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Controls on carbon consumption during Alaskan wildland fires

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Abstract

A method was developed to estimate carbon consumed during wildland fires in interior Alaska based on medium-spatial scale data (60 m cell size) generated on a daily basis. Carbon consumption estimates were developed for 41 fire events in the large fire year of 2004 and 34 fire events from the small fire years of 2006–2008. Total carbon consumed during the large fire year (2.72×10^6 ha burned) was 64.7 Tg C, and the average carbon consumption during the small fire years (0.09×10^6 ha burned) was 1.3 Tg C. Uncertainties for the annual carbon emissions ranged from 13% to 21%. Carbon consumed from burning of black spruce forests represented 76% of the total during large fire years and 57% during small fire years. This was the result of the widespread distribution of black spruce forests across the landscape and the deep burning of the surface organic layers common to these ecosystems. Average carbon consumed was 3.01 kg m^{-2} during the large fire year and 1.69 kg m^{-2} during the small fire years. Most of the carbon consumption was from burning of ground layer fuels (85% in the large fire year and 78% in small fire years). Most of the difference in average carbon consumption between large and small fire years was in the consumption of ground layer fuels (2.60 vs. 1.31 kg m^{-2} during large and small fire years, respectively). There was great variation in average fuel consumption between individual fire events (0.56–5.06 kg m^{-2}) controlled by variations in fuel types and topography, timing of the fires during the fire season, and variations in fuel moisture at the time of burning.

Keywords: boreal carbon dynamics, disturbance, fire ecology, fire emissions, fuel moisture, remote sensing

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Introduction

Fires and biomass burning serve as an important control on ecosystem processes and dynamics in a wide range of biomes (Wein & MacLean, 1983; Goldammer, 1990; Levine, 1996). Fire is similar to other disturbances in that it causes mortality or damage to vegetation, initiating changes to plant communities that alter carbon cycling via biological processes (photosynthesis and autotrophic and heterotrophic respiration). It is a unique disturbance because it also results in an instantaneous loss of carbon stored in a number of terrestrial pools (live vegetation, dead vegetation, litter, organic soil), which leads to the direct release of a number of carbon-based greenhouse gases into the atmosphere, as well as particulate matter that eventually is redeposited on the earth's surface. As a result, modeling the terrestrial carbon cycle in most regions requires accounting for biomass consumed from burning during fires (Kasischke *et al*., 1995a; Harden *et al*., 2000; Thonicke *et al*., 2001; van der Werf *et al*., 2003; Balshi *et al*., 2007).

Assessing the impact of biomass burning on carbon cycling calls for approaches to estimate the levels of carbon consumed and emitted at a variety of spatial and temporal scales, ranging from specific fire events that last several days to weeks (Michalek *et al*., 2000; Isaev *et al*., 2002; Guild *et al*., 2004; Campbell *et al*., 2007; French *et al*., 2011), to landscape and regional scales over the length of the fire season (Kasischke *et al*., 1995b; Kajii *et al*., 2002; Potter *et al*., 2002; French *et al*., 2003; Korontzi, 2005; Mendoza *et al*., 2005; Ruiz *et al*., 2005; Venkataraman *et al*., 2006; de Groot *et al*., 2007), to continental and global scales at annual and inter-annual time scales (Amiro *et al*., 2001, 2009; Schultz, 2002; Hoelzemann *et al*., 2004; Ito & Penner, 2004; Kasischke & Penner, 2004; van der Werf *et al*., 2004, 2006, 2010; Kasischke *et al*., 2005; Jain *et al*., 2006; Wiedinmyer *et al*., 2006; Balshi *et al*., 2007, 2009). Regardless of scale, estimating the direct release of carbon during fires requires data sources or approaches for quantifying the: (a) spatial extent and timing of fires; (b) levels of biomass or fuel in the fire impacted areas; and (c) fraction of biomass or fuels consumed from different carbon pools. Uncertainties in carbon consumption/emission estimates result from the approaches used to derive information products in each of these areas (French *et al*., 2004).

The use of information derived from geospatial data (both fire management and remotely sensed data) have provided information products that are widely used to estimate carbon release from biomass burning. These include burned area information products generated

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from satellite remote sensing data (Sukhinin *et al.*, 2004; Giglio *et al.*, 2006, 2010; Loboda *et al.*, 2011) and large fire databases (Kasischke *et al.*, 2002, 2010; Stocks *et al.*, 2003), maps of vegetation and fuel types (Michalek *et al.*, 2000; Campbell *et al.*, 2007; de Groot *et al.*, 2007; French *et al.*, 2011), and remote-sensing based fire severity indices used to scale fuel consumption (Michalek *et al.*, 2000; Isaev *et al.*, 2002; Campbell *et al.*, 2007; Verbyla & Lord, 2008). Because using geospatial data products alone does not provide the basis for estimating fraction of fuel or biomass consumed within individual fire events, field-based observations and studies are needed to provide this information (Campbell *et al.*, 2007; de Groot *et al.*, 2009; French *et al.*, 2011; Turetsky *et al.*, 2011). Even with these recent advances, uncertainties still exist in: (a) determining the biases in burned area estimates obtained from fire management records (in North America) and coarse-resolution satellite data; (b) determining the levels of fuel availability across all the vegetation types that are present in different regions; and (c) accounting for the influences of seasonal and inter-annual variations in climate on combustion efficiency, in particular quantification of depth of burning of deep surface organic layers that are common in boreal forests and peatlands (French *et al.*, 2004).

