

Patterns in the percent sediment organic matter of arctic lakes

Kenneth Fortino · Stephen C. Whalen ·
Joseph M. Smoak

Received: 3 January 2015/Revised: 9 February 2016/Accepted: 11 April 2016/Published online: 28 April 2016
© Springer International Publishing Switzerland 2016

Abstract Patterns of sediment organic matter deposition in lakes reflect the factors that affect the production of organic matter in the lake and watershed and the removal of organic matter from the sediments. We surveyed the percent sediment organic matter of 22 lakes in the Alaskan Arctic and the rate of organic matter loss with sediment age in 3 lakes in the same region. The variation in sediment organic matter among lakes was greater than the variation between shallow and deep locations within the same lake, which is consistent with landscape-scale control of variation in sediment organic matter. In shallow water 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 reflect differences in

benthic production. The percent organic matter of the sediments in deep water was correlated with the percent organic matter in the sediments from shallow water but not environmental variables. The results suggest that variation in sediment organic matter in this region may be influenced by variation in benthic organic matter production more than by the loss of organic matter via mineralization.

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. Despite the magnitude of this pool, variation in the organic matter content of lake sediments remains incompletely characterized.

The amount of organic matter present in lake sediments results from the balance of organic matter inputs and losses. Gross primary production and detrital import increase the amount of organic matter

Handling editor: Zhengwen Liu

K. Fortino (✉)
Department of Biological and Environmental Sciences,
Longwood University, Farmville, USA
e-mail: fortinok@longwood.edu

S. C. Whalen
Department of Environmental Sciences and Engineering,
University of North Carolina at Chapel Hill, Chapel Hill,
USA

J. M. Smoak
Department of Environmental Science, Policy, and
Geography, University of South Florida, Tampa, USA

in the system, while respiration, organic matter export, and non-biological oxidation remove organic matter (Lovett et al., 2006). However, in most lake sediments, the losses due to non-biological oxidation and fluvial export are likely minimal. In oligotrophic lakes typical of those in the Arctic, primary production is often resource limited. Low water column primary production results in relatively small exports of phytodetritus to the sediments (Wetzel, 2001), and 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, oligotrophic lakes are generally thought to receive most of their organic matter inputs from the deposition of organic particles that wash into the lake from the watershed (Molot & Dillon, 1996). The exception to this is shallow lakes with relatively large areas of illuminated sediments, where benthic primary production can make up a substantial 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 primary production and allochthonous input is constantly being countered by heterotrophic respiration, which depletes sediment organic matter content (Stanley, 1976b; Ask et al., 2009). Over the geologic time scales, only a very small proportion of the organic matter deposited in sediments will escape mineralization (Burdige, 2007). However, over shorter time scales, the rate of sediment organic matter decomposition is limited by temperature, the availability of electron acceptors (notably oxygen), and organic matter lability (Capone & Kiene, 1988; Canfield, 1994; Burdige, 2007; Fortino et al., 2014). Given the relationship between the input and destruction of sediment organic matter and environmental variables, sediment organic matter content should vary at both within-lake and landscape scales.

Landscape-scale descriptions of lake sediment organic matter content are not common in the literature and none that we know of exist for the lakes in the region surrounding Toolik Lake, but such descriptions are valuable to characterize the scale and magnitude of sediment organic matter variation. Since the organic matter content of a sediment sample will reflect the integrated effects of organic matter production, deposition, and mineralization history, we

hypothesized that variation in the organic matter content of the sediments of lakes surrounding Toolik Lake, AK would correlate with variation in the environmental parameters that reflect the relative rate of water column and sediment primary production, as well as the mineralization of sediment organic matter. Using a survey of sediment organic matter from 22 lakes in the Alaskan Arctic, we evaluate the variation of sediment organic matter both within and among lakes and correlate this variation with irradiance, dissolved oxygen concentration, and dissolved organic carbon (DOC) concentration in the same lakes. Furthermore, we estimate the loss of sediment organic matter with sediment depth (i.e., age) in 3 lakes to evaluate the rate of organic matter losses from sediment respiration.

Materials and methods

Study site

We sampled 22 small lakes (Table 1) 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 -10 and -8°C and annual precipitation ranges 140–270 mm, of which 40% is snow (Ping et al., 1998). During the summer, air temperatures moderate to an average of 11°C and the region experiences 24-h daylight (Oechel et al., 2000). The region has a complex glacial history with different aged glacial surfaces in close proximity (Hamilton, 2003). Lakes E-4, EX 1, GTH 110, GTH 112, GTH 114, GTH 91, and GTH 98 are located on the older Sagavanirktok surface, which is between 780 and 125 ka (ka: 1,000 years before present) (Hamilton, 2003). Of these, lakes GTH 112 and EX 1 are also identified to be on deposits of windblown loess (Hamilton, 2003). All of the remaining lakes except E-2, E pond, S-3, and GTH 110 are on the younger Itkillik drift phase II drift which is between 25 and 11.5 ka (Hamilton, 2003). Lakes E-2 and E pond are on the phase I drift which has an age of 120 to 55 ka (Hamilton, 2003). Lake S-3 is on subglacial meltwater deposits associated with the Itkillik drift and lake GTH 110 occurs partially on the older Sagavanirktok surface and partially on

