Respiration of aged soil carbon during fall in permafrost peatlands enhanced by active layer deepening following wildfire but limited following thermokarst

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Abstract

Permafrost peatlands store globally significant amounts of soil organic carbon (SOC) that may be vulnerable to climate change. Permafrost thaw exposes deeper, older SOC to microbial activity, but SOC vulnerability to mineralization and release as carbon dioxide is likely influenced by the soil environmental conditions that follow thaw. Permafrost thaw in peat plateaus, the dominant type of permafrost peatlands in North America, occurs both through deepening of the active layer and through thermokarst. Active layer deepening exposes aged SOC to predominately oxic conditions, while thermokarst is associated with complete permafrost thaw which leads to ground subsidence, inundation and soil anoxic conditions. Thermokarst often follows active layer deepening, and wildfire is an important trigger of this sequence. We compared the mineralization rate of aged SOC at an intact peat plateau (∼70 cm oxic active layer), a burned peat plateau (∼120 cm oxic active layer), and a thermokarst bog (∼550 cm anoxic peat profile) by measuring respired $^{14}$C-CO$_2$. Measurements were done in fall when surface temperatures were near-freezing while deeper soil temperatures were still close to their seasonal maxima. Aged SOC (1600 yrs BP) contributed 22.1 ± 11.3% and 3.5 ± 3.1% to soil respiration in the burned and intact peat plateau, respectively, indicating a fivefold higher rate of aged SOC mineralization in the burned than intact peat plateau (0.15 ± 0.07 versus 0.03 ± 0.03 g CO$_2$-C m$^{-2}$ d$^{-1}$). None or minimal contribution of aged SOC to soil respiration was detected within the thermokarst bog, regardless of whether thaw had occurred decades or centuries ago. While more data from other sites and seasons are required, our study provides strong evidence of substantially increased respiration of aged SOC from burned peat plateaus with deepened active layer, while also suggesting inhibition of aged SOC respiration under anoxic conditions in thermokarst bogs.

1. Introduction

Northern permafrost peatlands are global hot spots for soil organic carbon (C) storage, with up to 250 kg C m$^{-2}$ and an estimated total storage of 150 Pg within the northern circumpolar permafrost region (Hugelius et al 2014). The discontinuous permafrost zone of western Canada is a major peatland region with >150 000 km$^2$ of permafrost peatlands (Hugelius et al 2014). Peatland development in this region started about 9000 years ago, but permafrost only started aggrading after the Holocene thermal maximum and became widespread following a climate cooling around 1200 years ago (Zoltai 1995, Pelletier et al 2017). Peat plateaus are the dominant permafrost peatland type in this region, with 2–6 m thick peat deposits and a surface that is elevated 1–2 m above the surroundings due to excess ground ice (Zoltai 1972, Zoltai and Tarnocai 1975, Vitt et al 1994, Robinson and Moore 2000, Quinton et al 2009). Northern regions are rapidly warming (Johannessen...
et al 2004) and permafrost thaw (Payette et al 2004, Romanovsky et al 2010, Baltzer et al 2014) will expose vast stores of permafrost peatland C to microbial activity, and thus to potential mineralization and emission into the atmosphere as greenhouse gases carbon dioxide (CO₂) and methane (CH₄). Deep permafrost C reservoirs accumulated over millennia are depleted in radiocarbon, ¹⁴C, and their release to the atmosphere represents a net C addition to the modern C cycle. The magnitude and timing of greenhouse gas emissions derived from recently thawed soil C represents a critical uncertainty for our understanding of the permafrost C feedback to climate change (Schuur et al 2015).

