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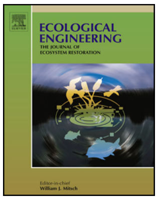

Carbon dioxide emissions from an oligotrophic temperate lake: An eddy covariance approach

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ABSTRACT

In recent years, several studies have suggested that most lakes are net carbon sources to the atmosphere rather than carbon sinks. Quantifying and understanding the environmental drivers of carbon dioxide (CO_2) flux from lakes is important in order to have a better understanding of the current and future greenhouse-gas budget of aquatic systems and the global ecosystem as a whole. In this study, we present observations of CO_2 fluxes in an oligotrophic lake in Northern Michigan during two full growing seasons. We used the eddy covariance technique to measure continuous fluxes of CO_2 and calculate the advective fluxes between the lake and the surrounding forest. We found that, at our measurement location far from shore, to the effects of horizontal advection were significantly lower than EC-observed vertical turbulent fluxes and contributed minimally to estimate of the seasonal totals. We found that during the summers the lake was an overall net carbon source, though at rates at much lower magnitude than nearby terrestrial ecosystems. Using a hierarchical modelling approach, we determined that net carbon flux from the lake is primarily correlated with wind speed, indicating the key role of mixing in the upper water layer. Variables indicative of microbial activity and lake gas storage were more highly correlated with the positive fraction of carbon flux than with carbon uptake.

1. Introduction

Engineered lakes and reservoirs are typically designed to maximize their ecosystem services. These services include flood mitigation and nutrient removal properties. Additionally, humans capitalize on biodiversity and recreational services of inland water bodies. A relatively understudied ecosystem service of lakes is their climatological effects. Lakes have a potentially globally significant role in the carbon cycle on Earth, though the quantitative estimates of that role are highly uncertain (Tranvik et al., 2009). Historically, lakes have been considered autotrophic ecosystems, where production via photosynthesis is higher than carbon consumption via respiration (Odum, 1956). This has been shown to be true in eutrophic lakes where the rates of assimilation are high due to high nutrient concentration (Schindler et al., 1997; Tranvik et al., 2009; Lee et al., 2014). However, recent research suggests that in oligotrophic to mesotrophic lakes, in both boreal and temperate regions, carbon emission is higher than autotrophic carbon assimilation (delGiorgio et al., 1997; Prairie et al., 2002; Huttunen et al., 2003; Duarte and Prairie, 2005). From an ecosystem exchange perspective, this suggests that the majority of clear-water lakes are carbon sources rather than carbon sinks. Higher carbon emissions in lakes occur in large part due to additional allochthonous inputs of terrestrial dissolved organic carbon (Lennon, 2004; Maberly et al., 2013) in the groundwater and runoff coming from the surrounding watersheds. The import of terrestrial material into the lakes is especially high from agricultural watersheds where rates of soil erosion are higher (Downing et al., 2008).

Lakes and wetlands accumulate organic carbon but the extent to which this accumulation results in mineralization and eventual release of CO_2 to the atmosphere is not yet clear. Tranvik et al. (2009) suggested that up to 50% of the carbon buried in sediment lakes is mineralized into CO_2 and CH_4, whereas Hanson et al. (2004) estimated that only 26% of that carbon is mineralized. These estimates can be highly variable as they depend on the specific physical, chemical and biological characteristics of each lake and on the different pathways of organic matter transformation, including aer-

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obic and anaerobic respiration in both benthic and pelagic habitats (Ask et al., 2009), methane production and oxidation (Bastviken et al., 2011), and inorganic carbon mineralization through calcite precipitation (Noges et al., 2016). In addition, the role that lakes will play in a warmer climate is uncertain. Both photosynthesis and respiration are predicted to increase with temperature, but is thought that the increases in respiration due to higher water temperatures will be higher than the increases in photosynthesis (Lopez-Urrutia et al., 2006), resulting in higher CO_2 emissions as the partial pressure of CO_2 in lakes increases (Kosten et al., 2010). In contrast, other studies have suggested that in a warmer planet, northern hardwater lakes will reduce their emissions of CO_2 to the atmosphere via increases in pH and chemical sedimentation of CO_2 (Finlay et al., 2015). To properly understand the role of lakes in a warmer planet, it is therefore important to quantify the current contributions of lakes to the global carbon emissions and to understand the effects of environmental conditions on these emission rates.