Here we present the results of a study aimed at addressing all these uncertainties. The study was carried out using fire events that occurred in the boreal forest region of Alaska for the fire seasons of 2004 and 2006–2008. These years were selected because they provided the opportunity to contrast and compare carbon consumed during a very large fire season[1] (2004) that experienced extreme fire conditions to those during small fire seasons (2006–2008) where fire activity was constrained by seasonal rainfall patterns that resulted in less extreme burning conditions.

Materials and methods

Study region

While fires occur throughout mainland Alaska, the majority of burning occurs in the boreal forests found in its interior region. For this study, we examined 75 different fire events from interior Alaska that were available from the USGS/USFS Monitoring Trends in Burn Severity (MTBS) program (http://www.mtbs.gov/) data set, ranging in size from 503 to 216 930 ha. We used data from 41 fire events from the 2004 fire season and from a total of 34 fire events from 2006 to 2008 seasons. The area within the perimeters of the 2004 fires represented 94% of the burned area reported by the Alaska Fire Service and 84% for the 2006–2008 fires (Table 1).

Based on records from the Alaska Fire Service (AFS), 2.71×10^6 ha were affected by fire in Alaska in 2004, the largest fire year dating back to 1940. Very few fires in 2004 occurred outside of the state's interior region, and >99% of the fire-affected area burned from fires ignited by lightning (Kasischke *et al.*, 2010). The large area burned during this unusual fire season was the result of warmer temperatures and abnormally low precipitation from June through September, which resulted in extremely active fires that rapidly spread over large areas. The total number of annual fires was lower during the 2006–2008 fire seasons, when the higher levels of precipitation in these years prevented most of the ignited fires from growing into large fire events as well. Area burned in the boreal forest region of Alaska during these years averaged 0.09×10^6 ha.

Approach

The overall approach is summarized in Fig. 1. This approach closely follows that developed by de Groot *et al.* (2007), with the exception that slightly different methods were used to estimate fuel consumption based on vegetation type and site drainage. A geographic information system (GIS) was used to integrate information from different data layers to create a single data set for each of the 75 fire events. Each pixel within the mapped fire perimeter was assigned a fuel type, drainage category, whether it burned or not, and a date when it was exposed to fire (whether the pixel actually burned or not). Fuel type within each fire perimeter was based on vegetation cover derived from an information product developed from satellite remote sensing data. Remote sensing data were also used to determine burned and unburned areas within fire perimeters, as well as the day on which specific locations burned. Topographic data were used to create two drainage categories for most fuel types.

Carbon consumption was calculated on a daily basis for each fuel/drainage category for three separate fuel categories: crown fuels, dead woody debris, and ground-layer fuels. Several different approaches were used to estimate fuel consumption, including: (a) algorithms based on variations in fuel moisture and fire behavior as expressed through a set of fire weather indices; and (b) algorithms that accounted for factors that control the burning of deep organic layers (ground-layer fuels) common to Alaskan fuel types.

Geospatial characterization of fuel types, drainage, and fire activity

The North American Land Cover Database (NLCD), ca. 2001, was used to map fuel types in the Alaskan boreal forest region. The NLCD is a land cover map generated through processing of Landsat TM/ETM+ data (Homer *et al.*, 2004). This map has an overall accuracy of 76%, with the accuracy of the evergreen cover category being 84% (Selkowitz & Stehman, 2010). The version of the NLCD used for this study had 19

[1]In this paper, the terms large fire year refers to a large area burned fire season and a small fire year refers to a small area burned fire season.

Table 1 Summary of the characteristics of the fire events used in this study

	Fire impacted area (ha)				Fire event size (ha)		
Year	AFS records	Perimeter of events used	Number of fires events	Number of events used	average	minimum	maximum
2004	2 708 783	2 546,424	384	41	62 108	3967	216 930
2006	107 548	109 530	173	9	11 288	641	50 606
2007	131 765*	83 372	355	20	4450	503	16 466
2008	41 739	41 822	223	5	6247	726	14 128

*Total does not include the 103 940 ha Anaktuvuk River fire that occurred on Alaska's North Slope, outside of the boreal forest region.

Data are for the boreal region of interior Alaska and are from Alaska Fire Service (AFS) reports.

