

Interactive effects of vegetation, soil moisture and bulk density on depth of burning of thick organic soils

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Abstract. The boreal biome is characterised by extensive wildfires that frequently burn into the thick organic soils found in many forests and wetlands. Previous studies investigating surface fuel consumption generally have not accounted for variation in the properties of organic soils or how this affects the severity of fuel consumption. We experimentally altered soil moisture profiles of peat monoliths collected from several vegetation types common in boreal bogs and used laboratory burn tests to examine the effects of depth-dependent variation in bulk density and moisture on depth of fuel consumption. Depth of burning ranged from 1 to 17 cm, comparable with observations following natural wildfires. Individually, fuel bulk density and moisture were unreliable predictors of depth of burning. However, they demonstrated a cumulative influence on the thermodynamics of downward combustion propagation. By modifying Van Wagner's surface fuel consumption model to account for stratigraphic changes in fuel conditions, we were able to accurately predict the maximum depth of fuel consumption for most of the laboratory burn tests. This modified model for predicting the depth of surface fuel consumption in boreal ecosystems may provide a useful framework for informing wildland fire management activities and guiding future development of operational fire behaviour and carbon emission models.

Additional keywords: bog, boreal, carbon, fire, ground-layer fuels, peat, peatland, smouldering, *Sphagnum*, surface fuel combustion.

Introduction

Wildfires are the dominant stand-replacing disturbance in boreal North America and have shown more than a doubling of annual area burned in recent decades (Kasischke and Turetsky 2006). Combustion of ground-layer fuels (defined here as moss, litter and organic soils) dominates total carbon (C) emissions during boreal wildfires (Amiro *et al.* 2009). Ground-layer vegetation and soil organic layers form a protective insulation layer for soils and permafrost. Thus, the depth of ground-layer burning has long-term effects on several important ecosystem functions, including post-fire succession (Johnstone and Chapin 2006; Benscoter and Vitt 2008; Johnstone *et al.* 2010), soil moisture and temperature regimes (Kasischke and Johnstone 2005), loss of permafrost (Robinson and Moore 2000; Jorgenson *et al.* 2001; Turetsky 2004), and ecosystem C storage (Harden *et al.* 2000; Bond-Lamberty *et al.* 2004).

Many boreal forests and peat-forming wetlands (peatlands) have thick surface fuel (moss and organic soil) layers due to an imbalance between net primary productivity and soil C losses (decomposition, disturbance-related losses and runoff). Although peatlands (i.e. ecosystems with more than 40 cm of

organic soil) have conventionally been considered resistant to wildfire due to their relatively wet soil conditions (Kuhry 1994), recent studies have shown peatland combustion during wildfire can be substantial, both in extent (Turetsky *et al.* 2004) and severity (Turetsky and Wieder 2001; Turetsky *et al.* 2002; Benscoter and Wieder 2003; Shetler *et al.* 2008).

In general, fuel combustion is influenced by the availability (fuel loading and structure), composition (fuel type) and condition (e.g. fuel bulk density and moisture) of both aboveground and surface fuels, as well as fire weather and behaviour characteristics (Van Wagner 1972). Smouldering is typically the dominant form of combustion in peat soils owing to the greater fuel packing ratio and soil moisture compared with other fuel types (Miyanishi and Johnson 2002). Soil moisture and bulk density can influence smouldering combustion by influencing the amount of energy required for combustion to occur (i.e. heat of ignition; Johnson 1992) and the amount of the heat released that is propagated to the combustion front (Van Wagner 1972). Smouldering peat fires are problematic for fire management because they require increased financial and suppression resource commitments. In addition to taxing fire management

resources, emissions from smouldering peat fires also pose higher human and ecosystem health risks owing to greater particulate and mercury emissions (Yokelson *et al.* 1999; Turetsky *et al.* 2006; Obrist *et al.* 2008).

Several laboratory-based studies have examined the influence of inorganic content and soil moisture (Frandsen 1987, 1991, 1997; Hartford 1989; Miyanishi and Johnson 2002; Rein *et al.* 2008) as well as fuel bulk density (Miyanishi and Johnson 2002) on combustion rates. Most of these studies have used commercial milled peat to simulate a peat fuel source, which has a higher bulk density than that of natural peat and will ignite when gravimetric water content (GWC) is below 93% moisture by peat dry weight (Frandsen 1987). However, natural *Sphagnum* peat has a 50% probability of ignition at a soil moisture of ~120% (Frandsen 1997) and fuel conditions (e.g. moisture, density) vary with depth. In this study, we conducted experimental ignition tests of natural peat monoliths under several moisture regimes to investigate the influence of fuel condition on depth of burning. We used these experimental data to explore a thermodynamic approach for predicting depth of burn using a modified version of Van Wagner's (1972) surface fuel consumption model. Although the present study does not rely on a process-based model of combustion, the ability to predict depth of burn following boreal wildfires would be useful for carbon-cycle studies as well as natural resource and fire management agencies, given the ecological significance of depth of ground-layer burning for vegetation recovery, permafrost stability and energy balance post-fire.

Methods

Study site

All samples were collected from the Athabasca Bog (54°43'N, 113°10'W), located ~5 km east of Athabasca, Alberta, Canada. The site is a raised bog island within a larger fen complex, with an organic peat layer ranging from 2 to 3 m in depth. The ground-layer is dominated by *Sphagnum fuscum* and *Pleurozium schreberi*, with sporadic populations of lichen (*Cladonia* spp.), true mosses and other *Sphagnum* moss species (including *S. angustifolium*, *S. magellanicum*, *S. capillifolium*). The vegetation and peat properties at this site (Benscoter *et al.* 2005a, 2005b) are typical of mid- to late-successional ombrotrophic bogs of continental western Canada (Vitt *et al.* 1995; Benscoter and Vitt 2008), making this site suitably representative of bogs in the region.

Sample collection and preparation

Pedons of surface peat ~60 × 40 cm (length by width) ranging from 20 to 30 cm in depth were extracted from the bog and transported to Meanook Biological Research Station (University of Alberta). A total of 18 pedons were collected, comprising six pedons of each of three common vegetation groups (i.e. fuel types) representative of the bog ground-layer vegetation (*Sphagnum fuscum* hummocks, *Pleurozium schreberi* feathermoss hummocks and mixed-species hollows). Two pedons of each fuel type were assigned to each of three fuel moisture (drying) treatments: (1) field moisture; (2) 2-week air-dried; and (3) 2-week air-drying followed by a 48-h period of oven-drying at 40°C (hereafter referred to as the oven-dried treatment). The

goal of these moisture treatments was not to create uniform fuel moisture within an entire pedon (or dry the pedon completely) but to alter the pedon fuel moisture profile.

Pedons assigned to the field-moisture treatment were ignited within 48 h of pedon collection (see methods on ignition tests below). Pedons assigned to the two drying treatments were placed in open-topped plastic bins with ~thirty 1.5-cm-diameter holes in the bottom of the bin to allow free-water drainage from the base of the pedon. The pedons were randomly arranged in a temperature-controlled laboratory (~20°C) on wooden planks to elevate the bottom of the container above the table, allowing unimpeded water drainage through the holes. An oscillating fan was positioned to provide air movement over the pedons at ~1 m s⁻¹, resulting in an average of 3.2 mm day⁻¹ of evaporation from an open water lysimeter placed among the pedons. After 4 days, the wooden runners were removed and the pedon positions re-randomised; this was repeated every 4 days for a period of 2 weeks before ignition. Pedons assigned to the oven-dried treatment were then placed in a drying room at the Northern Forestry Centre (Canadian Forest Service, Edmonton, Alberta, Canada) at a temperature of 40°C for 48 h before ignition.