Table 1 The surface area and sediment characteristics of the lakes used in the study

Lake	Surface area (ha)	Catchment: Lake area	Shallow core sediment	Deep core sediment
E-2	0.5	120.7	NA	NA
E pond			NA	No core
E-4	4.0	10.0	Surface sediment green and gray algal material. Deep sediment brown and gray fine	Surface sediment orange and dark gray loose. Deep sediment green and dark gray fine
EX 1	1.1	30.8	Surface sediment orange flocculent. Deep sediment light gray fine mud	No Core
GTH 110	8.2	15.2	NA	NA
GTH 112	2.8	9.1	Surface sediment gray flocculent. Deep sediment light gray fine mud	Surface sediment orange flocculent with numerous chironomidae tubes. Deep sediment light gray fine mud
GTH 114	4.0	2.7	Surface sediment orange flocculent. Deep sediment gray with visible coarse organic matter	Surface sediment orange flocculent. Deep sediment gray with visible coarse organic matter
GTH 156	3.3		Surface sediment green algal material. Deep sediment brown loose	Surface sediment black and orange flocculent. Deep sediment fine black
GTH 91	2.5	16.6	NA	NA
GTH 98	6.6		Surface sediment orange flocculent. Deep sediment black fine	No Core
N-1	4.4	6.2	NA	NA
NE-10	1.0		Surface sediments fine black and orange. Deep sediments uniform fine	Uniform fine black
NE-11			Surface sediments green and black algal material. Deep sediments fine black	No core
NE-3			Light gray and jelly-like	No core
NE-8			NA	No core
NE-9			Sediment surface orange, flocculent. Deep sediments fine black	No core
NE-9b			No Core	Uniform fine black
S-10			No Core	Surface sediment black and orange flocculent. Deep sediment light gray fine
S-11	0.4	83.0	Surface sediment black and orange flocculent. Deep sediment gray fine and small gravel	Black and orange flocculent
S-3	4.0	19.9	NA	NA
S-6	1.1	964.0	Green and black algal material	Surface sediment black and orange flocculent. Deep sediment black flocculent
S-7			Green and black algal material	No Core

Catchment: Lake Area is the ratio of the catchment area to the lake area. The descriptions of the sediment characteristics come from field notes collected at the time the cores were collected. The Shallow Core Sediment and Deep Core Sediment columns in table refer to the cores collected from the shallow and deep portions of the lake (see Table 2 for depths). Within each description, the “Surface sediments” describes the sediments just below the sediment–water interface (generally 0.5–2 cm), while “Deep sediment” describes the sediment below the surface sediments down to 10 cm. NA indicates that notes were not recorded for the core. No Core indicates that no core was collected from that depth in that lake

