A direct approach to quantifying organic matter lost as a result of peatland wildfire

M.R. Turetsky and R.K. Wieder

Abstract: We describe a direct approach to quantifying the amount of organic matter consumed in peatlands during a single fire event, based on differences in ash concentrations between burned peat at the surface of peat cores and underlying unburned peat. We collected six peat cores at each of two continental bog and two permafrost bog sites, 3 months after a March 1999 wildfire. Results suggest high within-site variation in the amount of organic matter burned, with no significant differences between the four peatland sites or between continental and permafrost bogs. Averaged across all sites, 2.2 ± 0.5 kg C·m^{-2} (mean ± SE, n = 24) of organic matter was consumed as a result of this single fire, a value consistent with those in the literature.

Résumé : Les auteurs décrivent une approche directe pour quantifier la quantité de matière organique qui est consumée dans les tourbières lors d'un feu. Cette approche est basée sur la différence entre la concentration de la cendre dans la tourbe située à la surface d'une carotte de tourbe et dans la tourbe sous-jacente non brûlée. Six carottes de tourbe ont été prélevées dans quatre sites : deux tourbières continentales et deux tourbières en zone de pergélisol, trois mois après un feu survenu en mars 1999. Les résultats suggèrent qu'il existe une grande variation intra-site dans la quantité de matière organique brûlée mais il n'y a pas de différence significative entre les quatre tourbières, ni entre les tourbières continentales ou celles en zone de pergélisol. En moyenne pour l'ensemble des sites, 2,2 ± 0,5 kg C·m^{-2} (moyenne ± écart-type; n = 24) de matière organique a été consumée suite à ce feu. Cette valeur correspond à celles qu'on retrouve dans la littérature.

[Traduit par la Rédaction]

Introduction

Lightning-initiated forest fires are a common disturbance in the boreal forest (Wein and MacLean 1983; Zoltai et al. 1998). Stocks (1991) estimates that 56 × 10^6 ha of boreal forest was burned globally throughout the 1980s alone. Fire has important consequences for carbon storage in the boreal forest and is linked to immediate pulses of CO_2 to the atmosphere through combustion as well as post-disturbance effects on biogeochemical processes directly involved in carbon cycling, such as the loss of net primary production and enhanced soil respiration (Auclair and Thomas 1993; Dixon and Krankina 1993; Krankina 1992; Zackrisson et al. 1996; Conard and Ivanova 1997). Conard and Ivanova (1997) estimated that total carbon fluxes caused by fires in the boreal forest may represent more than 20% of the emissions linked to global biomass burning.

Many studies have recorded long-term patterns of fire history in peatlands using the presence of charcoal layers in peat (cf. Zoltai 1993; Kuhry 1994; Hornberg et al. 1995; Mighall and Chambers 1995; Lavoie and Payette 1996; Simmons and Innes 1996; Segerstrom 1997; Pitkänen et al. 1999). However, there are few direct estimates of carbon or biomass loss during fire or of changes in carbon emissions following fire in peatlands (Zoltai et al. 1998; but see de Groot and Alexander 1986; Levine et al. 1990; Kasischke et al. 1995*a*). Methods to accomplish the former are not well developed. Here we describe a new approach for directly and quantitatively estimating organic matter loss through combustion associated with peatland wildfire.

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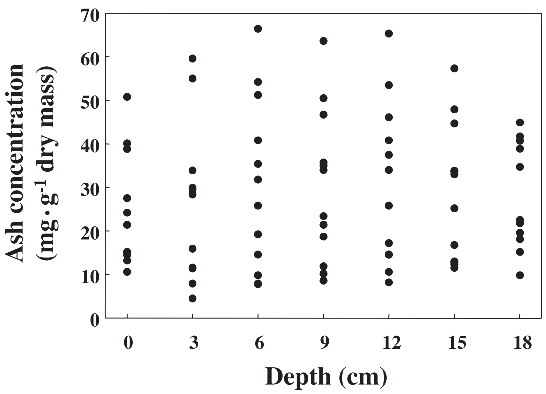
Methods