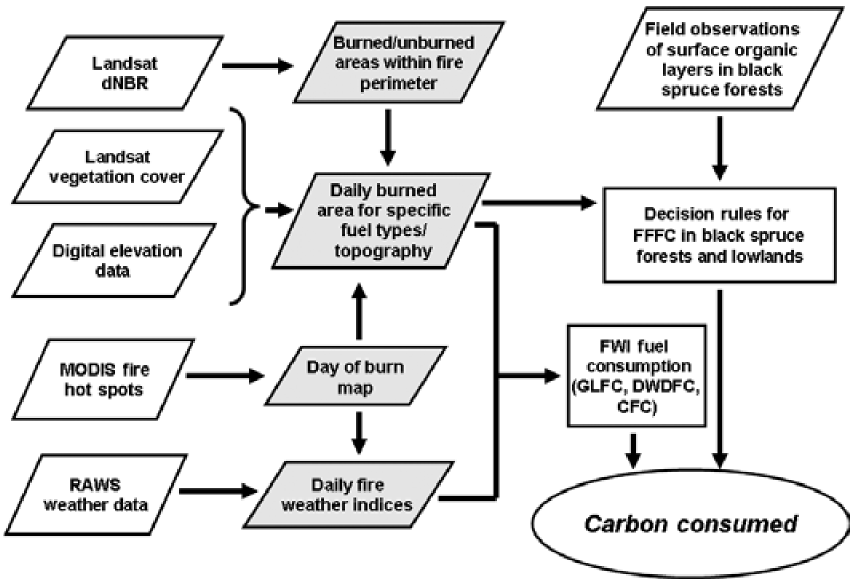

Fig. 1 Flow diagram of approach developed for estimating carbon consumption from wildland fires in Alaska.

land cover categories for Alaska, which we converted to eight fuel types by combining NLCD categories (Table 2). The six NLCD land cover categories combined into the 'other vegetation' category were areas with no or low vegetation cover and were not used in this study. The 'other vegetation' category represented <0.1% of all land within the fire events used in this study.

An additional analysis was carried out for a limited number of the 2004 fires using a land-cover map produced by the Bureau of Land Management (BLM) and Ducks Unlimited from Landsat TM/ETM+ data (the Alaska EarthCover dataset) to examine patterns of evergreen forest cover within fires in more detail.[2] This data set had several different categories for evergreen forests, including a closed-canopy evergreen forest category, which comprised 10% of all evergreen forests. For this study, we assumed that these closed canopy evergreen forests were white spruce forests, and that 10% of the area covered by the NLCD evergreen pixels was white spruce and 90% black spruce. As there are no maps of the extent of white vs. black spruce forests in interior Alaska, this assumption is based on personal observations of the authors that black spruce is the predominant conifer cover.

One of the characteristics of terrestrial ecosystems in Alaska is the presence of deep organic layers found in less-well-drained upland black spruce forests and all of vegetation cover types in lowlands with poorly drained soils. To create additional categories based on site drainage, we merged the fuel-type map with topographic data within a GIS. We first categorized individual fire events as either occurring in a predominantly flat region (such as the Yukon flats) or in a region containing predominantly upland terrain. Then, four of the fuel types used in this study were divided into two sub-types based on site drainage (moderate-poorly drained/lowland and well-drained/upland). The upland/lowland thresholds

[2]This data set did not cover the entire study region and therefore was not available for all fire events used in this study.

Table 2 Summary of assignment of NLCD land cover categories to fuel types used for this study

NLCD category	Fuel type
Evergreen forest	Black spruce/white spruce
Deciduous forest	Deciduous forest
mixed forest	Mixed forest
Dwarf scrub	Low shrub
Shrub/scrub	High shrub
Woody wetlands	High shrub
Grassland/herbaceous	Nonwoody
Sedge/herbaceous	Nonwoody
Moss	Nonwoody
Emergent herbaceous wetlands	Nonwoody
Perennial ice/snow	Other
Open water	Other
Developed land	Other
Barren land	Other
Cultivated crops	Other
Pasture hay	Other

used for fire events occurring in flat areas were determined using the methodology described in Barrett *et al.* (2011), where the drainage condition was determined by analyzing datasets derived from a U.S. Geological Survey digital elevation model (DEM) including elevation, slope, aspect and flow accumulation (a measure used to assess how much water is flowing across regions of differing elevations).

We used the Landsat differenced Normalized Burn Ratio (dNBR) product generated by the MTBS project to create maps of fire perimeters and burned and unburned islands within the perimeters. The thresholds used for separating burned vs. unburned areas were those determined individually for each fire event by the MTBS team during initial image analysis and creation of the dNBR.

The above approach resulted in a 60 by 60 meter pixel product for each fire event categorized by fuel type, topography, and whether or not the pixel was burned, unburned or not categorized (because of cloud or smoke cover or not classified because of the Landsat ETM+ scan line problem). For each medium resolution pixel,[3] we determined the day of probable fire activity based on a daily fire activity mask created from analysis of the MODIS active fire product (Giglio *et al.*, 2006). This mask was created using the kriging spatial analysis technique provided in the ArcMap GIS product.

For some fire events, the presence of smoke or clouds precluded classifying some of the pixels into burned or unburned categories (about 17% of the pixels from all fire events fell into this category). We assumed that a fraction of these uncategorized pixels actually burned based on the fraction of burned pixels for the specific fuel type for the entire fire event. This calculation was made on a daily basis for all uncategorized pixels on that date.

Biomass consumption

Two different approaches were used to calculate fuel consumption for this study. For surface fuels in areas with poor drainage and for black spruce forests on all topographic positions, fuel consumption was based on date of burning. For all other cases, we used equations developed for the Canadian Fire Effects Model (CanFIRE) (de Groot, 2006, 2010), which have been used to estimate wildland fire carbon emissions in Canada (de Groot *et al.*, 2007) and North America (French *et al.*, 2011).