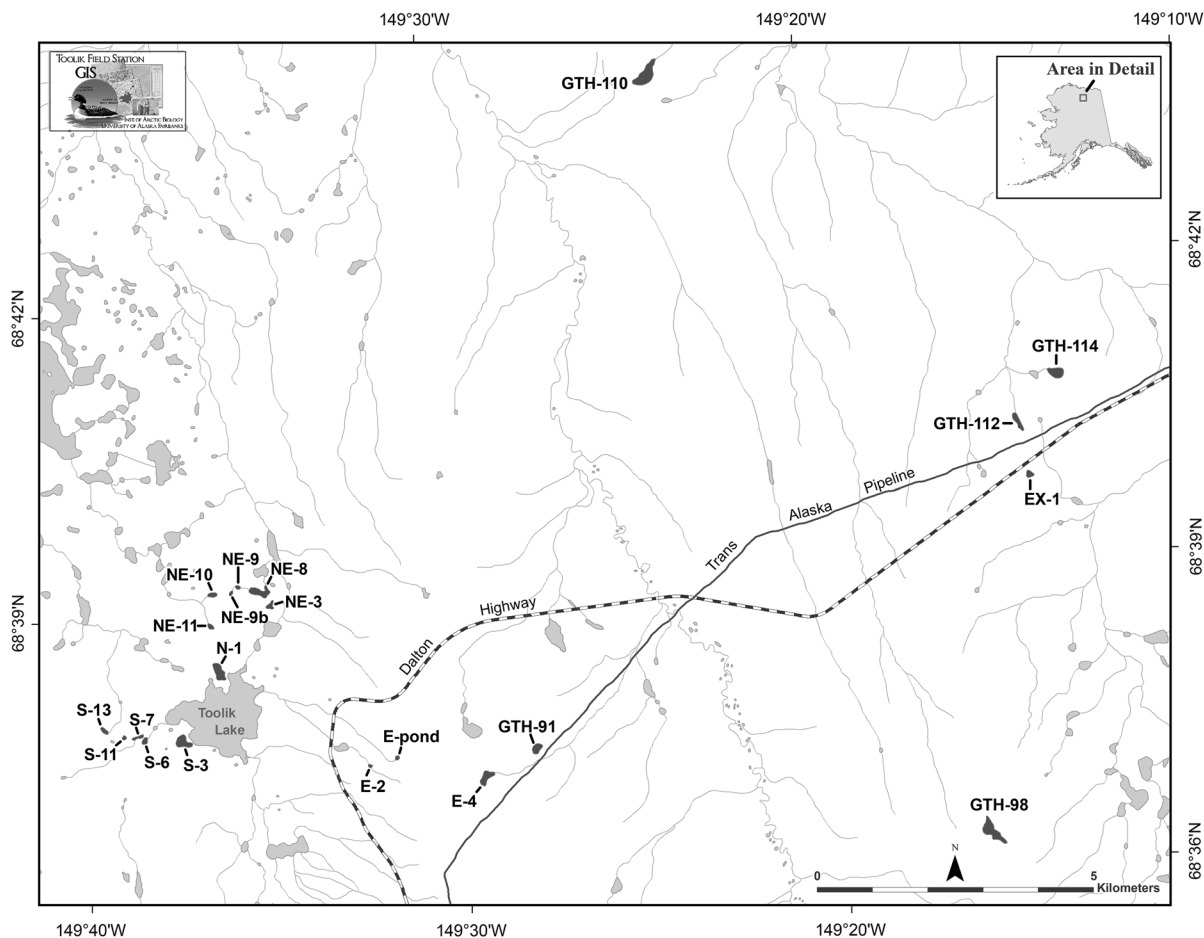


Fig. 1 Location of the study lakes. Lake GTH 156 is not shown but is located approximately 12.9 km north of Toolik Lake

solifluction deposits (Hamilton, 2003). The lake bottoms are a mixture of open mud, macrophyte beds, and cobble covered in fine sediment (Beaty et al., 2006). The open sediments are generally fine grained and organic (Table 1).

Core sampling and sediment collection

Sediments were collected from open mud habitats during the summer using a K-B style gravity corer (Wildlife Supply Company, Yulee, FL). In 2007, all lakes were sampled between June 18 and June 21, except lake NE-8 and GTH 156, which were sampled on June 15 and June 27, respectively. The exact sampling date of GTH 110 was not recorded. Sediment samples were collected in the field at 1 cm increments from the top 10 cm of each core by extruding the core upward into a basin that fit tightly over the top of the

core tube. The basin permitted the capture of the highly flocculent surface sediments and had an outlet at one end that allowed for the transfer of the entire 1 cm sediment column into a pre-weighed 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 3 replicate cores were collected from each

depth and the sediments were collected into a 15 ml glass centrifuge tube. The pore water was extracted from these sediments via centrifugation (1,000 or 2,000 rpm for 30 min) and the sediments were transferred to glass 20 ml scintillation vials. All sediments were dried at 40–60°C for at least 48 h or 105°C for 12 h. The proportion of organic matter in the sediments was determined via loss on ignition (LOI) where the mass lost from the dried sediments after combustion for 4 h at 550°C was divided by the total dry mass (Wetzel & Likens, 2000). All proportions were converted to percent for analysis and presentation. 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

At the same time, 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 1 N HCl, and stored at 4°C until analyzed for DOC on a Shimadzu TOC-V Total Carbon Analyzer (Shimadzu Scientific Instruments Columbia, MD).

^{210}Pb analysis

Sediment accumulation rates were determined for lakes E-4, S-3, and GTH 91 using the distribution of

^{210}Pb . 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 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 ^{210}Pb and ^{226}Ra 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 ^{210}Pb activity was determined by the direct measurement of the 46.5 keV gamma peak. The ^{226}Ra activity was determined following a 21 days ingrowth period via ^{214}Pb granddaughter measurement at 351.9 keV. Accumulation rates were calculated using the constant initial concentration (CIC) model (Appleby & Oldfield, 1992) fit to the portion of the sediment profile below the surface mixed layer, if mixing was evident.

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. To evaluate the general pattern of change in percent organic matter with depth, we evaluated the degree of correlation between mean and surface percent organic matter with Pearson's correlation, and 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), we estimated the rate of sediment organic matter loss with sediment depth in the deep cores by fitting a linear model (least squares) to the change in percent sediment organic matter with depth

