic matter in the sediments of the lakes on the younger (id) landscape than the older (sd) landscape in both the shallow (W = 73, Nid = 12, Nsd = 7, p = 0.001) and deep (W = 25, Nid = 7, Nsd = 4, p = 0.04) samples. The percent surface irradiance reaching the shallow sediments of the lakes on the younger surface (id) was significantly greater than the percent surface irradiance reaching the shallow sediments of the lakes on the older surface (W = 33, Nid = 9, Nsd = 4, p = 0.010). However, there was no significant difference in the DOC concentration (W = 24, Nid = 10, Nsd = 2, p = 0.305) and the distribution of depth of the shallow samples on the younger (id) surface was not significantly different than the depth of the shallow samples on the older (sd) surface (W = 36.5, Nid = 12, Nsd = 7, p = 0.887).

Mean percent organic matter in the shallow samples was positively correlated with percent surface irradiance (r = 0.73, df = 11, p = 0.004) and dissolved oxygen concentration in the water above the sediments (r = 0.74, df = 11, p = 0.006; Fig. 4). The percent surface irradiance of the shallow samples was not correlated with the depth from which the sample was taken (r = -0.307, df = 11. p = 0.308), thus indicating actual differences in lake clarity and not just an artifact of sampling depth. Mean percent organic matter in the deep sediments was not significantly correlated with any of the measured environmental factors.

Sediment accumulation rates were calculated for the deep sediments of lakes E-4, S-3, and GTH 91 (Table 3). The 210Pb profiles of lakes E–4 and S–3 showed evidence of sediment mixing down to 3 and 5 cm respectively but there was no evidence of mixing in lake GTH 91 (Fig. 5). The deep sediments of lake E–4 are accumulating at 12.00 mg cm-2 y-1, which is approximately twice the 6.09 mg cm-2 y-1 accumulation rate measured in lake S-3. Lake GTH 91 is intermediate with a sediment accumulation rate of 8.11 mg cm-2 y-1 (Table 3).

Below the mixing depth identified with the 210Pb profile, the rate of percent organic matter loss with depth in lake E-4 (-0.99 %OM cm-1) was approximately half that of lake S-3 (-2.06 %OM cm-1) and there was no significant linear relationship between percent organic matter and depth in lake GTH 91 (Fig. 5). Assuming a constant sediment accumulation rate and extrapolating from sediment mass and percent organic matter profiles of the cores, in lake E-4 the 10 cm core represented 38 years of accumulation and the sediments lost 0.26 percent organic matter per year. In lake S-3 the 10 cm core represented 66 years of accumulation and the sediments lost 0.31 percent organic matter per year and the sediments at 10 cm in lake GTH 91 were 156 years old (Table 3).

## Discussion

Overall, surface percent organic matter was greater than mean percent organic matter indicating that there is a loss of organic matter relative to total sediment mass with sediment depth. This loss of organic matter is consistent with the biological oxidation of sediment organic matter during diagenesis. We quantified these losses in the 3 lakes with 210Pb data. The overall rate of organic matter loss was similar between the two shallow lakes (E-4 and S-3) but this similarity masks differences in sediment accumulation and organic matter loss rate. The reduction in percent organic matter with depth in the deep sediments of lake E-4 was approximately half of what was measured in lake S-3 but since the sediment accumulation rate in the deep sediments of lake E-4 (12.00 mg cm-2 y-1) is approximately twice that of lake S-3 (6.09 mg cm-2 y-1), the rates of organic matter lost per year are similar between the lakes. These sediment accumulation rates are within the range of sedimentation rates (4.4 - 18.0 mg cm-2 y-1) observed in other shallow arctic lakes (Hermanson, 1990) but were greater than the rate of 2.7 mg cm-2 y-1 estimated for Toolik Lake (Cornwell and Kipphut, 1992).

Interestingly, the 210Pb profile of lake GTH 91 suggests that there is limited mixing of the sediments but there was no significant reduction in percent sediment organic matter with depth. Evaluation of the percent organic matter profile in lake GTH 91 shows that the organic matter content of the sediments does not decrease linearly below 4 cm. Interpreting the loss of sediment organic matter with sediment age as evidence of biological activity assumes that the input of organic matter to the sediments has remained constant over the age of the core. It is possible that there has been a reduction in the accumulation of organic matter in more recent sediments that has obscured patterns produced by biological oxidation.

