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## LETTER

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Increased deep soil respiration detected despite reduced overall respiration in permafrost peat plateaus following wildfire

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# Abstract

Wildfire in boreal permafrost peatlands causes a thickening and warming of the seasonally thawed active layer, exposing large amounts of soil carbon to microbial processes and potential release as greenhouse gases. In this study, conducted in the discontinuous permafrost zone of western Canada, we monitored soil thermal regime and soil respiration throughout the 2016 growing season at an unburned peat plateau and two nearby peat plateaus that burned 16 and 9 years prior to the study. Maximum seasonal soil temperature at 40 cm depth was 4 °C warmer in the burned sites, and active layers were  $\sim$ 90 cm thicker compared to the unburned site. Despite the deeper and warmer seasonally thawed active layer, we found higher soil respiration in the unburned site during the first half of the growing season. We partitioned soil respiration into contribution from shallow and deep peat using a model driven by soil temperatures at 10 and 40 cm depths. Cumulative estimated deep soil respiration throughout the growing season was four times greater in the burned sites than in the unburned site, 32 and 8 g C m<sup>-2</sup> respectively. Concurrently, cumulative shallow soil respiration was estimated to be lower in the burned than unburned site, 49 and 80 g C m $^{-2}$  respectively, likely due to the removal of the microbially labile soil carbon in the shallow peat. Differences in deep contribution to soil respiration were supported by radiocarbon analysis in fall. With effects of wildfire on soil thermal regime lasting for up to 25 years in these ecosystems, we conclude that increased loss of deep, old, soil carbon during this period is of similar magnitude as the direct carbon losses from combustion during wildfire and thus needs to be considered when assessing overall impact of wildfire on carbon cycling in permafrost peatlands.

## 1. Introduction

Climate change and associated landscape disturbances are leading to widespread thawing of permafrost as observed from the increase in thickness of the active layer (AL), i.e. the surficial soil layer that thaws and refreezes each year (Viereck *et al* 2008, Brown *et al* 2015, Olefeldt *et al* 2016, Gibson *et al* 2018). Permafrost thaw exposes previously frozen soil organic carbon to decomposition potentially increasing the release of carbon dioxide ( $CO_2$ ) to the atmosphere through soil respiration (Schuur *et al* 2015). Northern permafrost peatlands store globally significant quantities of soil organic carbon (Hugelius *et al* 2014) which are largely unavailable to microbial activity while frozen. Peat plateaus are a widespread type of permafrost peatland in the discontinuous permafrost zone of western Canada. In this region, peatland complexes are a mosaic of permafrost peat plateaus, and non-permafrost channel fens and thermokarst bogs (Quinton *et al* 2003), with peat plateaus often covering 40%–60% of the landscape. Peat plateaus commonly have peat depths of 2-6 m, active layer depths of approximately 55 cm, and the peat surface is elevated 1-2 m above their surroundings due to excess ground ice (Zoltai 1993, Robinson and Moore 2000, Quinton *et al* 2003). Because peat plateaus are elevated above their surroundings, their thawed soil layers are generally drained and unsaturated, and thus decomposition occurs under aerobic, but cool, conditions. A thickening and warming of the active layer, particularly in response to disturbances such as wildfire, could thus lead to rapidly increasing rates of soil respiration, yet there is a dearth of *in situ* measurements of soil respiration in disturbed peat plateaus.

Wildfire is an integral component of northern boreal ecosystems. Wildfires burn over 1500 km<sup>2</sup> annually in western Canadian peatlands, and releases an estimated ~6 Tg carbon to the atmosphere through combustion (Turetsky et al 2004). Climate change is likely to further increase fire frequency (Flannigan et al 2013), and in the last 30 years more than 25% of permafrost peat plateaus in the discontinuous permafrost zone of Boreal Western Canada have burned (Gibson et al 2018). Wildfire leads to soil warming and AL thickening (Yoshikawa et al 2002, Viereck et al 2008, Rocha and Shaver 2011, Nossov et al 2013, Brown et al 2015, Gibson et al 2018). The most pronounced effect on soil temperatures and AL thickening in peat plateaus in Boreal Western Canada is shown to occur 10-25 years post fire with AL increasing from 55 to >150 cm and maximum soil temperatures at 40 cm depth increase from 4 °C to 11 °C (Connon et al 2018, Gibson et al 2018). Wildfire also contributes to the development of taliks, soil layers between the permafrost and the seasonally frozen layer that remained unfrozen throughout the year (Gibson et al 2018). While the pulse of carbon released to the atmosphere through combustion has been studied and assessed in terms of magnitude (Walker et al 2018), the relevance of potential soil carbon losses through respiration due to warming and thickening of the AL in peat plateaus following wildfire remains poorly quantified.