Table 2 Environmental data from the lakes with shallow samples in 2007 and 2008

Lake	Year	Depth	Water temp.	DO	Perc. Irradiance	DOC	Mean Perc. OM	Surf. Perc. OM
E-2	2007	2.2	14.4	9.2	–	–	31.2	36.6
		4.8	6.8	4.4	–	–	37.6	42.2
E pond	2007	2.1	15.6	8.0	–	–	43.5	47.0
E-4	2008	2.0	10.1	7.4	11.8	–	30.6	43.6
E-4	2008	4.0	10.2	7.4	4.4	–	39.9	42.0
EX 1	2007	2.5	10.4	–	2.4	11.1	18.5	22.6
GTH 110	2007	2.0	–	–	–	7.7	17.2	20.9
GTH 112	2007	2.0	13.6	6.3	0.4	11.5	17.4	18.2
		5.0	8.6	1.4	0.0	21.1	19.6	21.1
GTH 114	2007	2.4	13.1	8.4	9.6	8.4	25.1	30.0
		6.5	6.5	5.6	0.2	6.2	29.2	33.1
GTH 156	2007	2.0	14.5	8.3	25.7	6.1	45.5	50.3
		4.0	14.3	7.9	12.0	6.1	47.0	56.0
GTH 91	2008	3.0	10.5	–	5.4	–	23.3	28.2
		9.9	4.6	–	0.0	–	23.1	26.9
GTH 98	2007	2.4	–	–	–	5.5	25.6	51.7
N-1	2007	2.0	14.0	10.0	30.0	5.0	53.0	62.6
		22.9	3.5	7.1	0.0	5.0	35.6	40.4
NE-10	2007	2.6	10.6	8.7	5.5	–	53.2	54.6
		4.0	7.9	6.1	1.1	–	50.3	47.1
NE-11	2007	2.0	15.1	10.0	57.0	11.0	68.9	74.3
NE-3	2007	3.5	6.6	13.3	–	7.8	57.5	54.9
NE-8	2007	1.5	–	–	–	8.6	62.7	64.4
NE-9	2007	2.0	17.3	10.7	–	10.5	62.3	56.6
NE-9b	2007	7.0	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	4.9	6.2	7.3	12.4	–	20.4	57.9
		10.9	4.0	2.6	0.0	–	36.8	40.3
S-3	2008	2.0	9.1	–	20.9	–	66.4	73.0
		5.5	9.0	–	2.9	–	42.2	42.9
S-6	2007	2.0	17.1	–	30.8	7.6	41.6	52.7
		7.2	5.7	–	0.0	7.9	43.1	48.4
S-7	2007	2.7	16.0	–	15.1	3.8	47.8	48.9

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). Water Temp. is the temperature of the water at the depth indicated (°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 are indicated with a “–”

below the sediment mixing depth identified by the ^{210}Pb 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 year^{-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 ($\text{mg cm}^{-2} \text{ year}^{-1}$) calculated using the ^{210}Pb 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 with the environmental variables. Due to missing data, not all lakes had data for all of the environmental variables (Table 2). 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. The correlations were calculated for the entire dataset and for the subset of shallow and deep samples separately. 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 and deep samples were collected from 20 and 13 of the total 22 lakes, respectively (Table 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 (Table 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 was 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).

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). Within these lakes, the difference between the mean percent organic matter of the shallow and deep samples ranged from -16.4 to 24.2% with a median difference of 1.5% , indicating there was slightly greater percent organic matter in the deep samples (Fig. 3). Variation in the mean

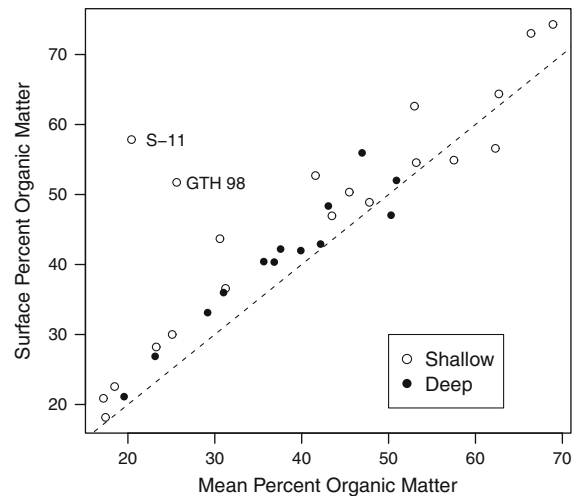


Fig. 2 Surface percent organic matter by mean percent organic matter of the deep and shallow sediment samples. Each point represents a shallow or deep sample taken from a single lake and the line indicates a 1:1 relationship. Lakes S-11 and GTH 98 are indicated because they appear as exceptions to the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

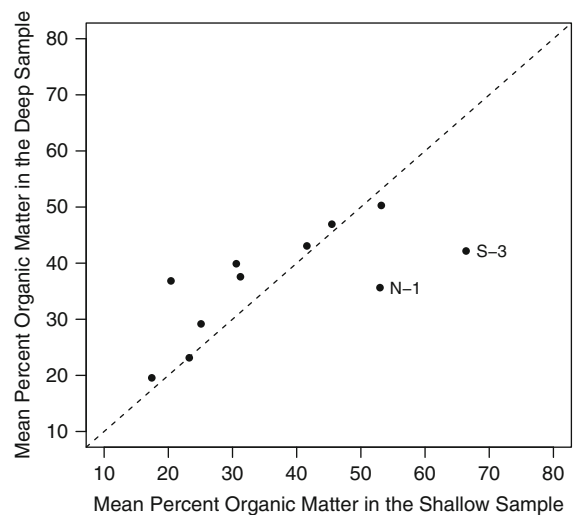


Fig. 3 Mean percent organic matter of the deep sample by the mean percent organic matter of the shallow sample. Each point represents a single lake and the line indicates a 1:1 relationship. Lakes S-3 and N-1 are indicated because they appear as exceptions to the general trend

