Quantifying terrestrial carbon sources of a small northern seepage lake

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Abstract

Many organisms use resources that have been transported to their habitat from another place. These outside resources, allochthonous resources, can often function as a resource subsidy, especially in low-productivity habitats such as oligotrophic lakes. In this study, we set out to quantify the sources of allochthonous resources transported to lakes, which can help us better understand the allochthonous support of aquatic food webs and carbon flow throughout an ecosystem. We focused on three main fluxes of terrestrial organic carbon into Long Lake, a 7.87 hectare northern seepage lake in the Upper Peninsula of Michigan. The terrestrial carbon sources we focused on were atmospheric deposition, groundwater discharge, and surface flow. We implemented surface deposition collectors, piezometers, and water samples from the inlet to quantify these sources, respectively. Inlet surface flow was the largest source of allochthonous carbon (43.1 mg C m^{-2} day^{-1}), although the inlet was not always flowing. Atmospheric deposition contributed a significant amount of resource to the surface of the lake (29.9 mg C m^{-2} day^{-1}) although highly variable due to weather conditions and spatially from shore. Groundwater was not a noteworthy source carbon to Long Lake since all measurements showed groundwater seeping out of the lake. This study suggests that even though atmospheric deposition and surface flow contribute the most allochthonous carbon to Long Lake, the system is highly variable due to a number of physical and biological factors.

Introduction

Despite the historical view of lakes as isolated ecosystems (Forbes, [1887] 1925), lake processes cannot be studied without taking into account terrestrial influences. The carbon produced outside of lakes, allochthonous carbon, can be a major source of carbon for aquatic heterotrophic organisms. In some mesohumic lakes, receiving high inputs of dissolved organic carbon (DOC), nearly 90% of the bacterial production was based on allochthonous carbon (Jansson et al., 1999; Hessen, 1992), and it has been recently recognized as a significant source of biomass for aquatic invertebrates (Pace et al., 2007).

Previous studies have shown that the majority of allochthonous carbon enters lakes as DOC from groundwater and surface flow (Wetzel and Otsuki, 1974). But airborne deposition of particulate organic carbon (POC) has also been shown to be labile enough to serve as an alternate food source for aquatic grazers (Preston et al., 2008). This source of carbon influences the productivity of a lake, starting with the base of the food web and having effects on higher trophic levels.

Few studies have addressed the multitude of sources and quantities of terrestrial carbon in lakes. Identifying the sources and quantities can have numerous applications including understanding microbial processes, zooplankton feeding phenology, global carbon cycle, and various trophic interactions. This project will attempt to quantify several routes of terrestrial carbon inputs into a northern seepage lake (Long Lake), including the groundwater, atmospheric deposition, and surface flow. We hypothesize that the atmospheric deposition will be similar (~ 5-10 mg C m^{-2} d^{-1}) to lakes studied in similar geographic location to Long Lake and that terrestrial material entering the lake via groundwater and surface flow will contribute a majority of the allochthonous carbon.

Materials and Methods

Site description

To address this hypothesis we studied groundwater DOC flow, surface flow DOC, and atmospheric deposition of carbon into Long Lake, a 7.87 hectare northern seepage lake located in Gogebic County, Michigan (89°32'W, 46°13'N) at the University of Notre Dame Environmental Research Center (Christensen, 1996; Klug and Cottingham, 2001).

Inlet DOC measurements

The inlet and outlet were sampled once weekly from May, 15 to June, 22. The last sampling day was June 22 because the inlet stream dried up shortly after. DOC samples were collected as the filtrate of epilimnetic water by passing through precombusted (4 h at 450°C) Whatman GF/F glass fiber filters under low vacuum pressure (less than 10 cm of Hg). The filtrate was collected directly in precombusted glass scintillation vials (4 h at 550°C) and then sealed and frozen until analysis (Biddanda and Cotner, 2002). The DOC samples were analyzed on a Shimadzu model 5050 high temperature TOC (total organic carbon) analyzer (Bade et al., 2007) at the University of Notre Dame in South Bend, IN and at the USDA Forest Service Northern Research Station in Grand Rapids, MN.

Stream discharge was estimated by averaging the discharge of 4 first order streams of similar channel dimensions measured in late May of 2007 on UNDERC property (C. Patrick, unpublished).

Piezometer installation

Groundwater contribution to Long Lake was determined by installing 16 piezometers in the near shore margins (water depth, <1.0m) and 4 piezometers in deeper water paired with near shore piezometers (water depth, 1.4-2.6m). The majority of the piezometers were installed in shallow water because most groundwater enters at the land-water margin (Freeze and Cherry, 1979; Winter, 1978) while most losses of lake water to the groundwater occur at deeper parts of the lake basin (Wetzel, 2001). Piezometer placement was based on potential hotspots of groundwater inflow and outflow after review of topographic maps of the area, survey of the upland characteristics, and analysis of data from a fiber optic Distributed Temperature Sensing (DTS) cable which was deployed on the bottom of Long Lake for 48 hours.