The vulnerability of aged soil C to microbial mineralization in peatland plateaus is likely influenced by the degree to which thaw causes drainage or flooding of the peat profile, thus determining the relative dominance of oxic versus anoxic conditions. In peat plateaus, the active layer is largely oxic as the elevated peat surface allows for efficient lateral drainage (Wright et al 2009). While active layer deepening is thus likely to expose previously frozen soil C to aerobic decomposition, mineralization rates of aged soil C may still be limited by the low soil temperatures near the base of the active layer, and by the fact that only a fraction of the peat profile has thawed. Complete permafrost thaw, however, causes substantial ground subsidence and the formation of thermokarst bogs where almost the entire peat profile becomes inundated and anoxic (Camill 1999, Turetsky et al 2007). While anoxic conditions may restrict respiration of aged C (Schädel et al 2016), studies of carbon stocks along Alaskan thermokarst bog chronosequences suggest large C losses (>30% of initial C stocks) within decades following thaw (Jones et al 2017). Mechanisms for such rapid C loss are currently unknown and direct field observations of aged soil C loss during or following thermokarst bog expansion have found limited contribution of aged soil C to CH₄ or CO₂ release (Klapstein et al 2014, Cooper et al 2017, Estop-Aragó et al 2018). However, these studies were carried out during the growing season and in thermokarst peatlands with relatively shallow peat deposits (<2 m) while the potential for detecting aged soil C losses may be greater in fall or in larger peat deposits.

Wildfire is a dominant and increasingly common disturbance in western Canada (Gillett et al 2004, Kasischke et al 2010, Rogers et al 2015). Wildfire in boreal forests accelerates permafrost thaw through active layer deepening (Burn 1998, Yoshikawa et al 2002, Viereck et al 2008, Fisher et al 2016) and a similar response has been recently documented in burned peat plateaus, where a deeper active layer can, if permafrost is able to recover, last about 20 years (Gibson et al 2018). However, observations of charcoal in peat profiles (Zoltai 1993, Myers-Smith et al 2007) suggest that wildfire may also trigger thermokarst bog formation. Thus, both active layer deepening and thermokarst bog expansion are accelerated following wildfire and the contrasting soil environmental conditions associated with the mode of thaw may influence vulnerability of aged soil C.

We present a case study measuring the ¹⁴C content of CO₂ respired from soils at the end of the growing season to assess whether and to what extent contrasting soil environmental conditions in peat plateaus and thermokarst bogs may influence the mineralization and atmospheric release of aged soil C in permafrost peatlands in northern Alberta. We selected an intact peat plateau, a burned peat plateau with a deepened active layer, and a thermokarst bog with a deep (>5 m) peat profile where distance to the peat plateau edge was related to time since thaw from decades to centuries. Sampling was done in fall when we assumed aged soil C mineralization to be near its seasonal maximum rate and thus the aged soil C contribution to total soil respiration sufficient for detection. We hypothesized higher respiration rates of aged soil C in both the burned and thermokarst sites relative to the intact peat plateau, given the larger quantity of aged soil C available to decomposition in these sites due to thaw.

2. Methods

2.1. Site description and experimental design

Study sites were located in the discontinuous permafrost zone (Brown et al 1997) of western Canada (59.5°N, 117.2°W), and included a burned peat plateau affected by wildfire in 2007, an intact peat plateau not burned at least in the last 70 years, and an adjacent thermokarst bog where we differentiate between a developmentally young thermokarst bog site near its edge and a mature thermokarst bog site in its center (figure 1). We selected sites with soil environmental conditions and peat stratigraphy that are representative of peat plateaus and thermokarst bogs in the region (Zoltai and Tarnocai 1975, Zoltai 1995, Pelletier et al 2017). Vegetation at the intact peat plateau consisted of a stunted, open-canopy black spruce (Picea mariana (MILL.) B. S. P.) forest with Labrador tea (Rhododendron groenlandicum OEDER) shrubs, and a ground cover of lichens (Cladonia spp.). At the burned peat plateau, fire had caused complete tree mortality, but vegetation recovery nine years after the fire was largely limited to Labrador tea and most of the ground was still charred. However, fire severity and peat combustion during this fire was likely low, as pre-fire lichen and litter could still be seen on the charred ground. Thermokarst bogs are associated with a drastic change of vegetation due to the associated waterlogging and anoxic soil conditions when peat plateaus collapse (Camill 1999, Turetsky et al 2007). Accordingly, the thermokarst bog was treeless, and the young thermokarst bog was dominated by hydrophilic Sphagnum fuscum ÅNGSTR. and water sedge (Carex aquatilis WAHLEN.) while the mature thermokarst bog was dominated by Sphagnum fuscum (SCHIMP.)
KLINGGR. and leatherleaf (*Chamaedaphne calyculata* (L.) Moench) shrubs with scattered tussock cotton-grass (*Eriophorum vaginatum* L.).