The shallow sediments of lakes S-11 and GTH 98 have much higher surface percent organic matter than mean percent organic matter. Our data do not suggest any biological or physical reason why these lakes do not conform to the patterns seen in the other lakes in the dataset.

The percent organic matter of the lake sediments in our survey (17.2 - 68.9%) was greater than the 10 - 5% sediment organic matter content reported from other arctic lakes (Livingstone et al., 1958; Cornwell and Kipphut, 1992) and spans the range of percent organic matter expected for gyttja (< 50%) and dy (> 50%) sediments (Wetzel 2001). Loss on ignition at 550o C has been shown to overestimate sediment organic matter content in sediments with high carbonate or clay content (Frangipane et al. 2009). We do not have data on the composition or grain size of the sediments but the range of bulk densities between 0.008 and 0.416 g cm-3 suggest that they contain very little inorganic material that would bias our LOI measurements.

Sediment percent organic matter varied mainly among lakes and not at different depths within a lake, suggesting that sediment organic matter varies with processes occurring at a landscape scale. We do not have data on the relative proportion of autochthonous and allochthonous organic matter within the lake sediments but the correlations between mean percent organic matter and the measured environmental variables suggest that differences in percent organic matter among lake sediments is due to differences in the amount of benthic primary production. In the shallow sediments, greater percent organic matter was correlated with principal indicators of photosynthesis (e.g., higher percent surface irradiance and dissolved oxygen in the overlying water). Although it is possible that differences in organic matter content of the sediments are driving variation in benthic primary production (e.g., via nutrient release), we are interpreting our results as evidence that benthic primary production is supplementing other sources of organic matter to the shallow sediments, as has been seen in other systems within (Stanley, 1976a) and outside of the arctic (Ask et al., 2009). Most of the variation in the benthic algal production of shallow arctic ponds is due to variation in light (Whalen et al. 2006) and or temperature (Stanley et al. 1976b), which would not be affected by sediment organic matter content.

Despite the absence of benthic photosynthesis in the sediments below the photic zone, variation in the percent organic matter of the deep sediments also may be a function of variation in benthic primary production in the shallow portions of the lake. There was a significant positive correlation between the organic matter content of the shallow and deep sediments and in most of the lakes the percent organic matter of the deep sediments was greater than or approximately equal to the percent organic matter of the shallow sediments. Thus the levels of organic matter observed in the deep regions of the lakes may result from the redistribution of organic matter produced in the photic sediments to the deeper portions of the lake (i.e., focusing). Previous work in the region has found that the material sedimentating from the water column in shallow lakes within the region is derived mainly from resuspended sediments and not phytoplankton biomass (Fortino et al., 2009).

The above pattern does not completely describe the behavior of lakes S-3 and N-1, which were among those with the highest percent organic matter in their sediments. In these lakes the shallow sediments had much greater organic matter content than the deep sediments. Although the overall high percent organic matter of the deep sediments in these lakes suggests that organic matter from the shallow portions of the lake are being redistributed, it appears that the build-up of organic matter in the euphotic sediments exceeds the transfer of organic matter to the aphotic region of the lake by focusing. It is not clear why these highly organic sediments are not redistributed as in the other lakes. One possibility is that the accumulation of benthic algal biomass is greater than in the other lakes and therefore sufficient to impede the resuspension of the sediments (Holland et al., 1974; Paterson, 1989). In lake N-1 this may be partially the result of a past whole-lake fertilization experiment (Lienesch et al., 2005) which could have stimulated benthic algae production but we do not have any evidence as to why S-3 may differ in this respect.

