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Environmental controls of C, N and P biogeochemistry in peatland pools

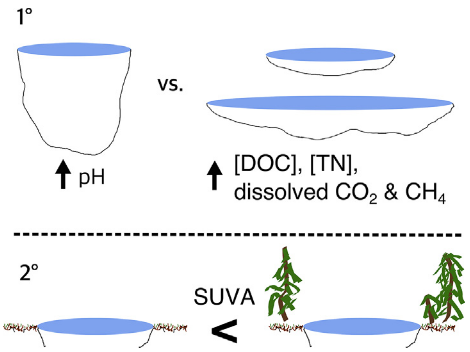
Julien Arsenault [a,*], Julie Talbot [a], Tim R. Moore [b]

[a] *Département de Géographie, Université de Montréal, 520 chemin de la Côte-Sainte-Catherine, Montréal, QC H2V 2B8, Canada*
[b] *Department of Geography, McGill University, 805 Sherbrooke Street West, Montréal, QC H3A 0B9, Canada*

HIGHLIGHTS

- Little is known about peatland open-water pool biogeochemistry.
- Pool depth largely controls nutrient concentrations.
- Vegetation surrounding pools influences carbon lability.
- Pools are phosphorus-limited.

GRAPHICAL ABSTRACT



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ABSTRACT

Pools are common in northern peatlands but studies have seldom focused on their nutrient biogeochemistry, especially in relation to their morphological characteristics and through seasons. We determined the environmental characteristics controlling carbon (C), nitrogen (N) and phosphorus (P) biogeochemistry in pools and assessed their evolution over the course of the 2016 growing season in a subboreal ombrotrophic peatland of eastern Canada. We showed that water chemistry variations in 62 pools were significantly explained by depth (81.9%) and the surrounding vegetation type (14.8%), but not by pool area or shape. Shallow pools had larger dissolved organic carbon (DOC) and total nitrogen (TN) concentrations and lower pH than deep pools, while pools surrounded by coniferous trees had more recalcitrant DOC than pools where vegetation was dominated by mosses. The influence of depth on pool biogeochemistry was confirmed by the seasonal survey of pools of different sizes with 47.1% of the variation in pool water chemistry over time significantly explained. Of this, 67.3% was explained by the interaction between time and pool size and 32.7% by pool size alone. P concentrations were small in all pools all summer long and combined with high N:P ratios, are indicative of P-limitation. Our results show that pool biogeochemistry is influenced by internal processes and highlight the spatial and temporal heterogeneity of nutrient biogeochemistry in ombrotrophic peatlands.

1. Introduction

Northern peatlands are of great importance in the global carbon (C) cycle, because they have accumulated ~450 Gt C since the Last Glacial Maximum (Loisel et al., 2017). Within peatlands, there can be a mosaic of different dominant vegetation and microtopographic elements (Rydin and Jeglum, 2013). At the regional and global scales, maritime peatlands are more often covered with pools than more continental bogs (Glaser, 1983; Glaser and Janssens, 1986). These pools are of different size, shape and spatial arrangement in relation to climatic, topographic and hydrological factors (Belyea, 2007) and they

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[*] Corresponding author.
E-mail address: julien.arsenault.1@umontreal.ca (J. Arsenault).

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develop over long time-periods through differential peat accumulation compared to the surrounding soil (Belyea and Lancaster, 2002; Foster and Fritz, 1987). In steep-sloping raised peatlands, pools can be connected by subsurface natural peat pipes (Price, 1992). This heterogeneity between pools and vegetated surfaces in peatlands influences their capacity to accumulate C (Waddington and Roulet, 2000).

Pools are net C sources to the atmosphere (e.g. Hamilton et al., 1994; McEnroe et al., 2009; Pelletier et al., 2014; Repo et al., 2007; Waddington and Roulet, 2000). This is due to a combination of peat decomposition on their bottoms, limited C uptake by aquatic vegetation and photo- and microbial degradation of dissolved organic carbon (DOC) (Pelletier et al., 2015). These processes, with the exception of photodegradation, are dependent on the availability of nutrients in the environment to support biological activity. Turner et al. (2016) demonstrated the spatial heterogeneity of pool biogeochemistry in regions of northern United Kingdom, where pool biogeochemistry differed among regions, but within-peatland variability was small.

Nitrogen (N) and phosphorus (P) play a role in the peatland's capacity to accumulate C by taking part in both primary production and decomposition. Ombrotrophic peatlands are nutrient-poor environments as they are topographically and hydrologically isolated from the surrounding terrestrial landscapes (Rydin and Jeglum, 2013). Nitrogen fixation, through methanotrophic organisms or via symbiotic *Sphagnum*-cyanobacteria associations, increases N availability in bogs (Turetsky, 2003; Vile et al., 2014) while P inputs are solely atmospheric (Bragazza et al., 2004). Peat accumulation results in an increase in the N:P ratio in the lower part of the peat profile, as P is recycled to the surface, resulting in co-limitation of N and P (Wang et al., 2015, 2014).

Pool nutrients can be influenced by limnological processes, with pool depth, area and shape influencing light penetration and wind-induced mixing, which in turn have an impact on water temperature and bacterial communities on the pool's bottom and in the water column (Wetzel, 2001). Carrer et al. (2016) showed that shallow pools of a boreal patterned fen experienced daily water mixing during summer and they estimated pool water residence time to be >10 years, the turnover being driven by evapotranspiration rather than by horizontal water movement. Hence, in non-hydrologically connected pools, C, N and P biogeochemistry could be controlled by in-pool processes rather than by the vegetation-soil interactions with the surrounding peatland.