In 3rd–4th September 2016, we installed three pairs of PVC collars with 25 cm inner-diameter at the intact and burned peat plateau, and two pairs of collars each at the young and mature bog. In each pair, one collar was open at both ends and thus allowed for the entire peat profile to contribute to respiration as measured by chamber techniques (henceforth referred to as ‘full-profile collar’) while the other collar had a sealed bottom and thus excluded respiration from depths below the base of the collar (‘near-surface collar’) (Cooper et al. 2017, Estop-Aragonés et al. 2018).

Installation of full-profile collars required inserting the collars in the soil to depths of 25 cm (intact and burned peat plateau) or 35 cm (young and mature thermokarst bog). Installation of the near-surface collars required extracting peat monoliths of 25 cm (intact and burned peat plateau) or 35 cm (young and mature thermokarst bog), inserting them into the near-surface collar, and reinserting the collar in the open pit. Stainless steel probes (6 mm outer-diameter, 1 mm wall thickness, Swagelok) were inserted near each collar pair to extract soil pore space CO₂ at depths of 50 cm (intact and burned peat plateau), 150 cm (young bog), and 200 cm (mature bog). These probes had a perforated base covered with a waterproof but gas-permeable membrane (Accurel GmbH, Wuppertal, Germany). Different depths of the probes were chosen to collect CO₂ from peat layers with similar age (approximately 1600 yrs BP, table S1 is available online at stacks.iop.org/ERL/13/085002/mmedia).

2.2. Peat profile characteristics and age determination

Soil cores were collected at the intact peat plateau, young and mature bog a year prior to collar installation. A Russian peat corer (4.5 cm inner-diameter, Eijkelkamp, Giesbeek, Netherlands) was used in thawed peat, and a Snow, Ice, Permafrost Research Establishment coring auger (10 cm inner-diameter) in frozen peat. We identified the transition from *Sphagnum* to sylvic peat at the young and mature bog, which indicates the shift from peat plateau to thermokarst bog vegetation and thus the timing of collapse (O’Donnell et al. 2012). This transition depth was visually identified from the clear stratigraphic change between post-thaw and plateau peat (figure S1). Peat depths, as indicated by transition into underlying silt, varied between 500 and 600 cm among sites (peat depth at the burned site was determined to be >300 cm and was likely similar to the intact site). Peat samples from ten depths each from the intact peat plateau and mature bog cores were ¹⁴C-dated (table S1) using accelerator mass spectroscopy (AMS) by separating 50–100 mg of clean, identifiable plant
macrofossils analyzed in the A. E. Lalonde AMS Laboratory, Ottawa.