There are several techniques to directly measure CO_2 fluxes between ecosystems, including between lakes and the atmosphere. Flow-through and static accumulation chambers have been traditionally used to measure carbon fluxes from lakes (e.g. Duchemin et al., 1999; Riera et al., 1999; Striegl et al., 2001; Huttunen et al., 2003; Ojala et al., 2011). However, chamber measurements sample very small areas of the lake surface (a few m^2) and, when manual chamber campaigns are employed, do not provide continuous measurements of fluxes, making the temporal and spatial resolution of the measurements limited. Continuous measurements of carbon flux can be achieved through the eddy covariance (EC) technique, where sensors installed on a tower above the water measure carbon flux by calculating the covariance of high frequency fluctuations of carbon concentration and vertical wind velocity. The measurement footprint area of EC towers varies with tower height, wind, and boundary-layer stability conditions (Detto et al., 2006; Kljun et al., 2015), but typically covers an area on the order of few km^2, and thus provides better representation of the whole lake ecosystem than chamber measurements. EC towers have been used to measure carbon flux in arctic lakes (e.g. Eugster et al., 2003), bogs (e.g. Neumann et al., 1994), boreal lakes (e.g. Vesala et al., 2006; Mammarella et al., 2015) and temperate lakes (e.g. Anderson et al., 1999; Shao et al., 2015). The fetch length of the flux footprint may grow at about a factor of 100 to the height of the tower (here approximately 2.5 m above the water surface) (Leclerc and Thurtell, 1990; Vesala et al., 2008). Therefore, in small lakes, flux towers need to be installed close to the water surface and far from the shore to assure that fluxes coming from the land are not recorded (Assouline and Mahrer, 1993; Tanny et al., 2011; Bouin et al., 2012). A low tower is also important because it minimizes the contributions of horizontal advection to the total flux measurements (Higgins et al., 2013), which can be significant in heterogeneous surfaces (Sun et al., 2007). Lakes are intrinsically affected by such heterogeneities as the aquatic lake surface is surrounded by dry land which, in mid-latitudes, is typically covered by forest ecosystems. However, too short a tower can be problematic as well, resulting in not accounting for fluxes mixed by larger scale eddies. Short towers are also more likely to be flooded as lake water level fluctuates or when water is splashed due to wind and waves, necessitating that sensors and equipment are installed a safe height above the water surface. To date, few studies have monitored carbon fluxes in temperate lakes (Aubinet et al., 2012; Huotari et al., 2011; Vesala et al., 2006, 2012), and accounts of the vertical turbulent fluxes and horizontal advection are similarly rare (Higgins et al., 2013). In this study, we use the EC technique to measure fluxes from Douglas Lake – a small, oligotrophic, temperate lake in northern Michigan, during the growing seasons of two consecutive years. We use two flux towers, one located in the lake and the other located on land, to estimate the contribution of advective fluxes to total carbon flux. Such information can be used to better inform the design and management of inland water bodies to optimize their carbon budgets.

2. Methods

2.1. Site description

Douglas Lake is a freshwater lake in northern Michigan, completely surrounded by a mid-successional deciduous temperate forest, some of which is owned by the University of Michigan Biological Station. Heavy logging from 1880 to 1920 resulted in increased erosion (Francis, 1997). The lake is approximately 13.74 km^2 in area and up to 24 m deep (Kwon et al., 2015) with a relatively shallow sandbar on the eastern side. Douglas Lake has two small tributaries, Beavertail creek and Bessey Creek, and one outlet, the East Branch Maple River. Water leaves the lake as groundwater, trickling into the nearby Carp creek and eventually Burt Lake. The EC tower was constructed on the sandbar, approximately 6 m deep at the time of the tower construction.

Half-hourly, quality controlled EC flux and meteorological data used for this study are available through the Ameriflux network, site ID US-UM3 (lake tower, http://ameriflux.lbl.gov/sites/siteinfo/US-UM3#overview) and US-UMB (forest tower, http://ameriflux.lbl.gov/sites/siteinfo/US-UMd#overview) (Gough et al., 2016). Eddy covariance data above the lake was collected during the growing seasons of 2013 (June 7 through September 18) and 2014 (May 22 through October 13).

2.2. Eddy covariance data collection

The lake station was equipped with an Infra-Red Gas Analyzer (IRGA) for CO_2 and H_2O (LI-7500, LI-COR Bioscience, Lincoln, NE), a 3D sonic anemometer (CSAT3a, Campbell Scientific, Logan, UT), an air temperature/humidity probe (HMP45C, Vaisala, Helsinki, Finland), and a 4 channel net radiometer (NR01, Huskeflux, Delft, the Netherlands). The tower also supported two clusters of water sensors. The lower cluster was placed 0.6 m above the lake bottom while the upper was placed 1.5 m above the lake bottom. Both clusters included a water temperature sensor (107L, Campbell Scientific – Logan, UT) and a dissolved oxygen probe (CS511-L, Sensorex, Garden Gove, CA). The upper cluster was also equipped with a pressure sensor (Acculevel, Keller, Newport News, VA) which was used to determine water level. Data were collected on a CR3000 data logger (Campbell Scientific, Logan, UT) and were sent in real time via wide spread-spectrum radio (RF450, Campbell Scientific, Logan, UT) to the University of Michigan Biological Station for storage and processing. 3D wind speed, CO_2 and H_2O concentrations, and water level were recorded at 10 Hz. All other data were logged every 1 min. All data were aggregated into 30 min values through bulk averaging. Water 'choppiness' was calculated as the variance of the high speed water level data.

The flux calculation approach for the site is fully outlined in Morin et al. (2014b). In brief, a 3D rotation was applied to wind observations to set the vertical and cross wind components to average to 0 for each half-hour (Lee et al., 2004). To correct for the separation of the sensors, the time series of concentration measurements were shifted in time using the maximal-covariance approach. CO_2 (net ecosystem exchange, *NEE*) and water vapor flux (latent heat flux, *LE*) were corrected according to Webb et al. (1980) to account for the effects of changes in the densities of dry air and water vapor. Frequency response corrections for *LE* and CO_2 fluxes were calculated using the approach of Massman (2000). Day-night transition was calculated using incoming shortwave radiation observations. Night was defined as when the incoming shortwave radiation dropped below 10 W/m^2. If no shortwave radiation value

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