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Evaluation of the composite burn index for assessing fire severity in Alaskan black spruce forests

Eric S. Kasischke[A,F], *Merritt R. Turetsky*[B,C], *Roger D. Ottmar*[D], *Nancy H. F. French*[E], *Elizabeth E. Hoy*[A] *and Evan S. Kane*[B]

[A]Department of Geography, University of Maryland, 2181 LeFrak Hall, College Park, MD 20742, USA.
[B]Departments of Plant Biology, and Fisheries & Wildlife, Michigan State University, East Lansing, MI 48824, USA.
[C]Present address: Department of Integrative Biology, University of Guelph, Guelph, ON, N1G 2W1, Canada.
[D]USDA Forest Service, Pacific Northwest Research Station, 400 N 34th St, Seattle, WA 98103, USA.
[E]Michigan Tech Research Institute, Michigan Technological University, 3600 Green Court, Suite 100, Ann Arbor, MI 48113-4001, USA.
[F]Corresponding author. Email: ekasisch@umd.edu

Abstract. We evaluated the utility of the composite burn index (CBI) for estimating fire severity in Alaskan black spruce forests by comparing data from 81 plots located in 2004 and 2005 fire events. We collected data to estimate the CBI and quantify crown damage, percent of trees standing after the fire, depth of the organic layer remaining after the fire, depth of burning in the surface organic layer (absolute and relative), and the substrate layer exposed by the fire. To estimate pre-fire organic layer depth, we collected data in 15 unburned stands to develop relationships between total organic layer depth and measures of the adventitious root depth above mineral soil and below the surface of the organic layer. We validated this algorithm using data collected in 17 burned stands where pre-fire organic layer depth had been measured. The average total CBI value in the black spruce stands was 2.46, with most of the variation a result of differences in the CBI observed for the substrate layer. While a quadratic equation using the substrate component of CBI was a relatively strong predictor of mineral soil exposure as a result of fire ($R^2 = 0.61$, $P < 0.0001$, $F = 60.3$), low correlations were found between the other measures of fire severity and the CBI ($R^2 = 0.00$–0.37). These results indicate that the CBI approach has limited potential for quantifying fire severity in these ecosystems, in particular organic layer consumption, which is an important factor to understand how ecosystems will respond to changing climate and fire regimes in northern regions.

Introduction

Fire is an important process in many ecosystems, particularly in boreal forests where burning represents a dominant form of disturbance (Wein and MacLean 1983; Goldammer and Furyaev 1996; Kasischke and Stocks 2000). Most area burned in the North American boreal forest is the result of natural processes, where lightning ignited fires accounted for 80 to 90% of the total area burned in the 1980s and 1990s (Stocks *et al.* 2002; Kasischke and Turetsky 2006). In response to recent climate change, average annual burned area across the North American boreal region doubled between the 1960s/70s and 1980s/90s. In addition, the amount of late season burning has substantially increased in western ecozones found in continental Canada and Alaska (Gillett *et al.* 2004; Kasischke and Turetsky 2006).

Recent changes in the North American fire regime have likely impacted several ecosystem processes. However, the exact nature of these effects depends on changes in fire frequency and fire type (e.g. ground, surface, or crown), which determines the intensity, rate of spread, and duration of burning. Together, these characteristics control the severity of the fire (e.g. the rate of tree mortality, the amount of aboveground biomass, dead woody debris and ground layer organic matter consumed during the fire, ash deposition, and changes to the soil hydrophobicity; Lentile *et al.* 2006). Quantifying fire severity is important to understand carbon and nutrient cycling and to predict how an ecosystem will change in response to a fire event (e.g. burn severity; Key and Benson 2006; Lentile *et al.* 2006).

A review of recent literature shows that while many studies have developed approaches to quantify fire and burn severity, most have focussed on measures that deal with a relatively narrow range of ecosystem types and fire-damage characteristics. Odion and Hanson (2006) used tree mortality to assess fire severity in conifer forests in the Sierra Nevada range of California. Keyser *et al.* (2006) measured crown and stem damage to assess factors that affect mortality in ponderosa pine stands. Knapp and Keeley (2006) evaluated how stand characteristics and site geomorphology influenced scorch height and percent of ground burned. Kemball *et al.* (2006), Jayen *et al.* (2006), and Greene *et al.* (2007) evaluated how exposure of mineral soil during fires affected seedling germination and survival in Canadian coniferous forests. Kasischke and Johnstone (2005) evaluated how depth of the remaining organic layer influenced post-fire

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soil temperature and moisture in Alaskan black spruce forests, while Johnstone and Kasischke (2005) evaluated how depth of the remaining organic layer affected tree recruitment and community structure. Finally, while Lewis *et al*. (2006) found that exposed mineral soil and litter cover were the best predictors of burn severity as measured by soil water repellency (hydrophobicity), Doerr *et al*. (2006) found that approaches to measure fire severity based on damage to vegetation were not useful in this regard.

Recognising the need for a systematic approach that could be applied in different regions across different ecosystems, the composite burn index (CBI) was developed as a method to visually estimate the ecological impacts of fire on forests (Key and Benson 2006). To generate the CBI metric, the degree of damage from the fire and the patterns of vegetation regrowth are rated on a scale of 0 to 3 for different characteristics in five strata or layers (substrate, low vegetation and shrubs, high shrubs, understorey trees, and overstorey trees). Because four strata address above ground vegetation, the average CBI value weighs changes to vegetation more heavily than changes to the ground and soil layers. While many of the factors used to estimate the CBI relate to fire severity, the observed changes in characteristics of vegetation regrowth represent measures of burn severity. In addition, since the CBI approach can be applied at different times after a fire, the values produced using this approach are time dependent.

The CBI approach was initially developed as a means to evaluate the use of the Normalized Burn Ratio (NBR), an index derived from Landsat satellite data (TM and ETM+) for mapping patterns of burn severity. The NBR is calculated using Band 4 (0.76 to 0.90 μm) and Band 7 (2.08 to 2.35 μm). While correlations between CBI and NBR, or change in NBR (dNBR), have demonstrated that this index has the potential to map fire severity using satellite data, this approach has not been independently validated for most regions (see French *et al*. 2008 for a review).

Here we evaluated the use of the CBI index to assess fire severity in black spruce (*Picea mariana* (Mill.) BSP) ecosystems, a dominant forest type across the North American boreal region. Specifically, we assessed the utility of the total CBI and the individual components of the CBI to estimate post-fire site characteristics that can be used to predict ecosystem responses to fire. We focussed on comparing the CBI to measures associated with vegetation damage and depth of burning of the surface organic layer.