2.3. Measurements of CO2 fluxes and 14CO2
We measured CO2 fluxes and collected CO2 for 14C analysis using dark chambers on 19th–21st September 2016. We chose to sample during fall because we consider the environmental conditions at that time of year favorable to detect the contribution of aged soil C to soil respiration. At time of sampling, vegetation was senescing and daytime air temperatures were <5 °C, while seasonal thaw depths and soil temperatures at 50 cm were near their annual maxima. Daily average soil temperatures at 50 cm were 1.5 °C, 6.6 °C, 9.2 °C and 9.5 °C at time of sampling at the intact plateau, burnt plateau, young bog and old bog, respectively, while maximum temperatures occurred in mid-August and were 2.7 °C, 9.5 °C, 14.1 °C and 12.1 °C (figure S2). Fluxes were measured by monitoring CO2 concentration (EGM-4, PP Systems, Amesbury, MA, USA, accuracy ±0.20 ppm) inside deployed chambers (11 l) for 6 min. Linear regressions (R² > 0.97) of change in CO2 concentration over time were used to calculate flux rates while accounting for differences in headspace volume and temperature. Fluxes from full-profile collars represent soil respiration (SR), and the difference between SR and fluxes from near-surface collars represents the respiration from sources deeper than the collar (SRNSep). Note that SRNSep is not a measure of the contribution of aged soil C to SR, due to potential respiration of young material translocated to deeper layers.

Collars were left enclosed after flux measurements until concentrations reached approximately 1500 ppm after which CO2 was collected for 14C analysis (Lupascu et al 2013): headspace air was circulated for 15 min (0.51 min⁻¹) through drierite desiccant before passing through a molecular sieve (Zeolite 13X) to adsorb the CO2. All connections were air-flushed before sampling.

The measurement uncertainty for 14C was <0.002 fraction modern (fM). Values for 14C are reported in fM notation and ages refer to conventional radiocarbon ages (uncalibrated) expressed as years before present (yrs BP). Fraction modern expresses the isotope ratio 14C/12C of the sample normalized to a 13C of −25‰ to remove fractionation effects and divided by 0.95 the measured ratio of the OX-I standard (Stuiver and Polach 1977).

ContributionAged

2.4. Estimating contributions of aged soil carbon to soil respiration
The fM of respired CO2 from each collar (fMResp) was calculated after accounting for the proportion of atmospheric and respired CO2 (PAtm and PResp) inside the chamber at the time of 14CO2 sampling:

\[ fM_{Resp} = \frac{fM_{Chamber} - P_{Atm} \times fM_{Atm}}{P_{Resp}}, \] (1)

where fMChamber and fMAtm refers to the measured fM of CO2 in the chamber and atmosphere, respectively. The sum of PAtm and PResp is 1, and PAtm is calculated from the measured CO2 concentrations in the atmosphere ([CO2]Atm) and in the chamber ([CO2]Chamber) at the time of 14CO2 sampling:

\[ P_{Atm} = \frac{[CO2]_{Atm}}{[CO2]_{Chamber}} \] (2)

Carbon dioxide respired from aged soil C will have a lower fM value than that respired from recently photosynthetically-fixed C (table S1). Thus, CO2 released from full-profile collars with a lower fM value than in near-surface collars indicates a contribution to SR from aged soil C. We estimated the fractional contribution of aged soil C to SR (ContributionAged) at each location using the fM value of CO2 from the full-profile (fMRespFy) and near-surface (fMRespNS) collars and...
the fM value of CO2 from the probes which defines the age of aged soil C (fM_{AgedSoilC}) (see supplementary information): \[
\text{Contribution}_{Aged} = \frac{fM_{\text{RespFP}} - fM_{\text{RespNS}}}{fM_{\text{AgedSoilC}} - fM_{\text{RespNS}}}. \tag{3}
\]

At two locations (one at the intact peat plateau and another at the young bog) there was insufficient CO2 collected from the probes for 14C determination, and we therefore used the mean of the available measurements within the same site to solve equation (3) (table S2). The estimate of Contribution_{Aged} depends on the 14C signature of ‘aged soil C’ (fM_{AgedSoilC}) used in equation (3). Therefore, in addition of using the fM value of CO2 collected with the probes to calculate estimates of Contribution_{Aged}, we also performed a sensitivity analysis where we used fixed ages across all sites to yield alternative estimates. In the sensitivity analysis we assigned fM_{AgedSoilC} a fixed value across all sites in equation (3), rather than the fM value of CO2 sampled with the probes. These fixed values were based on the age of the peat at the depth of the probes as well as the age of the peat at >3 m. By multiplying Contribution_{Aged} with SR we estimated the rate of mineralization of aged soil C at each site (SR_{Aged}).