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

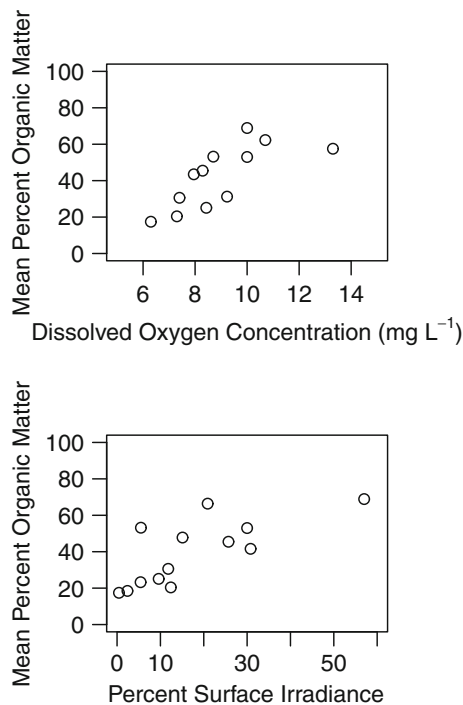


Fig. 4 The relationship between the mean percent organic matter in the sediments and the dissolved oxygen concentration of the water overlying the sediments or the percent of surface irradiance reaching the sediments. Mean percent organic matter was significantly correlated with both dissolved oxygen concentration ($r = 0.74$, $df = 11$, $P = 0.006$) and percent surface irradiance ($r = 0.73$, $df = 11$, $P = 0.004$)

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).

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 ^{210}Pb 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 exponential decay model fits (R^2) for the unmixed portion of the ^{210}Pb profile in lakes E-4 ($n = 8$), S-3 ($n = 6$), and GTH 91 ($n = 8$) were 0.97, 0.93, and 0.98, respectively (Fig. 5). The deep sediments of lake E-4 are accumulating at $12.00 \text{ mg cm}^{-2} \text{ year}^{-1}$, which is approximately twice the $6.09 \text{ mg cm}^{-2} \text{ year}^{-1}$ accumulation rate measured in lake S-3. Lake GTH 91 is intermediate with a sediment accumulation rate of $8.11 \text{ mg cm}^{-2} \text{ year}^{-1}$ (Table 3).

Below the mixing depth identified with the ^{210}Pb profile, the rate of percent organic matter loss with depth in lake E-4 ($-0.99\% \text{ OM cm}^{-1}$) was approximately half that of lake S-3 ($-2.06\% \text{ OM cm}^{-1}$), and there was no significant linear relationship between percent organic matter and depth in lake GTH 91 (Fig. 5). Since the ^{210}Pb profile of the lakes indicated that sediment accumulation rate was constant, we extrapolated from sediment mass and percent organic matter profiles of the cores to calculate that the 10 cm

Table 3 Results of the ^{210}Pb analysis on cores from Lakes E-4, S-3, and GTH 91

Lake	Year	Depth	Bulk density	Sediment accumulation rate	Sediment accumulation time	OM loss rate
E-4	2008	4.0	72.7 (62.8–80.0)	12.00	62.2 (57.6–66.7)	–0.16
S-3	2008	5.5	74.3 (71.7–77.8)	6.09	120.8 (117.7–123.4)	–0.17
GTH 91	2008	9.9	127.4 (122.2–133.5)	8.11	146.6 (135.6–155.9)	NS

Depth indicates the water depth where the core was collected, which was the deepest location in the lake. Bulk Density is the mean (+range) dry bulk density of the sediments (mg cm^{-3}). Sediment Accumulation Rate is the mean (+range) estimated rate of sediment accumulation in the lake based on the distribution of ^{210}Pb in the cores ($\text{mg cm}^{-2} \text{ year}^{-1}$) the estimates have an error of $\pm 10\%$. Sediment Accumulation Time is the mean (+range) 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 ($\% \text{ organic matter year}^{-1}$). NS indicates a rate that is not significantly different from 0