Immediately preceding the ignition tests, a monolith (20 × 25 cm) was extracted from the central portion of the original pedon to prevent any possible edge effects of drying on the lateral faces of the pedon. Small subsamples of the central monolith were collected at 3-cm-depth intervals along the profile of the monolith for pre-burn fuel condition analyses (e.g. peat type, bulk density, soil moisture; see below for methods). Each monolith was then placed into a burn box constructed of 1.3-cm-thick ceramic fibreboard (Cotronics Corp, Brooklyn, NY) of the same length and width as the monolith, extending 9 cm above the monolith surface. Depth arrays of four heat-resistant 14-gauge thermocouples (Omega Engineering, Inc., Stamford, CT) were inserted laterally into each monolith at 2, 5, 10 and 20 cm beneath the surface with a lateral insertion depth of ~10 cm from the face of the monolith (Fig. 1). During the ignition tests, temperature was logged every 30 s using a CR10X datalogger and AM16/32 multiplexer (Campbell Scientific, Logan, UT).

Topography of the monolith surface was mapped before ignition. The distance from the top of the burn box to the monolith surface was measured for the entire surface in 3-cm regular grid spatial intervals ($n = 48$ grid points) to derive a 3-D map of the surface. This process was repeated at the end of combustion (described below) to generate point-specific fuel consumption depths as well as total average depth of burn for each monolith.

Subsamples collected from the monolith profiles were analysed for botanical composition, bulk density and soil moisture. Components of the peat (moss species, presence of woody debris, roots, etc.) were identified and relative proportions were assessed through macrofossil analysis. The 3 cm-deep, 49-cm² subsamples were then weighed, dried at 65°C to constant dry mass (~3–4 days), and reweighed to obtain values of gravimetric (water mass per unit dry fuel mass, expressed as %) and volumetric (water volume per sample volume, m³ m⁻³) water content as well as fuel bulk density (dry fuel mass per sample volume, kg m⁻³). The dried subsamples were then homogenised

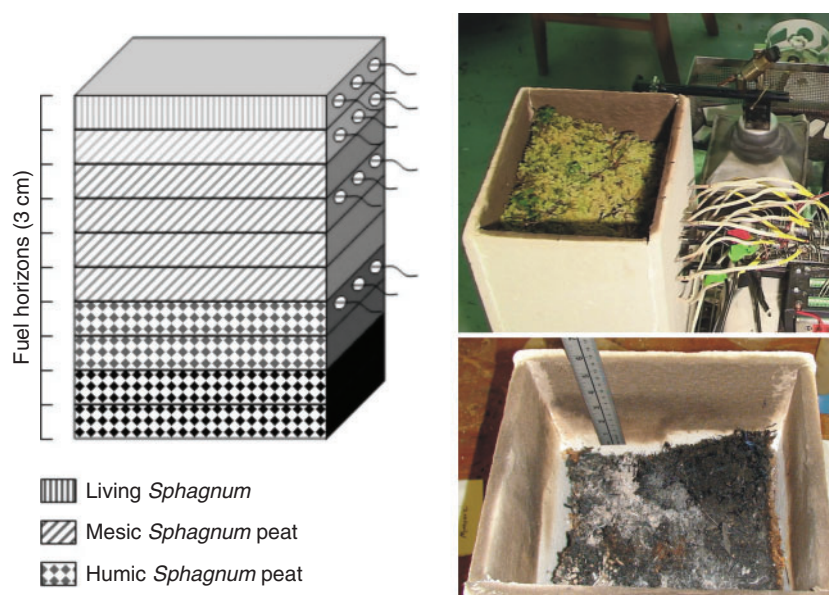


Fig. 1. Example of *Sphagnum* peat monolith ignition trial set-up. Monolith schematic (left) illustrates fuel horizons and stratigraphic changes in peat type (represented by patterning of individual fuel horizons) and general fuel condition (e.g. increasing bulk density and moisture with depth, represented by degree of shading). Thermocouple placement is illustrated by ovals and curved lines on right face of monolith schematic and shown in pre-trial photograph (top right). Single thermocouples were inserted at the outer positions to a lateral depth of 10 cm; two thermocouples were inserted at the central position to lateral depths of 10- and 15-cm, comprising arrays of four thermocouples per measurement depth.

using a UDY Cyclone Sample Mill (UDY Corporation, Fort Collins, CO) and 0.5 g of each subsample was combusted in a muffle furnace at 550°C for 4 h. The residual ash was weighed to determine the inorganic (mineral) content of each subsample. Regression analysis was used to test for depth-dependent changes in fuel properties and a mixed-effects general linear model (PROC MIXED) was used to assess differences among drying treatments and fuel types, with the drying and fuel treatments as fixed effects and monoliths as random. All statistical tests were performed using *SAS v9.1* (SAS Institute, Cary, NC).

Ignition tests

Ignition tests were conducted in the indoor combustion facilities at the Northern Forestry Centre and sample collection and preparation were staggered for the drying treatments, enabling all ignition trials to be conducted over a 48-h period to minimise variability in ambient environmental conditions. A modified propane-fired radiator was used to ignite the surface of each monolith. The radiator consisted of an enclosed heating element surrounded by an aluminium heat shield of the same dimensions as the burn boxes with a height of 15 cm from the heating element to the top of the box (24 cm to the monolith surface). The radiator was ignited and placed over the peat monolith for a period of 5 min, which was equivalent to the cumulative application (heat load) of $1.87 \times 10^6 \text{ J m}^{-2}$ to the monolith surface as determined using a water-bath calorimeter. This cumulative heat load to the fuel surface is analogous to the cumulative

radiant energy received by a horizontal black-body element ahead of a fast-moving, intense fire based on radiative transfer from a planar surface (Incropera and de Witt 1990) similar to that of Butler and Cohen (1998) with the addition of an angled flame. After 5 min, the radiator was removed and continuous temperature measurements were taken for 1 h. After 1 h, the monolith was placed aside for a minimum of 24 h before the final assessment of depth of burning was performed. Depth of burn was calculated for each monolith as the difference between pre- and post-combustion topography of the monolith surface averaged across the 48 grid points.

We assessed the effects of bulk density, soil moisture and their interaction on peat combustion by comparing fuel conditions of horizons that burned to the conditions of unburned horizons. Conditions of horizons contained entirely within the burned zone were compared with the horizon immediately below the maximum depth of burn (e.g. the unburned horizon directly beneath the burned–unburned interface) within each monolith. Horizons deeper than the initial unburned horizon at the maximum burn depth did not have the opportunity to combust (i.e. received no ignition energy) and were therefore excluded from analysis of fuel condition and combustion success. Comparisons and patterns of fuel conditions between burned and unburned samples were made using ANOVA and regression approaches.