2.5. Statistical analysis
All statistical analysis was carried out in R (Version 3.3.2) (R Core Team 2014). We performed t-tests to evaluate differences in fluxes and in 14CO2 between collar types and one-way ANOVA to evaluate differences in fluxes between sites. When the ANOVA test indicated statistically significant differences between sites, we performed a post hoc Tukey HSD for pairwise comparisons of differences between sites. The suitability of parametric analysis was checked by examining the normal distribution and the homogeneity of variances of the data. For t-tests, the homogeneity of variances was checked using an F test. For ANOVA, the homogeneity of variances was checked using Levene’s test in the car package (Fox and Weisberg 2011) in addition to Shapiro–Wilk test on the residuals to validate normality. Normality was also verified by visually inspecting the residuals with quantile-quantile plots. When the homogeneity of variances test failed, instead of a t-test, the non-parametric Wilcoxon test was used to check 14CO2 differences between collar type in oxic soils (intact and burned peat plateaus). We define the statistical significance level at 5% or below in the text.
3. Results

3.1. Physical and environmental characteristics of peat profiles

All four sites had deep peat profiles, but physical and environmental characteristics differed significantly and determined the quantity and age of soil C available for decomposition at time of sampling (figure 2). Active layer depth at the intact peat plateau was on average 71 cm (60–80 cm range), with a peat age of about 1700 yrs BP (0.807 fM) at the active layer base (figure 2(a), table S1). Active layer depth at the burned site was on average 120 cm (88–141 cm range), which assuming a similar profile as at the intact site suggested a peat age at the active layer base of approximately 2100 yrs BP (0.767 fM). Peat depth at the intact peat plateau site was 6 m, with a basal date of about 8100 yrs BP (0.365 fM). Neither the intact nor burned peat plateau had a water table above the frost table. Soil temperatures at the burned site were 2.3°C–3.0°C warmer than at the intact peat plateau at comparable depths throughout the active layer (figure 2(b)). Both the young and mature thermokarst bog had peat depths >5 m with a basal peat age of about 8200 yrs BP (0.361 fM) (figure 2(a), table S1). The transition between Sphagnum to sylvic peat was found at 88 cm depth in the mature bog, suggesting that thermokarst development occurred 360 yrs BP (0.956 fM) based on the peat 14C measurements at the transition (figure 2(a), table S1). The transition from Sphagnum to sylvic peat was found at 32 cm depth at the young bog, suggesting that thermokarst development was more recent, likely within the last few decades based on 210Pb dating in similar sites (figure S4). The water table was at the peat surface in the young bog, and 18 cm below the surface at the mature bog at the time of flux measurements. Soil temperatures were 0.3°C–1.2°C warmer at the young than the mature bog throughout the peat profile, but both thermokarst bog sites were up to 9°C warmer than the peat plateau sites, particularly at depths >20 cm (figure 2(b)).

Our methodology for estimating the contribution of aged soil C to soil respiration (ContributionAged) requires that peat accumulated since the 1950s (i.e. peat with the 14C bomb-peak) is fully contained within the near-surface collars. All near-surface collars at the plateau and mature bog contained peat accumulated before the 14C bomb-peak period (figure 2(a)). The bottom of near-surface collars corresponded to depths with peat ages of approximately 150 yrs BP (0.982 fM) at the mature thermokarst bog and 450 yrs BP (0.946 fM) at the intact peat plateau. We assume that the burned site has a similar peat profile as the intact peat plateau given their proximity and low fire severity. In the young bog the collars were installed to 35 cm depth and thus included 3 cm of sylvic peat below the Sphagnum peat (transition from Sphagnum to sylvic peat at 32 cm depth). Based on 210Pb dating of similar young thermokarst bog cores from sites within the same region, we assume peat at the bottom of the near-surface collars (35 cm depth) accumulated before the 14C bomb-peak period (figure S4). Given the slow accumulation of sylvic peat (Pelletier et al. 2017, Estop-Aragonés et al. 2018), this is likely a conservative assumption, and thus we consider the 14C bomb-peak fully contained in the near-surface collars also at the young thermokarst bog site.