In March of 1999, a forest fire burned through portions of our field site, a peatland complex near Patuanak, Sask. (55°51′N, 107°41′W), located in the discontinuous permafrost zone of boreal, continental, western Canada. Three months after the fire, evident damage to aboveground vegetation ranged from complete charring and death (especially of *Picea mariana* (Mill.) BSP stands underlain by permafrost) to minimal impact. The top 5–10 cm of peat showed evidence of varying degrees of combustion. Three months after the fire, we collected six surface peat cores (10 cm diameter × 30 cm deep) in each of four peatland features affected by the fire (two continental bogs and two permafrost bogs surrounded by continental bog). Prior to the fire, both continental bogs were dominated by *Picea mariana*, *Ledum groenlandicum* Oeder, and *Sphagnum fuscum* (Schimp.) Klinggr. The permafrost bogs had closed canopies of *Picea mariana*, while moss cover typically consisted of *Pleurozium schreberi* (Brid.) Mitt. and *Sphagnum fuscum*. Surface peat (i.e., approximately the top 20 cm) in this region is bryophyte dominated, with little woody debris.

In the field, we extruded each core and, based on visual inspection, separated peat into an upper at least partially burned (typically 0–10 cm) section and a lower unburned (typically 10–20 cm) section, the latter with no evidence of ash or charcoal from combustion. Peat samples were dried at 70°C for 48 h, weighed, and homogenized using a Cyclotec mill. For each burned and unburned peat sample, we determined the ash concentration on three sub-

Fig. 1. Ash percentages for peat samples in the top 18–21 cm of 12 peat cores collected in three continental bogs and three permafrost bogs adjacent to the burned area. The mean of slopes calculated by linear regression of ash concentration on depth for each peat core was not significantly different from zero (slopes ranged from –0.1690 to 0.2126, mean slope ± 95% confidence interval = 0.0125 ± 0.0641), suggesting no regional trend of varying ash concentrations with depth in surface peat.



samples by loss on ignition at 450°C for 4 h (standard deviation among subsamples always less than 1.5%). Our approach assumes that ash concentrations within the surface 20 cm of peat in continental bogs and permafrost bogs does not vary consistently with depth. This assumption seems reasonable for peatlands in boreal, continental, western Canada (e.g., Kuhry 1994). Using undisturbed peat cores collected prior to the 1999 burn in nearby sites, we found no relationship between ash concentrations and depth (Fig. 1). All initial calculations are based on a 10 cm diameter core (78.5 cm^2 surface area), with subsequent extrapolation to a per square metre basis.

Terms used in calculations

We used the following variables for the top (burned) section of peat core:

TM, top dry mass (g)

TAC, top ash concentration (mg/g) (= mg ash/TM)

TOMC, top organic matter concentration (mg/g) (= 1000 – TAC)

For the bottom (unburned) section of peat core the variables were as follows:

BM, bottom dry mass (g)

BAC, bottom ash concentration (mg/g) (= mg ash/BM)

BOMC, bottom organic matter concentration (mg/g) (= 1000 – BAC).

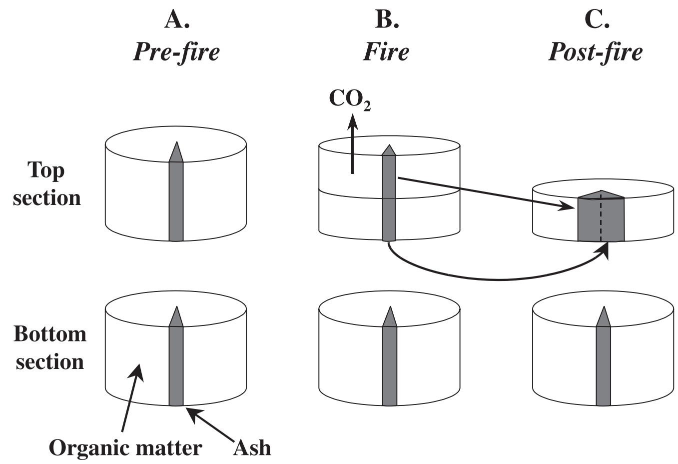
Calculations and rationale

Post-fire, the total amount of ash associated with surface peat includes ash associated with the matrix of any residual unburned peat and the ash left behind from the burned peat (Fig. 2). To calculate the amount of ash in the top, burned peat section not associated with combustion processes (TUA, top unburned ash), we multiplied the total organic matter mass of the top peat section by the ash/organic matter ratio of the bottom, unburned peat section:

$$[1] \qquad \text{TUA (mg)} = (\text{TM} \times \text{TOMC}) \times \left(\frac{\text{BAC}}{\text{BOMC}}\right)$$