To examine whether changes in physical properties influencing heat transfer affects the downward propagation of combustion, the thermal diffusivity (κ , $\text{m}^2 \text{ s}^{-1}$) or rate of heat movement

through a fuel horizon (Oke 1987) was calculated for the burned fuel horizons and the adjacent unburned horizon at the maximum burn depth as:

$$\kappa = \frac{\lambda}{(\theta C_w) + (\rho_b C_{\text{peat}})} \quad (1)$$

where C_w is the heat capacity of water ($4.186 \text{ J g}^{-1} \text{ water } ^\circ\text{C}^{-1}$), θ is the fuel volumetric water content ($\text{m}^3 \text{ m}^{-3}$), ρ_b is the fuel bulk density (g m^{-3}), C_{peat} is the specific heat of peat ($1.92 \text{ J g}^{-1} \text{ fuel } ^\circ\text{C}^{-1}$ for peat from Oke 1987), and λ is the thermal conductivity of the fuel horizon ($\text{W m}^{-1} \text{ } ^\circ\text{C}^{-1}$). Thermal conductivity (k) or the energy flux through a volume of peat with a unit temperature gradient, analogous to hydraulic conductivity of saturated soils, was calculated using the model of Côté and Konrad (2005) to incorporate bulk density and volumetric water content:

$$k = [(k_s^{1-f} 0.6^f) - k_{\text{dry}}] \left[\frac{K S_r}{1 + (K - 1) S_r} \right] + [X 10^{-\eta}] \quad (2)$$

where k_s is the thermal conductivity of the solid particle ($0.25 \text{ W m}^{-1} \text{ K}^{-1}$), f is the porosity ($\text{m}^3 \text{ m}^{-3}$), k_{dry} is the thermal conductivity of dry peat of average porosity ($0.06 \text{ W m}^{-1} \text{ K}^{-1}$), K represents a soil type factor specific to fibrous peat (0.6), S_r is the percentage of pores that are saturated, equal to θ/f , and X ($0.3 \text{ W m}^{-1} \text{ K}^{-1}$) and η (0.87, unitless) are particle shape parameters. The significance of the change in thermal diffusivity between successive burned layers and the burned–unburned interface within each monolith was examined and depth-dependence of thermal diffusivity was tested using regression analysis.

Thermodynamic fuel consumption model

Van Wagner (1972) proposed a model for calculating the mass of duff fuels consumed during combustion based on experimental burns in upland pine forests. Using an energy balance approach, Van Wagner (1972) calculated surface fuel consumption as the total incoming energy from a flame front to the fuel surface divided by the energetic ignition threshold (or magnitude of the energetic sink) per unit of fuel mass. However, Van Wagner's fuel consumption model is limited in its application to peat soils by its assumptions of uniform density and moisture of the fuel layer. In this model, duff is expressed in units of mass per unit area. Fuel moisture is treated similarly, expressed only as a ratio to fuel mass. This assumes a given mass of fuel occupies a uniform volume and that volume has uniform moisture content through the entire fuel bed. Although this may be a reasonable approximation for shallow forest-floor duff layers, thick organic soil layers have been found to vary considerably in moisture and bulk density both laterally and with depth through the soil column as a result of botanical composition and proximity to watertable (Zoltai *et al.* 2000; Benscoter *et al.* 2005b). Therefore, such assumptions of uniformity are invalid for thick organic soil fuels.

In addition to using spatially uniform fuel characteristics, studies of smouldering in organic soils typically focus on lateral spread of the combustion front and neglect downward combustion. Although this may be sufficient for shallow organic soils

such as those typically found in upland boreal forests, peatland and lowland forest organic layers are much thicker, making downward propagation of combustion of equal importance.

By viewing thick organic soils as a series of heat sinks with depth, each of which must be successively overcome for ignition to occur and propagate downward, we modified Van Wagner's (1972) duff consumption model to account for depth-dependent variation in fuel condition. In our thermodynamic model, peat combustion is modelled using the generation and downward transfer of heat (heat inputs) and the magnitude of the heat sink of successive fuel horizons to determine the depth at which the thermodynamic limit for ignition is exceeded and downward propagation ceases.

In its simplest form, the energy balance of a fuel horizon can be modelled as the difference between the incoming energy ($H_{\text{cumulative}}$), either from external application or combustion release from the overlying layer, and the energy required to ignite that fuel layer (H'_{ign}). When this difference is positive or equal, combustion occurs and heat is propagated downward, whereas when the difference is negative, combustion stops owing to energetic limitation. In this way, the model determines the depth where

$$H_{\text{cumulative}} < H'_{\text{ign}} \quad (3)$$

By using the fuel characteristics of the samples collected from the monoliths before the ignition trials, the potential energy release and energetic threshold for combustion could be calculated for successive fuel horizons with depth through the monoliths. Samples were collected with uniform area (49 cm^2) and depth interval (3 cm), alleviating the need for variable volumetric considerations of fuel conditions. On an areal basis, the critical cumulative heat load for ignition (H'_{ign} , J m^{-2}) of a fuel horizon (i) can be calculated as:

$$H'_{\text{ign}(i)} = h_{(i)} \rho_b(i) x_{(i)} \quad (4)$$

where ρ_b and x are the bulk density (g m^{-3}) and thickness (0.03 m in this study) of the fuel horizon i respectively and h (J g^{-1} fuel) is Van Wagner's (1972) heat of ignition for the fuel horizon. Using the equation of Johnson (1992), the heat of ignition can vary as a function of fuel moisture:

$$h = m C_w (T_V - T_A) + L_V m + C_f (T_{\text{comb}} - T_A) + S \quad (5)$$

where m is the fuel gravimetric moisture content (g water g^{-1} fuel by dry weight), C_w is the heat capacity of water ($4.186 \text{ J g}^{-1} \text{ water } ^\circ\text{C}^{-1}$), C_f is the specific heat of the dry fuel ($1.47 \text{ J g}^{-1} \text{ fuel } ^\circ\text{C}^{-1}$ for pine duff from Van Wagner 1972; $1.92 \text{ J g}^{-1} \text{ fuel } ^\circ\text{C}^{-1}$ for peat from Oke 1987), T_V is the vaporisation temperature of water (100°C), T_{comb} is the combustion temperature of duff (300°C from Van Wagner 1972), T_A is the ambient temperature in degrees Celsius, L_V is the latent heat of vaporisation of water (2250 J g^{-1} from Johnson 1992), and S is the energy required to liberate water molecules sorbed to organic material (50.4 J g^{-1} fuel from Van Wagner 1972). Assuming a peat fuel with an ambient pre-trial temperature of 20°C , Eqn 5 can be simplified to:

$$h = 2585m + 588 \quad (6)$$

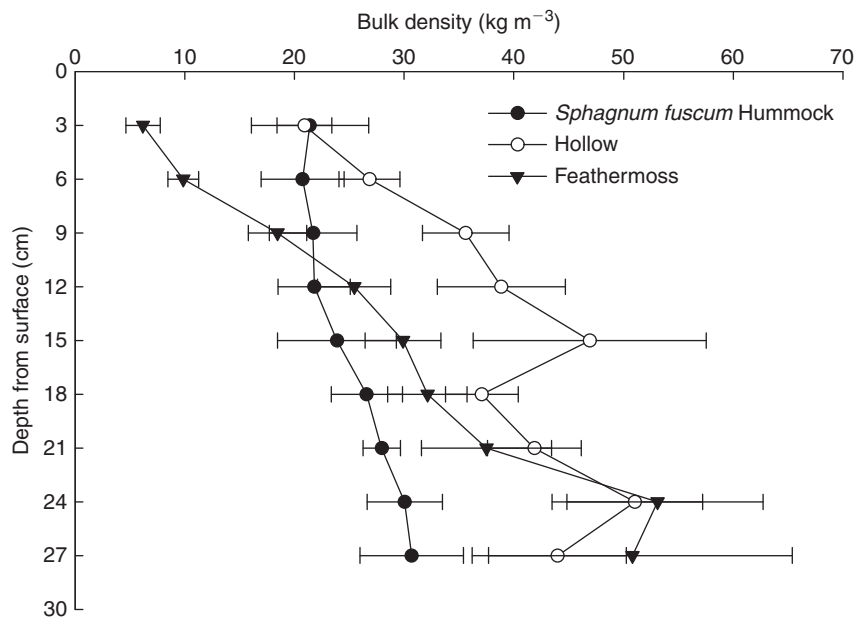


Fig. 2. Profiles of mean bulk density (\pm s.e.) with depth through the monolith for each surface community type ($n=6$). Values of depth from the surface represent the depth to the bottom of the 3-cm soil horizon.

expressing the ignition threshold of a unit of dry fuel mass as a function of fuel moisture (J g^{-1} fuel).