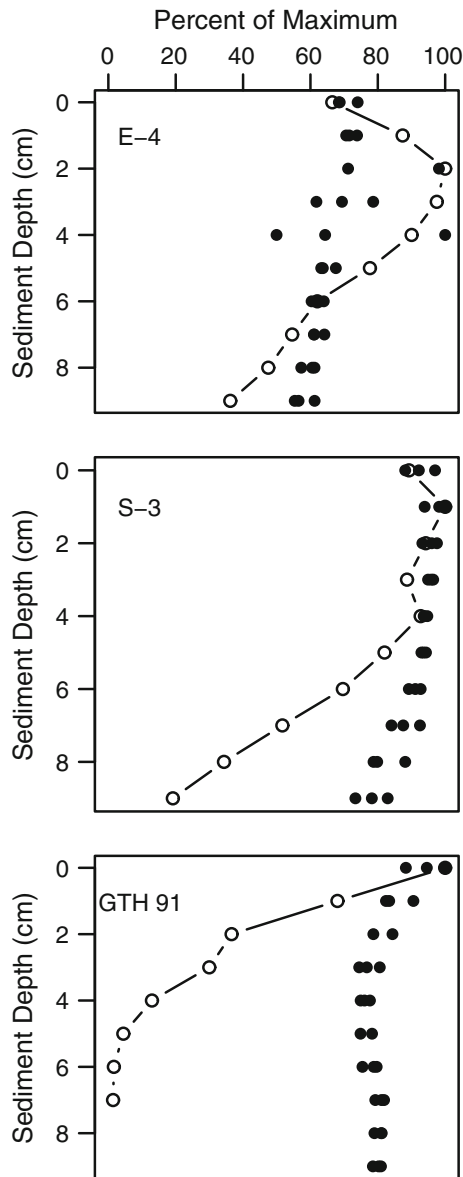


Fig. 5 Depth profiles of excess ^{210}Pb (*open circles*) and percent organic matter (*closed circles*) in lakes E-4, S-3, and GTH 91. The data are shown as the percent maximum value recorded, so that they could be plotted on the same figure. The maximum excess ^{210}Pb in lakes E-4, S-3, and GTH 91 was 25.0, 17.7, and 26.0 dpm g^{-1} , respectively. Each *open circle* is the value determined from combining 2 replicate cores from the deepest point in the lake. Each *closed circle* is the percent organic matter measured in one of three replicate cores collected simultaneously with the cores used for the determination of excess ^{210}Pb . The maximum percent organic matter in lakes E-4, S-3, and GTH 91 was 59.7, 46.4, and 28.5%, respectively

core in lake E-4 represented approximately 62 years of accumulation and the sediments lost 0.16 percent organic matter per year (Table 3). Using the same method, we calculated that in lake S-3, the 10 cm core represented approximately 121 years of accumulation and the sediments lost 0.17 percent organic matter per year and the sediments at 10 cm in lake GTH 91 were approximately 146-year old (Table 3).

Discussion

The percent organic matter of the shallow (1–10 cm) lake sediments in our survey ranged from 17.2 to 68.9%, which is bracketed by the 9–34% (Bretz & Whalen, 2014) and 55–81% (Whalen et al., 2013) reported for the shallow sediments of other lakes in the region. These values generally exceeded the <20% sediment organic matter content reported for other arctic lake muddy sediments (Livingstone et al., 1958; Cornwell & Kipphut, 1992; Beaty et al., 2006). The high sediment organic matter of the surface sediments of these lakes is likely the result of low inorganic sediment inputs. The majority of the lakes in the study are located on acidic tundra underlain by permafrost (Ping et al., 1998), which should greatly limit the input of inorganic sediment from the watershed. This observation is supported by the fact that the two lakes with the lowest mean percent organic matter (GTH 112 and EX 1; Table 2) are located on loess deposits (Hamilton, 2003; Fortino et al., 2009), which would provide a source of inorganic sediment to the lakes.

Overall, surface percent organic matter was greater than mean percent organic matter (Fig. 2) 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 ^{210}Pb data. Our estimate of the rate of organic matter loss was similar between the two shallow lakes (E-4 and S-3), but this similarity masks differences in the estimates of sediment accumulation and organic matter loss rate. The reduction in percent organic matter with depth in the deep sediments of lake E-4 ($-0.99\% \text{ OM cm}^{-1}$) was approximately half of what

was measured in lake S-3 (-2.06% OM cm^{-1}) but since the sediment accumulation rate in the deep sediments of lake E-4 ($12.00 \text{ mg cm}^{-2} \text{ year}^{-1}$) is approximately twice that of lake S-3 ($6.09 \text{ mg cm}^{-2} \text{ year}^{-1}$), the rates of organic matter lost per year are similar between the lakes (Table 3). Our comparison of the sediment accumulation rate among lakes contains uncertainty associated with the assumption that the two cores that we collected are representative of the sediment accumulation in the whole lake including bias introduced by sediment focusing. We did not calculate the focus factor for our lakes but sediment focusing at the site of our core collection would result in an overestimate of the sediment accumulation rate (Heathcote & Downing, 2012). Nonetheless, our estimate of sediment accumulation rates are within the range of sedimentation rates ($4.4\text{--}18.0 \text{ mg cm}^{-2} \text{ year}^{-1}$) observed in other shallow arctic lakes (Hermanson, 1990) but were greater than the rate of $2.7 \text{ mg cm}^{-2} \text{ year}^{-1}$ estimated for nearby but larger Toolik Lake (Cornwell & Kipphut, 1992).

To estimate the amount of organic matter accumulating in the sediments in these three lakes, we used the bulk density measurements to calculate that a column of sediment equal to the depth of our sampling (10 cm) would contain 727, 743, and 1274 mg cm^{-2} in lakes E-4, S-3, and GTH 91, respectively. Using the mean percent organic matter of the sediments from each of these lakes (Table 2), and the sediment accumulation times (Table 3), we estimate that, respectively, lakes E-4, S-3, and GTH 91 are storing 222, 493, and $297 \text{ mg of organic matter cm}^{-2}$ in the upper 10 cm of sediment that is accumulating at a rate of 3.6, 4.1, and $2.0 \text{ mg of organic matter cm}^{-2} \text{ year}^{-1}$.

Interestingly, the ^{210}Pb 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 (Fig. 5). 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 (Fig. 2). 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, thus we cannot speculate on mechanisms for their uncommon pattern other than to note that under certain conditions, the surface sediments of Arctic lakes may differ dramatically from sediments deeper in the sediment column.

Sediment percent organic matter varied mainly among lakes and not at different depths within a lake (Fig. 3). The similarity between the sediment percent organic matter of the shallow and deep sediments in the lake is likely due to multiple factors. Sediment focusing in the deeper portions of the lake means that shallow and deep cores represent different time scales for sediment and organic matter accumulation in the lake. The combination of this difference, the overall, slow sediment accumulation rate, and our sampling resolution may have obscured some of the variability between the shallow and deep cores within a lake. The lack of difference between the sediment percent organic matter of cores from the shallow and deep portions of the lake may also suggest that sediment organic matter varies with processes occurring at a landscape scale.