Our data suggest that the factors controlling the percent organic matter of the sediments are operating at a whole-lake or greater spacial scale by altering benthic primary production. The glacial history of the lakes may be contributing to differences in percent organic matter in the sediments but altering benthic primary production via lake transparency. We found significantly greater percent of surface irradiance reaching the sediments (and sediment percent organic matter) in lakes on the younger landscape surface (id). Since light availability is a key factor limiting benthic photosynthesis in arctic lakes (Stanley et al. 1976a, Whalen et al. 2006), lakes on the younger landscape surface may support higher benthic photosynthesis, resulting in greater percent organic matter in the sediment. There was no significant difference in the depth from which the samples were collected on each landscape surface, which indicates that the differences in the availability of light to the sediments is due to a difference in the transparency of the lake water and not the depth of the samples. The mechanism driving the differences in light attenuation between the two landscape surfaces is unknown, however DOC concentration is often a major factor regulating the transparency of lake water (Fee et al. 1996, Wetzel 2001, Houser 2006). Hamilton (2002) identifies significant geologic and vegetation differences between the surfaces which could potentially alter the DOC composition of the lake water, however we found no significant difference in DOC concentration among lakes on the different landscape surfaces. We do not believe that this is evidence for the influence of factors other than DOC but rather a consequence of our limited DOC sampling.

Although we only have measures from 3 lakes, the variation in the loss of sediment organic matter with age is small relative to the variation in organic matter content, which is consistent with what has been observed in other systems (Hobbie et al., 1980; den Heyer and Kalff, 1998; Pace and Prairie, 2005). Furthermore, loss of sediment organic matter was unrelated to the environmental conditions that we quantified in the lakes. These observations support our hypothesis that differences in the percent organic matter of the lake sediments is principally driven by variation in organic matter inputs rather than losses. Benthic algal production is variable and can contribute substantial amounts of organic matter to the sediments in small lakes (Ask et al. 2009). Although benthic primary production is a relatively labile and can be respired rapidly (Karlsson et al. 2008), it has been shown to persist. In shallow arctic ponds Stanley (1976b) found that 97% of benthic net primary production was buried as detritus and the ponds accumulate 500 to 1000 mg C m-2 y-1. Thus, it is likely that variation in benthic autochthonous organic matter production and not loss of sediment organic matter determines patterns in the sediment organic matter content among most small lakes in this region. If these patterns are representative of arctic lakes, then climate mediated changes to arctic lake carbon cycling may be affected by factors that alter benthic primary production, namely lake transparency.

