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Carbon dioxide and methane exchange at a post-extraction, unrestored peatland

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ABSTRACT

Peatlands, in their pristine state, are important long-term sinks of carbon. The extraction of peat for horticultural purposes or for biofuel however, may lead to a shift in the carbon dynamics. Additionally, the change in environmental conditions after extraction could allow for invasive species to establish and spread across the peatland. While the benefits and advantages of various restoration management practices have been identified, there has been less attention paid to the carbon exchange from unrestored peatlands at the ecosystem level. This study analyzed the carbon dioxide (CO_2) fluxes from a post-extraction, unrestored peatland in Eastern Québec at both the plant community level, using chamber methods, and at the ecosystem level, using eddy covariance techniques for two successive years. Methane flux at the plant community level was also measured. The site is an overall source of CO_2, releasing a cumulative annual total of 173 and 259 $g\,C\,m^{-2}$ for 2014 and 2015, respectively and a small source of methane, releasing an average annual cumulative total of 1 $g\,C\,m^{-2}$. Results from this study will help managers assess the importance of post-extraction peatland restoration, by comparing the differences in CO_2 exchange between restored and unrestored peatlands.

1. Introduction and background

Northern peatlands play a significant role in the global carbon cycle, covering about 3% of the earth's surface, but storing up to 30% of the world's soil carbon (C) (Gorham, 1991). Following the last glaciation, Canadian peatlands have accumulated C at an average rate of 22–28 $g\,m^{-2}\,yr^{-1}$ (Loisel et al., 2014), with Frolking et al. (2010) finding C accumulation rates that reached as high as 35 $g\,m^{-2}\,yr^{-1}$ in a temperate bog in Eastern Ontario. Natural peatlands are therefore considered long-term sinks of carbon.

Peatlands take up carbon dioxide (CO_2) through photosynthesis by the surface vegetation and release CO_2 through respiration and peat decomposition. On average, photosynthesis is greater than respiration and decomposition rates due to low temperatures and anoxic conditions that both lead to the favoring of biomass production over decomposition (Humphreys et al., 2006). However, peatlands are large sources of methane (CH_4). It has been estimated that northern peatlands contribute between 40 and 155 Tg annually to global CH_4 emissions (Neef et al., 2010; Turetsky et al., 2014; Waddington and Roulet, 1996). Although the atmospheric concentration of CH_4 is lower than that of CO_2, it has a global warming potential 28 times more potent over a 100 year time scale (Myhre et al., 2013).

Anthropogenic disturbances (e.g. peat extraction) can drastically alter the carbon dynamics of a peatland; consequently, they may change from a sink of carbon to a source (Strack and Zuback, 2013). Although CH_4 emissions decrease following the extraction of peat (Waddington and Price, 2000), if left unrestored, extracted peatlands can remain a persistent source of carbon, releasing a large amount of CO_2 to the atmosphere (Waddington et al., 2002).

The extraction of peat has increased over the last decade. An estimated 28,000 ha of peatlands have been extracted in Canada (mainly for horticultural purposes), which is an increase of 4000 ha since 2010 (Canadian Sphagnum Peat Moss Association 2016). The most common method of extraction used in Canada is 'vacuum–harvesting' (Daigle and Gautreau-Daigle, 2001; Poulin et al., 2005). Over several years, metres of peat may be removed in the process thereby reducing the peat depth. A detailed description of the vacuum–harvesting method is given in Graf et al. (2012). While the extraction of peat has high economic value, large amounts of greenhouse gases are released to the atmosphere as a result. Other negative impacts that follow the extraction of peat are an increase in organic matter decomposition and a decrease in soil moisture. Plant species that are adapted for wetter areas, such as *Sphagnum* mosses, that would normally take up a large amount of CO_2, are not able to re-establish easily in the resulting conditions (Glatzel

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et al., 2004; Poulin et al., 2005; Waddington et al., 2010). The carbon and water budgets of peatlands are intricately linked (Waddington et al., 2014). As the water table drops beyond a certain depth, plant productivity substantially decreases, decomposition increases and the peatland becomes a source of carbon rather than a sink (Van Seters and Price, 2001).

Efforts to remediate peatlands following extraction aim to restore peatland functioning in terms of hydrology, plant community and carbon exchange (Rochefort et al., 2003). In Canada, many of the restoration efforts have returned the peatland to a state of carbon-sink and high biodiversity in fewer than 20 years (Lucchese et al., 2010). A typical restoration technique following extraction is described in (Rochefort et al., 2003). Briefly, restoration includes rewetting the soil by blocking the ditches, which causes a rise in the water table. This allows for more water to be available to a variety of plants that lack complex root structures, thereby providing the potential for increased uptake of CO_2. Restoration also includes the reintroduction of *Sphagnum* moss fragments from a donor site (i.e. moss layer transfer technique; Graf and Rochefort, 2016). The peatland is then covered in a layer of mulch to protect the newly transplanted diaspores from desiccation, and to facilitate plant growth (Rochefort et al., 1990). It has been suggested that filling in the ditches with peat, which provides a flatter surface, may help facilitate the growth of mosses as well (Graf et al., 2012).