A sensitivity study by French *et al.* (2004) showed the greatest uncertainty in estimating carbon consumption/emissions from fires in boreal forests was from burning of the deep organic layers common to the biome. Based on this conclusion, a study was carried out that included the collection and compilation of depth of burning data from black spruce forests, the most common ecosystem with deep organic layers in interior Alaska. This study also included the collection and analysis of bulk density and percent carbon data, and analysis of data from unburned stands across different topographic positions (Kane *et al.*, 2007; Shetler *et al.*, 2008; Turetsky *et al.*, 2011).

Turetsky *et al.* (2011) carried out a detailed statistical analysis of depth of burning in black spruce forests in interior Alaska, and used depth of burning to estimate carbon consumption. This analysis used data from 178 sites located across upland and lowland sites, and included sites that burned during different parts of the fire season. Unlike similar studies conducted in Canadian black spruce forests, Turetsky *et al.* (2011) found that variations in fire weather indices were not able to explain variations in depth of burning. Therefore, we were not able to develop statistically based, dynamic fuel consumption models similar to those developed by Canadian researchers (e.g., de Groot *et al.*, 2009).

Turetsky *et al.* (2011) found that three factors explained most of the variation in depth of burning/carbon consumption in the surface organic layers of black spruce forests:

1 Topography is an important control, with higher fractions of consumption occurring in upland sites compared to lowland sites;
2 Higher consumption occurred during late season fires, most likely because seasonal thawing of permafrost resulted in drier ground-layers as the fire season progressed. Thus, the date of burn during the growing season can be used to estimate depth of burning; and
3 In upland sites, higher consumption occurred in early season fires in large fire years compared to small fire years because of drier conditions and more extreme fire behavior.

Based on these observations, we developed seasonal ground-layer consumption curves for fuel types with deep organic soils (see table 1, figs 1 and 2 in Turetsky *et al.*, 2011).

[3]For this paper, we use the following convention used for satellite remote sensing data to describe spatial scales: Fine resolution = 1 to 10 m pixels or cell sizes; Medium resolution = 20 to 100 m pixels or cell sizes; Moderate resolution = 250 m to 1 km pixels or cell sizes; coarse resolution = greater than 5 km pixels or cell sizes.

For the black spruce fuel type, we used the ground-layer carbon consumption levels from Turetsky *et al.* (2011). For other fuel types, we assumed a maximum fuel consumption of 2.4 kg C m^{-2} during large fire years. This value was based on the observation that the ground-layer moisture is higher in other lowland areas compared to lowland black spruce forests, resulting in lower levels of fuel consumption. Figure 2 presents the carbon consumption curves used for the 2004 fires and the average of the curves used for the 2006–2008 fires, where the ground-layer carbon consumption was ca. 20% lower than in 2004.

For crown fuels and dead woody debris for all fuel types, consumption during fires was estimated using equations developed for CanFIRE. These equations calculated fuel consumption independent of fuel type based on data collected during controlled burns (de Groot *et al.*, 2007).

The equation parameters to estimate crown fuel consumption (CFC in kg m^{-2}) are summarized by Forestry Canada Fire Danger Group (1992). CFC is calculated as

$$\mathrm{CFC} = \mathrm{CFL} \cdot \mathrm{CFB} \tag{1}$$

where CFL is the crown fuel load (kg m^{-2}) and CFB is the crown fraction burned calculated as

$$\mathrm{CFB} = 1 - e^{-0.23 \times (\mathrm{ROS} - \mathrm{RSO})} \tag{2}$$

where ROS is the surface fire spread rate and is the RSO critical fire spread rate. ROS is calculated as

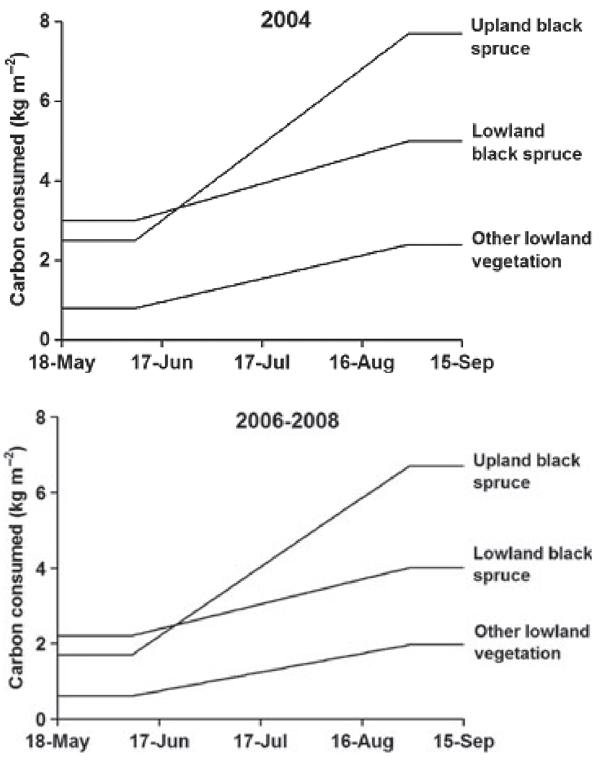

Fig. 2 Variations in ground layer fuel consumption as a function of date of burning for black spruce forests and for all other fuel types found on poorly drained sites.