Soil temperature is a key driver of soil respiration (Davidson and Janssens 2006). The response of soil respiration to temperature in situ is often evaluated using a single soil temperature near the surface (e.g. Lafleur et al 2005) that usually accounts for the majority of the variability in soil respiration rates (e.g. Chivers et al 2009). Using temperature measured close to the soil surface to model total soil respiration is often appropriate since a majority of the labile soil carbon is stored near the surface and thus accounts for a large proportion of the overall CO<sub>2</sub> release in comparison with colder and more decomposed deeper soil carbon (Estop-Aragonés and Blodau 2012). Additionally, non-permafrost peatlands usually only have a shallow oxic layer above the water table, and thus deeper layers are commonly anoxic, which further reduces the respiration rate of deep peat. However, peat plateaus are elevated relative to their surrounding



where they drain and thus have a thicker oxic active layer (Quinton et al 2003). In fire-disturbed sites where thicker AL develops, the relative contributions of deep peat layers to soil respiration likely increases due to a thicker oxic layer. Also, given that the labile peat near the surface is partly removed during wildfire through combustion, deep peat layers may be expected to have a greater relative a contribution to soil respiration. Shallow and deep peat soil temperatures in peat plateaus differ both with regards to annual averages, seasonal amplitude, and seasonal lag to air temperature (Gibson et al 2018). Therefore, we hypothesized that using soil temperatures from multiple depths would improve our model of soil respiration. Using more than a single depth of soil temperature would also allow us to partition soil respiration into shallow and deep components to test whether deep peat layers of fire-disturbed sites contribute more to total soil respiration.

The contributions of deep (older) versus shallow (younger) peat to soil CO<sub>2</sub> fluxes are typically determined using radiocarbon (<sup>14</sup>C) measurements (Trumbore 2006). The <sup>14</sup>C content of respired CO<sub>2</sub> is indicative of the time since atmospheric CO<sub>2</sub> was fixed by plants from the atmosphere and was transferred to soil organic carbon. Soil respiration <sup>14</sup>C measurements have been increasingly used in disturbed permafrost ecosystems to estimate release rates of old, previously frozen carbon currently being added to the global carbon cycle (Schuur *et al* 2008, Czimczik and Welker 2010, Pries *et al* 2013).

In this study we use in situ measurements to examine the effect of wildfire on post fire soil respiration from sites that burned 9 and 16 years ago compared with nearby unburned site to (1) quantify and compare soil respiration from burned and unburned peat plateaus, (2) determine whether including more than one soil temperature depth improves models of soil respiration and partitioning of soil respiration, and (3) compare estimates of deep carbon respiration using <sup>14</sup>C measurements of CO<sub>2</sub>, with those from modeling based on multiple depths of soil temperature, as radiocarbon measurements are expensive and thus alternate methods for estimating old C release is of high interest. Our results will allow us to assess the impact of wildfire on the vulnerability of deeper, older carbon to release to the atmosphere, and as such provide key insights into our understanding of interactions between climate change, disturbances and carbon cycling in permafrost ecosystems.

#### 2. Methods

#### 2.1. Study area

This study was conducted in 2016 in two burned and one unburned peat plateau near Lutose, AB (59° 29'4 N, 117°10'43 W). The sites are located within the discontinuous permafrost zone (Zhang *et al* 1999) of