3.2. CO2 flux measurements and 14CO2 monitoring

Soil respiration (SR, i.e. CO2 flux from full-profile collars) decreased in the order intact peat plateau > burned peat plateau > young bog > mature bog with statistically significant differences between the intact site and both young bog (p = 0.034, post hoc Tukey HSD tests) and mature bog (p = 0.007, post hoc Tukey HSD tests), and between the burned site and mature bog (p = 0.039, post hoc Tukey HSD tests) (figure 3(a)). A contribution to SR originating from sources at depths below the base of near-surface collars (SRDeep) was found at all locations, as CO2 fluxes from full-profile collars were consistently greater than fluxes from near-surface collars (figure 3(a)). SRDeep decreased in the order burned peat plateau > young bog > intact peat plateau > mature bog, but without statistically significant differences between sites (p = 0.083, one-way ANOVA test). The average relative contribution from SRDeep to SR decreased in the order young bog (49 ± 6%, ±1σ SD) > burned plateau (48 ± 13%) > mature bog (31 ± 17%) > intact plateau (21 ± 8%) (figure 3(a)).

A significant contribution of aged soil C to SR (ContributionAged), as suggested by SRDeep, requires the fM values of CO2 respired from full-profile collars to be lower than that from near-surface collars. Accordingly, we did observe a lower fM of CO2 from full-profile than near-surface collars at all six peat plateau locations (3 pairs of collars each at intact and burned peat plateaus), but only at one of four locations in the young and mature thermokarst bog (figure 3(b)). As such, the CO2 released from full-profile collars had significantly lower fM than that from near-surface collars (p = 0.026, Wilcoxon test) in sites with oxic active layers (intact and burned peat plateaus). In contrast, there was no significant difference in fM of CO2 released between full-profile and near-surface collars (p = 0.130, two-sample independent t-test) in sites with predominately anoxic peat profiles (young and mature thermokarst bogs).

To estimate ContributionAged using equation (3), we needed to define the age of ‘aged soil C’ (fM_AgedSoil). Our first estimate of ContributionAged defined aged soil C using the fM of CO2 collected with probes at each location. The CO2 from the probes had ages ranging from 180 to 540 yrs BP at the intact site, 440–1175 yrs BP at the burned, 95 yrs BP at the young bog, and 210–270 yrs BP at the mature bog (figure 3(b)). As such, the CO2 collected by probes was...
1000–1400 yrs BP younger than the peat at the same depths as the probes (figure 2, tables S1 and S2). Using equation (3), Contribution\textsubscript{Aged} was estimated to be greater at the burned (30.9 ± 9.9%, ±SD) than the intact peat plateau (10.0 ± 10.5%), the difference being marginally significant (p = 0.066, two-sample independent t-test). Expressing this as a rate, SRAged doubled at the burned compared to the intact peat plateau (0.21 ± 0.06 and 0.09 ± 0.10 g CO$_2$–C m$^{-2}$ d$^{-1}$, respectively) (figure 3(c)). Aged soil C contribution was only detectable at one of the four thermokarst bog locations (YB2; 2.5%) (figure 3(b)), representing a SRAged of 0.01 g CO$_2$–C m$^{-2}$ d$^{-1}$ (figure 3(c)).