$$\mathrm{ROS} = \mathrm{RSI} \times \mathrm{BE} \tag{3}$$

where RSI is the rate of spread index and BE is the buildup effect. RSI is calculated as

$$\mathrm{RSI} = a[1 - e^{(-b \times (\mathrm{ISI}))}]^{c} \tag{4}$$

where *a*, *b*, and *c* are fuel-specific parameters provided in Forestry Canada Fire Danger Group (1992) and ISI is the initial spread index, a component of the Canadian Forest Fire Weather Index (FWI) system (Van Wagner, 1987).

The BE is calculated as

$$\mathrm{BE} = e^{[50 \ln (q) ((1/\mathrm{BUI}) - (1/\mathrm{BUI0}))]} \tag{5}$$

where *q* and BUI0 are fuel-specific parameters provided in Forestry Canada Fire Danger Group (1992), and BUI is the build up index of the FWI system.

RSO is calculated as

$$\mathrm{RSO} = \mathrm{CSI}/(300 \times \mathrm{GLFC}) \tag{6}$$

where CSI is the critical surface fire intensity and GLFC is the ground layer fuel consumption (discussed below [see Eqn 9]).

The CSI is calculated as

$$\mathrm{CSI} = 0.001\ \mathrm{CBH}^{1.5}\ (460 + 25.9\ \mathrm{FFMC})^{1.5} \tag{7}$$

where CBH is a fuel specific crown base height provided in Forestry Canada Fire Danger Group (1992), and FFMC is the fine fuel moisture content index of the FWI system.

Dead and downed woody material fuel consumption (DWDFC in kg m^{-2}) is calculated as

$$\begin{aligned}\mathrm{DWDFC} = -0.131 + 0.108\ (\text{fuels} > 7\ \text{cm}) + 0.436 \\ (\text{fuels} < 7\ \text{cm}) + 0.00144\ \mathrm{DC}\end{aligned} \tag{8}$$

where (fuels > 7 cm) is the fuel load (kg m^{-2}) of branches and stems larger than 7 cm in diameter, (fuels < 7 cm) is the fuel load (kg m^{-2}) of branches and stems smaller than 7 cm in diameter, and DC is the Drought Code generated by the FWI system.

Forest floor or ground-layer fuel consumption (GLFC in kg m^{-2}) was calculated for non black spruce forests and sites on moderately to well drained topographic positions using the 'all fuel types combined' equation of de Groot *et al.* (2009)

$$\mathrm{GLFC} = -4.252 + 0.671\ \mathrm{Ln}\ (\mathrm{GL}) + 0.71\ \mathrm{Ln}\ (\mathrm{DC}) \tag{9}$$

where GL is preburn forest floor fuel load (kg m^{-2}) and DC is the Drought Code generated from the FWI system.

We assumed that 45% of the consumed biomass in Eqns (1), (8), and (9) was carbon. Values for the fuel loads in Eqns (1), (8), and (9) were based on data from previous studies in Alaska (Kasischke *et al.*, 2000; Boby *et al.*, 2010) and estimates from similar fuel types in Canada (W. de Groot, personal communication; Forestry Canada Fire Danger Group, 1992) (Table 3).

The DC, ISI, BUI, and FFMC values were obtained from records maintained by the AFS, who calculated FWI system values on a daily basis during the fire season based on weather data from more than 100 Remote Access Weather Stations (RAWS) located throughout Alaska. For each fire event,

Table 3 Fuel categories for the Alaskan boreal forest region along with the fuel levels used to estimate carbon emissions

	Fuel levels (kg C m^{-2})			
Fuel type	Ground layer	Crown	DWD >7 cm	DWD <7 cm
Black spruce – upland		0.36	0.09	0.05
Black spruce – lowland		0.27	0.09	0.05
White spruce	2.70	0.54	0.30	0.15
Deciduous forest	0.95	0.00	0.30	0.15
Mixed forest	1.80	0.18	0.30	0.15
Tall shrubs – upland	0.68	0.36	0.00	0.09
Tall shrubs – lowland		0.36	0.00	0.09
Low shrubs – upland	0.68	0.18	0.00	0.09
Low shrubs – lowland		0.18	0.00	0.09
Non woody vegetation – upland	0.68	0.09	0.00	0.00
Non woody vegetation – lowland		0.09	0.00	0.00

we obtained data from the closest 3–5 RAWS stations to create average FWI system values for each day the fire was active.

Finally, for estimating CFC, we assumed that no crown fuels were consumed in deciduous forests based on the low amounts of flammable vegetation in the crowns of this forest type. We assumed that mixed conifer/deciduous forests were half conifer and half deciduous. We used the surface fuel consumption estimates for white spruce for estimating CFC for black spruce canopies.