Background – fire behaviour and fire effects in black spruce forests

The ericaceous shrubs found in the understorey of the open, mature black spruce stands in interior Alaska have a high content of volatile organic oils, which makes them highly flammable (Johnson 1992). As a result, surface fires can readily spread through these stands. As black spruce trees mature they do not shed their lower dead branches, which then provide ladder fuels to convey surface fires into the canopy, where the highly flammable needles and small branches are readily ignited. Through torching behaviour, this fuel matrix allows surface fires to spread upwards into the branches and foliage of individual black spruce trees, which frequently leads to the development of crown fires that propagate over large areas (10 000 to >100 000 ha) when weather conditions permit. Finally, during dry conditions the upper portion of the surface organic layer is sufficiently dry (<150% volumetric moisture; Ottmar and Baker 2007) to allow ignition and extensive smouldering combustion of the litter, moss, lichen, and organic soil lying on the ground surface.

Some coniferous tree species have thick bark that protects the tree from the lethal effects of fire; thus, fire severity is often measured through rates of tree mortality (Keyser *et al*. 2006; Odion and Hanson 2006). The thin bark of black spruce trees, however, does not protect the underlying phloem and xylem layers from damage during fires. As a result, even relatively low intensity surface fires have high enough temperatures to cause death, and the rate of tree mortality during fires in black spruce stands often approaches or reaches 100%. Because of this, canopy mortality is not a useful indicator of fire severity in black spruce forests.

Factors that can be used to assess fire severity in black spruce forests are summarised in Table 1. Factors that affect seed availability and dispersal can be used to assess fire severity as this attribute determines tree recruitment. Black spruce trees have semi-serotinous cones with openings that are accelerated by the heat from fires (Viereck 1983). The growth patterns of black spruce results in a mass of cones that form a dense sphere or spheroid 10 to 30 cm in diameter located at the top of the tree bole. Even during high intensity crown fires, only the outer layer of cones is scorched, with the inner-layers remaining undamaged. Given these characteristics, there is likely a minimum level of crown foliage consumption that is required to provide heat sufficient to open the canopy cones; however, high levels of crown consumption may reduce seed availability through burning of cones. The percentage of tree boles that remain standing after a fire can also be used as a measure of fire severity, as the positioning of the cone mass at the top of the crown is a characteristic that promotes an increase in the distance over which wind can disperse seeds (J. Johnstone, pers. comm., June 2007). Since the roots of black spruce trees in many stands grow in the organic soil layer, deep burning fires often remove all tree roots, which results in a large percentage of trees falling over, which in turn, will reduce the area of seed dispersal.

A key characteristic of fires in black spruce stands is the substantial burning of the deep organic layers common to these forests (Dyrness and Norum 1983; Swanson 1996; Kasischke *et al*. 2000; Harden *et al*. 2004, 2006; Kasischke and Johnstone 2005). Variation in the depth of burning in black spruce forests controls a variety of ecosystem processes. Many (if not most) plant species present in the understorey of black spruce ecosystems regenerate by vegetative reproduction (Zasada *et al*. 1983). Thus, even when severe ground fires kill all understorey vegetation and consume aboveground plant parts, post-fire shrub species' richness and diversity are unlikely to change unless there is a removal of plant propagules (roots, rhizomes, and plant stems) during fires that burn deeply into the surface organic layer (Johnstone and Kasischke 2005).

The depth of the organic layer has a strong control on soil temperature, where deeper organic layers are an important factor in the formation of permafrost in many physiographic settings. The presence of permafrost, in turn, influences site drainage by keeping soil moisture in the surface soil layers (Viereck 1983;

Table 1. Site characteristics used to quantify fire severity in black spruce forests and their possible effects on ecosystems

Post fire sites characteristic	Ecosystem/environmental effect
Tree canopy characteristics	
Level of consumption of canopy foliage and stems	Seed dispersal level
Percent of tree boles standing after the fire	Seed dispersal distance
Surface organic layer depth characteristics	
Depth of burning	Carbon emissions, loss of nutrients
Characteristics of exposed substrate (fibric, mesic, humic, or mineral soil)	Seedbed characteristics (seedling recruitment, survival and growth), propagule level for vegetative reproduction, water soil repellency
Relative depth of burning (percent reduction compared with pre-burn depth)	Changes in soil temperature and moisture, propagule level for vegetative reproduction
Organic and mineral soil physical and chemical characteristics	
Bulk density	Seedbed characteristics, water soil repellency, carbon storage and loss
Percent carbon	Carbon storage and loss
Nutrient content	Nutrient storage and loss
Ash deposition	Nutrient availability
Water repellency and infiltration rate	Soil water repellency

Slaughter and Viereck 1986; Yoshikawa *et al.* 2002). Removal of organic matter during fires increases soil temperature and reduces soil moisture in black spruce forests (Van Cleve and Viereck 1981). The magnitude of these effects is proportional to the depth of the organic layer that remains after the fire relative to the pre-fire organic layer depth (Kasischke and Johnstone 2005). Post-fire changes in soil temperature and moisture influence patterns of soil respiration (O'Neill *et al.* 2002; Bergner *et al.* 2004) and patterns of tree recruitment (Kasischke *et al.* 2007).

In black spruce forests with permafrost, the groundwater is disconnected from supplies of water that originate from the downward drainage of precipitation through surface layers of organic and mineral soils. When severe fires remove deep layers of surface organic matter, the ground often warms sufficiently to eliminate permafrost, and reconnects the flow of surface waters into ground water (Hinzman *et al.* 2006). However, variations in exposure of different soil layers as well as physical changes to the soil matrix also influence soil hydrophobicity (Doerr *et al.* 2006; Lewis *et al.* 2006), which in turn will influence surface runoff. To date, there have not been any soil water repellency studies or research on the effects of fire on erosion carried out in Alaska. Our own observations are that sediment loads in river and stream valleys do increase after fires.

Many plant species cannot germinate and grow on seedbeds that have a low bulk density because of low moisture holding capacity. Deep burning fires expose denser soil layers (humic and mineral soil) with higher moisture holding capacity, which allows more seedlings to survive and grow (compared with shallow-burning fires), which allows for the invasion of deciduous tree species (Landhausser and Wien 1993; Johnstone and Kasischke 2005; Jayen *et al.* 2006).

Finally, the depth of burning of the surface organic layer determines the amount of carbon and other nutrients that are either converted into trace gases or deposited in the form of ash. As a result, the amount of ground-layer biomass consumed during fires is an important factor that regulates carbon and other nutrient cycling.

Methods

Study area description

Hollingsworth *et al.* (2006) found that site conditions (primarily soil acidity and site drainage) control community composition of mature black spruce forests in Alaska, where open-canopy stands are much more common than closed-canopy forests. Our study was designed to include stands that were representative of the range of sites dominated by black spruce (Fig. 1). On the driest sites where soils are well drained, stands have low tree densities and shallow organic layer depths (<12 cm), with a mixture of lichens (*Cladonia* and *Cetraria* spp.) and feathermosses (*Hylocomium splendens* and *Pleurozium schrebri*) covering the ground surface (Fig. 1*a*). In sites with moderately well to somewhat poorly drained soils, the 16 to 24 cm-deep surface organic layer is covered by an almost continuous layer of feathermosses, which may contain some patches of *Sphagnum* spp. (Fig. 1*b*). In sites that are poorly to very poorly drained, deep organic layers (>32 cm) are typically associated with coverage of the ground surface being dominated by *Sphagnum* spp. (Fig. 1*c*).