Western Boreal Canada (figure 1). The two burned sites were affected by wildfire in 2000 (1472 ha) and 2007 (2245 ha), respectively (Canadian National Fire Database 2017), while the unburned site had no record or indications of any fires within at least the last 60 years (figure 1). Unlike surrounding bogs and fens, the permafrost peat plateaus in this study region have permafrost which elevates the surface by frost heave and support an open canopy black spruce (Picea mariana) forest. The permafrost is shallow and only reaches a few meters into the mineral soils that underlie the peat deposits (Zoltai 1993). Vegetation within the unburned site was dominated by black spruce 2.3  $\pm$  1.9 m tall and an understory of predominantly Rhododendron groenlandicum, Vaccinimum vitis-idaea, and Vaccinium uliginosum. Vegetation in the burned sites were dominated by Rhododendron groenlandicum and sparse cover of <1 m tall black spruce trees. Nonvascular vegetation ground cover in the unburned site was 80% lichen (Cladonia rangiferina), with the remainder being Sphagnum mosses and feather mosses. Burned sites had little to no recovery of nonvascular vegetation with 95%-100% of the groundcover being bare, charred soil. The unburned site had a thaw depth of ~50 cm at the end of the season (i.e. active layer), while the burned sites had thaw depths greater than 150 cm (Gibson et al 2018). Given that the burned site displayed similar pre-fire stand densities (Gibson et al 2018) as the unburned site and the sites were within five kilometers of each other, we assumed sites had similar soil properties and thermal regimes prior to the fires.

We estimate that <4 cm of surficial peat was combusted during the two fires based on a comparison of peat stratigraphy. In the unburned site we found at several locations that there was a pronounced shift in peat type at  $\sim$ 4 cm depth: from a buried *Sphagnum* peat to root dominated silvic peat at the surface. This shift marks the transition into a mature peat plateau. We similarly found this transition still present at several locations in the two burned sites, suggesting that the wildfires had not combusted the thin, near-surface layers of silvic peat.

# 2.2. Measurements: soil respiration, soil temperature, and soil moisture

Soil heterotrophic respiration fluxes were measured biweekly during the 2016 summer (23 May-11 October) using static chambers (diameter = 0.4 m). Collars were installed to a depth of 10 cm in six locations within a 300  $\times$  300 m plot in each peat plateau. We selected locations for soil collars and temperature loggers avoiding strong microtopographic features (i.e. pronounced hollows and hummocks) given their specific soil thermal regimes (Wright et al 2009). Our peat plateau sites had relatively little microtopography; hummocks covered 8% of the 300  $\times$  300 m plot in the unburned site and 5% and 14% in the 2000 and 2007 burn sites, respectively. Pronounced hollows were absent in the burned sites and covered <7% of the unburned site. In the unburned site, collars were installed in lichen areas that had no or minimal presence of vascular vegetation. In the 2000 and 2007 burned sites, collars were installed in areas that were presumed to have had a lichen cover pre-fire but were now charred. Overall, collar had very little or no vegetation apart from lichens, when present. Both the burned and unburned sites had relatively dense shrub layer, and we did not exclude roots below  ${\sim}10\,\text{cm}$ (base of collar). Flux measurements started two weeks after collar installation, to allow for any effects of



disturbance associated with collar insertion to be minimized. We used opaque PVC chambers (volume = 37.7 l), sealed with adhesive tape to the collars during the measurement, and monitored air temperature inside the chamber during measurements (Thermoworks, American Fork, UT, USA). Headspace  $CO_2$  concentration was recorded every 1.6 s for 2–3 min using an EGM-4 portable infrared gas analyzer (EGM-4, PP Systems, Amesbury, MA, USA). The  $CO_2$  flux rate was calculated as the slope of the linear relationship between headspace  $CO_2$  concentrations and time. We excluded any slopes with  $R^2 < 0.8$ , which accounted for less than 3% of measurements.

Air and soil temperatures were measured from May 2016 through July 2017 using temperature loggers, recording data every two hours. Soil temperature loggers (Pendant HoboProV2, Onset Corp.) were installed in the soil profile at 10 and 40 cm depth in two locations at each site. Air temperature was measured using a temperature logger 1 m above the ground shielded from direct sunlight. Soil temperatures from the two loggers were averaged for a given depth at each site to create a single site temperature record. During times of sensor failure due to wildlife disturbance (July in the 2000 burn site), only data from the working logger was used. Additional soil temperature measurements were performed at soil respiration locations at 5, 10, and 40 cm depth using a handheld thermometer (Thermoworks, American Fork, UT, USA) during CO<sub>2</sub> flux measurements. Handheld thermometers for 40 cm depth were unavailable in early May and data from the soil temperature loggers at 40 cm was used instead. A comparison between data from handheld thermometers and loggers at 40 cm showed no significant difference between methods (t = 0.92, p < 0.05, t-test). Soil moisture was measured for the 0-5 interval in four locations adjacent to the collar using a Delta-T HH2 portable soil moisture meter (Delta, United Kingdom). Unlike permafrost-free bogs where soil moisture changes with depth (O'Neill 2002), permafrost peatlands have an elevated surface with a deep water table (Quinton et al 2003). Given this, water content at depth in peat plateaus is relatively constant and in general CO<sub>2</sub> production is most sensitive to changes in moisture in the uppermost portions of the peat profile (Lafleur et al 2005).