If the total energy applied is greater than the energetic threshold for ignition of a fuel horizon H'_{ign} , combustion is considered successful and the energy stored within the fuel horizon is released. The energy released during combustion of a dry fuel horizon i ($H_{\text{comb}(i)}$, J m^{-2}) is calculated as:

$$H_{\text{comb}(i)} = \rho_{b(i)} x(i) E_{\text{comb}} \quad (7)$$

where E_{comb} is the low heat of combustion per unit mass of peat ($14\,200 \text{ J g}^{-1}$ for milled peat from Frandsen 1991).

For the surface fuel horizon ($i=1$), heat input is solely from the external propane radiator ignition source described previously ($H_{\text{cumulative}(1)} = H_{\text{radiator}} = 1.87 \times 10^6 \text{ J m}^{-2}$). For underlying horizons ($i>1$), heat inputs can originate from residual surface ignition energy or from energy released during combustion of the overlying layer ($H_{\text{comb}(i-1)}$). The cumulative heat load ($H_{\text{cumulative}}$, J m^{-2}) transferred downward to underlying ($i>1$) fuel horizons can be calculated as:

$$H_{\text{cumulative}(i)} = (H_{\text{cumulative}(i-1)} - H'_{\text{ign}(i-1)} + H_{\text{comb}(i-1)})\varepsilon \quad (8)$$

where ε is the downward efficiency (unitless) of heat transfer to the unburned organic material below the combustion zone. The downward efficiency term is an empirically derived value that partitions the total heat transfer to the layers below but does not attempt to resolve or apportion heat transfer to the mechanisms of radiation, conduction or convection. In this way, it is similar to the propagating flux ratio for surface spread propagation in Rothermel's (1972) well-known semiphysical surface fire

spread model. An optimal downward efficiency value for the organic fuels studied here was empirically derived from the observed results of the burning experiments.

The critical heat load for ignition ($H'_{\text{ign}(i)}$, Eqn 4) was calculated for each fuel horizon. Ignition and combustion were then simulated in a stepwise fashion, propagating downward through the monolith until the minimum depth where the condition of Eqn 3 (available energy $<$ ignition threshold) was fulfilled, indicating the maximum projected depth of burn for the monolith. The projected depth of burn was then compared with the observed mean depth of burn to assess model accuracy. Because our monoliths were sampled at a 3-cm depth interval resolution, the observed depth of burn was reclassified to match this resolution (i.e. if >1.5 cm of a horizon was consumed, the horizon was classified as burned). If the projected and observed depth of burn results for a monolith (trial) were equal, the trial was a success; unequal results were a failed trial. Model accuracy was calculated as the percentage of trials producing successful model results.

Results

Fuel characteristics

Bulk density increased with depth for all three surface vegetation type groups (*Sphagnum fuscum* hummocks ($F_{1,49} = 7.25$, $P = 0.009$, $r^2 = 0.13$), feathermoss hummocks ($F_{1,49} = 73.49$, $P < 0.001$, $r^2 = 0.60$), and mixed-species hollows ($F_{1,45} = 16.31$, $P < 0.001$, $r^2 = 0.27$)), although bulk density was more consistent with depth in the *S. fuscum* monoliths (Fig. 2). Inorganic matter content showed no significant relationship with depth ($F_{8,85} = 0.98$, $P = 0.460$, $r^2 = 0.02$), although there were slight but significant differences among fuel types ($F_{2,15} = 20.28$, $P < 0.001$) with *S. fuscum* hummocks

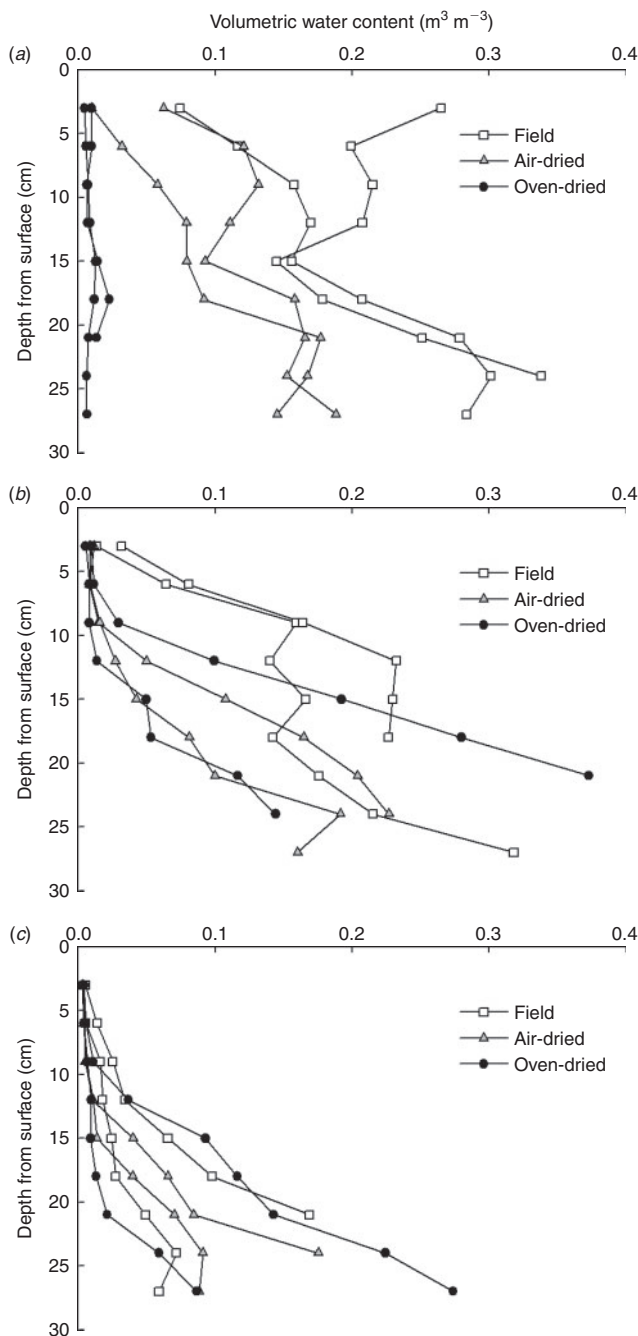


Fig. 3. Volumetric water content depth profiles in monoliths collected within: (a) *Sphagnum fuscum* hummocks; (b) mixed-species hollows; and (c) feathermoss communities. Data are plotted for each experimental moisture treatment. Values of depth from the surface represent the depth to the bottom of the 3-cm soil horizon.