The study was conducted using plots in burned black spruce forest stands from 11 separate fire events that occurred during 2004 and 2005 (Table 2). During these two years, 2.72×10^6 ha (2004) and 1.76×10^6 ha (2005) were affected by fire, which represents nearly 10% of the land surface below the tree line of the boreal forest ecozones in interior Alaska (Kasischke *et al.* 2002). These two years represent the highest and third highest burned areas recorded for Alaska since 1940. In addition to data collected in the burned plots, we also collected data in 15 unburned black spruce stands located near Fairbanks and Delta Junction and along the Taylor Highway.

CBI observations

We used the approach of Key and Benson (2006) to collect the observations necessary to calculate the CBI in 81 plots (Table 2) as part of a study to evaluate the utility of the dNBR approach to map fire severity in black spruce forests (Hoy *et al.* 2008). Our

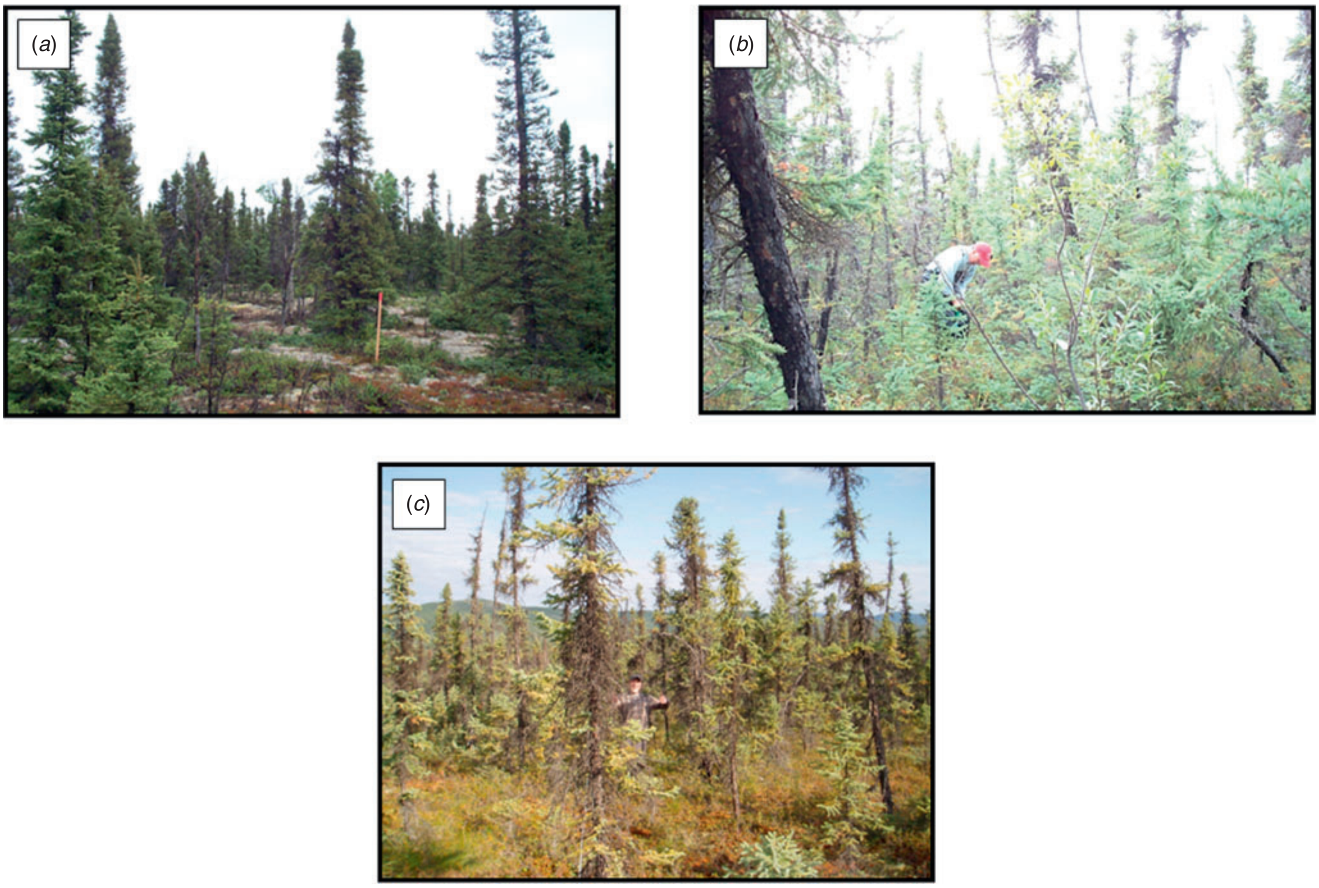


Fig. 1. Typical mature black spruce forests found in Interior Alaska: (*a*) black spruce–lichen woodland with a 10 cm-deep surface organic layer; (*b*) black spruce–feathermoss forest with a 24 cm-deep surface organic layer; and (*c*) black spruce–sphagnum moss forest with a 40 cm-deep surface organic layer.

approach differed from the Key and Benson (2006) method in that we focussed on a single forest type and did not select our sample plots according to variations in dNBR values derived from Landsat imagery. Instead, we stratified our plots according to factors that control depth of burning in black spruce forests, which include topography (Kane *et al.* 2007), site drainage characteristics, and timing of the fire during the growing season. Plots were also chosen to represent the range of fire severity observed within the 2004 and 2005 fires (Fig. 2).

In conjunction with scientists (from the USA Bureau of Land Management, USA National Park Service, USA Fish and Wildlife Service, and the University of Alaska) who were also evaluating the use of the dNBR/CBI approach to map fire severity in Alaska, the CBI field data sheet (and therefore the approach) of Key and Benson (2006) was modified to account for factors unique to Alaskan forests. The changes made to the form included: (*a*) location data were recorded in latitude and longitude using the WGS84 baseline datum; (*b*) elevation was recorded for each site; (*c*) a 10-m radius plot was used for both overstorey and understorey observations; (*d*) the height range for Stratum C (tall shrubs and trees) was changed from 1–5 m to 1–2 m; (*e*) the height range for Stratum D (intermediate trees) was changed from 8–20 m to 2–8 m; (*f*) the height range for Stratum E (big trees) was changed from >20 to >8 m; and (*g*) the strata rating factors for the substrates category were changed as follows: (1) the litter/light fuel consumed was changed to litter/grass/1 h fuel consumed; (2) medium fuel, 7.6–20.3 cm (3–8 inches) was changed to medium fuel, 7.6–20.3 cm or tussocks basal area; and (3) soil and rock cover/colour was changed to exposed mineral soil cover. In all of the plots sampled, only one plot contained canopy and sub-canopy trees; therefore, data were not collected for Stratum E in most plots. In our study, we used four CBI strata: substrate, low vegetation, shrub, and canopy tree (combining Strata D and E).