We constructed piezometers using 1.25” PVC pipe. The screen was 10 cm from the capped end of the pipe (Figure 1) and this end was pounded into the sediment at varying depths (insertion depth, 0.288-2.676m) given the characteristics of the sediment and ease of installation. The piezometers were cleaned out of any sediments and muck that may have seeped in during installation. The hydraulic conductivity was measured for each piezometer shortly after installation. After allowing the groundwater to equilibrate inside the pipes, we measured the hydraulic heads (internal water level minus lake water level) of each piezometer at least once a week after installation (June 23). Water samples were collected from two of the piezometers for DOC analysis. The samples were processed the same way as the inlet and outlet DOC samples (see above).

Atmospheric deposition measurements

We measured atmospheric carbon deposition using metal collectors containing 1L of filtered water floating in pool noodles on the surface of the lake (Preston et al., 2008). The collectors had a wetted surface to simulate deposition on the lake surface (Lewis, 1983) and low sides (height, 4.5 cm) to avoid wind turbulence that might increase POC deposition (Cole et al., 1990). These collectors were placed in a line from shore to represent the various locations at which terrestrial carbon could enter the lake from the surface. A total of 8 transects, 4 in each basin, were spaced around the lake at roughly each cardinal direction perpendicular from shore to give a better representation of the terrestrial carbon falling on the entire surface. Three deposition collectors were placed in the middle of each basin, roughly 50 meters from shore.

The terrestrial material was collected and filtered into large and small terrestrial particulate organic carbon. Samples were filtered through a 35 μm Nitex net and large particulate organic carbon (LPOC) was considered to be greater than 35 μm and small particulate organic carbon (SPOC) was between 0.7 and 35 μm. The carbon samples were collected as the retentate of the collected water passed through precombusted (4 h at 450°C) Whatman GF/F glass fiber filters under low vacuum pressure (less than 10 cm of Hg). The filters were dried for 24 hours at 62°C before being weighed to estimate the amount of carbon falling on the lake every day. LPOC was determined to be 50% of the dry mass (Preston et al., 2008). This data was then compared to the groundwater DOC, and surface flow DOC data to determine their relative contribution of allochthonous carbon to Long Lake.

Statistical Methods

Atmospheric deposition data was log-transformed and fit to a linear regression model as a function of distance from shore using the statistical software SYSTAT. Deposition between transects, particle size, and deployment date were compared using one and two-way ANOVA's. Since the various routes of carbon input were measured using different methods, comparing them statistically is difficult. Instead, the mean and standard error for each source of terrestrial carbon was calculated and visually compared to the other modes of delivery.

Results

Atmospheric deposition

Total carbon deposition did not differ between transects in the East and West basin of Long Lake ($F_{7, 42} = 0.562$, $P = 0.782$), with the mean TPOC across all collectors being 37.2 ± 3.1 mg C m^{-2} day^{-1} (n = 54). The atmospheric deposition collectors placed nearest to shore (distance from shore, 2 m) accumulated the most carbon ($F_{3, 50}$ = 6.382, P = 0.001) (Figure 4). This trend was driven by the LPOC size fraction (>35 μm), which decreased as a function of distance from shore ($F_{1, 51}$ = 21.756, P < 0.0001, R^2 = 0.299), while SPOC (35 μm < x > 0.7 μm) deposition did not change significantly with increasing distance from shore ($F_{1, 52}$ = 0.650, P = 0.424, R^2 = 0.012).

Even though TPOC was significantly different with increasing distance from shore, a post-hoc Tukey 95% Simultaneous Confidence Interval showed that collectors 2 m and 7 m from shore did not differ significantly as well as collectors 27 m and 50 m from shore. Therefore, the collectors were split into two groups, near shore (distance from shore, <7 m) and off shore (distance from shore, >7 m), and TPOC was significantly higher in the near shore collectors ($F_{1, 105}$ = 17.426, P < 0.0001) (Figure 5).

In order to estimate the amount of TPOC that Long Lake receives from atmospheric deposition, mean TPOC was calculated for near shore (49.9 ± 9.9 mg C m^{-2} day^{-1}, n = 55) and off shore (25.0 ± 4.4 mg C m^{-2} day^{-1}, n = 52). Since 79% of the surface of Long Lake is further than 7 meters from the shore, a majority of the atmospheric deposition occurs as off shore deposition (characteristic of less LPOC than near shore). Correcting for this percent area reveals that atmospheric deposition contributes 29.9 ± 5.0 mg C m^{-2} day^{-1} (n = 107) (Figure 7) to Long Lake and 47% of the deposition is SPOC.

By chance, we happened to deploy the deposition collectors during a major rain event (53 mm of precipitation over 31 hours from June 21 to June 22). This rain significantly increased the SPOC deposition (26.1 ± 1.9 mg C m^{-2} day^{-1}, n = 24) from the other deployment which had no rain (6.1 ± 1.2 mg C m^{-2} day^{-1}, n = 29) ($F_{1, 52}$ = 79.744,

$P < 0.0000001$) (Figure 6). However, the rain did not increase LPOC deposition with average deposition during the rain event being 22.1 ± 3.9 mg C m^{-2} day^{-1} (n = 24) and no rain being 22.4 ± 3.5 mg C m^{-2} day^{-1} (n = 29) ($F_{1, 51} = 0.003$, $P = 0.957$) (Figure 6).