Uncertainty assessment

There are still significant uncertainties in the different components of the approach developed for this study. First, the thresholds selected for the dNBR of individual fire events can be difficult to determine. While it is suggested that local knowledge of a fire event be used to create the burned/unburned threshold, it is difficult to have the level of detail needed to determine the burned and unburned areas over large fire events with high precision. This difficulty could alter total area burned for different vegetation types within different fire events. Second, the vegetation cover maps used for this study had an accuracy of 76% across all vegetation types. Third, there are different approaches that can be used to determine well drained vs. poorly drained sites. We chose an approach which combined topographic data from a DEM with user defined thresholds of upland/lowland areas. The DEM we used was available at only a 60 by 60 m resolution in Alaska, while it is available at a 30 by 30 m resolution in much of the remaining United States. Fourth, additional field data are needed to quantify the factors that control variations in fuel loads for different vegetation cover types. In particular, ground layer fuels in poorly drained areas for all vegetation cover types have not been well quantified. Fifth, we used generalized fuel consumption equations that were independent of fuel type, and improved accuracy would result from the development of equations for individual fuel types. Sixth, the FWI system values for Eqns (1)–(9) were based on data collected from weather stations that in most cases were 20–50 km away from a specific fire event.

To assess the uncertainties in the estimates of carbon consumption generated in this study, we followed the approach of French *et al.* (2004). We randomly varied the values of each variable used in estimating carbon consumption using a specified coefficient of variation (CV) defined as

$$CV = \text{standard deviation}/\text{mean} \qquad (10)$$

Table 4 summarizes the CVs used in the uncertainty assessment, which are based on levels of uncertainty observed for specific parameters as well as those used in other studies (French *et al.*, 2004). Two different levels of uncertainty were used (low and high) to analyze the sensitivity of the errors. The uncertainty levels used in this study are higher than those used in a previous study (French *et al.*, 2004). For the assessment of the impacts of uncertainties in vegetation cover, we assumed that no areas that burned during the 2002–2008 fire years reburned in the years used in this study.

Assessments were carried out using data from the large fire year (2004) alone and from the three small fire years combined (2006–2008). Daily burned area estimates for the different vegetation/topography (aspect and upland/lowland for black spruce and upland/lowland for all non forest vegetation) categories were used. The average daily FWI system values from 36 RAWS stations throughout interior Alaska were used, with 3 years of data averaged for small fire years. To

Table 4 Coefficients of variation used in uncertainty assessment

	Burned area			Carbon consumed/fuel load	
	Fraction of burn perimeter*	Fuel/topographic position	FWI**	Black spruce ground layer	All others fuels
Low uncertainty	10%	15%	20%	15%	30%
High uncertainty	15%	25%	30%	25%	50%

*This parameter is associated with uncertainties in the Monitoring Trends in Burn Severity (MTBS) product, e.g., what fraction of the area within the MTBS burn perimeter actually burned.
**FWI, Fire Weather Index.

determine the CV for all parameters, the values from 1000 separate runs of the model were used. To determine the CV for individual or groups of parameters (e.g., the FWI system values), the values from 500 separate runs of the model were used.

Results

Carbon consumption in the 2004 and 2006–2008 fires

For the fire events used in this study, total carbon consumed through biomass burning ranged from 0.5 Tg in 2008 to 60.8 Tg in 2004 (Table 5). Adjusted for total burned area reported in a specific year (Table 1), the estimates of carbon consumed increased to 64.7 Tg for 2004 and 2.4 Tg for 2007. There were distinct seasonal profiles of carbon consumption/emissions, with large daily consumption/emissions occurring at times of increased fire activity. During the 2004 fire season, there were 23 days when total consumption/emissions were above 1 Tg C, and 3 days when they were above 2 Tg C (Fig. 3).

During the large fire year of 2004, 85.7% of the carbon consumed came from burning of the ground layer, 8.8% from the crown layer, and 5.2% from dead woody debris. During the small fire years of 2006–2008, 77.5% of the carbon consumed came from burning of the ground layer, 15.8% from the crown layer, and 6.6% from dead woody debris.

Table 5 Total carbon consumed (in Tg) during the 2004 and 2006–2008 fires as a function of fuel category

	Total	Ground	Crown	DWD	Black spruce ground
2004	60.78	52.06	5.32	3.18	42.37
2006	1.14	0.87	0.19	0.08	0.63
2007	1.53	1.18	0.24	0.10	0.79
2008	0.49	0.40	0.07	0.03	0.28

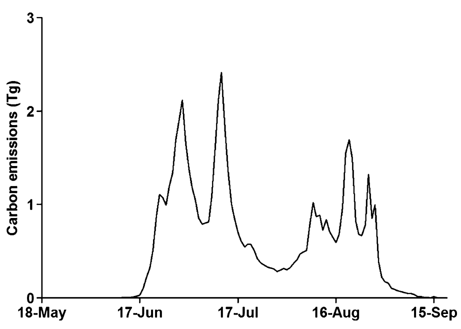

Fig. 3 Daily carbon emissions during the 2004 fires in Alaska.