# 2.3. Statistical analysis and modeling of soil respiration

Soil temperature and moisture measurements at the locations of soil respiration (spot measurements) were averaged for each measurement day at each site. The daily site average for both of these variables did not differ between the 2000 and 2007 burn sites (p > 0.05, paired *t*-test). The lme4 package (Bates *et al* 2015) in *R* (R Core Team 2014) was used for mixed-effects modeling to determine differences in soil respiration

between unburned and burned sites with site and collar ID as random effects. Site (either 2000 or 2007 burn scar) was used as a random effect and was found to be non-significant. Therefore, we combined data from the two burned (2000 and 2007) with a total of 12 collars and compared it to one unburned site with six collars. Differences in soil respiration rates between the combined burned sites and the unburned site was assessed using a repeated measures ANOVA.

To determine if persistent differences in soil moisture were due to microtopography we used a mixed effects model with fixed effects of temperature at 10 and 40 cm below the ground surface and soil moisture. Collar ID and site were treated as random effects to determine if persistent differences in soil moisture due to microtopography (Kettridge *et al* 2012) were a significant predictor of respiration. Soil moisture was not found to be a significant predictor of respiration (p > 0.05, mixed effect model). Therefore, given that soil moisture did not differ between sites and was a non-significant predictor of respiration, only soil temperature at 10 and 40 cm was used to model respiration over the growing season.

We examined the temperature dependence of ecosystem respiration using nonlinear least square regression during the growing season using the following soil temperature models, which include either one- or two-depth soil temperatures:

$$R = (a \times Q_{10} \left(\frac{T_5}{10}\right) \times B) + (b \times Q_{10} \left(\frac{T_5}{10}\right) \times U)$$
(1)

$$= (a \times Q_{10}^{\left(\frac{1}{10}\right)} \times B) + (b \times Q_{10}^{\left(\frac{1}{10}\right)} \times U)$$
(2)

R

$$R = (a \times Q_{10}^{\left(\frac{I_{40}}{10}\right)} \times B) + (b \times Q_{10}^{\left(\frac{I_{40}}{10}\right)} \times U)$$
(3)

$$R = [(a \times Q_{10} \left( \frac{T_5}{10} \right) + c \times Q_{10} \left( \frac{T_{40}}{10} \right)) \times B)] + [(b \times Q_{10} \left( \frac{T_5}{10} \right) + d \times Q_{10} \left( \frac{T_{40}}{10} \right)) \times U)] \quad (4)$$

$$R = [(a \times Q_{10}^{\left(\frac{T_{10}}{10}\right)} + c \times Q_{10}^{\left(\frac{T_{40}}{10}\right)}) \times B)] + [(b \times Q_{10}^{\left(\frac{T_{10}}{10}\right)} + d \times Q_{10}^{\left(\frac{T_{40}}{10}\right)}) \times U)],$$
(5)

where *R* is the rate of soil respiration ( $\mu$ mol C m<sup>-2</sup> s<sup>-1</sup>) and *a*–*d* are parameters that represent the rate of respiration ( $\mu$ mol C m<sup>-2</sup> s<sup>-1</sup>) at 0 °C which is associated with the depth at either 5, 10, or 40 cm as indicated by the specific equation. We assumed the temperature sensitivity,  $Q_{10}$ , would be the same for burned and unburned sites as well as for shallow and deep soil respiration, and  $T_5$ ,  $T_{10}$ , and  $T_{40}$  are the soil temperature (°C) from handheld thermometer measurements at 5, 10, and 40 cm depth. We used dummy variables, *B* (burned site) and *U* (unburned site), of either 1 or 0 in order to run the model on the entire dataset. The *a*, *b*, *c*, *d*, and  $Q_{10}$  parameters were estimated using nonlinear least squares (nls) package in





*R* (Bates 1992). The Akaike information criterion (AIC) was used to determine the most parsimonious model and to compare models.

Models based on equations (4) and (5) used two soil temperatures, which allowed us to partition respiration into a shallow and deep component. The contribution of deep respiration during the growing season was calculated dividing either the  $c \times Q_{10}^{(T40/10)}$ in the burned site or the  $d \times Q_{10}^{(T40/10)}$  in the unburned site by total soil respiration (*R*).