The majority of CBI plot data were collected in June, July, and August of 2005 (the growing season that followed the 2004 fires and within six weeks of the 2005 fires), with data for one plot collected in June 2006. Upon selecting a candidate study area, we conducted a reconnaissance to identify a $100 \times 100\text{-m}^2$ (1 ha) area that was homogeneous in terms of stand density, tree height, and fire severity. A stake was placed in the centre of this homogenous area, which also marked the centre of the plot used to collect measurements of fire severity. This step was taken to ensure that the site was representative of an area that was large enough to be observed by the Landsat satellite, which has a $30 \times 30\text{-m}^2$ pixel size. In addition to making the observations and ratings required to obtain data for the CBI worksheets, we collected a set of field photographs in the four cardinal directions looking outwards from or inwards to the plot centre, plus one photograph of the ground surface at the centre of the plot. We

Table 2. Summary of fire events and number of burned plots used in this study

Year	Fire/study area name	Event #	Fire size (ha)[A]	Number of plots	Stand age (avg. ± s.d.)[B]
Fire severity plots					
2004	Bolgen Creek	424	79 000	3	87 ± 9
2004	Boundary	193	217 000	28	120 ± 10
2004	Dall City	384	169 000	7	96 ± 6
2004	Porcupine	293	115 000	27	106 ± 8
2004	Tors	477	13 000	13	117 ± 15
2005	Chapman Creek	164	66 000	1	80
2005	North Bonanza	272	77 000	2	78 ± 24
Total plots				81	
Organic layer depth algorithm development plots					
na	Delta Junction	na	na	12	158 ± 26
na	Fairbanks	na	na	2	na
na	Taylor Highway	na	na	1	80
Total plots				15	
Organic layer depth validation plots[B]					
2004	Kings Creek	307	16 800	2	n/c
2004	Porcupine	293	115 000	14	n/c
2004	Wall Street	303	46 000	1	n/c
Total plots				17	

[A] Includes area within burn perimeter and does not account for unburned islands within the perimeter.
[B] n/c indicates no data collected.

also recorded the slope and aspect of the site. Finally, we cut a 2–4 cm-thick disc from the base of two canopy trees and counted the tree rings to estimate stand age when the stand burned.

Measurement of tree canopy characteristics

Our field surveys in the 2004 fires as well as those from other years showed that most of the area burned in black spruce forests was the result of stand-replacing crown fires that also consume most ground layer vegetation (Fig. 2). Only at the edge of fires or within small unburned islands did we encounter situations where herbs and foliage and small and large branches of low and tall shrubs were not consumed during fires. Because of this, we focussed our efforts on collecting detailed data on fire severity for canopy trees only.

Tree canopy characteristics were collected in the same 81 plots where CBI data were obtained. For most plots, these additional data were collected at the same time the CBI observations were collected. The exception was in the Tors fire event, where for some of the plots the CBI data were collected in July/August of 2005 and the additional fire severity observations (8 plots) were collected in June 2006. A 40 m-long baseline was established in a random direction at the centre of the plot. This baseline bisected three 30-m sample transects, one located at the plot centre and on each side of the centre at a random distance between 5 and 20 m from centre (to avoid resampling the area covered by the centre transect).

We sampled each black spruce tree that was within ±1 m of the three sample transects. For each tree bole, we measured the basal diameter, noted when a tree bole was not standing because its roots had been consumed during the fire, and assigned a rating that quantified the degree of canopy consumption based on a scale from 0 to 6, as follows: (0) No tree mortality with no needles or branches consumed; (1) tree deceased with no needles branches consumed; (2) tree deceased with all needles and some secondary and tertiary branches consumed; (3) tree deceased with all needles and tertiary branches consumed, few secondary branches remain; (4) tree deceased with all needles, tertiary, and secondary branches consumed, >30% of primary branches remaining; (5) tree deceased with all needles, tertiary, and secondary branches consumed, <30% of primary branches remaining; and (6) tree deceased with all needles and branches consumed, bole charring present.

Measurement of ground-layer characteristics

Ground-layer data were collected in the same 81 plots used to sample CBI and aboveground fire severity characteristics. Data collection points were located every 5 m along each sample transect established for the tree severity observations, as well as every 10 m along the baseline (at 5, 15, 25, and 35 m). At each of the 25 sample points, we extracted a 20 × 20-cm^2 core of the surface organic layer using a flat-bladed shovel. We measured the total depth of the organic layer above the mineral soil along with the depth of each organic layer (live/dead moss, and fibric, mesic, and humic soil) following Harden *et al.* (2004). We identified the closest black spruce tree >2 m in height to each point along each sample transect (21 total), and measured the distance of the topmost adventitious root above the mineral soil (AR_d). These data were used to estimate the depth of the surface organic layer using the methods described in the following section.

To quantify burn severity in the ground layer, four variables were calculated: (*a*) the average depth of the remaining organic layer; (*b*) total depth reduction of the organic layer; (*c*) relative depth reduction (total depth reduction divided by pre-fire depth) of the surface organic layer; and (*d*) the percentage of soil organic layer measurements where the entire organic layer was consumed to expose mineral soil. This measure is indicative of the overall severity of the burn as determined by the fraction of sites that can potentially be invaded by deciduous tree species.

Estimating pre-fire surface organic layer depth from measures of adventitious roots

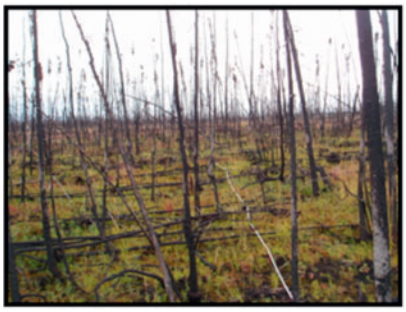
Previous studies have shown that adventitious root characteristics might allow for assessment of pre-burn soil organic soil depths and thus could form the basis for a new approach to assess soil organic matter consumption during fire activity (Kasischke and Johnstone 2005). Black spruce trees develop adventitious roots in response to the cold wet conditions that occur in sites underlain by permafrost (LeBarron 1945; DesRochers and Gagnon 1997). As black spruce stands mature, organic soil layers become deeper and active layer thicknesses increase. These soil climate conditions cause basal roots to be in frozen soil for much or all of the growing season. Under such conditions, black spruce trees form adventitious roots above the basal roots to obtain water and nutrients (Fig. 3*a*). Remnants of adventitious roots remain after fire (Fig. 3*b*), and the distance from the tops of these roots to the mineral soil can be easily measured.