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**Tables**

Table 1. Environmental data from the lakes with shallow samples in 2007 and 2008. Year refers to the year the samples were collected. Depth is the depth of the overlying water from which the sediment or water sample was collected (m). Till indicates that age since the most recent glaciation, where “sd” = 780 - 125 ka and “id” = 120 - 11.5 ka. Water Temp. is the temperature of the water at the depth indicated (o C). DO is the dissolved oxygen concentration of the water at the depth indicated (mg L-1). Perc. Irradiance is the percent of surface photosynthetic photon flux density reaching the depth indicated. DOC is the dissolved organic carbon concentration of the water at the indicated depth (mg L-1). Mean Perc. OM is the mean percent organic matter of the 10 cm core. Surf. Perc. OM is the percent organic matter of the sediments near the sediment water interface (0 - 1 cm). Missing data is indicated with a ”-”.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Lake | Year | Depth | Till | Water Temp. | DO | Perc. Irradiance | DOC | Mean Perc. OM | Surf. Perc. OM |
|  |  |  |  |  |  |  |  |  |  |
| E-2 | 2007 | 2.2 | id | 14.4 | 9.2 | - | - | 31.2 | 36.6 |
|  |  |  |  |  |  |  |  |  |  |
| E-4 | 2008 | 2.0 | sd | 10.1 | 7.4 | 11.8 | - | 30.6 | 43.7 |
|  |  |  |  |  |  |  |  |  |  |
| E pond | 2007 | 2.1 | id | 15.6 | 8.0 | - | - | 43.5 | 47.0 |
|  |  |  |  |  |  |  |  |  |  |
| EX 1 | 2007 | 2.5 | sd | 10.4 | - | 2.4 | 11.1 | 18.5 | 22.6 |
|  |  |  |  |  |  |  |  |  |  |
| GTH 110 | 2007 | 2.0 | sd | - | - | - | 7.7 | 17.2 | 20.9 |
|  |  |  |  |  |  |  |  |  |  |
| GTH 112 | 2007 | 2.0 | sd | 13.6 | 6.3 | 0.4 | 11.5 | 17.4 | 18.2 |
|  |  |  |  |  |  |  |  |  |  |
| GTH 114 | 2007 | 2.4 | sd | 13.1 | 8.4 | 9.6 | 8.4 | 25.1 | 30.0 |
|  |  |  |  |  |  |  |  |  |  |
| GTH 156 | 2007 | 2.0 | - | 14.5 | 8.3 | 25.7 | 6.1 | 45.5 | 50.3 |
|  |  |  |  |  |  |  |  |  |  |
| GTH 91 | 2008 | 3.0 | sd | 10.5 | - | 5.4 | - | 23.3 | 28.2 |
|  |  |  |  |  |  |  |  |  |  |
| GTH 98 | 2007 | 2.4 | sd | - | - | - | 5.5 | 25.6 | 51.7 |
|  |  |  |  |  |  |  |  |  |  |
| N-1 | 2007 | 2.0 | id | 14.0 | 10.0 | 30.0 | 5.0 | 53.0 | 62.6 |
|  |  |  |  |  |  |  |  |  |  |
| NE-10 | 2007 | 2.6 | id | 10.6 | 8.7 | 5.5 | - | 53.2 | 54.6 |
|  |  |  |  |  |  |  |  |  |  |
| NE-11 | 2007 | 2.0 | id | 15.1 | 10.0 | 57.0 | 11.0 | 68.9 | 74.3 |
|  |  |  |  |  |  |  |  |  |  |
| NE-3 | 2007 | 3.5 | id | 6.6 | 13.3 | - | 7.8 | 57.5 | 54.9 |
|  |  |  |  |  |  |  |  |  |  |
| NE-8 | 2007 | 1.5 | id | - | - | - | 8.6 | 62.7 | 64.4 |
|  |  |  |  |  |  |  |  |  |  |
| NE-9 | 2007 | 2.0 | id | 17.3 | 10.7 | - | 10.5 | 62.3 | 56.6 |
|  |  |  |  |  |  |  |  |  |  |
| S-11 | 2007 | 4.9 | id | 6.2 | 7.3 | 12.4 | - | 20.4 | 57.9 |
|  |  |  |  |  |  |  |  |  |  |
| S-3 | 2008 | 2.0 | id | 9.1 | - | 20.9 | - | 66.4 | 73.0 |
|  |  |  |  |  |  |  |  |  |  |
| S-6 | 2007 | 2.0 | id | 17.1 | - | 30.8 | 7.6 | 41.6 | 52.7 |
|  |  |  |  |  |  |  |  |  |  |
| S-7 | 2007 | 2.7 | id | 16.0 | - | 15.1 | 3.8 | 47.8 | 48.9 |
|  |  |  |  |  |  |  |  |  |  |
| Mean |  | 2.4 |  | 12.6 | 9.0 | 17.5 | 8.0 | 40.6 | 47.5 |
| Standard Deviation |  | 0.7 |  | 3.4 | 1.9 | 15.6 | 2.5 | 17.9 | 16.6 |