Cumulative soil respiration over the growing season (1 June–15 September) was calculated using the most parsimonious model with input of continuous data from the soil temperature loggers. A comparison between hand held thermometers and continuous soil temperature logger data at 10 cm and 40 cm showed no significant difference between methods (t = 0.92, p < 0.05, t-test). Therefore, we applied our model to the continuous soil temperature records. Model coefficients plus standard error were used for statistical bootstrapping with 300 iterations to determine an instantaneous flux rate and its uncertainty for each 2 h interval. The instantaneous rates were then used to calculate cumulative respiration over the growing season at both the unburned and burned sites (1 June– 15 September 2016).

#### 3. Results

#### 3.1. Soil temperature and active layer depth

Spot soil temperatures during the 2016 growing season were significantly warmer in the burned (pooled 2000 and 2007 data) compared to the unburned both at 10 cm (t = 2.705, p < 0.0001, paired t-test) and at 40 cm (t = 5.414, p < 0.05, paired *t*-test). However, there was no difference in soil temperature between sites at 5 cm (p < 0.05). The maximum differences in soil temperature between sites occurred during the mid-season when the burned soils were more than 2 °C and 4 °C warmer at 10 and 40 cm, respectively (figures 2(a) and (b)). Late in the growing season (September measurements), temperatures were similar between burned and unburned sites at 10 cm but soil was still approximately 3 °C warmer in the burned site at 40 cm (figure 2(b)). Late in the growing season the difference in the depth of the seasonally thawed layer and the proportion of taliks was the greatest, with





**Figure 3.** Soil respiration ( $\mu$ mol C m<sup>-2</sup> s<sup>-1</sup>) from burned (in 2007 and 2000) and unburned peat plateaus sites in Boreal Western Canada (a) throughout the growing season and (b) its relationship to soil temperature at 10 cm. Panel (b) shows the average rate of soil respiration for collars within burned and unburned sites during each sampling occasion. Note the difference in soil respiration between sites during early growing season, and its convergence during the late growing season which caused different hysteretic relation between respiration and soil temperature at 10 cm.

both measures being greater in the burned site (Gibson *et al* 2018) (figure 2(c)).

**Table 1.** Modeled equations for burned and unburned sites, arranged in order of decreasing model fit based on Akaike information criterion (AIC).

#### 3.2. Soil respiration

Soil respiration was significantly higher in the unburned site than in the burned sites throughout the growing season (F = 11.42, p < 0.05, Repeated Measures ANOVA). Both the burned and unburned sites had clear seasonal patterns, peaking towards July and August (figure 3(a)). However, there were differences between the unburned and burned sites, the greatest of which were from June until August, although they converged again in September and October, (figure 3(a)). The relationship between soil temperature at 10 cm depth and soil respiration had opposing hysteresis patterns, with the unburned sites having relatively lower rates of respiration in fall compared to spring at similar temperatures, while the opposite was found for the burned site (figure 3(b)). This relationship between soil temperature at 10 cm depth and soil respiration indicated distinct patterns of soil respiration between the sites, with the burned sites having relatively higher respiration late in the growing season (fall) in comparison to early summer.

#### 3.3. Models of soil respiration

The most parsimonious model based on the AIC used two soil temperatures, at 10 and 40 cm (equation (5)). The model which used one soil temperature at 10 cm (equation (2), table 1) had an AIC value which was close to the two-temperature model, and should thus be considered to have almost equal power to model soil respiration (Burnham and Anderson 2004). However, given our objective of partitioning soil respiration into a shallow and deep contribution, we only report the estimated temperature sensitivity ( $Q_{10}$ ) and a-d parameters (respiration at 0 °C for shallow and

| Model        | Soil temperature depths used in the model | $R^2$ | AIC    |
|--------------|---|-------|--------|
| Equation (5) | 10 and 40 cm                              | 0.90  | -34.21 |
| Equation (2) | 10 cm                                     | 0.88  | -33.61 |
| Equation (4) | 5 and 40 cm                               | 0.88  | -28.19 |
| Equation (1) | 5 cm                                      | 0.79  | -16.40 |
| Equation (3) | 40 cm                                     | 0.70  | -5.65  |

deep soil respiration) for equation (5) (table 2). In order to estimate seasonal respiration, we applied these coefficients at equation (5) to the continuous record of soil temperatures at 10 and 40 cm from the burned and the unburned sites. There was good agreement between modeled and measured soil respiration (figure 4, burn:  $R^2 = 0.79$ , unburned:  $R^2 = 0.71$ ), yielding confidence in the use of continuous soil temperature data for estimating seasonal respiration.