($2.4 \pm 1.0\%$) < feathermoss hummocks ($4.6 \pm 2.7\%$) < mixed-species hollows ($6.6 \pm 3.0\%$).

Soil moisture profiles (volumetric water content, VWC) were highly variable among monoliths, even from similar fuel types or drying treatments (Fig. 3). However, there was a significant overall increase in VWC with depth ($F_{1,147} = 54.07$, $P < 0.001$, $r^2 = 0.27$). *Sphagnum fuscum*

monoliths showed the greatest response to the drying treatments, with a $\sim 90\%$ reduction in VWC between the field and oven-dried moisture treatments (Fig. 3a). Mixed-species hollow monoliths showed little effect of the drying treatments on VWC profiles, with the exception of moderate drying of the surface (0–6 cm) compared with field conditions (Fig. 3b), and feathermoss monoliths showed no discernable effect of drying throughout the profiles (Fig. 3c).

Peat ignition and combustion

Successful sustained ignition, defined by peat consumption to a minimum depth of 3 cm, was achieved for 12 of the 18 monoliths. Of the remaining six monoliths, three exhibited less than 3 cm of fuel consumption and three had no ignition. The majority of peat consumption was through smouldering combustion, although some dependent flaming combustion was observed immediately after removing the heat source (< 30 s duration). However, extended, sustained flaming was observed for one oven-dried feathermoss monolith, consuming the entire monolith in < 5 min. This was the only burn trial where flaming combustion played a significant role. Mean depth of burn (DOB) varied greatly across the three moisture treatments ($F_{2,15} = 8.66$, $P = 0.003$), averaging 17.2 ± 4.7 , 4.2 ± 0.9 and 1.2 ± 1.1 cm for the oven-dried, air-dried and field moisture treatments respectively (mean \pm standard error). Depth of burning was not significantly different among fuel types ($F_{2,15} = 0.10$, $P = 0.908$), although examination of potential interactions between fuel type and drying treatment was limited by the small sample size.

Ignition at the uppermost surface of the monolith showed no significant difference in bulk density ($F_{1,16} = 0.09$, $P = 0.774$) between successful ($15.6 \pm 1.6 \text{ kg m}^{-3}$) and unsuccessful ignitions ($17.2 \pm 3.5 \text{ kg m}^{-3}$). However, average surface VWC for successful ignitions ($0.007 \pm 0.001 \text{ m}^3 \text{ m}^{-3}$) was significantly less than unburned monoliths ($0.074 \pm 0.025 \text{ m}^3 \text{ m}^{-3}$; $F_{1,16} = 5.89$, $P = 0.027$), as was GWC ($61 \pm 44\%$ and $359 \pm 333\%$ respectively; $F_{1,16} = 9.92$, $P = 0.006$). The maximum VWC observed in successful ignition tests ($0.013 \text{ m}^3 \text{ m}^{-3}$ or 84% GWC) is lower but comparable with that of surface *Sphagnum* ($0.026 \text{ m}^3 \text{ m}^{-3}$ or 118% GWC) or feathermoss fuels ($0.034 \text{ m}^3 \text{ m}^{-3}$ or 81% GWC) with a 50% probability of smouldering ignition from Frandsen (1997). Similarly, the range in VWC of the surface of *S. fuscum* monoliths from the field moisture treatment ($0.07\text{--}0.265 \text{ m}^3 \text{ m}^{-3}$ or 644–855% GWC), which did not ignite, was well above the 50% ignition probability threshold, corresponding to an ignition probability of $\sim 4\%$ based on Frandsen's (1997) framework.

Combustion of fuels deeper in the peat monoliths, which received variable heat inputs via downward heat transfer, occurred across a wider range of moisture conditions (Fig. 4) than observed for the uppermost layer. Increased bulk density deeper in the peat column may increase the moisture threshold supporting combustion (Fig. 5). Successful combustion of peat fuels with a bulk density $< 40 \text{ kg m}^{-3}$ occurred at a maximum GWC of 187% ($0.066 \text{ m}^3 \text{ m}^{-3}$). However, when fuel bulk density was $> 40 \text{ kg m}^{-3}$, the maximum observed GWC to support successful combustion was 295% ($0.142 \text{ m}^3 \text{ m}^{-3}$) and all layers $> 40 \text{ kg m}^{-3}$ that received heat inputs were successfully burned (Fig. 5).

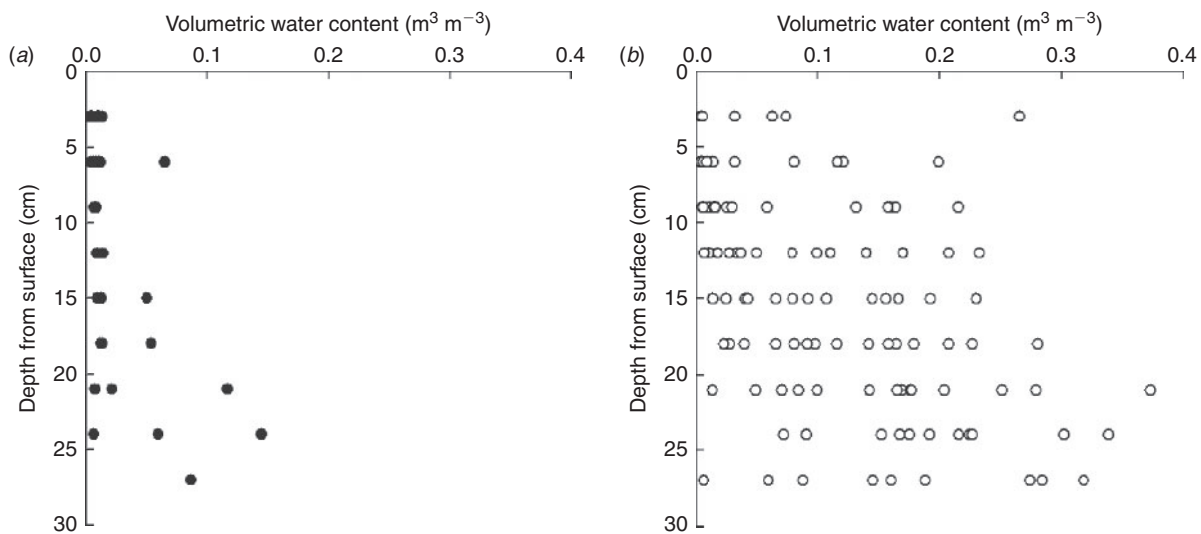


Fig. 4. Scattergrams of pre-burn volumetric water content with depth (3-cm peat layers) in the 18 monoliths. Closed symbols (a) correspond to fuel horizons that burned. Open symbols (b) correspond to horizons that did not burn, determined by the maximum depth of burn through the peat monolith. Values of depth from the surface represent the depth to the bottom of the 3-cm soil horizon.