We assessed the depth of adventitious roots beneath the surface of the organic layer in relation to total organic soil thickness using data obtained from plots located in 15 Alaskan unburned

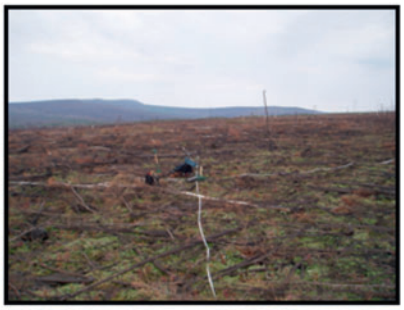
Low severity
CBI = 1.60

CBI = 2.02

Moderate severity
CBI = 2.58



CBI = 2.85



High severity
CBI = 2.98

	CBI values			
	Substrate	Low veg.	Shrubs	Trees
Low	0.73	1.12	2.08	2.50
	1.00	2.33	2.50	2.26
Moderate	1.63	2.80	2.88	3.00
	2.50	2.90	3.00	3.00
High	3.00	2.90	3.00	3.00

Fig. 2. Variations in fire severity and associated CBI values in Alaskan black spruce forests from the sites sampled for this study.

black spruce stands. Twelve plots were from stands near Delta Junction, two plots were near Fairbanks, and one plot was located along the Taylor Highway (previously studied by Kane *et al.* 2005). The plots were located in mature black spruce stands that originated in fires that occurred between 1695 and 1910 in sites that had shallow, moderately deep, and deep surface organic layers (the photos in Fig. 1 were collected in three of the stands used in this study). For the 12 Delta Junction sites, we used data reported in Kasischke and Johnstone (2005), where the organic soil horizon thickness was measured at 40 points within the plots.

At all sites, we quantified site-level variability in adventitious root depths by (1) establishing a 40-m baseline transect in a random direction, (2) establishing sample transects 30 m in length at the centre of the baseline transect and at random distances on either side of the centre transect between 5 and 20 m, and (3) identifying the nearest living black spruce tree >2 m in height every 5 m along each transect and measuring basal diameter and the distance of the upper-most adventitious root to the surface of the organic soil layer. We extracted a $20 \times 20\text{-cm}^2$ profile of organic soil layers to the mineral soil transition with a shovel or saw near each sampled black spruce tree and measured the depths of duff layers. At the Fairbanks and Taylor Highway sites only, we also measured the depths of the duff layers at each point along the sample transect, as well as at four points along the baseline to calculate the total organic layer depth throughout the plot.

To evaluate the ability of using measurements that use adventitious roots to estimate total organic layer depth, we collected data in 17 plots where both pre-fire and post-fire depth measurements were available (Table 2): (*a*) data for one plot located along the Taylor Highway in the Porcupine fire event where organic layer depth measurements were collected in 2002 by Kane *et al.* (2005); and (*b*) data from 16 plots measured by the US Forest Service (USFS). In 2004, USFS researchers located sites in front of advancing fires, including the Porcupine, Wall Street, and Kings Creek fire events (Ottmar and Baker 2007). At each site, USFS crew members placed between 9 and 18 plots along two parallel transects, with each plot separated by ~1 chain (66 ft or 20.1 m). At the centre of each plot, two 4-m sample transects were laid out perpendicular to one another. A 30-cm metal pin was established every 0.5 m along each sample transect ($n = 16$).

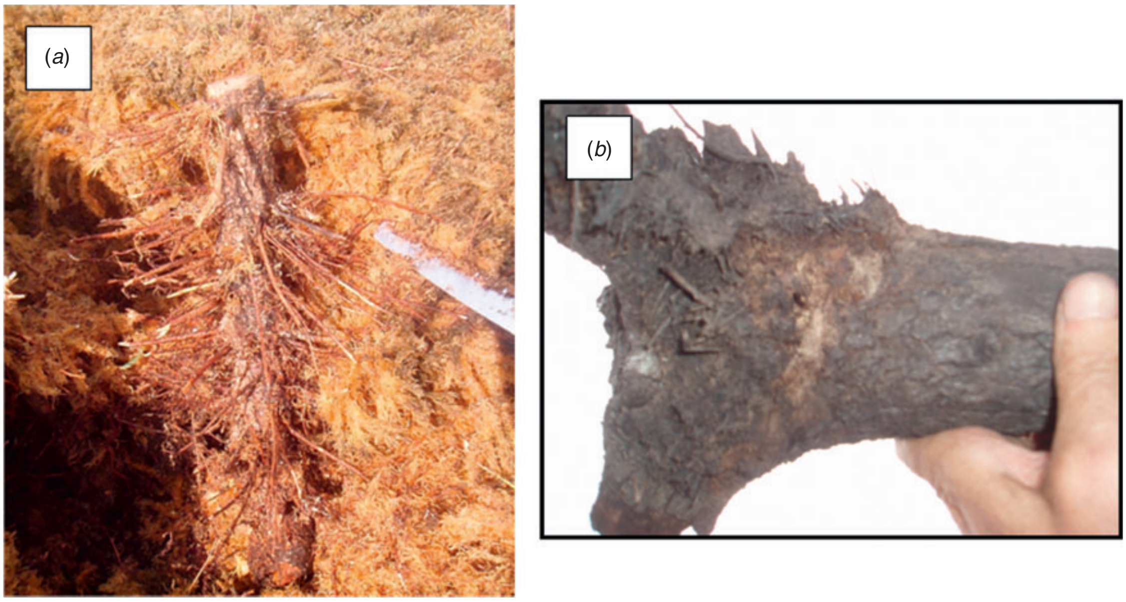


Fig. 3. Photographs of adventitious roots found on the base of burned black spruce trunks. (*a*) The trunk of a black spruce tree in a singed sphagnum hummock with the unburned adventitious roots exposed. (*b*) The trunk of a burned black spruce tree with remnants of adventitious roots.

These pins were used to identify the locations for measuring the pre- and post-fire surface organic layer depths. The depths of the upper duff (moss, lichen, and fibric soil) and lower duff (mesic and fibric soil) layers were measured at sampling points offset by 0.5 m from the end of each sample transect ($n = 4$).

In 2006, we returned to the USFS and Kane *et al.* (2005) stands that burned during the 2004 fires. We used the same sampling approach described previously to measure the depth of the adventitious roots above mineral soil. We were able to collect data two years following the fire because black spruce trees are resistant to decomposition and the burned adventitious roots could still be identified (note: Kasischke and Johnstone (2005) measured adventitious roots on burned black spruce trees in sites that had burned eight years previous to their study). Several of our sites were well drained stands with shallow soil organic layers and thus lacked adventitious roots. In these sites, we measured the distance from the top of the basal root to mineral soil.

Analytical methods

We used linear correlation to examine the relationships between total CBI and CBI from the individual stratum. We used linear and quadratic regression to examine the relationship between the different fire severity measures, in particular to assess the potential of using the total CBI and its components as predictors for the other fire severity parameters. We compared total CBI to all surface measures of fire severity, canopy tree CBI to the canopy damage rating and % trees standing, and substrate CBI to % canopy trees standing, post-fire organic layer depth, absolute depth reduction, relative depth reduction, and the percentage of sites with exposed mineral soil.