# 3.4. Partitioning of soil respiration into a shallow and deep component

Using the two-depth temperature model (equation (5)) we partitioned soil respiration and estimated the contributions of the  $CO_2$  flux derived from a shallow and deep component, i.e. soil respiration driven by temperatures at either 10 cm depth or at 40 cm depth, respectively. The proportion of soil respiration associated with the deep component was overall greater in the burned sites where it increased from ~35% early in the growing season to ~55% in late fall. This is in contrast to the unburned site where the contribution of deep respiration was lower and only increased, from





**Figure 4.** Comparisons of measured soil respiration during the growing season (1 June 1—15 September) and modeled soil respiration using the continuous soil temperatures from the soil temperature loggers in (a) the 2000 and 2007 burn sites and (b) the unburned site. Modeled data is based on equation (5) using soil temperatures at 10 and 40 cm and parameters in table 2. Inset compares modeled to measured fluxes and plots along a 1:1 line.



Figure 5. Contribution of deep respiration to total soil respiration in the burned and unburned sites using the two-depth temperature model (circles and triangles, equation (5)) and  $^{14}$ C measurements of respired CO<sub>2</sub> (diamonds and squares, see Estop-Aragonés *et al* 2018b). Both approaches showed greater contribution from deep soils in the burned sites. Burned sites had a marked increase in the contributions of deep respiration during the growing season in comparison to the unburned site based on the two-depth temperature model.

Table 2. Coefficients ( $\pm$ 1 SE) for parameters of the most parsimonious model (equation (5)) estimating soil respiration in peat plateaus during the growing season.

| Parameter  | Coefficient                            |  |
|--|--|--|
| $Q_{10}$ —Temperature dependence of soil respiration | $2.56 \pm 0.31$ (unitless)             |  |
| a—Shallow soil respiration at 0 °C, burned site      | $0.14\pm 0.05\mu{ m molCm^{-2}s^{-1}}$ |  |
| b—Shallow soil respiration at 0 °C, unburned site    | $0.14\pm 0.06\mu{ m molCm^{-2}s^{-1}}$ |  |
| c—Deep soil respiration 0 °C, burned site            | $0.30\pm 0.08\mu{ m molCm^{-2}s^{-1}}$ |  |
| d—Deep soil respiration 0 °C, unburned site          | $0.05\pm 0.09\mu{ m molCm^{-2}s^{-1}}$ |  |
|  |  |  |

~9% of total respiration early in the growing season to  $\sim$ 14% in late fall (figure 5).

Independent estimates of the contribution of deep respiration were obtained through radiocarbon measurements at the same burned site (Estop-Aragonés *et al* 2018b) which were compared to those from the two-temperature model approach. To this aim, we used an age of 1000 years before present for deep peat sources at ~40 cm based on interpolation between <sup>14</sup>C dated layers and used it to estimate the contribution of this deep source to <sup>14</sup>C measurements of respired CO<sub>2</sub> (Estop-Aragonés *et al* 2018b). While the estimates of





**Figure 6.** Cumulative growing season soil respiration (1 June–15 September 2016) from burned (bottom line in (a) and top line in (b) and unburned peat plateaus partitioned into shallow and deep respiration using equation (5) with upper and lower bounds based on predicted coefficients (table 2). Panel (a) Cumulative shallow respiration (respiration driven by temperatures at 10 cm). Panel (b) Cumulative carbon deep respiration (respiration driven by temperatures at 40 cm).

both approaches are not directly comparable, the shallow and deep components were obtained from similar soil interval depths in each approach and thus, their comparison provides indirect evidence to examine the reliability of the two-temperature model approach. The site differences we report here are in agreement with the observations using <sup>14</sup>C measurements of respired CO<sub>2</sub> in fall at the same sites (figure 5).