Previous studies have analyzed the benefits and advantages of various restoration management practices from extracted peatlands (Lavoie et al., 2003; Rochefort et al., 2003), but the carbon exchange that results from unrestored peatlands is not well quantified. To the best of our knowledge, continuous measurements of CO_2 exchange from unrestored peatlands, where no restoration efforts have been made (i.e. no blocking of the ditches or plant reintroduction), have yet to be obtained. Furthermore, CO_2 flux measurements from unrestored peatlands reported in previous studies have almost exclusively been obtained at the plant community level, using chamber methods (e.g., Waddington et al., 2010; Wilson et al., 2015). Therefore, there is a need to determine the fluxes of this dominant greenhouse gas at both the ecosystem and plant community levels from unrestored peatlands, as this will provide the trajectory that a peatland may follow if no restoration efforts are implemented following extraction. The measurements would also provide the peat industry with a baseline case with which to compare the results from restored peatlands, thereby depicting the true net benefit (from a carbon uptake perspective) of implementing restoration practices. Thus, the main objective of our study was to determine the net carbon exchange to the atmosphere of a post-extraction, unrestored peatland at both the ecosystem level, using eddy covariance techniques, and the plant community level, using chamber methods. To accomplish this, CO_2 fluxes at the ecosystem level were collected continuously across two study years (2014–2015) and static chamber measurements of CO_2 and CH_4 were made throughout the snow-free seasons over the same two years (May–September 2014 and 2015). Results were compared with other peatlands that have been restored. Environmental variables were measured to determine the controls on the inter-annual variability in CO_2 exchange results.

2. Materials and methods

2.1. Site description

This study was conducted at a post-extraction, unrestored peatland in the Saint-Alexandre-de-Kamouraska region (47°44′0.35″N, 69°36′38.30″W), approximately 11 km west of Rivière-du-Loup, Quebec (Fig. 1). For simplicity, the site will be referred to as SAK. The 30-year climate normals (1981–2010) for the St-Arsène weather station, located about 37 km from the peatland site, give a mean annual temperature of 3.5 °C, with mean January and July temperatures of -12.4 °C and 17.6 °C, respectively. The mean annual precipitation is 963.5 mm, with 28% falling as snow (Environment Canada, 2015).

Peat extraction started in the 1970's and was halted in 1999 when there was too much woody debris to continue extraction economically. No active restoration was done and the ditches were not blocked. As a result, *Sphagnum* has not regenerated and the site consists mainly of bare peat fields with sparse *Eriophorum vaginatum. Phragmites australis* and *Typha latifolia* (commonly known as reed and cattail, respectively), both invasive species, have established themselves in the ditches. These species contain aerenchymous tissue which allows CH_4 to bypass the distance between the water table and the surface where CH_4 would otherwise be oxidized into CO_2. Thus, these species can act as direct conduits for CH_4 release to the atmosphere.

2.2. Eddy covariance flux measurements

The eddy covariance (EC) technique (Baldocchi, 2003) was used to directly and continuously measure the surface-atmosphere exchange of CO_2 fluxes at the ecosystem level. The EC system consisted of a three-dimensional sonic anemometer (CSAT-3, Campbell Scientific, Edmonton, Canada) and an open-path infrared gas analyzer (IRGA; LI-7500A, LI-COR, Lincoln, NE). All data were recorded at 10 Hz via an analyzer interface unit (LI-7550, LI-COR Biogeosciences, Lincoln, NE). The instruments were mounted ~1.5 m above the peatland surface. CO_2 fluxes were measured year round.

The storage flux (Fs), which is the rate of change in CO_2 concentration in the air column sampled by the EC sensors (i.e. ~1.5 m above ground level), integrated from one 30-minute period to the next, was calculated following Morgenstern et al. (2004) as

$$F_s = h_m \bar{\rho}_a (\Delta \bar{S}_c / \Delta t) \tag{1}$$

where h_m is the measurement height, $\bar{\rho}_a$ is the mean molar density of dry air, and $\Delta \bar{S}_c$ is the difference between S_c of the previous and following half hours, representing the mean molar mixing ratio of CO_2. The net ecosystem exchange (NEE) was then determined by

$$\text{NEE} = F_c + F_s, \tag{2}$$

where F_c represents the turbulent eddy flux of CO_2 calculated by the EC tower.

2.2.1. Data handling

Data were processed using EddyPro software (v.5.2.0, LI-COR Biogeosciences, Lincoln, NE). Quality controls followed FluxNet protocols (e.g. Bergeron and Strachan, 2012). A two-axis rotation and the WPL correction were applied. Data were rejected if they were greater than three standard deviations from the mean. Nighttime data were filtered for low turbulence using a friction velocity threshold (u^*) value of 0.1 m/s, determined following the procedure in Mkhabela et al. (2009). Data were also rejected when the IRGA's path became dirty or was obscured by precipitation. Quality control, power loss, and precipitation events resulted in 49% and 54% of the data being rejected for the CO_2 fluxes in the two consecutive years of measurements. Removing between 40% and 60% of the data is typical of EC operations (e.g. Humphreys et al., 2006; Rinne et al., 2007).

Small gaps (fewer than four half-hour periods) in the continuous 30-min NEE data were filled by linear interpolation. Larger gaps were filled using the marginal distribution sampling method (Reichstein et al., 2005), using photosynthetically active radiation (PAR; μmol m^{-2} s^{-1}), air temperature (T_a; °C) and water vapour pressure deficit (VPD, kPa) as lookup table variables.

The NEE data follow the micrometeorological convention of positive values indicating a net release of CO_2 to the atmosphere and negative values indicating a net uptake of CO_2. NEE itself is comprised of the ecosystem respiration (ER) and the gross primary productivity (GPP)

$$NEE = ER - GEP, \tag{3}$$

such that when productivity is greater than respiration, a negative NEE