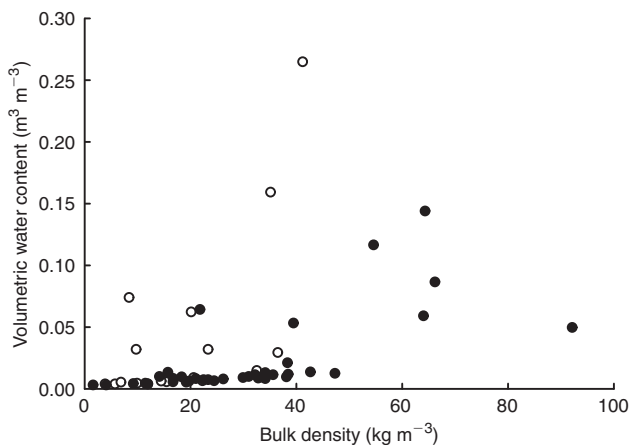


Fig. 5. Relationship between bulk density and volumetric water content of fuel horizons receiving heat inputs that burned ($n = 38$; closed circles) and those that did not burn ($n = 16$; open circles).

In situ temperature changes during the combustion trials from the thermocouple arrays coupled with distributions of fuel moisture and density further illustrate the interactive influence of these fuel characteristics on the downward extent of combustion. For example, in an oven-dried *Sphagnum fuscum* monolith with relatively uniform fuel condition profiles (Fig. 6a), smouldering combustion propagated downward and consumed the entire 27-cm peat column. Downward propagation slowed briefly between 60 and 100 min post ignition, most likely owing to increases in fuel bulk density in the coinciding 12–20-cm-depth horizons. During this period, smoke production was diminished and temperature change in the underlying 20-cm thermocouples was slower and more gradual than during combustion of the top 10 cm of the monolith. Downward propagation increased once these dense fuels were consumed, indicated

by temperature spikes ($>300^{\circ}\text{C}$) in the 5- and 10-cm thermocouples and increased smoke production coinciding with combustion of the fuels at the 20-cm thermocouple (115 min post ignition). Smouldering proceeded steadily until the remainder of the monolith was consumed.

Conversely, a *Sphagnum angustifolium* hollow monolith (Fig. 6b), which had greater bulk density and VWC and steeper gradients with depth relative to the *S. fuscum* monolith, did not support extensive combustion. The rapid increase in VWC with depth through the upper horizons (top 10 cm) was likely energetically limiting, impeding propagation of combustion through the monolith and resulting in a mean DOB of 8.0 ± 0.6 cm.

The combined effect of fuel bulk density and moisture on downward heat transfer may have influenced the depth of fuel combustion. For monoliths with successful ignitions, thermal diffusivity of the fuel horizon underlying the maximum DOB was significantly lower than for the adjacent burned fuel (paired $t_9 = 2.65$, $P = 0.027$), with a mean difference of $3.9 \times 10^{-4} \pm 4.7 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$. Overall, thermal diffusivity decreased with depth through the peat column ($F_{1,147} = 12.03$, $P < 0.001$, $r^2 = 0.08$). However, the change in thermal diffusivity at the terminal combustion interface was not significantly different than the gradient between successive burn horizons higher in the monolith ($F_{1,46} = 0.06$, $P = 0.81$), with almost complete overlap in the range of thermal diffusivities of burned horizons and unburned material at the terminal combustion interface.

Thermodynamic model accuracy

When compared with the observed results of the ignition trials, our model had 100% accuracy in predicting surface ignition of the monoliths. The model had 67% accuracy for predicting mean DOB for the 18 monoliths (Fig. 7). Accuracy was greater for *Sphagnum fuscum* hummock monoliths (83%) than feathermoss (67%) or hollow monoliths (50%). In one *S. fuscum*-dominated hummock monolith, the model overestimated DOB by 5 cm,

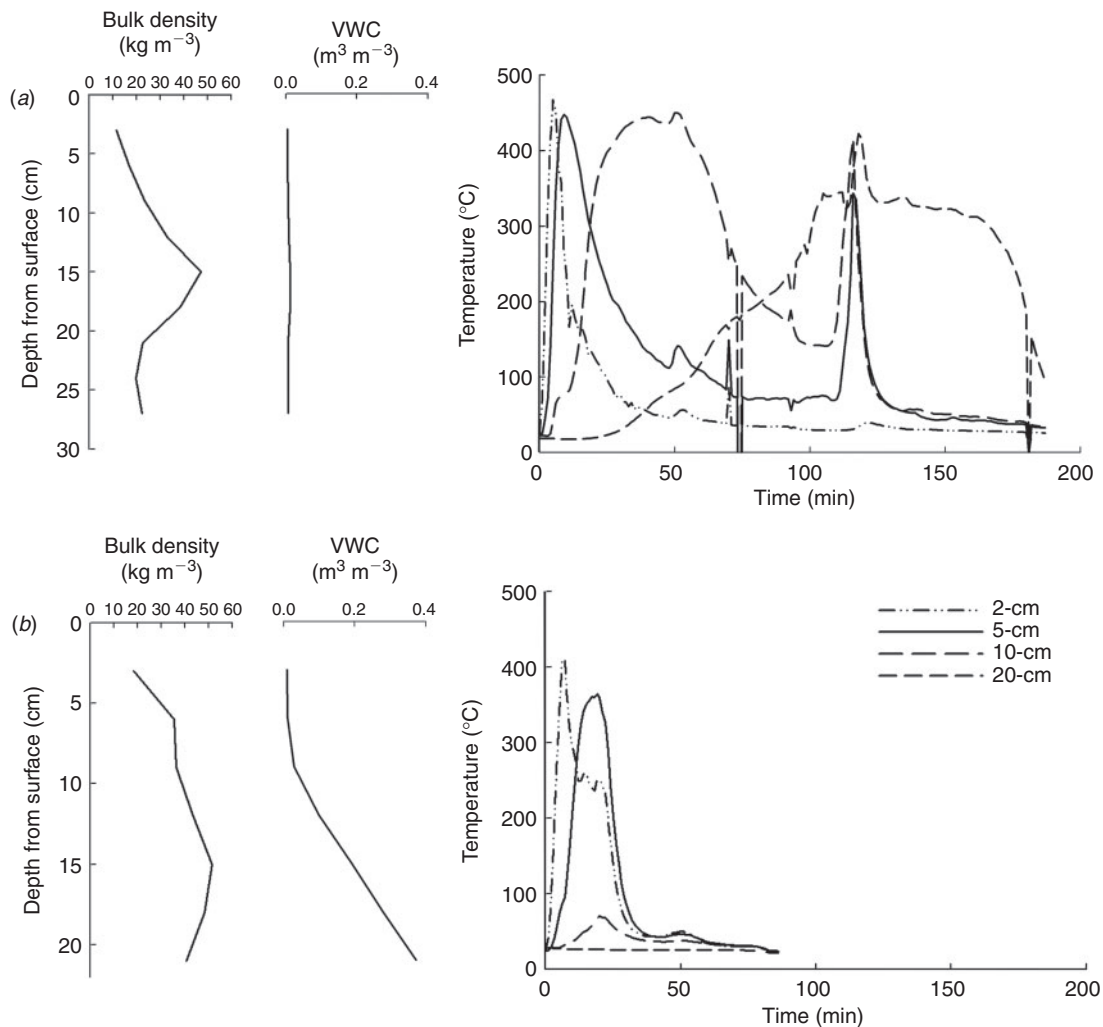


Fig. 6. From left to right, bulk density and volumetric water content (VWC) profiles with depth and temperature changes over time during combustion from two monoliths, including (a) an oven-dried *Sphagnum fuscum* hummock monolith, and (b) an oven-dried mixed-species hollow monolith. Temperatures are an average of measurements from four thermocouples inserted in each depth horizon (2, 5, 10 and 20 cm) from the surface of the monolith (legend corresponds to both graphs). Plots begin (time = 0) at the start of the 5-min ignition and continue until combustion ceased.

whereas DOB was underestimated in three hollow monoliths by 5, 6 and 15 cm (Fig. 7).