To analyse the relationships between organic layer depths and distance of the adventitious root above mineral soil, we used split-sample validation to explore the relationship between the depth of organic soil layers and the depth of adventitious roots in stands. Two relationships were explored: (1) the distance of the adventitious root above mineral soil ($\mathrm{AR_d}$) and the total organic layer depth ($\mathrm{OL_d}$); and (2) the distance of the adventitious root above mineral soil and the distance of the adventitious root below the organic layer surface ($\mathrm{AR_s}$). The relationship between organic soil depth and adventitious root depth at the unburned stands was validated using the USFS dataset obtained from the burned stands.

All analyses were performed in SAS; data reported represent means ± one standard error.

Results

Estimating pre-fire surface organic layer depths

Our unburned black spruce stands used to evaluate the relationship between adventitious roots and organic layer depth represent the range of surface organic layer depths and soil drainage classes typically found in interior Alaska (Fig. 1), with organic soil depths at plot centre ranging from 9.6 ± 0.9 cm to 37.6 ± 1.7 cm. The average depth of the organic layer at the centre of the plot (22.7 ± 2.2 cm) was not significantly different to the organic layer depth at the tree (21.7 ± 2.2 cm; paired *t*-test, $P = 0.33$, d.f. = 80). Across unburned sites, the uppermost adventitious roots were situated 5.1 ± 0.2 cm beneath the top of the surface organic layer and 16.6 ± 0.7 cm above the mineral soil.

The distance of adventitious roots above the mineral soil surface was positively related to total organic soil layer thickness (Fig. 4*a*), which suggests that the position of adventitious roots moves upward with organic soils as they aggrade over time. However, while the distance of the adventitious root below the surface of the organic layer increased in shallower organic layer profiles, it appears a maximum distance below the organic surface is eventually reached (Fig. 4*b*). Visual observation of the residuals from the relationships in Fig. 4 showed no evidence of non-linearities.

The depth of the adventitious root below the surface of the organic layer (Fig. 4*b*, method 2) was a better predictor of total organic layer depth than the depth of the adventitious root above the mineral soil (Fig. 4*a*, method 1). The average depth of the surface organic layer in our validation plots was 15.9 ± 1.3 cm, compared with the predicted depths of 19.7 ± 0.9 cm using method 1 and 18.1 ± 1.4 cm using method 2. The RMS error was lower for method 2 (3.2 cm) compared with method 1 (4.6 cm). Finally, the slope of the regression equation of predicted *v.* observed was not significantly different than 1.0 for method 2, but was significantly different than 1.0 for method 1 (Table 3). For these reasons, we used method 2 to estimate unburned organic layer depths in evaluating approaches to assess fire severity.

Burned stand characteristics

The stands used in the burn severity study averaged 110 ± 5 years in age, with a range from 56 to 210 years. Within the individual burns, the stand age ranged between 78 ± 24 years and 120 ± 10 years in age. The average estimated pre-burn organic layer depth for these stands was 29.9 ± 0.8 cm, and ranged between 15.4 ± 1.3 cm and 46.1 ± 1.2 cm. Across sites, the average depth of the organic layer in the burned stands was 10.3 ± 0.7 cm, and ranged from 0.04 ± 0.02 cm to 30.6 ± 2.3 cm. Fires reduced the organic layer depth by 67 ± 2.1% (19.6 cm). Across sites, 15.4 ± 2.9% of the measurements of the depth of the surface organic layers reached mineral soil. The average canopy damage rating was 3.45 ± 0.14. A large majority of trees (83.3 ± 3.4%) remained standing after the fires.

The total CBI from our sites averaged 2.46 ± 0.04 and ranged from 1.34 to 2.99. Black spruce stands that experienced moderate (which is the average based on CBI) fire severity (Fig. 2) corresponded to the following general characteristics: (*a*) all the low lying shrubs and vegetation as well as the foliage and most stems of shrubs were consumed by the fires; (*b*) all foliage and a significant fraction (>50%) of the stems of canopy trees were consumed, with all boles exhibiting significant charring; and (*c*) >90% of the organic layer atop the mineral soil was charred,

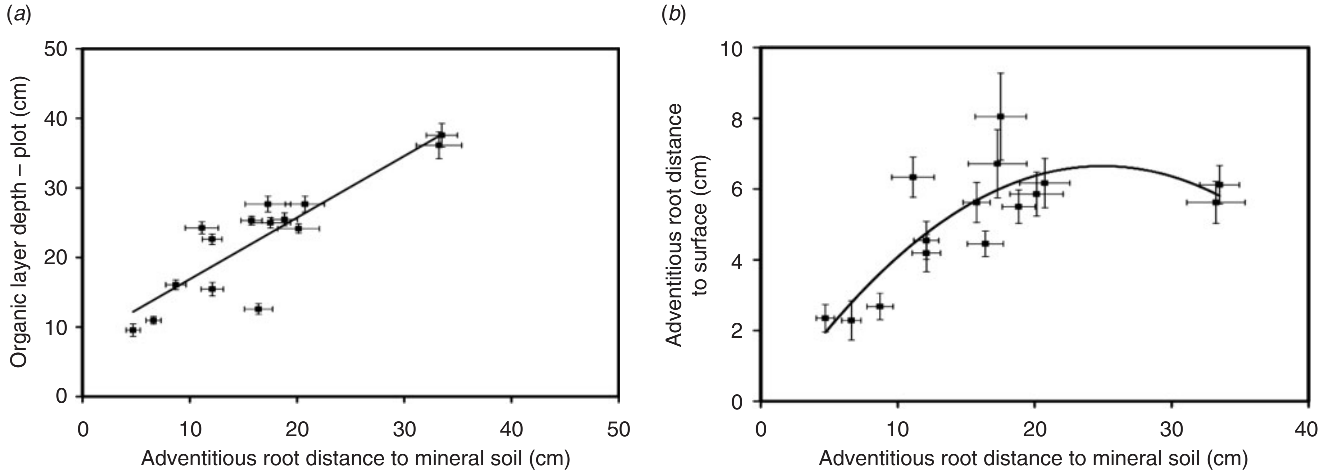


Fig. 4. Relationships between the depth of the adventitious root above mineral soil and the depth of the surface organic layer and the distance of the adventitious root below the surface of the organic layer. Error bars represent ± s.e. (*a*) OL_d as a linear function of AR_d [model $P < 0.0001$; adjusted $R^2 = 0.76$; intercept = 8.01 ± 2.43 ($P = 0.006$; confidence interval = 2.74 to 13.27); coefficient = 0.89 ± 0.13 ($P < 0.0001$; confidence interval = 0.60 to 1.17)]. (*b*) AR_s as a quadratic function of AR_d [model $P = 0.0012$; adjusted $R^2 = 0.62$; intercept = −0.51 ± 1.22 ($P = 0.68$; confidence interval = −3.17 to 2.15); coefficient for $AR_d = 0.57 \pm 14$ ($P = 0.0013$; confidence interval = 0.28 to 0.87); coefficient for $AR_d^2 = -0.0115$ ($P = 0.0052$; confidence interval = −0.0188 to −0.0041)].