The organic matter in the lakes certainly derives from a combination of autochthonous and allochthonous sources but we found that the mean percent organic matter was correlated with the dissolved oxygen concentration of the overlying water and the percent irradiance reaching the sediment surface. We acknowledge that sediment percent organic matter, transparency, and oxygen concentration reflect processes occurring over different time scales; however, the correlations that we observe suggest that variation in percent organic matter among lake sediments is affected by differences in the amount of benthic primary production. In the shallow sediments, principal indicators of photosynthesis (e.g., higher percent surface irradiance and greater dissolved oxygen in the overlying water) were correlated with greater percent organic matter (Fig. 4). 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 these 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). Benthic primary production in shallow arctic ponds is typically limited by light (Whalen et al., 2006) and or temperature (Stanley, 1976b), not nutrients, and therefore should not be affected by variation in 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 affected by 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 (Fig. 4). Thus the amount of organic matter observed in the deep regions of the lakes may be influenced by 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 sedimenting from the water column of shallow lakes 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 (Table 2). In these lakes, the shallow sediments had much greater organic matter content than the deep sediments (Fig. 3). 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 littoral 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).

Conclusions

Our survey of arctic lake sediment organic matter on the Alaskan North Slope found that the surface sediments

had high levels of organic matter and are accumulating substantial amounts of organic matter. Our findings further suggest that some of the variation in the organic matter content in arctic lake sediments is due to variation in benthic primary production. Our data show that variation in the organic matter content of the lake sediments occurs mainly at the lake-scale and that the percent organic matter of the shallow sediments is correlated with variation in environmental variables associated with benthic photosynthesis. We acknowledge that other factors operating at the catchment scale can have a profound impacts on sediment organic matter and undoubtedly much of the unexplained variation in our data is related to these factors; however, the significant correlation between variation in sediment organic matter, and light and oxygen, suggests that benthic photosynthesis is affecting sediment organic matter accumulation in small lakes in this region.

Consistent with what has been observed in other systems (Hobbie et al., 1980; den Heyer & Kalff, 1998; Pace & Prairie, 2005), we found that organic matter losses from the sediment via mineralization was minor relative to overall variation in sediment organic matter suggesting that differences among lakes are principally driven by variation in organic matter inputs rather than losses.

Acknowledgments Invaluable field assistance was provided by Dendy Lofton, Matthew Harrell, Tim Yarborough, and all the members of the Geomorphic Trophic Hypothesis project. We would like to thank the Toolik Lake staff for all of their support during this project. Comments by Dina Leech improved a previous draft of this manuscript. The calculation of the lake and watershed areas and the production of the map in Fig. 1 were performed by Randy Fulweber and Jason Stuckey of the Toolik Lake GIS support staff. Funding was provided by National Science Foundation Grants NSF 0323557 and NSF 0516043.

References

- Appleby, P. G. & F. Oldfield, 1992. Uranium series disequilibrium: Application to Earth, Marine and Environmental Science in Application of lead-210 to sedimentation studies. Oxford Science Publications, London: 731–783.
- Ask, J., J. Karlsson, L. Persson, P. Ask, P. Byström & M. Jansson, 2009. Terrestrial organic matter and light penetration: effects on bacterial and primary production in lakes. *Limnology and Oceanography* 54: 2034–2040.
- Beaty, S. R., K. Fortino & A. E. Hershey, 2006. Distribution and growth of benthic macroinvertebrates among different patch types of the littoral zone of two arctic lakes. *Freshwater Biology* 51: 2347–2361.