To calculate the amount of ash in the top section left behind from peat combustion (EA, excess ash), we subtracted TUA from the total amount of ash in the top section:

Fig. 2. Conceptual basis for using post-fire ash concentrations to estimate C losses during a peatland wildfire. Prior to fire, peat has a high organic matter concentration that is uniform throughout the upper 20 cm of peat (A; cf. Fig. 1). Fire results in the loss of organic matter, mainly as CO_2 released to the atmosphere, with the inorganic constituents (ash) of that burned organic matter remaining behind (B). After a fire, ash concentration in the upper peat layers consists of both the inorganic material in the unburned peat and the ash remaining from the burned organic matter; hence, fire results in an increase in ash concentration (and a decrease in organic matter concentration) in near-surface peat (C). Neither ash nor organic matter concentrations in deeper peat layers are affected directly by fire.



$$[2] \qquad \text{EA (mg)} = (\text{TM} \times \text{TAC}) - \text{TUA}$$

Having estimated the quantity of ash in the top section associated with the burned peat (EA), we then calculated the amount of organic matter (BOM, burned organic matter) that must have been burned off to produce the excess ash in surface peat. For each top peat section, we multiplied EA by the organic matter/ash ratio of the corresponding lower, unburned peat section:

$$[3] \qquad \text{BOM (mg)} = \text{EA} \times \left(\frac{\text{BOMC}}{\text{BAC}}\right)$$

Results

Assuming no consistent increases in ash concentrations throughout the surface layers of a peat profile (Fig. 1), as well as negligible migration of ash particles in peat following a fire, burned peat near the surface will have higher ash concentrations than unburned peat deeper in the peat core (Fig. 2). Four of the 24 peat cores did not show this pattern (Table 1), leading to small negative values for excess ash. As these cores displayed no evidence of combustion, we assigned to them values of zero for the amount of organic matter burned.

Our estimates of burned organic matter per square metre of peatland surface area showed considerable within-site variability, with coefficients of variation (variance/mean × 100) averaging 101%. A one-way analysis of variance revealed no significant differences in BOM among the four sites (F = 1.66, p = 0.2080). A nested analysis of variance, treating the two bog and two permafrost sites as nested within their respective feature types (continental bog and

Table 1. Average ash concentrations (mean of three replicate combustions) of the top, burned peat sections (top ash concentration, TAC), average ash concentrations (mean of three replicate combustions) of the deep, unburned peat sections (bottom ash concentration, BAC), and the dry mass of the top, burned peat sections (top mass, TM) for each peat core collected in four peatlands affected by wildfire. These values are used to calculate the total amount of burned organic matter (BOM) within a peatland following a fire event.

	Core No.	TAC ($mg \cdot g^{-1}$ dry mass)	BAC ($mg \cdot g^{-1}$ dry mass)	TM (g dry mass)	BOM ($kg \cdot m^{-2}$)
Continental bog 1	1	30.2	37.5	51.99	0
	2	59.1	47.9	35.95	1.07
	3	79.2	49.0	34.46	2.70
	4	74.9	37.6	35.66	4.50
	5	43.3	27.2	27.47	2.07
	6	151.6	31.0	29.44	14.58
	Mean ± SE				4.16 ± 2.18
Continental bog 2	1	81.9	36.2	15.51	2.49
	2	40.4	41.0	15.25	0
	3	48.3	32.0	18.15	1.18
	4	66.2	37.6	9.11	0.88
	5	60.1	42.4	14.24	0.76
	6	59.7	41.8	20.30	1.11
	Mean ± SE				1.07 ± 0.33
Permafrost bog 1	1	53.2	52.0	52.19	0.15
	2	45.3	25.4	42.47	4.24
	3	50.2	26.0	30.01	3.56
	4	50.7	21.3	43.20	7.59
	5	58.0	18.2	34.71	9.66
	6	132.0	58.1	112.03	18.140
	Mean ± SE				7.22 ± 2.57
Permafrost bog 2	1	50.1	33.7	65.40	4.05
	2	54.4	20.3	59.11	12.64
	3	67.6	49.6	53.32	2.46
	4	36.1	43.6	12.31	0
	5	47.2	57.6	29.72	0
	6	73.2	32.9	40.65	6.34
	Mean ± SE				4.25 ± 1.95