While several studies have been conducted on the biogeochemistry of large thaw ponds and lakes in the permafrost zone (e.g. Manasypov et al., 2015; Pokrovsky et al., 2014; Polishchuk et al., 2017; Shirokova et al., 2013), we are unaware of a study which has focused specifically on C, N and P biogeochemistry in subboreal peatland pools, in relation to their morphological characteristics and seasonally. Our goal here is to determine the environmental controls on variations in pool water biogeochemistry and changes over the growing season in a cool temperate ombrotrophic bog. We hypothesize that pool depth and area, along with time, influence biogeochemistry by controlling the internal biological activity of non-connected pools.

2. Material and methods

2.1. Site description

The study was conducted at the Grande plée Bleue peatland, a 15 km^2 raised ombrotrophic bog located 12 km southeast of Québec City, Québec, Canada (71°03′N, 46°47′W; altitude ~88 m) (Fig. 1). The climate is cool continental and mean annual air temperature was 4.6 ± 1.2 °C for the interval 1981–2010 at the nearest meteorological station (4.2 km from the study site) (Environment Canada, 2017). Mean annual precipitation was 1179 mm for the same period, of which 275 mm fell as snow. The peatland formation was initiated 9500 years ago over marine sediments of the Goldthwait sea and spatial expansion occurred through the paludification of a balsam fir and white birch forest (Lavoie et al., 2012). Ombrotrophic conditions prevailed starting 8300 years ago. Peat depth reaches 450–500 cm in the center of the bog (Lavoie et al., 2012; unpublished data). The southwestern portion of the peatland was previously drained to supply the surrounding agricultural fields, but the drainage ditch was closed in the mid-1980s.

There are >650 open-water pools of different shape, area and depth in the southern part of the peatland (Fig. 1). Deeper pools are found near the center of the peatland. Vegetation is segregated in zones dominated either by mosses (e.g. *Sphagnum fuscum*, *S. magellanicum* and *S. angustifolium*) with a sparse shrub or graminoid cover; by shrubs (*Kalmia angustifolia*, *Rhododendron* spp., *Chamaedaphne calyculata*, *Vaccinium* spp.) underlain by *Sphagnum* mosses; or by black spruce (*Picea mariana*) and eastern larch (*Larix laricina*) in the forested central part of the bog.

2.2. Pool measurements and sampling scheme

In 2015 and 2016, we measured depth and area for 156 pools. Depth was estimated by dropping a 400 g and 20 cm diameter disk on to the pool unconsolidated bottom sediments, using a graduated rope. Three to 10 measurements, depending on the pool size, were taken in each pool and averaged. Area was measured based on a 0.46 m resolution satellite photo. For each pool, a shape index (SI) was also estimated with $\mathbf{SI} = \frac{\mathbf{P}}{2\sqrt{\pi a}}$, where P is the perimeter of the pool and a is the area (Moser et al., 2002; Turner et al., 2016). SI is a unitless parameter and has a value range of ≥1, where 1 is a perfect circle and larger values indicate increasing shape complexity. Dominant vegetation surrounding the pools was visually estimated in situ and pools were sorted into three classes: surrounding vegetation dominated by mosses, by ericaceous shrubs or by spruce trees. Pools where little (<20% in coverage) or no tree or shrub vegetation (<0.25 m in height) was found in a 2 m radius from the pool were sorted into the mosses class and pools where coniferous trees (>2 m in height) were covering >50% of this radius were sorted into the spruce trees category. The other pools were sorted into the shrubs class.

To determine which environmental variables influenced pool water chemistry, we sampled 62 of the 156 pools on July 26, 2016. These pools were scattered in different parts of the peatland, chosen for accessibility reasons, and they were not hydrologically connected. They were selected to represent different depths, areas, shapes and vegetation types. Water samples were collected in each pool and analyzed for dissolved organic carbon (DOC), total nitrogen (TN), total phosphorus (TP), pH and specific UV absorbance (SUVA), an estimator of DOC lability and aromatic composition (Weishaar et al., 2003).

To evaluate the temporal pattern of water chemistry in pools of different size, we selected 9 of the 62 surveyed pools, representing triplicates of extremes in both depth and area of pools found at the study site: small and shallow, small and deep, and large and shallow (Fig. 2), and were located in the center of the peatland where there is a large diversity of pool size. Water samples were collected from each pool 10 times from mid-May to late October 2016 and analyzed for total and dissolved N (TN/TDN), organic C (TOC/DOC) and P (TP/DP), pH, SUVA, dissolved carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and oxygen (O_2) and temperature (T). All samples were taken at 20 cm below the water surface and O_2 and T were measured for the entire profiles, every 10 cm. Nitrate (NO_3^-), ammonium (NH_4^+) and orthophosphate (PO_4^{3-}) were measured three times during the summer, in early June, late July and late September.

To sum up, the physical characteristics of 156 pools were measured to determine the size and depth distribution of the pools of the study site. Of these, 62 pools were sampled in 1 day to determine the spatial variability of biogeochemical parameters. Finally, a subset of 9 pools representative of the most frequent depth-size combinations present on the site were followed over one growing season.