We used the two-depth temperature model (equation (5)) to estimate cumulative soil respiration and associated cumulative shallow and deep respiration during the growing season (figure 6). The estimated cumulative soil respiration was slightly, yet insignificantly, greater in the unburned site compared to the burned site during the growing season (88.31, 95% CI [8.87,168.51] g C m<sup>-2</sup> versus 81.36, 95% CI [24.53, 146.93] g C m<sup>-2</sup>). However, the sources of such cumulative values were clearly different between sites. Deep respiration (driven by soil temperature data at 40 cm) contributed substantially in the burned sites with a cumulative loss of 32.1, 95% CI [9.9, 60.4] g C  $m^{-2}$  compared to the unburned site with a cumulative loss of 8.1, 95% CI [0, 40.6] g C m<sup>-2</sup> (figure 6(b)). This represents nearly four times more soil carbon respired from deep layers in the burned compared to the unburned sites by the end of the season.

### 4. Discussion

Despite wildfires having impacted ~25% of permafrost peatlands in the last 30 years (Gibson *et al* 2018), there is very limited data on the impacts of wildfire on soil respiration and on the mobilization of old carbon sources in these ecosystems (Estop-Aragonés *et al* 2018b). Given their widespread coverage and frequent disturbance by wildfire, even a small proportional change on soil respiration, and its sources, could be important for determining regional soil carbon balance. Wildfire decreased overall soil respiration in our study sites. This decrease was found despite warmer post-fire soils. Wildfires have a large impact on the soil thermal regime, (e.g. O'Neill *et al* 2006, Gibson *et al* 2018) potentially affecting and the large carbon stocks in boreal peatlands (Hugelius *et al* 2014). Our results suggests that wildfire's effects on soil respiration are mediated by not only the quantity of soil organic matter available, but also other factors, such as the quality of this material.

We also found that both the unburned and burned peat plateaus had relatively low rates of soil respiration compared to other northern sites, including black spruce stands (O'Neill et al 2006), treed bogs (Lund et al 2010), and drained peatlands (Minkkinen et al 2007). This difference could be due to a combination of factors, such as lower soil temperatures (dry peat insulates the soil temperature (Kettridge et al 2012)) or reduced autotrophic respiration (Heinemeyer et al 2011). Our results may be representative for sites that have thick organic horizons with more than 2 m of peat, which is common in peat plateaus in Boreal Western Canada. In shallow peatlands, where fire would burn off the majority of the peat stock, the results could be different, as the influence of fire on total carbon stocks would be greater.

Soil respiration is generally modeled using a single temperature at a shallow depth. Single depth models may be sufficient in other boreal ecosystems, either where there is a small amount of soil organic carbon below the near-surface layer or in peatlands where the bulk of soil organic carbon at depth is water logged and, therefore, anoxic (Chivers *et al* 2009). In contrast, the permafrost peat plateaus studied here have thick oxic layers and relatively stable soil moisture at the surface. Furthermore, they have relatively low rates of autotrophic (plant and root) respiration meaning the majority of carbon emitted from the ecosystems is due to heterotrophic respiration. Given these unique characteristics of these permafrost peatlands, we hypothesized that using a two-temperature model that uses both shallow and deep temperatures would better predict soil respiration. In addition, this method would allow it to be partitioned into shallow and deep contributions. Our model assumed that  $Q_{10}$  does not vary between depths or between burned and unburned sites. Using a common Q<sub>10</sub> among sites and layers standardizes the temperature sensitivity of our peats to respiration. Because decomposed organic matter is expected to have a greater temperature sensitivity (Bosatta and Agren 1999) and thus a higher  $Q_{10}$ , we feel that standardizing our  $Q_{10}$  values between sites can be considered conservative. In addition, determining difference in Q<sub>10</sub> among sites would have required an incubation study in order to remove cofounding factors, which was beyond the scope of this study.

The partitioning of the soil respiration indicated that shallow soil respiration was significantly lower in the burned peat plateau compared to the unburned peat plateau. By the end of the growing season, respiration from shallow depths accounted for 86% of total soil respiration in the unburned site, but just 45% in burned sites-despite similar rates of overall soil respiration (figure 6). Though we cannot determine which mechanism is dominant, there are likely two main causes of this lower shallow respiration: the loss of a labile surface peat layer through combustion and decreased root respiration. During a fire event, some surface peat is combusted (Turetsky et al 2011). This peat contains the recent inputs of fresh, labile carbon that exhibits higher turnover rates, as opposed to carbon at depth that is more recalcitrant (Knorr et al 2010). Additionally, recent work by Whitman et al (2018) showed that fire occurrence and severity can influence microbial community composition, which in turn influences the rate of decomposition.