Our sensitivity analysis indicates that differences in Contribution\textsubscript{Aged} and SRAged between sites were robust regardless of the assumption of aged soil C (fM\textsubscript{AgedSoilC}) used (figure 4). For this sensitivity analysis we varied the definition of aged soil C between 1600 yrs BP (age of peat at depth of probes) and 4000 yrs BP (age of peat in a potential active layer deepening of >3 m). The contribution remains negligible on average at the young and mature thermokarst bog regardless of the definition of aged soil C, due to higher fM of CO$_2$ in full-profile relative to near-surface collars, which yields negative estimates. At the peat plateau sites, changing aged soil C to the age of the peat at the depth of the probes (1600 yrs BP) reduced Contribution\textsubscript{Aged} to 22.1 ± 11.3% in the burned and 3.5 ± 3.1% in the intact site with SRAged 0.15 ± 0.07 and 0.03 ± 0.03 g CO$_2$–C m$^{-2}$ d$^{-1}$, respectively. Assumptions of yet older soil C led to lower estimates; assuming aged soil C of 4000 yrs BP reduced Contribution\textsubscript{Aged} to 11.4 ± 5.9% in the burned and 1.8 ± 1.6% in the intact peat plateau, and SRAged to 0.08 ± 0.04 and 0.02 ± 0.01 g CO$_2$–C m$^{-2}$ d$^{-1}$, respectively (figure 4).

4. Discussion

Our findings suggest that soil aeration, rather than the quantity of soil C exposed to decomposition through thaw, was the main control on aged soil C respiration in fall at our sites. We could only detect a significant contribution from aged soil C to respiration at the peat plateau, where the active layer was predominately oxic. Furthermore, the peat plateau that burned 10 years prior to the study was estimated to have a three to fivefold greater rate of aged soil C respiration than the intact peat plateau, and was associated with both warmer soils and deeper active layer (70 versus 120 cm on average). In contrast, respiration of aged soil C was minimal or undetected in the thermokarst bog regardless of whether thaw had occurred decades or centuries ago. Loss of aged soil C as CO$_2$ from the thermokarst bog was undetected despite its substantially warmer peat profile, and its much larger (>5 m peat) and overall older (~8000 yrs BP basal age) C store that was available for microbial activity.

The minimal mineralization of aged soil C (SRAged) in thermokarst bog despite substantial respiration originating below the near-surface collars (SR\textsubscript{Deep}) suggests that recent C sources largely dominated C cycling at depth. Recently photosynthesized carbon at the surface of bogs has been shown to be
leached several meters downward where it is available for mineralization, resulting in depth profiles of dissolved organic C (DOC), CH₄, and CO₂ that are substantially younger than the peat (Aravena et al 1993, Charman et al 1994, Chanton et al 1995, Chasar et al 2000, Wilson et al 2016). In agreement with these observations, our measurements of CO₂ collected at depth with probes were consistently younger than peat at the same depth (figure 2). Our CO₂ flux measurements indicated considerable respiration occurring at depths below the near-surface collar base with SRDeep (i.e. full-profile collar minus near-surface CO₂ flux, figure 3(a)) being 20%–50% of the total flux across all sites. However, the estimates of SR_Aged were much lower (i.e. solved using equation (3), figure 3(c)). The discrepancy between SRDeep and SR_Aged occurred in all sites but was more pronounced in the thermokarst bog. It is well established that thermokarst bog development causes rapid accumulation of peat at the surface (Camill 1999, Turetsky et al 2000, Jones et al 2017, Wilson et al 2017). The large difference between SRDeep and SR_Aged could thus be explained by the translocation and mineralization at depth of leachates/exudates with recently fixed C from the productive Sphagnum mosses and sedges. The contribution of these recent C sources, in addition to spatial variability, could also explain observations of CO₂ with lower fM in near-surface than in full-profile collars in some sampling locations (YB1, MB1, MB2, figure 3(b)). In any case, the fact that respiration of aged soil C was so limited despite the very large C store available for decomposition is actually quite remarkable. The low or undetectable SR_Aged in the thermokarst bog could also be explained by the argued inactivation of anaerobic respiration due to energetic constraints when large pools of metabolic products accumulate in water-logged conditions (Blodau et al 2011).