Average carbon consumption varied by a factor of two across the four different years used in this study (Table 6), with the highest level (3.01 kg m^{-2}) occurring in 2004 and the lowest (1.48 kg m^{-2}) in 2006. During small fire years, the average fuel consumption (1.69 kg m^{-2}) was 56% of that during large fire years, with the majority of this difference in ground-layer fuel consumption (2.60 vs. 1.31 kg m^{-2} in large vs. small years, respectively). Average CFC was slightly lower in 2004 than during the small fire years, while dead woody debris fuel consumption was slightly higher in (Table 6), most likely as a result of variations in fuel types. Variations in average consumption of ground layer fuels accounted for the most differences between small fire years (Table 6).

Sources of variations in carbon consumed during Alaskan forest fires

There was high variability in average carbon consumed during the individual fire events (Fig. 4). Most of this variation was in average ground layer fuel consumption, which ranged from 0.54 to 4.62 kg C m^{-2} during the large fire year (2004) and from 0.33 to 2.93 kg C m^{-2} during the small fire years. CFC ranged between 0.12 and 0.34 kg C m^{-2} during large fire years and between 0.14 and 0.36 kg C m^{-2} during small fire years. Dead woody debris fuel consumption ranged between 0.09 and 0.28 kg C m^{-2} during large fire years and between 0.09 and 0.23 kg C m^{-2} during small fire years.

Based on using dNBR to analyze burned/unburned pixels within fire perimeters, an earlier analysis indicated that the fraction of area that actually burned was greater in the large fire year of 2004 compared to the small fire year of 2006 (Kasischke *et al.*, 2010). However, analyses of the data from all fire perimeters used in this study showed there was no difference in the fraction of area burned between small and large fire years, with an average of 80% of the area within fire perimeters being burned. Thus, differences in the fraction of area burned within a fire perimeter between large and small fire years would not contribute to variations in estimates of total carbon consumption.

There were three important sources of variation in average fuel consumption for the different fire events discussed above: (a) variations of fuel types within individual fire events; (b) factors influencing moisture of the surface organic layer, including topography and timing of burning during the growing season that controls seasonal permafrost thawing; and (c) variation in fire behavior and fuel moisture that controls consumption of crown fuels (e.g., the role of ISI, BUI and FFMC in

Table 6 Average carbon consumed (kg m^{-2}) during the 2004 and 2006–2008 fires as a function of fuel type and fuel category

	Fuel category	All fuel types	Black spruce forest	White spruce forest	Deciduous forest	Mixed forest	Shrub	Non woody
2004	Total	3.01	6.15	2.99	1.40	1.93	1.35	1.13
	Ground	2.60	5.64	2.07	1.01	1.45	0.81	0.95
	Crown	0.25	0.34	0.54	0.00	0.14	0.41	0.09
	DWD	0.16	0.16	0.37	0.38	0.34	0.12	0.08
2006	Total	1.48	3.54	1.81	0.91	1.45	0.98	0.11
	Ground	1.13	3.20	1.22	0.67	1.11	0.48	0.08
	Crown	0.25	0.23	0.37	0.00	0.08	0.36	0.02
	DWD	0.10	0.11	0.22	0.24	0.26	0.12	0.00
2007	Total	1.81	2.96	1.86	1.96	1.19	1.03	0.69
	Ground	1.40	2.63	1.28	1.49	0.89	0.61	0.50
	Crown	0.28	0.20	0.34	0.00	0.08	0.31	0.10
	DWD	0.13	0.13	0.23	0.43	0.22	0.10	0.09
2008	Total	1.90	3.73	1.80	0.95	1.31	1.06	0.77
	Ground	1.52	3.45	1.32	0.70	0.99	0.60	0.65
	Crown	0.26	0.15	0.25	0.00	0.09	0.36	0.08
	DWD	0.12	0.13	0.23	0.25	0.23	0.10	0.04
Small years	Total	1.69	3.28	1.83	1.34	1.24	1.00	0.32
	Ground	1.31	2.96	1.27	1.02	0.93	0.55	0.24
	Crown	0.27	0.20	0.34	0.00	0.06	0.34	0.05
	DWD	0.12	0.12	0.23	0.32	0.22	0.11	0.03

CFC) and consumption of dead woody debris (e.g., the role of DC).

Influence of vegetation type. There were distinct differences in fuel types that burned during the fire events in each year of this study (Fig. 5). These differences were the result of variations in vegetation cover based on the occurrence of fire events in different ecoregions in the different years of the study. During the 2004 fires, 63.9% of the area within the fire perimeters that burned was forested, where only 43.6% of the burned area was forested in the small fire year events. During the small fire years, 52.5% of the burned area was in the shrub fuel categories, whereas only 34.0% of the burned area in 2004 was in these types. With all other factors being equal, these differences would result in higher DWD carbon consumption in the 2004 fires because of the higher average fuel loads in forests than in non forests (Tables 3 and 6).

Because of their deep organic layers, burning of black spruce forests contributed to the highest fraction of carbon consumed in all fire years (Fig. 6) – 76% of carbon consumed in 2004 and 57% in the small fire years. While shrub fuel types were 53% of the fuel types that burned in the small fire years, they contributed only 28% of the carbon consumed.