Our findings of increased deep respiration based on the two-temperature model were consistent with a radiocarbon study done at the same sites (Estop-Aragonés *et al* 2018b). The radiocarbon estimates show a lower percentage of contribution from old peat as compared to this study's two temperature approach. This offset is likely due differences in the definition of shallow/young and deep/old respiration. Nonetheless, both approaches were consistent in showing a greater contribution from deep/aged soil carbon to total respiration in the burned site compared to the unburned site (figure 5).

At our study sites, increased deep soil respiration following wildfire was associated with deeper seasonally thawed soil layers and higher soil temperatures. These results are consistent with radiocarbon results from tussock tundra ecosystems (Nowinski *et al* 2010), polygonal landscapes (Vaughn and Torn 2018), and arctic tundra (Czimczik and Welker 2010), all of which show a deepening of the seasonally thawed layer being associated with a great contribution from old carbon



pools to overall respiration. Our modeled results during the growing season from the studied peat plateaus indicate that cumulative respiration of deep sources increased following disturbance from ~8 (unburned site) to  $\sim$ 32 g C m<sup>-2</sup> (burned site). This increase of more than 20 g C m<sup>-2</sup> is equivalent to nearly two times the long-term accumulation of peat plateaus (Treat et al 2016) despite only being for the period from June to September. If we extrapolate these rates out 25 years, it means an additional  $\sim$ 500 g C m<sup>-2</sup> of deep soil carbon could be released to the atmosphere following fire. This value is also potentially conservative value as it does not include the potential higher temperature sensitivity of deep organic matter or winter respiration. Soil respiration during the winter likely represents an important fraction of annual respiration, especially in burned peat plateaus given their widespread talik coverage (Connon et al 2018, Gibson et al 2018). Indeed, our model shows higher contributions of deep respiration contributions in the early season (May-June) when such taliks are present (June values in the burned site in figure 5). Thus, long term carbon accumulation rates in peat plateau may be low not only due to combustion losses during the fires, which are of high frequency (Robinson and Moore 2000), but also due to a high rate of carbon loss by decomposition in the years following fire.

Wildfires in peatlands contribute to a large pulse event of carbon to the atmosphere during burning (Turetsky et al 2004). The total carbon loss in black spruce stands due to combustion was estimated at  $3.5 \text{ kg C m}^{-2}$  in black spruce stands across the region (Walker et al 2018). The effect of fire on permafrost peatlands following AL thickening could be even greater when considering the enhanced respiration from depth that we document in this study. Wildfire may also trigger accelerated thermokarst development (Gibson et al 2018), which, due to anoxic conditions, can slow the respiration of deep, aged soil carbon (Estop-Aragonés et al 2018b). Thermokarst areas also experience increased peat accumulation rates (Cooper et al 2017, Jones et al 2017, Pelletier et al 2017, Estop-Aragonés et al 2018a), also offsetting any carbon losses. Therefore, the impacts of wildfire on carbon losses also depends highly on landscape transformations associated with thermokarst and to what degree wildfire accelerates thermokarst.

## 5. Conclusion

Changes in the frequency and severity of wildfires in northern boreal forests as a result of climate change, are causing widespread permafrost thaw (Gibson *et al* 2018) and affecting the carbon cycle in these environments (Schuur *et al* 2015). Our study shows that when permafrost peat plateaus undergo fire, and subsequent active layer deepening, total soil respiration does not increase in the years to decades following fire, but the source of the carbon does change. We found a substantially greater contribution to soil respiration from deep carbon in the burned site compared to the unburned site likely due to a combination of the loss of the surface labile carbon pools in unburned sites and increased deeper soil temperatures (and increased active layer thickness) stimulating old soil carbon decomposition. Loss of old soil carbon is of high consequence as it may represent a net carbon additions to the contemporary carbon cycle. Ultimately, wildfire is increasing losses of old soil carbon previously stored in permafrost when these systems follow active layer thickening. The soil thermal regime of burned peat plateaus may also be representative of the soil thermal regime of unburned sites under climate warming. In such case, the gradual warming of peat plateaus would similarly thicken the active layer enhancing deep soil carbon respiration.

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#### Data availability

The data supporting the findings of this study are openly available at https://dataverse.harvard.edu/ dataverse/ERL2019.

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