Surface flow

The inlet contained over 8 times as much DOC as the lake itself (inlet, 65.7 ± 3.7 mg/L, n = 11; Long Lake, 8.2 ± 0.2 mg/L, n = 44) ($F_{1, 54} = 82.34$, $P < 0.0000001$) (Figure 8), meaning that it could be a significant source of DOC to the lake when it is flowing. However, it is not always flowing and we did not get a chance to measure its discharge when it was flowing. Despite this fact, we estimated that its discharge was 0.000598 m^3 s^{-1}, based on the mean discharge in late May of 2007 of 4 first order streams of similar channel dimension on UNDERC property (C. Patrick, unpublished). Using this discharge value allows us to estimate the amount of DOC that the stream may contribute to Long Lake, which we estimated to be 43.1 ± 2.5 mg DOC m^{-2} day^{-1} (n = 11) (Figure 7).

Groundwater discharge

All of the piezometers that we installed had negative hydraulic heads during the time we measured them from June 29 to July 12 (-0.316 ± 0.2 cm, n = 14). The deeper piezometers (water depth, 1.6 to 2.1 m) had a significantly lower hydraulic head than the shallow piezometers (water depth, 1.1 to 0.56 m) ($F_{1, 11} = 7.87$, $P = 0.0171$). Shoreline placement (North, South, East, or West) did not have a significant effect on the hydraulic head ($F_{2, 10} = 0.605$, $P = 0.565$).

Discussion

In this study, we quantified the three sources of terrestrial carbon inputs, atmospheric deposition, surface flow, and groundwater discharge, into a small Northern seepage lake. Few studies have simultaneously quantified these three sources of allochthonous carbon into lakes and quantifying these routes can help us better understand the role of terrestrial carbon in freshwater lakes. Throughout this study, we observed that groundwater was seeping out of the lake, meaning that this route did not contribute any organic carbon. We also observed that the largest source of organic carbon was the inlet, although it was not always flowing throughout the study. And finally, we found that atmospheric deposition is a major source of carbon, although highly variable due to distance from shore and weather conditions such as rain and wind.

Atmospheric deposition

Increasing distance from shore significantly reduced the amount of total atmospheric deposition on the lake surface. This trend was driven by LPOC which was significantly higher in the near shore collectors, while SPOC did not show any trend with increasing distance from shore. LPOC size fraction (>35 μm) is mostly dominated by tree debris such as leaf litter, twigs, and small coniferous cones. These large particles are not blow far by the wind and are usually observed only in the near shore margins. Furthermore, leaf canopies along a forest edge, like those seen along a lake edge, collect atmospheric deposition (Weathers et al., 2001) which can be deposited on the lake surface through wind currents or throughfall. The high amount of deposition in near shore margins on Long Lake can therefore be attributed to its well-established forested vegetation surrounding the lake edge.

Seasonal variation in atmospheric deposition was not observed in this study because we only measured deposition during the month of June. But one would expect the LPOC size fraction to increase greatly, especially in the near shore margins, during autumn months due to trees losing their leaves. The vegetation surrounding Long Lake is second-growth mixed hardwood forest with the west basin being dominated by conifers with 63.2% of the forest basal area while deciduous comprise only 36.8%. The east basin is nearly the opposite in forest composition with 74.1% deciduous and only 25.9% coniferous (Christensen et al., 1996). This could have a significant spatial effect on the seasonal atmospheric deposition due to the fact that deciduous trees lose their leaves every fall. We did not see a significant difference in deposition between the 8 transects or 2 basins during the summer. However, we might expect that higher amounts of leaf litter would be deposited in the east basin during the fall due to its forest composition dominated by deciduous trees.

We also observed that variation in weather had a significant effect on the amount of atmospheric deposition. When the collectors were deployed during a major rain event (53 mm of precipitation) we saw a significant increase in SPOC deposition across all distances from shore, but we did not see any difference in LPOC amounts. This increase in deposition is not only important for estimating the total amount of carbon deposition but also what type of deposition is occurring. SPOC (0.7 – 35 μm) can be an important alternate food source for aquatic grazers, such as zooplankton. In a previous study on Crampton Lake, located near Long Lake, SPOC carbon-to-nitrogen ratios (C:N) were similar to the Redfield ratio of algae and even lower than the algae sampled on Crampton Lake. Low C:N ratios are an indicator of lability, meaning that the organic matter is available for metabolism (Preston et al., 2008). So high rain events can significantly increase the amount of SPOC, providing an important resource to aquatic grazers in low-productivity lakes. And since SPOC contributed 47% of the total deposition in this study, the atmospheric route can be an important source of allochthonous carbon to lakes.

But this does not mean that LPOC is an unimportant source of carbon. Particles too large for zooplankton consumption can be an important resource for the benthic community through sedimentation (Cole et al., 2006) and even to plankton through leaching (Preston et al., 2008), further signifying the importance of atmospheric carbon deposition.

Surface flow

DOC samples from the first order inlet were over 8 times as high as the lake samples (Figure 8). This means two things: first, that the inlet is potentially a large source of DOC to the lake, and second, that the DOC is being processed by organisms within the lake, especially the microbial community. However, the stream is not always flowing, so this route of carbon addition to Long Lake is highly variable, which has been seen in similar systems (Wetzel, 2001). Surface flow can be influenced by a number of physical and biological factors, such as soil type, vegetation cover, and precipitation. Since the soil type around Long Lake is not going to change significantly, we can focus on the seasonal and yearly variation in precipitation and seasonal variation in vegetation.