We carried out a sensitivity analysis of the downward efficiency parameter (ε) by conducting independent runs of our model using values of ε ranging from 0 to 1.0; optimal model performance was achieved when $\varepsilon = 0.17$ (Fig. 8). This value seemed realistic assuming the majority of energy emitted from an object should be transferred upward (through both convection and radiation) and laterally (through radiation and conduction). Measured and calculated fuel properties of individual fuel horizons as well as observed and modelled depth of burning are available in the Accessory publication (Table A1, see http://www.publish.csiro.au/?act=view_file&file_id=WF08183_AC.pdf).

Discussion

Our simple heat budget model uses a limited number of easily measured variables to project DOB in thick organic soils,

thereby providing a valuable tool for carbon cycle studies and fire management activities. The observed ranges of burn depth and associated combustion C losses observed in our experiment are comparable with field observations from wildfires in western Canadian peatlands (Turetsky and Wieder 2001; Turetsky *et al.* 2002; Benscoter and Wieder 2003) and Alaskan lowlands (Kasischke and Johnstone 2005; Kasischke *et al.* 2008; Shetler *et al.* 2008). Additionally, the experiment recreated the 'Sphagnum sheep' phenomenon commonly observed in burned peatlands and poorly drained lowland black spruce forests (Benscoter and Wieder 2003; Shetler *et al.* 2008), in which extensive combustion occurs in low-lying microtopographies (hollows or lawns) with little or no combustion on the elevated hummocks, thereby creating the 'Sphagnum sheep' and resulting in a high degree of spatial heterogeneity in depth of fuel consumption and post-fire microhabitat conditions. This pattern is most likely due to differences in ecophysiological characteristics of hummock and hollow species. Hummock species

(i.e. *S. fuscum*) form dense populations capable of maintaining consistent soil moistures even under drought stress (Rydin 1993). Hollow species form more loosely arranged populations that are more prone to water loss (Rydin 1993), resulting in

greater surface drying compared with hummocks under similar water stress. In our experiment, *S. fuscum* hummocks did not burn under field moisture conditions and did not burn substantially (>3 cm DOB) under air-drying conditions. Conversely, hollow monoliths showed substantial combustion under all three moisture treatments, suggesting a greater likelihood of burning compared with hummocks under uniform climatic conditions.

The influence of fuel moisture and bulk density on combustion observed in this study is consistent with previous studies using commercial milled peat (Frandsen 1987, 1991; Hartford 1989) or a variety of natural organic soils (Van Wagner 1972; Frandsen 1997; Lawson et al. 1997; Miyanishi and Johnson 2002; Reardon et al. 2007). Although several of these previous studies also found mineral content to influence organic soil combustion, very little variation in inorganic matter content is present within the Athabasca bog ($4.7 \pm 2.9\%$, $n = 127$, present study; $5.1 \pm 2.5\%$, $n = 552$, Benschoter et al. 2005b) or among western Canadian continental bogs ($5.9 \pm 5.2\%$, $n = 506$ from 145 bogs; Zoltai et al. 2000). Our results showed no predictive relationship of inorganic content with depth, suggesting inorganic content is not an important factor for predicting DOB in boreal bog soils. However, small but significant differences in inorganic content were found among fuel types, with hollows having greater inorganic content than *Sphagnum fuscum* or feathermoss hummocks. Reardon et al. (2007) found a positive relationship between wetland soil mineral content and smouldering combustion probability when total mineral content was less than 10%. Although the physical reason for this relationship is unknown, the greater average inorganic matter content of hollow peat may explain our model's underestimation of hollow peat consumption. However, future studies are needed to

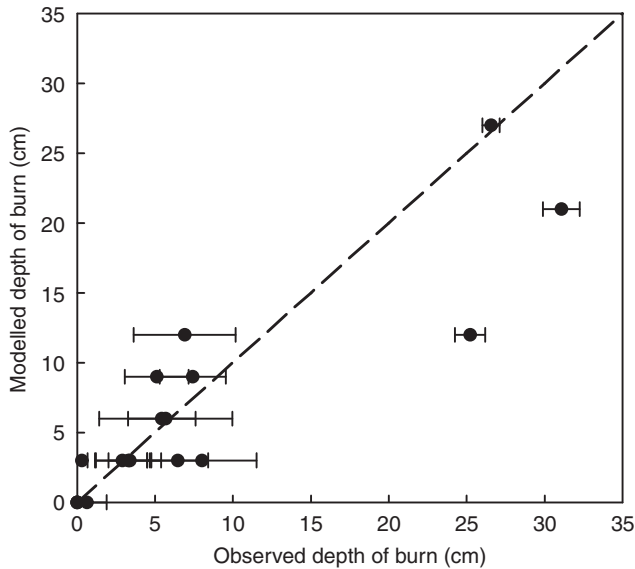


Fig. 7. Observed versus predicted depths of burn in the 18 peat monoliths. The symbols represent the mean observed depth of burn (\pm s.d.) of each monolith across the 48 grid points (described in Methods). The modelled depth of burn data represents the bottom of the lowermost fuel horizon predicted to combust by the model.

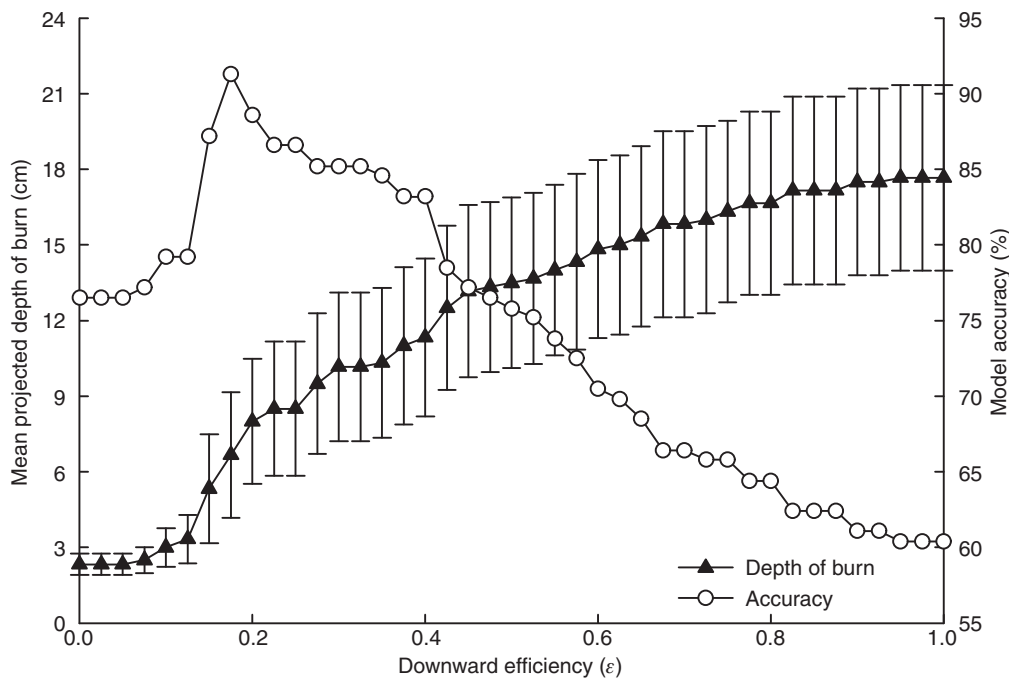


Fig. 8. Influence of the downward efficiency parameter (ϵ) on projected depth of burn (\pm s.d.) and model accuracy. Model accuracy reflects the percentage of the total number of fuel horizons for which the model correctly projected the occurrence or lack of combustion during the experimental combustion trials.

examine this relationship and to understand the potential mechanism controlling DOB.