Analysis of C stocks in Alaskan thermokarst bog cores suggest rapid loss of aged soil C within decades following thaw (Jones et al 2017) but we currently lack evidence for the processes explaining such large C losses following thermokarst development. Our findings in the late growing season in a deep peat deposit provide evidence against rapid old C losses as CO₂ during the thermokarst bog stage, but we cannot rule out substantial C losses either through CH₄, DOC, or as CO₂ at other times of the year or at sites with different permafrost/peatland development histories. The available measurements of ¹³CO₂ and ¹⁴CH₄ during the growing season in other thermokarst bogs (Klapstein et al 2014, Cooper et al 2017, Estop-Aragonès et al 2018) suggest low respiration rates of aged soil C that cannot explain the substantial reduction of C stocks in peat plateaus suggested by the analysis of soil cores in chronosequences (Jones et al 2017). Peat plateau edges may exhibit increased active layer depths extending 3–15 m onto the peat plateau (Baltzer et al 2014). Losses of aged soil C could occur in these near-edge areas during the decades just before thermokarst development if the soil profile remains oxic when the active layer deepens. Such losses could also occur through waterborne export of dissolved and particulate carbon but these measurements are not reported in permafrost peatlands and measurements in non-permafrost peatlands show considerably younger DOC than the peat (Chasar et al 2000, Campeau et al 2017). It also remains unknown if aged soil C
losses occur during winter when the pool of translocated young DOC at depth may become exhausted. Additionally, differences regarding peat incorporation in permafrost could influence its susceptibility to mineralization post-thaw; the bulk of the peat in our sites accumulated under non-permafrost stages whereas it was rapidly incorporated in permafrost in the Alaskan sites (syngenetic permafrost). Overall, the dearth of available data cannot explain the inferred large C losses following thermokarst development (Jones et al 2016) and further measurements are needed to characterize the spatial and temporal variability of aged soil C mineralization following thaw in peatlands.

This study shows that wildfire has the potential to both increase and decrease respiration of aged soil C through deepened active layer and accelerated thermokarst, which suggests that the overall influence will be dependent on temporal trajectories of soil thermal recovery and thermokarst expansion following wildfire. We observed increased release of aged soil C with active layer deepening when comparing the intact and burned plateaus but not in our thermokarst bog. Wildfire causes a deepening of the active layer, an effect which lasts about 20 years before recovery of the soil thermal regime is complete and active layer depth returns to values before disturbance (Gibson et al 2018). However, wildfire also accelerates thermokarst bog development (Zoltai 1993, Myers-Smith et al 2007). Several factors such as the intensity of disturbance, local climate and landscape position (Jorgenson et al 2010) likely influence the thaw trajectory towards either recovery or thermokarst development. Critically, the time elapsed between a fire event and the potential thermokarst development would determine the exposition of aged soil C to oxic conditions in a deepened active layer stage before transitioning into anoxic conditions in thermokarst bogs. Thus, the peatland thaw trajectory would largely control the exposition time to either oxic or anoxic soil conditions potentially determining the magnitude of permafrost (aged) C loss. The intensified fire regime over the last 30 years (Gillett et al 2004, Kasischke et al 2010), with about 25% of peat plateaus burned in western Canada, further emphasizes the need to consider differences in thaw trajectories following wildfire to project future peatland C storage.

5. Conclusions

We present estimates of in situ mineralization rates of aged soil C released as CO₂ at the end of the growing season in permafrost peatlands with contrasting soil environmental conditions. Sampling locations dominated by soil oxic conditions in peat plateaus resulted in detectable contributions of aged soil C loss, and rates of aged soil C loss were about five times greater in the fire-affected site associated with a deeper and warmer active layer than in the intact peat plateau. In contrast, contributions of aged soil C were low or undetected in the waterlogged and anoxic soils at the thermokarst bog both in locations thawed decades and centuries ago. If these observations are representative of processes occurring throughout the year, our results have important implications for our understanding not only of the response to thaw of aged peat carbon stocks but also of belowground carbon cycling in northern peatlands.

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