Table 3. Validation of organic layer depth prediction algorithms based on measurement of adventitious root characteristics

Validation was based on regression of predicted organic layer depths as a function of observed organic layer depths. The regression model and regression coefficients and intercepts were all significant at $P < 0.0001$, with the exception of the intercept for method 2, where $P = 0.11$

Validation	Average unburned depth ± s.e. (cm)	RMS error (cm)	Regression model statistics					
			R^2	*F*-value	Coefficient ± s.e.	95% CI	Intercept ± s.e.	95% CI
Validation plots	15.9 ± 1.3							
Method 1 – Prediction using depth of the adventitious root above mineral soil	19.7 ± 0.9	4.6	0.81	65.4	0.64 ± 0.08	±0.17	9.5 ± 1.3	±2.9
Method 2 – Prediction using depth of the adventitious root below the surface of the organic layer	18.1 ± 1.4	3.2	0.81	64.8	0.93 ± 0.12	±0.25	3.4 ± 1.9	±4.1

with a 30 to 50% reduction in the depth of the total surface organic layer. The primary difference between stands that experienced moderate and severe fire severity with the depth of burning of the surface organic layer. The average organic layer depths that remained after fire in moderately burned sites were between 10 and 20 cm, depending on the depth of the pre-fire surface organic layer. Severely burned plots had between <0.1 and 4.0 cm of organic matter remaining after fire, which represents an 80–100% reduction. Our classifications of low, moderate, and high burn severity for black spruce forests differ significantly from those presented by Lentile *et al.* (2006; see Fig. 1), with our low severity classification matching the moderate severity classification of Lentile *et al.* (2006), and our moderately severe classification matching the severe classification of Lentile *et al.* (2006).

Most of the variability in the total CBI across our sites was a result of the CBI values from the substrate strata, where substrate CBI values averaged 1.76 ± 0.06 and ranged from 0.56 to 3.00. Total CBI and values from the individual stratum were positively related ($r = 0.76$ to 0.91, $P < 0.0001$) (Table 4). While the CBI from the different strata were positively related, their correlations were not as strong as with the total CBI (Table 4).

Comparison of fire severity measures

Overall, we found very low correlations between total CBI, substrate CBI and tree canopy CBI, and the other measures of fire severity collected in the burned black spruce stands (Table 5, Fig. 5). The total CBI and canopy tree CBI explained 36–37% of the variation in the average canopy damage rating (Fig. 5*a*). The substrate CBI explained only 35% of the variation of the percent of standing trees (Fig. 5*b*). While the substrate CBI had greater potential for predicting the organic layer depth following the fire compared with total CBI, this variable only explained 35% of the variation in the dependent variable (Fig. 5*c*). The substrate CBI only explained 6% of the variation in absolute reduction in depth of the surface organic layers by fire (Fig. 5*d*), which increased to 34% for relative depth reduction (Fig. 5*e*). Finally, a quadratic relationship for substrate CBI explained 61% of the variation in the percent of observations where mineral soil was present in the burned stands, which indicates there is some potential for using substrate CBI to estimate this fire severity parameter. This result is not surprising since we modified the criteria used in estimating substrate CBI to include an observation related to exposure of mineral soil in black spruce forests. This single factor explained 61% of the variation in the substrate CBI.

Table 4. Linear correlation (r) between total CBI and the individual CBI stratum

The correlations were all significant at $P < 0.0001$

Correlation	Substrate	Low vegetation	Shrub	Canopy tree
Substrate				
Low vegetation	0.63			
Shrub	0.61	0.75		
Canopy tree	0.44	0.66	0.54	
Total	0.84	0.91	0.84	0.76

Discussion and conclusions

To date, the focus on using the CBI has been to provide a basis for calibrating satellite observations of burn severity (Key and Benson 2006), with the CBI being used to define thresholds when using multispectral satellite data to generate burn or fire severity maps. However, one must realise that the CBI is a unitless measure of severity, unlike most field-based measurements that have been developed to quantify fire severity, including those we collected for this study. Those promoting the NBR/CBI approach for satellite mapping of fire and burn severity have assumed that the relative ratings of damage used to estimate CBI can be scaled against specific measures of burn or fire severity. This was the approach we adopted for the canopy severity rating, which can be directly correlated with the fractions of canopy biomass that are consumed during fires, and therefore can be used to estimate biomass/carbon consumption of trees during fires (see, e.g. Kasischke *et al.* 2000).

We found that the total CBI was not well correlated with specific measures of fire severity in Alaskan black spruce forests that can be used to either quantify specific changes that result from fire (e.g. biomass/carbon consumption) or predict ecosystem responses to the damage inflicted by burning (changes in soil temperature and moisture, changes in species composition, the likelihood of invasion of deciduous tree species). For the most

Table 5. Summary of linear regression model outputs for fire severity characteristics as a function of the composite burn index (CBI)

Dependent variable	Independent variable											
	Total CBI				Canopy tree CBI				Substrate CBI			
	Adj. R^2	s.e.	F-value	P	Adj. R^2	s.e.	F-value	P	Adj. R^2	s.e.	F-value	P
Linear regression												
Canopy damage rating	0.37	1.0	46.99	<0.0001	0.36	1.0	46.84	<0.0001				
% standing trees	0.10	28.9	9.94	0.0023					0.35	24.5	44.37	<0.0001
Organic layer depth	0.26	6.0	28.96	<0.0001					0.35	0.6	44.45	<0.0001
Absolute depth Reduction									0.06	6.3	5.17	0.028
Relative depth reduction	0.18	16.8	19.09	<0.0001					0.34	15.1	42.40	<0.0001
Percent mineral soil exposed	0.15	24.3	14.76	0.0002					0.41	20.2	57.03	<0.0001
Quadratic regression												
Percent mineral soil exposed									0.61	16.4	60.29	<0.0001