When the stream is flowing, we estimated the average input of DOC to be 43.1 ± 2.5 mg DOC m^{-2} day^{-1} (n = 11). The last sample collected before the stream dried up was on June 22, and assuming that the stream was flowing since snowmelt (~mid March, NOAA mean temperature), this means that the stream is flowing for at least one quarter of the year. However, spring stream flow does not account for the total stream flow (Hodgkins et al., 2003), and the stream likely flows during the fall as well due to higher precipitation, lack of vegetation, and lower evapotranspiration. Even if the stream only flows in the spring and fall (about 1/3 to 1/2 of the year), the inlet is still a significant source of DOC to Long Lake. In 1996, Christensen and others noted that the forest of the east basin is dominated by deciduous trees while the west was dominated by coniferous trees, meaning that the west basin should have higher DOC and color, based on coniferous dominated forest composition alone (Engstrom, 1987; Xenopoulos et al., 2003). However, after separation of Long Lake, the *east* basin had elevated DOC and color, meaning that there is something else contributing to the elevated DOC. After analysis of carbon sources in this study, it seems as though the inlet could be the major contributor to the elevation in DOC in the east basin.

Groundwater discharge

Groundwater contribution to Long Lake was not observed during our study due to the fact that all the hydraulic head measurements were negative, meaning that the groundwater was seeping out of the lake. Lack of or minimal contribution of groundwater has been seen in previous studies of seepage lakes (Schindler et al., 1976; Likens et al., 1985; Christensen et al., 1996). However, groundwater inflow and outflow can fluctuate and even reverse seasonally (Anderson and Munter, 1981), and inflow rates are especially sensitive to seasonal changes (Krabbenhoft et al., 1990). This means that the sites of our piezometers, which all showed groundwater recharge during the months of June and July, could show groundwater discharge during high soil water saturation, such as during the fall or after snowmelt.

But even if the groundwater contributes to Long Lake during a certain period of the year, it does not necessarily mean that it will contribute a significant amount of DOC. Christensen and others observed that the groundwater DOC in their piezometers installed in Long Lake was not significantly different from the lake DOC (1996). This indicates that groundwater DOC contribution to Long Lake is minimal if any contribution at all.

Relative contribution

This study aimed to quantify the various routes of terrestrial organic carbon inputs into Long Lake. We hypothesized that surface flow and groundwater inputs would contribute the most TOC while atmospheric deposition would be comparable to other studies in similar geographic location. We observed that surface flow does contribute the most TOC when the inlet was flowing, however, groundwater proved to be the lowest source of carbon into Long Lake, if even a source at all. Atmospheric deposition was slightly higher than previous studies of comparable lakes and this route's importance may be underestimated, especially with the high percentage of the deposition being SPOC, a readily available alternate food source for aquatic grazers.

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Figures

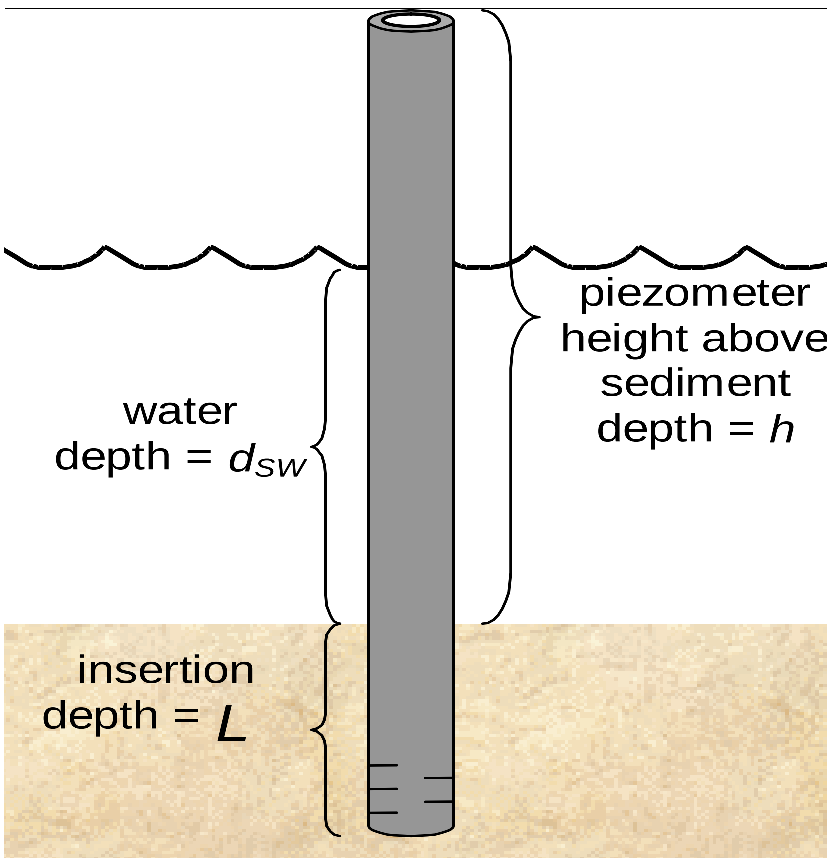

Figure 1. Diagram of a piezometer including the measurements that we recorded. Piezometer height above sediment depth was subtracted from the total length of the piezometer to calculate the insertion depth. Insertion depth is the length the screen was below the sediment surface. Water depth is the length from the sediment surface to the lake water surface. Not shown is the hydraulic head measurement, which was the length from the top of the piezometer to the external water level subtracted from the length from the top of the piezometer to the internal water level.