Table 2. Environmental data from the lakes with deep samples in 2007 and 2008. Year refers to the year the samples were collected. Depth is the depth of the overlying water from which the sediment or water sample was collected (m). Till indicates that age since the most recent glaciation, where “sd” = 780 - 125 ka and “id” = 120 - 11.5 ka. Water Temp. is the temperature of the water at the depth indicated (oC). DO is the dissolved oxygen concentration of the water at the depth indicated (mg L-1). Perc. Irradiance is the percent of surface photosynthetic photon flux density reaching the depth indicated. DOC is the dissolved organic carbon concentration of the water at the indicated depth (mg L-1). Mean Perc. OM is the mean percent organic matter of the 10 cm core. Surf. Perc. OM is the percent organic matter of the sediments near the sediment water interface (0 - 1 cm). Missing data is indicated with a “-”.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Lake | Year | Depth | Till | Water Temp. | DO | Perc. Irradiance | DOC | Mean Perc. OM | Surf. Perc. OM |
|  |  |  |  |  |  |  |  |  |  |
| E-2 | 2007 | 4.8 | id | 6.8 | 4.4 | - | - | 37.6 | 42.2 |
|  |  |  |  |  |  |  |  |  |  |
| E-4 | 2008 | 4.0 | sd | 10.2 | 7.4 | 4.4 | - | 39.9 | 42.0 |
|  |  |  |  |  |  |  |  |  |  |
| GTH 112 | 2007 | 5.0 | sd | 8.6 | 1.4 | 0.0 | 21.1 | 19.6 | 21.1 |
|  |  |  |  |  |  |  |  |  |  |
| GTH 114 | 2007 | 6.5 | sd | 6.5 | 5.6 | 0.2 | 6.2 | 29.2 | 33.1 |
|  |  |  |  |  |  |  |  |  |  |
| GTH 156 | 2007 | 4.0 | - | 14.3 | 7.9 | 12.0 | 6.1 | 47.0 | 56.0 |
|  |  |  |  |  |  |  |  |  |  |
| GTH 91 | 2008 | 9.9 | sd | 4.6 | - | 0.0 | - | 23.1 | 26.9 |
|  |  |  |  |  |  |  |  |  |  |
| N-1 | 2007 | 12.9 | id | 3.5 | 7.1 | 0.0 | 5.0 | 35.6 | 40.4 |
|  |  |  |  |  |  |  |  |  |  |
| NE-10 | 2007 | 4.0 | id | 7.9 | 6.1 | 1.1 | - | 50.3 | 47.1 |
|  |  |  |  |  |  |  |  |  |  |
| NE-9b | 2007 | 7.0 | id | 3.5 | 0.7 | 0.1 | 9.7 | 51.0 | 52.0 |
|  |  |  |  |  |  |  |  |  |  |
| S-10 | 2007 | 5.1 | - | 6.0 | 8.1 | 0.0 | - | 31.0 | 36.0 |
|  |  |  |  |  |  |  |  |  |  |
| S-11 | 2007 | 10.9 | id | 4.0 | 2.6 | 0.0 | - | 36.8 | 40.3 |
|  |  |  |  |  |  |  |  |  |  |
| S-3 | 2008 | 5.5 | id | 9.0 | - | 2.9 | - | 42.2 | 42.9 |
|  |  |  |  |  |  |  |  |  |  |
| S-6 | 2007 | 7.2 | id | 5.7 | - | 0.0 | 7.9 | 43.1 | 48.4 |
|  |  |  |  |  |  |  |  |  |  |
| Mean |  | 6.6 |  | 7.0 | 5.1 | 1.7 | 9.3 | 37.4 | 40.6 |
|  |  |  |  |  |  |  |  |  |  |
| Standard Deviation |  | 2.9 |  | 3.1 | 2.7 | 3.5 | 6.0 | 9.7 | 9.7 |

Table 3. Results of the 210Pb analysis on cores from Lakes E-4, S-3, and GTH 91. Depth indicates the water depth where the core was collected, which was the deepest location in the lake. Sediment Accumulation is the estimated rate of sediment accumulation in the lake based on the distribution of 210Pb in the cores (mg cm-2 y-1). Accumulation time is the estimate of the number of years required to accumulate a 10 cm core (see methods for details). OM loss is the loss of percent organic matter estimated from the rate of change in percent organic matter with sediment depth and the age of the sediments in the core (% organic matter y-1). NS indicates a rate that is not significantly different from 0.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Lake | Year | Depth | Sediment Accumulation | Accumulation Time | OM Loss |
|  |  |  |  |  |  |
| E-4 | 2008 | 4.0 | 12.00 | 38 | -0.26 |
|  |  |  |  |  |  |
| S-3 | 2008 | 5.5 | 6.09 | 66 | -0.31 |
|  |  |  |  |  |  |
| GTH 91 | 2008 | 9.9 | 8.11 | 156 | NS |

## Figure Legends

Figure 1: Location of the study lakes. Lake GTH 156 is not shown but is located approximately 12.9 km north of Toolik Lake.

Figure 2: Surface percent organic matter by mean percent organic matter of the deep and shallow sediment samples. Each point represents a shallow or deep sample taken from a single lake and the line indicates a 1:1 relationship. Lakes S–11 and GTH 98 are indicated because they appear as exceptions to the general trend.

Figure 3: Mean percent organic matter of the deep sample by the mean percent organic matter of the shallow sample. Each point represents a single lake and the line indicates a 1:1 relationship. Lakes S–3 and N–1 are indicated because they appear as exceptions to the general trend.

Figure 4: The relationship between the mean percent organic matter in the sediments and the dissolved oxygen concentration of the water overlying the sediments or the percent of surface irradiance reaching the sediments.

Figure 5: Percent maximum excess 210Pb (open circles) and percent organic matter (closed circles) by sediment depth in lakes E–4, S–3 and GTH 91.

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