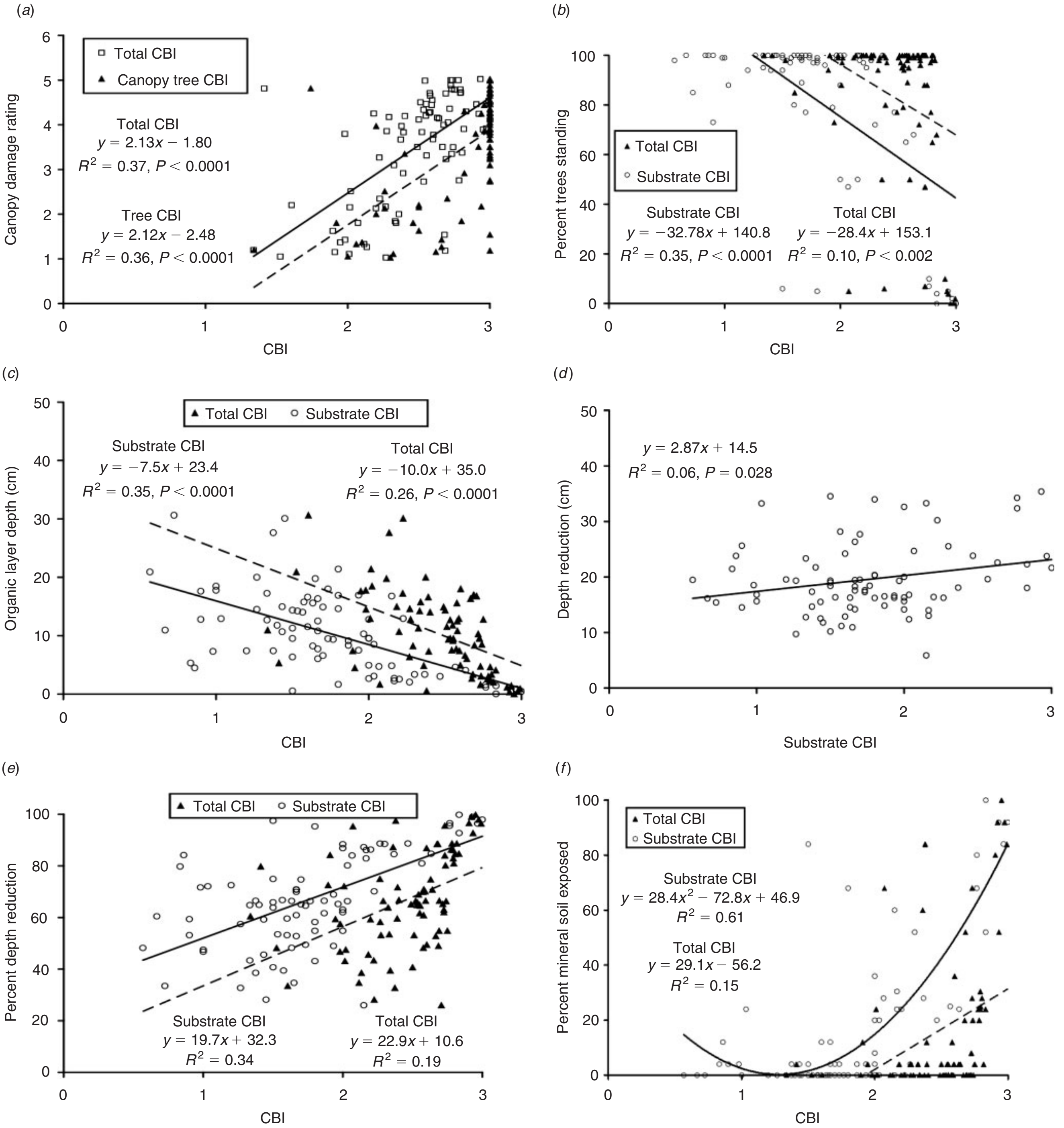


Fig. 5. Plots of the relationship between total CBI, canopy tree CBI, and substrate CBI and the different measures of fire severity derived from field observations. In these plots, the best-fit line for the total CBI are presented as dashed lines, while those for canopy tree CBI and substrate CBI are solid lines. We only present the plots where significant relationships were found (Table 5). (*a*) Canopy damage rating as a function of the total CBI and canopy tree CBI. (*b*) Percentage of trees standing as a function of total CBI and substrate CBI. (*c*) Organic layer depth as a function of the total CBI and substrate CBI. (*d*) Depth reduction as a function of substrate CBI. (*e*) Percentage depth reduction as a function of total CBI and substrate CBI. (*f*) Percentage mineral soil exposed as a function of total CBI and substrate CBI.

part, we found better relationships between field fire severity measures and CBI values derived for individual stratum (Table 5, Fig. 5). Generally, these relationships were still weak, with the exception of the relationship between the percent mineral soil exposed and substrate CBI (Fig. 5*f*). These weak correlations indicate that for the most part, CBI observations made for the individual stratum have little or no potential for estimating factors that are important to estimate fire severity in black spruce forests. Our results indicate that even if strong correlations are found between CBI and the satellite-derived indices, the maps generated using such correlations would be difficult to interpret with respect to predicting how black spruce forest ecosystems will respond to variations in fire severity.

The effectiveness of CBI to assess fire severity in black spruce forests is limited in two important areas. First, the CBI criteria do not adequately address variations in the level of consumption of crown biomass during fires. Since a high fraction of the burned area in black spruce forests occurs during crown fires, variations in crown fuel consumption is an important characteristic for assessing fire severity. Variations in crown fuel consumption are related to consumption of and damage to the serotinous cones found at the peak of the tree canopy, and hence influence availability of seeds for reproduction. Second, the CBI criteria do not adequately account for many of the important variations in burning of the deep surface organic layer that is present in most black spruce forests, which includes the amount of organic matter that remains after a fire, the amount of organic matter consumed during a fire, and the substrate layer exposed by the fire. These characteristics are extremely important in determining how black spruce forests will respond to the impacts of fire.

The validation of an approach to use measurements of adventitious roots to estimate pre-burn organic layer depths was the key to our ability to assess ground-layer fire severity in burned black spruce stands. This approach offers the ability to better quantify organic soil depths that were present at a site before the most recent fire activity, and thus will improve the ability to assess relative depth of burning and quantify rates of duff and carbon consumption in northern regions.

One should not assume that the results for using CBI to assess fire severity from our study in the boreal forest extend to other biomes and regions. The CBI was initially developed to assess variations in fire and burn severity in western USA pine forests (Key and Benson 2006). It is possible that the criteria used to assess fire and burn severity for calculating the CBI are adequate for quantifying fire and burn severity effects in western pines and other forest types that experience a range of fire types (e.g. from light surface fires to crown fires) and where changes to substrate characteristics play a less central role in determining how ecosystems respond to fire. However, scientists and managers that wish to use the CBI to quantify fire and burn severity need to carefully assess how the observations made for estimating CBI relate to specific measurements that are used to predict the impacts of fire on site recovery in the ecosystems within their region of interest. Without such assessment, questions will remain with respect to how to utilise satellite-based fire severity maps whose thresholds are determined using the CBI.

As an alternative to the CBI approach, we relied on a set of additional ecologically based measurements to assess fire severity in black spruce forests. These observations included measurements of depth of the surface organic layer above the mineral soil, the mineral/organic layer type exposed at each sample location, the depth of adventitious roots above the mineral soil on black spruce trees (which can be used to estimate pre-burn organic layer depth), the degree of canopy consumption, and the number of standing *v.* downed trees within the stand. We suggest that these measures (which can be collected with relative ease in the field) are an effective alternative to the CBI approach in black spruce forests.

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