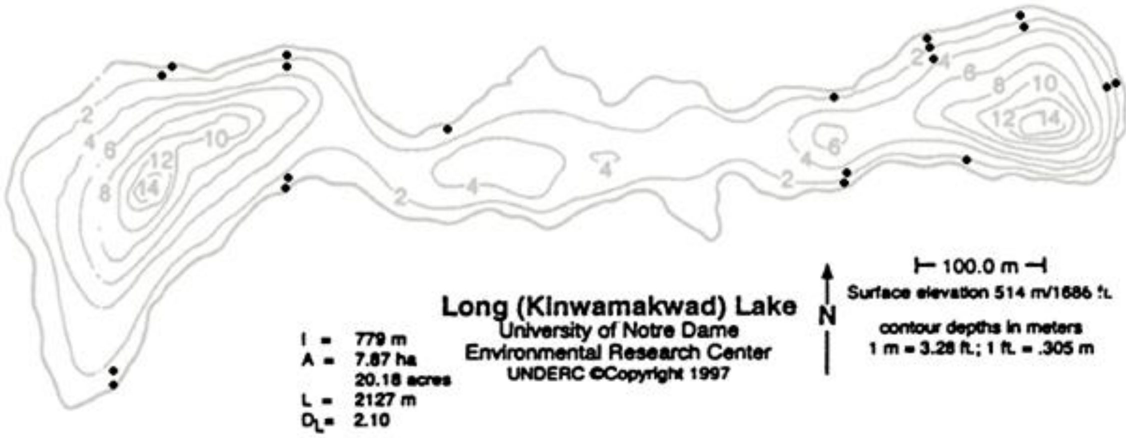

Figure 2. Map of Long Lake on UNDERC East property showing the locations of piezometer installation. A total of 20 piezometers were installed, with 8 in the west basin, 11 in the east basin, and 1 near the boat landing. 11 of the piezometers were placed on the north shore, 7 on the south shore, and 2 on the east shore near the inlet. 4 of the piezometers were installed in deep water (water depth, 1.4 – 2.6 m) and 16 piezometers were installed in shallow water (water depth, 0.3 – 1.0 m).

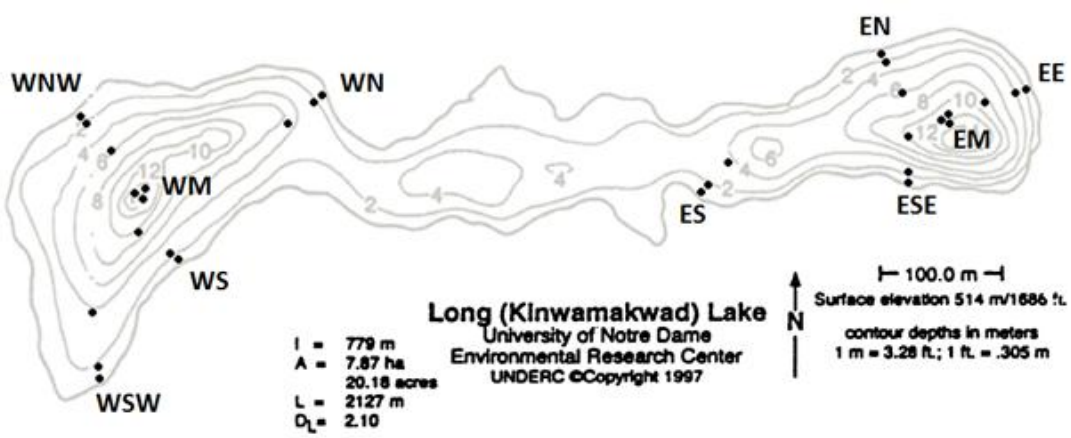

Figure 3. Map of Long Lake on UNDERC East property showing the location of TPOC collector transects. Four transects were deployed in each basin with each transect containing collectors 2, 7, and 27 meters from shore. Three replicate collectors were deployed in the center of each basin 50 meters from shore.