permafrost bog), and hence the individual cores as subsamples, showed no significant difference in BOM between continental bogs and permafrost bogs ($F = 2.56$, $p = 0.1251$). On average, the amount of organic matter burned during the recent fire was 4.2 ± 1.0 $kg \cdot m^{-2}$ (mean ± SE, $n = 24$). Using a peat carbon content of approximately 52% of organic matter mass, our estimate of the amount of carbon lost to the atmosphere as a result of this single fire event is 2.2 ± 0.5 kg $C \cdot m^{-2}$.

Discussion and conclusion

Existing approaches to estimating organic matter lost from peatlands as a result of fire include comparison of long-term (100s to 1000s of years) carbon accumulation from dated peat cores with different fire histories as inferred from charcoal layers (e.g., Kuhry 1994; Zoltai et al. 1998; Pitkänen et al. 1999), remote sensing analysis of post-fire landscapes (e.g., Kasischke et al. 1995*a*), and modeling (e.g., Kasischke et al. 1995*b*). Although each approach has merit, all suffer from being indirect. The extent to which any approach accurately reflects organic matter losses resulting from fire in peatlands is largely untested, as reliable field-based methods to gather corroborative data have not been available.

We outline a direct and quantitative approach to estimating the amount of organic matter lost from peatlands following a single peatland fire based upon ash concentrations in burned and unburned peat. Our average value of 2.2 ± 0.5 kg $C \cdot m^{-2}$ agrees well with other values of biomass combustion associated with peatland fire (2.5–3.0 kg $C \cdot m^{-2}$, Kasischke et al. 1995*a*; 5–15 kg biomass$\cdot m^{-2}$ (1.3–3.9 kg $C \cdot m^{-2}$, assuming 5% ash concentration and organic matter C concentration of 52%), de Groot and Alexander 1986; 4.9 kg $C \cdot m^{-2}$, Zoltai et al. 1998; 2.5 kg $C \cdot m^{-2}$, Pitkänen et al. 1999; 4.0 kg $C \cdot m^{-2}$, estimated by Pitkänen et al. 1999 from data in Kuhry 1994).

We note that the 1999 fire at our field site may have been typical in creating spatial heterogeneity on the landscape. In all four of our peatland sites, the recent fire produced irregular patterns on the landscape, with areas of highly combusted peat often lying within 50 cm of areas of lightly scorched or unburned peat. This heterogeneity is reflected in the large statistical variation in burned organic matter within each site (Table 1). As a result, we were unable to demonstrate either site or feature (continental bog vs. permafrost bog) differences in the amount of burned organic matter. We might have been more successful in this regard if we had used a more intensive within-site core sampling strategy, designed to more fully capture the spatial variation in fire activity at the site level. The focus of our efforts, however, was to develop a novel approach to quantifying the effects of a single fire on the organic matter loss from peatlands. We conclude that this approach is conceptually and mathematically straightforward, requires only a single visit to any site soon after a fire, and involves simple laboratory analysis. Field sampling intensity can be adjusted depending on the spatial scale of the specific question under investigation.

General circulation models predict increased fire weather severity and longer fire seasons for western Canada under near-term future climate change scenarios (Flannigan and Van Wagner 1991; Wotton and Flannigan 1993; Bergeron and Flannigan 1995; Starfield and Chapin 1996; Stocks et al. 1998). Given that boreal and subarctic peatlands contain 455 Pg of stored C (Gorham 1991), accelerated fire regimes in the boreal forest may have implications for global carbon cycling. Peat core analysis, modeling, and remote sensing will continue to be used as important tools for assessing peatland fire and global carbon cycling. For peatlands, a direct, straightforward method of quantifying carbon losses resulting from fire can now be applied to support these existing indirect approaches.

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