- Bjork-Ramberg, S., 1983. Production of epipellic algae before and during lake fertilization in a subarctic lake. *Holarctic Ecology* 6: 349–355.
- Bretz, K. A. & S. C. Whalen, 2014. Methane cycling dynamics in sediments of Alaskan Arctic Foothill lakes. *Inland Waters* 4: 65–78.
- Burdige, D. J., 2007. Preservation of organic matter in marine sediments: controls, mechanisms, and an imbalance in sediment organic carbon budgets? *Chemical Reviews* 107: 467–485.
- Canfield, D. E., 1994. Factors influencing organic matter preservation in marine sediments. *Chemical Geology* 114: 315–329.
- Capone, D. G. & R. P. Kiene, 1988. Comparison of microbial dynamics in marine and freshwater sediments: contrasts in anaerobic carbon catabolism. *Limnology and Oceanography* 33: 725–749.
- Cole, J. J., Y. T. Prairie, N. T. Caraco, W. H. McDowell, L. T. Tranvik, R. G. Striegl, C. M. Duarte, P. Kortelainen, J. A. Downing, J. J. Middelburg & J. Melack, 2007. Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. *Ecosystems* 10: 171–184.
- Cornwell, J. C. & G. W. Kipphut, 1992. Biogeochemistry of manganese- and iron-rich sediments in Toolik Lake, Alaska. *Hydrobiologia* 240: 45–59.
- den Heyer, C. & J. Kalf, 1998. Organic matter mineralization rates in sediments: a within and among lake study. *Limnology and Oceanography* 43: 695–705.
- Fortino, K., A. E. Hershey, M. D. Keyes & S. C. Whalen, 2009. Summer sedimentation in six shallow arctic lakes. *Hydrobiologia* 621: 75–84.
- Fortino, K., S. C. Whalen & C. R. Johnson, 2014. Relationship between lake transparency, thermocline depth, and sediment oxygen demand in Arctic lakes. *Inland Waters* 4: 79–90.
- Hamilton, T. D., 2003. *Glacial Geology of the Toolik Lake and Upper Kuparuk River regions*. University of Alaska Fairbanks, Institute of Arctic Biology, Fairbanks, AK.
- Hansson, L. A., 1992. Factors regulating periphytic algal biomass. *Limnology and Oceanography* 37: 322–328.
- Heathcote, A. J. & J. A. Downing, 2012. Impacts of eutrophication on carbon burial in freshwater lakes in an intensively agricultural landscape. *Ecosystems* 15: 60–70.
- Hermanson, M. H., 1990. ^{210}Pb and ^{137}Cs chronology of sediments from small, shallow Arctic lakes. *Geochimica et Cosmochimica Acta* 54: 1443–1451.
- Hobbie, J. E., T. Traaen, P. Rublee, J. P. Reed, M. C. Miller & T. Fenchel, 1980. *Limnology of Tundra Ponds in Decomposers, Bacteria, and Microbenthos*. Dowden, Hutchinson & Ross, New York.
- Holland, A. F., R. G. Zingmark & J. M. Dean, 1974. Quantitative evidence concerning the stabilization of sediments by marine benthic diatoms. *Marine Biology* 27: 191–196.
- Karlsson, J., P. Byström, J. Ask, P. Ask, L. Persson & M. Jansson, 2009. Light limitation of nutrient-poor lake ecosystems. *Nature* 460: 506–510.
- Livingstone, D. A., K. Bryan & R. G. Leahy, 1958. Effects of an arctic environment on the origin and development of freshwater lakes. *Limnology and Oceanography* 3: 192–214.
- Lovett, G. M., J. J. Cole & M. L. Pace, 2006. Is net ecosystem production equal to ecosystem carbon accumulation? *Ecosystems* 9: 1–4.
- Molot, L. M. & P. J. Dillon, 1996. Storage of terrestrial carbon in boreal lake sediments and evasion to the atmosphere. *Global Biogeochemical Cycles* 10: 483–492.
- Oechel, W. C., G. L. Vourlitis, S. J. Hastings, R. C. Zulueta, L. Hinzman & D. Kane, 2000. Acclimation of ecosystem CO_2 exchange in the Alaskan Arctic in response to decadal climate warming. *Nature* 406: 978–981.
- Pace, M. & Y. T. Prairie, 2005. *Respiration in Aquatic Ecosystems in Respiration in lakes*. Oxford University Press, New York.
- Paterson, D. M., 1989. Short-term changes in the erodibility of intertidal cohesive sediments related to the migratory behavior of epipellic diatoms. *Limnology and Oceanography* 34: 223–234.
- Ping, C. L., J. G. Bockheim, J. M. Kimble, G. J. Michaelson & D. A. Walker, 1998. Characteristics of cryogenic soils along a latitudinal transect in Arctic Alaska. *Journal of Geophysical Research* 103: 28917–28928.
- R Development Core Team, 2009. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna.
- Stanley, D. W., 1976a. Productivity of epipellic algae in tundra ponds and a lake near Barrow, Alaska. *Ecology* 57: 1015–1024.
- Stanley, D. W., 1976b. A carbon flow model of epipellic algal productivity in Alaskan Tundra ponds. *Ecology* 57: 1034–1042.
- Vadeboncoeur, Y., D. M. Lodge & S. R. Carpenter, 2001. Whole-lake fertilization effects on the distribution of primary production between benthic and pelagic habitats. *Ecology* 82: 1065–1077.
- Vadeboncoeur, Y., G. Peterson, M. J. Vander Zanden & J. Kalf, 2008. Benthic algal production across lake size gradients: interactions among morphometry, nutrients, and light. *Ecology* 89: 2542–2552.
- Wetzel, R. G., 2001. *Limnology: Lake and River Ecosystems*. Academic Press, Orlando, FL.
- Wetzel, R. G. & G. E. Likens, 2000. *Limnological Analyses*. Springer-Verlag, New York.
- Whalen, S. C., B. A. Chalfant, E. N. Fischer, K. Fortino & A. E. Hershey, 2006. Comparative influence of resuspended glacial sediment on physiochemical characteristics and primary production in two arctic lakes. *Aquatic Sciences* 68: 65–77.
- Whalen, S. C., B. A. Chalfant & E. N. Fischer, 2008. Epipellic and pelagic primary production in Alaskan Arctic lakes of varying depth. *Hydrobiologia* 614: 243–257.
- Whalen, S. C., D. D. Lofton, G. E. McGowan & A. Strohm, 2013. Microphytobenthos in shallow arctic lakes: fine-scale distribution of chlorophyll a, radiocarbon assimilation, irradiance, and dissolved O_2 . *Arctic Antarctic and Alpine Research* 45: 285–295.