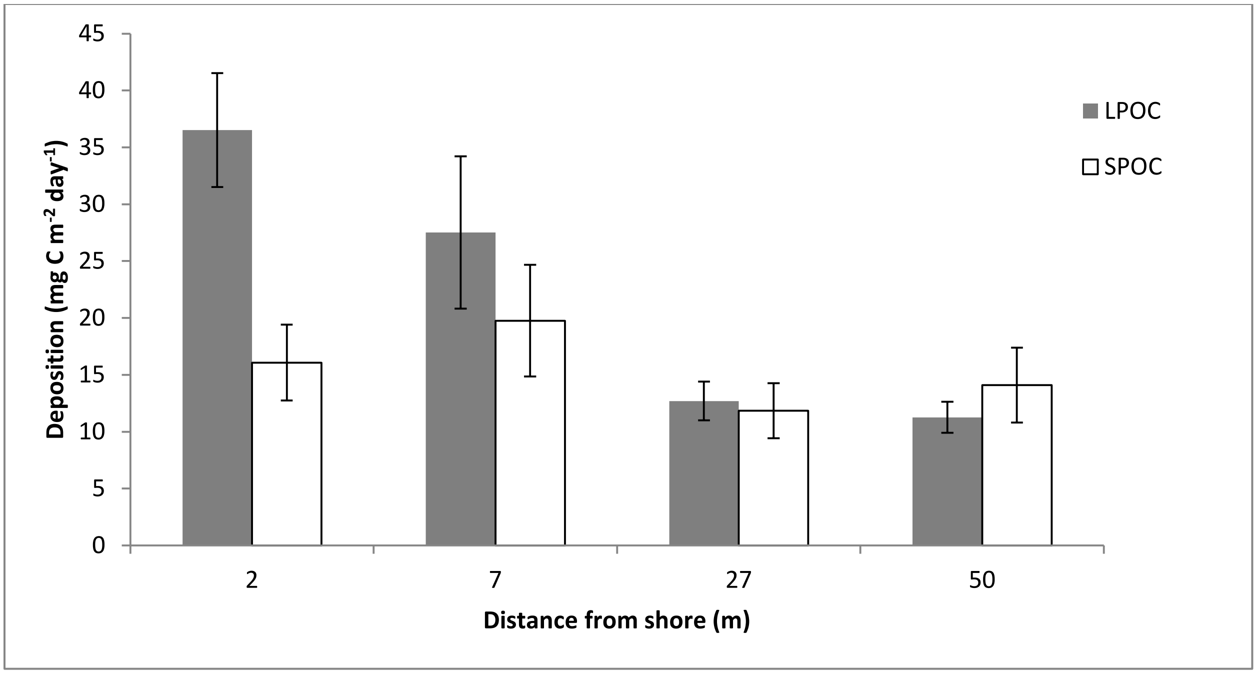

Figure 4. Atmospheric deposition of organic carbon with increasing distance from shore for all collectors deployed on Long Lake from 23 June to 29 June 2011. Deposition was categorized as either LPOC (>35 μm) or SPOC (0.7 – 35 μm). Total organic carbon significantly decreased with increasing distance from shore ($P = 0.001$), a trend mostly driven by LPOC, which decreased significantly with increasing distance from shore ($P < 0.0001$) while SPOC did not show any difference ($P = 0.424$). Standard error is given as error bars on graph ($n = 107$).

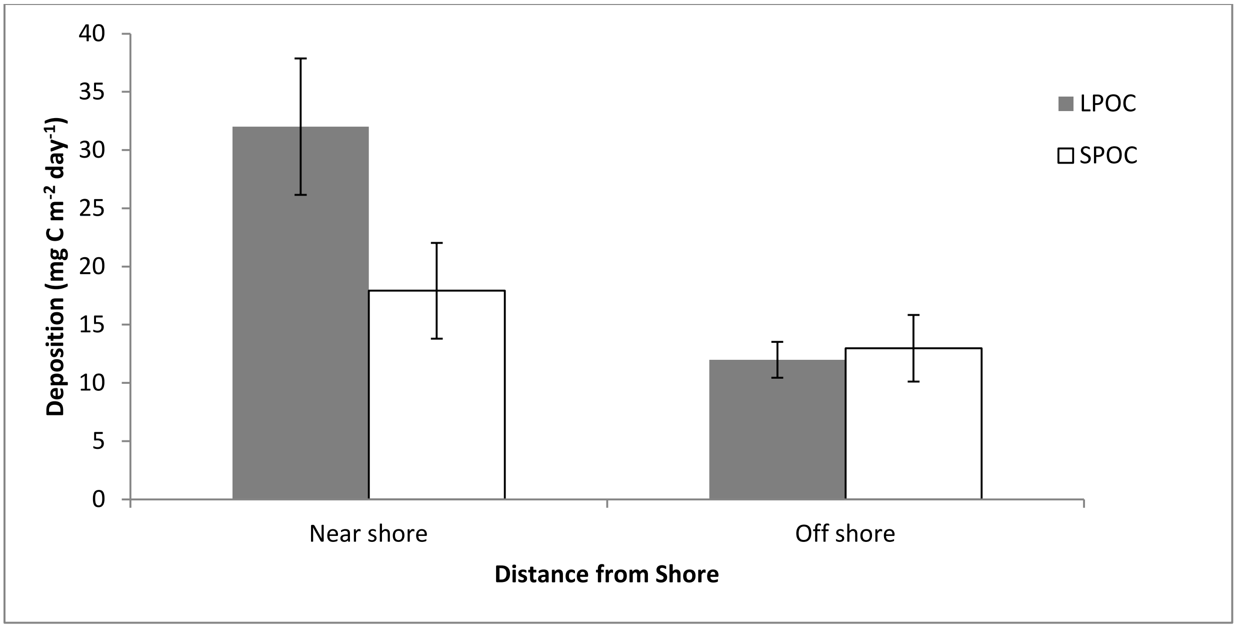

Figure 5. Atmospheric deposition of organic carbon between near shore (distance from shore, <7 m) and off shore (distance from shore, >7 m) for all collectors deployed on Long Lake from 23 June to 29 June 2011. TPOC was significantly higher in the near shore margins ($P < 0.0001$). Standard error is given as error bars on graph ($n = 107$).