We did not observe simple relationships between fuel moisture or bulk density and DOB, likely owing to the confounding effects between these fuel conditions. Changes in bulk density not only alter fuel loading but also affect the fuel moisture threshold supporting combustion (Fig. 5). In our combustion trials, we achieved successful combustion of fuel layers with soil moistures as high as 295% by dry mass, more than three times the published limit (93%) for milled *Sphagnum* peat (Frandsen 1987). This disparity may be due to the nature and arrangement of the fuels. Whereas Frandsen (1987) used discrete fuel beds of uniform soil moisture, our monoliths represent a continuous gradient of fuel conditions, potentially allowing the combustion front to gradually move through successive fuel horizons that would otherwise be unsuitable for ignition.

Thermodynamic constraints and the influence of depth-dependent variation in fuel condition on depth of surface fuel consumption were further supported by our modified energy budget model. The model performed well for the *Sphagnum* moss-derived fuels, which dominate thick organic soils throughout the boreal region. The model accurately predicted DOB for both successful (three) and unsuccessful ignitions (four) in all but one *Sphagnum* moss monolith (an oven-dried *S. fuscum* monolith), for which the model overestimated DOB by 3 cm. As *Sphagnum* mosses typically cover 50 to nearly 100% of the ground layer in boreal bogs and poorly drained black spruce forests (Vitt and Andrus 1977; Vitt 2000; Bisbee *et al.* 2001; Bond-Lamberty *et al.* 2004; Fenton and Bergeron 2006), the accuracy of the model for this fuel type makes it a valuable tool for assessing surface fuel consumption potential in many boreal ecosystems.

However, the model was less accurate for feathermoss or mixed-species hollow peat. Inaccuracy was largely due to underestimations of depth of burning in deep-burning samples (>10 cm DOB). This inaccuracy may be in part due to the fuel conditions and combustion characteristics found in the deeper portions of these soils. Feathermoss and mixed-species hollow peat columns exhibit greater and more rapid changes in bulk density and soil moisture with depth than *Sphagnum fuscum* peat (present study; Zoltai *et al.* 2000; Benscoter *et al.* 2005b), primarily owing to differences in decomposition and compaction rates among their dominant species (Benscoter *et al.* 2005b; Turetsky *et al.* 2008). Dense, moist fuel conditions coupled with greater mineral content may make hollow and feathermoss hummock fuels more conducive to smouldering combustion, although these potential effects could not be assessed in our experiments.

Although the downward heat transfer efficiency (ε) had an optimal value of 0.17 in our DOB model, values ranging from 0.15 to 0.4 maintained a reasonable degree of model accuracy (Fig. 8). The optimal value of ε , which captures the total downward heat transfer from the combustion zone (but which does not attempt to partition this energy transfer further to describe the actual mechanism), seemed reasonable given that the combustion interface would be radiating uniformly in all directions (thus limiting downward energy) and buoyant convection would be transferring significant heat from combustion upward into the surroundings. Data from Schneller and

Frandsen (1998) and Frandsen (1998) on fuel load and cumulative heat load transferred to an underlying calorimeter indicate a downward efficiency ranging from 0.3 to 0.9, with a mean (\pm s.d.) of 0.7 ± 0.1 . Smouldering, however, typically results in the deposition and accumulation of char and ash at the surface as combustion proceeds downward and laterally. Frandsen (1998) suggested this ash layer may have an insulating effect on radiant and convective heat loss, potentially causing a greater proportion of energy to be transferred downward to underlying fuel layers. It is uncertain if this insulating efficiency of deposited ash would exist in a natural setting where the combustion zone is subject to ambient winds, which could carry not only heat but ash away from the combustion interface.

Furthermore, Van Wagner (1972) found flame emissivity to vary with fuel moisture content for upland forest duff, suggesting similar relationships between fuel properties and heat movement may exist within variable thick organic soils. A dynamic downward efficiency term accounting for variability in fuel properties (e.g. bulk density, porosity, particle geometry) and combustion characteristics (i.e. flaming *v.* smouldering) may increase model accuracy. Similarly, other static parameters in our model, such as the heat of combustion, could potentially vary among fuel types. Future research will be required to examine these relationships and possibly develop more accurate parameter estimates.

Implications for wildland fire management

With current and predicted future increases in global wildfire activity, there are several practical fire management needs for a reliable fuel consumption and DOB model for thick organic soils. Although ~30% of the terrestrial C stock is stored in thick organic soils primarily in the boreal region (Gorham 1994), currently there is no operational fire management model to estimate potential surface fuel combustion C losses in ecosystems with such soils. Development of new models that predict surface fuel consumption in these ecosystems will have substantial influence on future forest C accounting procedures, development of climate-change adaptation strategies (e.g. adaptive fire management practices), and ultimately policy at several levels.

Not only do wildfires have an effect on C stocks and storage, the emissions generated can have immediate and far-reaching human health implications. Owing to their characteristic slow, incomplete combustion, smouldering fires lead to high levels of emissions of CO, CH₄ and other trace gases (Yokelson *et al.* 1999; Rein *et al.* 2009) and are associated with increased public health hazards such as high fine particulate matter and mercury emissions (Obriest *et al.* 2008). In northern communities with limited access, smoke from local fires often requires evacuation of residents with respiratory illness or other serious ailments. During serious smoke events, entire communities can be evacuated and long-term smouldering can lead to repeated or extended evacuations. These evacuations are costly, both economically and socially, and increase wildland fire management resource demands.

Additionally, smouldering of surface and deeper organic soil layers can last for several months, sometimes overwintering (Wein 1981). Deep-burning peat fires are extremely difficult to extinguish, requiring long-term commitment of suppression resources to 'mop-up' these fires. Even with sustained

suppression, peat fires can reignite after suppression activities have ended, resulting in costly redeployment of fire management resources (Frandsen 1987). Deep-burning peat fires generally occur during periods of extended drought when extreme burning conditions are generally occurring at a landscape scale and fire management resource needs are highest. Therefore, greater understanding of combustion potential in deep organic soils will provide a useful tool for informing wildland fire management decisions, allowing for more efficient and effective allocation of limited resources during periods of greatest demand.

Acknowledgements

We thank Ross Conner (Canadian Forest Service, Northern Forestry Centre) for laboratory assistance and the Northern Forestry Centre (Canadian Forest Service) for use of their indoor combustion facilities, as well as the associate editor and reviewers for their comments. Funding was provided by the National Aeronautics and Space Administration (NASA, grant NNG05GD25G) and Natural Sciences and Engineering Research Council of Canada (NSERC) Strategic Project grant.

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Manuscript received 29 October 2008, accepted 8 September 2010