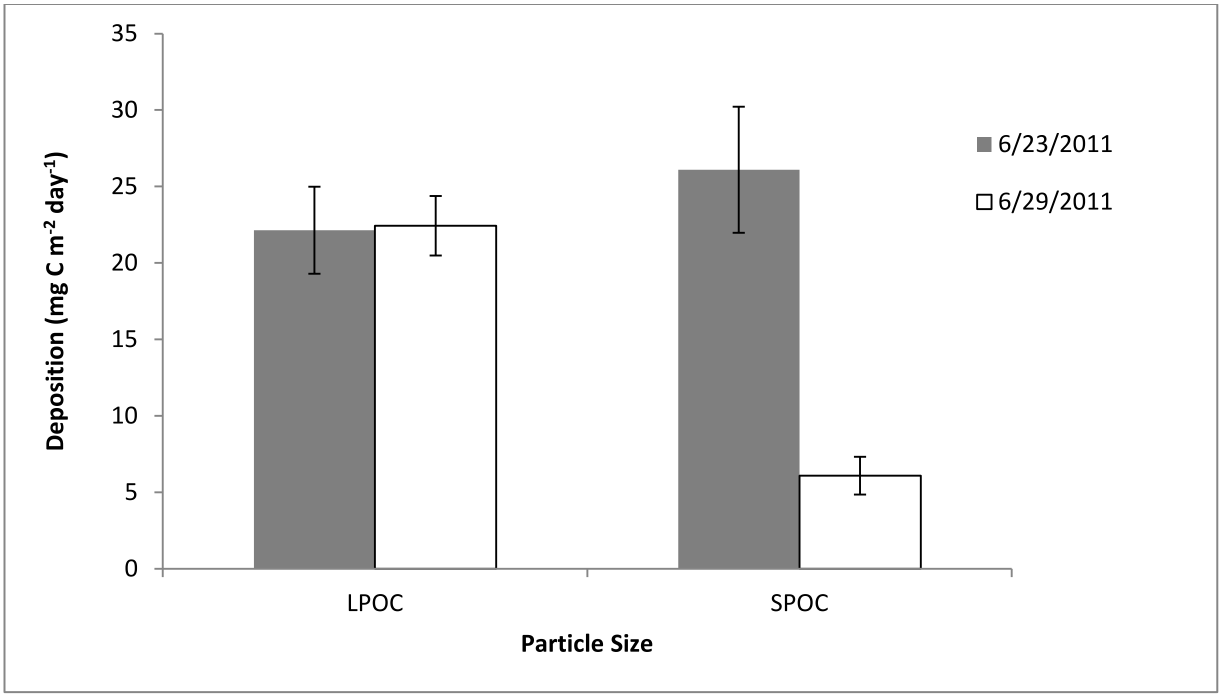

Figure 6. Atmospheric deposition of organic carbon between deployment dates for all collectors deployed on Long Lake from 23 June to 29 June 2011. A major rainfall event occurred during the 23 June deployment (53 mm of precipitation) while the 29 June deployment received no precipitation. LPOC deposition did not change between deployments ($P = 0.957$) but SPOC was significantly higher during the 23 June deployment ($P < 0.0000001$). Standard error is given as error bars on graph ($n = 107$).

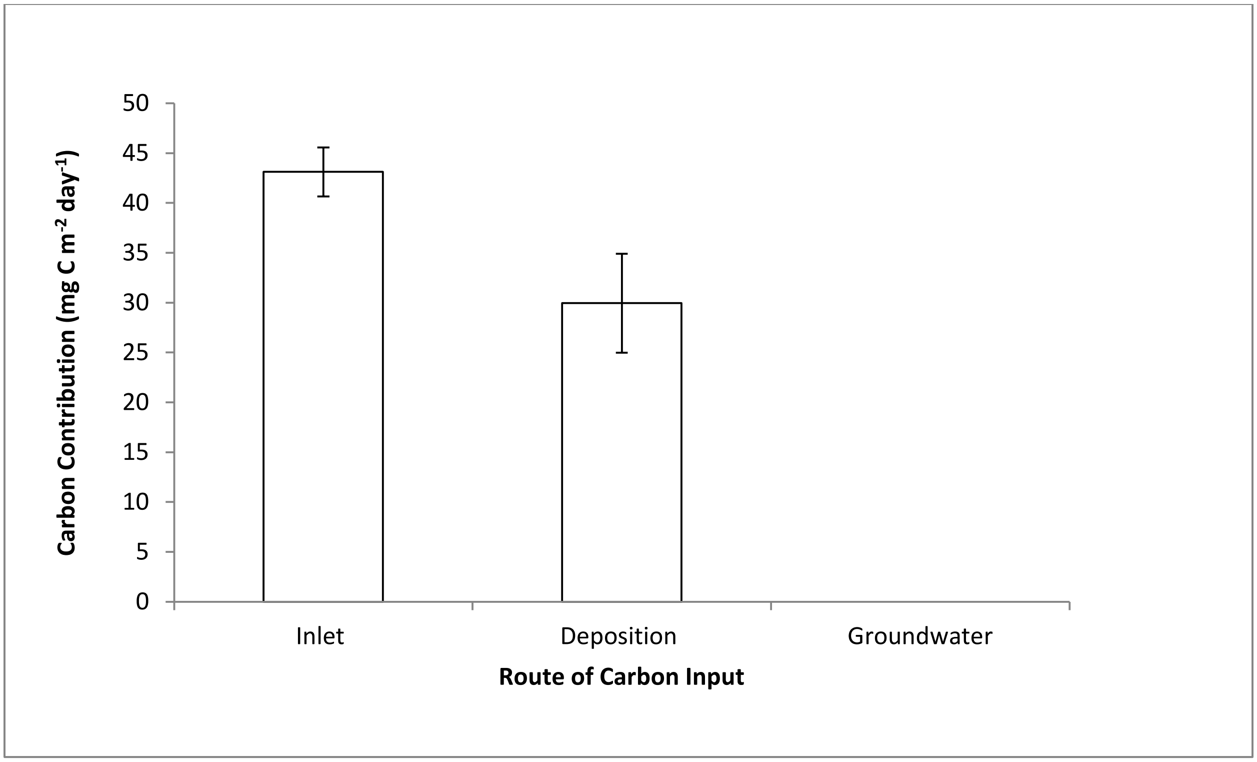

Figure 7. Comparison of carbon contribution to Long Lake by source. Inlet was measured as mg DOC m^{-2} day^{-1} while the stream was flowing from 25 May to 22 June 2011 (n = 11). Deposition was measured as mg POC m^{-2} day^{-1} across all collectors deployed on Long Lake from 23 June to 29 June 2011 and corrected for percent surface area coverage (79% of total deposition was considered off shore) (n = 107). Groundwater was measured as mg DOC m^{-2} day^{-1} across all piezometers installed in Long Lake from 29 June to 12 July 2011. Since all piezometers showed groundwater seeping out of Long Lake, carbon contribution was considered to be zero. Standard error is given as error bars on graph (n = 20).

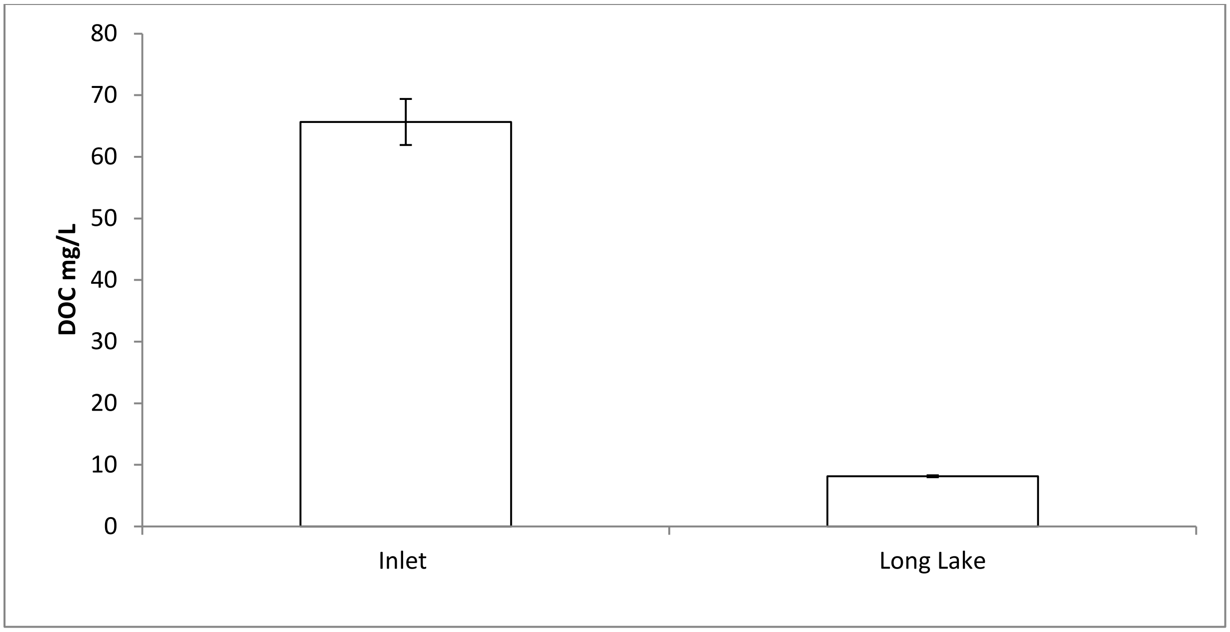

Figure 8. DOC concentration of the Long Lake inlet (n= 11) and the lake itself (n = 44) from 25 May to 22 June 2011. The inlet contained over 8 times as much DOC as the lake ($P < 0.0000001$). Standard error is given as error bars on graph.

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