Influence of seasonal timing on burning of deep organic layers. During 2004, 45.1% of all burned area was in black spruce, while an additional 15.9% of the area was in nonforest vegetation located on poorly drained sites with deep organic layers. During the small fire years of 2006–2008, 32.3% of all burned area was in black spruce, while an additional 29.4% of the burned area was in non forest vegetation located on poorly drained sites with deep organic layers. Thus, during all years, more than 60% of the area that burned contained deep organic soils.

Lower levels of surface fuel consumption in deeper organic layered sites occurred during the small fire years for two reasons: (a) lower levels of fuel consumption driven by seasonal weather differences that are reflected in the approach used to estimate forest floor fuel consumption (Fig. 2); and (b) differences in seasonal patterns of burning between small and large fire years. Poorly drained sites in black spruce forests and other sites in Alaska are often underlain by permafrost. In these sites, the moisture of the ground layer fuels is strongly influenced by the seasonal thawing of the ground layer (Harden *et al.*, 2006), with drier conditions occurring later during the growing season (Kasischke & Johnstone, 2005; Turetsky *et al.*, 2011). During the 2006–2008 fires, 78% of the burning occurred during the first half of the fire season (before 11 July), while during the

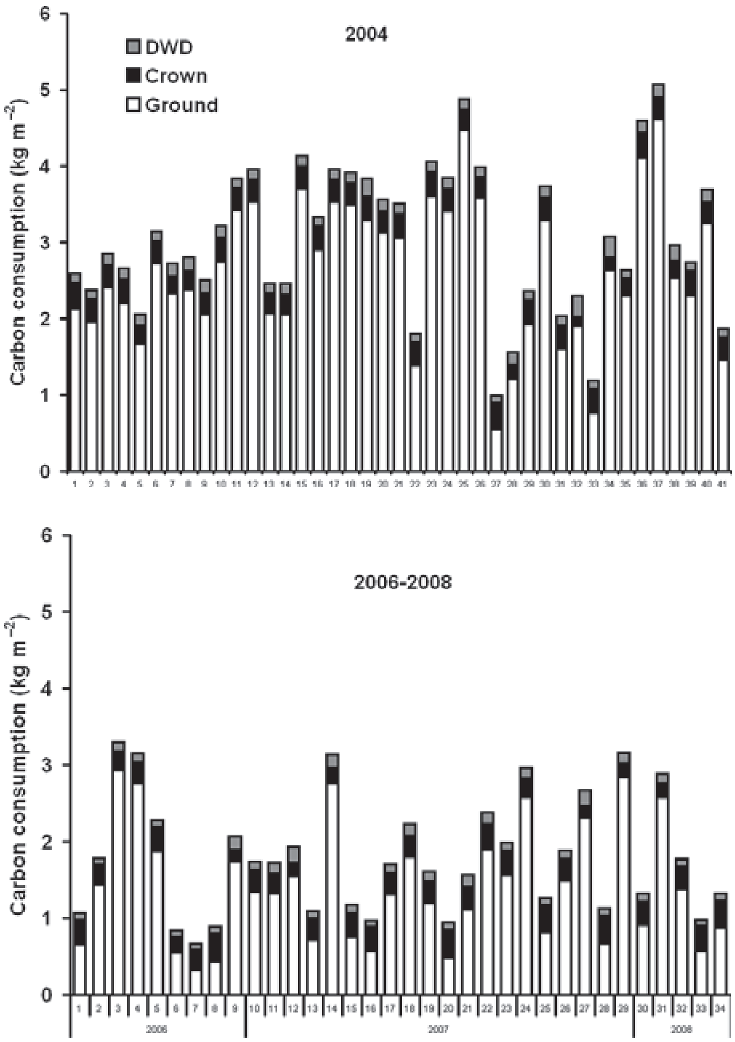

Fig. 4 Average fuel consumption for individual fire events from the 2004 (upper plot) and 2006–2008 fire events in Alaska (lower plot).

2004 fires 58% of the burned area occurred after 11 July (Fig. 7). These seasonal patterns of burning contributed to the higher GLFC in black spruce forests and lowland sites during the 2004 fires compared to the 2006–2008 fires.

Influence of seasonal and inter-annual variations in weather. Seasonal variations in the Drought Code (DC) control GLFC in non black spruce sites and moderately drained sites for all other vegetation types, as well as for DWDFC for all fuel types (Eqns 2 and 3). Variation in the ISI was a primary control on CFC for all fuel types. For all years used in this study, there was a continuous increase in DC throughout the fire season, where higher DCs occurred in 2004 compared to the small fire years (2006–2008) (Fig. 8a). While the seasonal variations were much greater for the ISI for all years, the ISI was higher in 2004 than in the smaller fire years (Fig. 8b). The temporal patterns of burning that occurred during the fire events (Fig. 6) will also contribute to variations in fuel consumption driven by variations in seasonal fuel moisture. The area weighted average DC and ISI were unique for each year used in this study (Fig. 8c), and in turn, contributed to variations in carbon consumed with the burning of crown fuels and coarse woody debris for different fuel types (Table 6).

Uncertainty assessment

The overall levels of uncertainty were very similar for the large and small fire years, with the CVs being 13.5% and 21.4% for the low and high CV scenarios during the large fire year and 13.0% and 20.6% during the

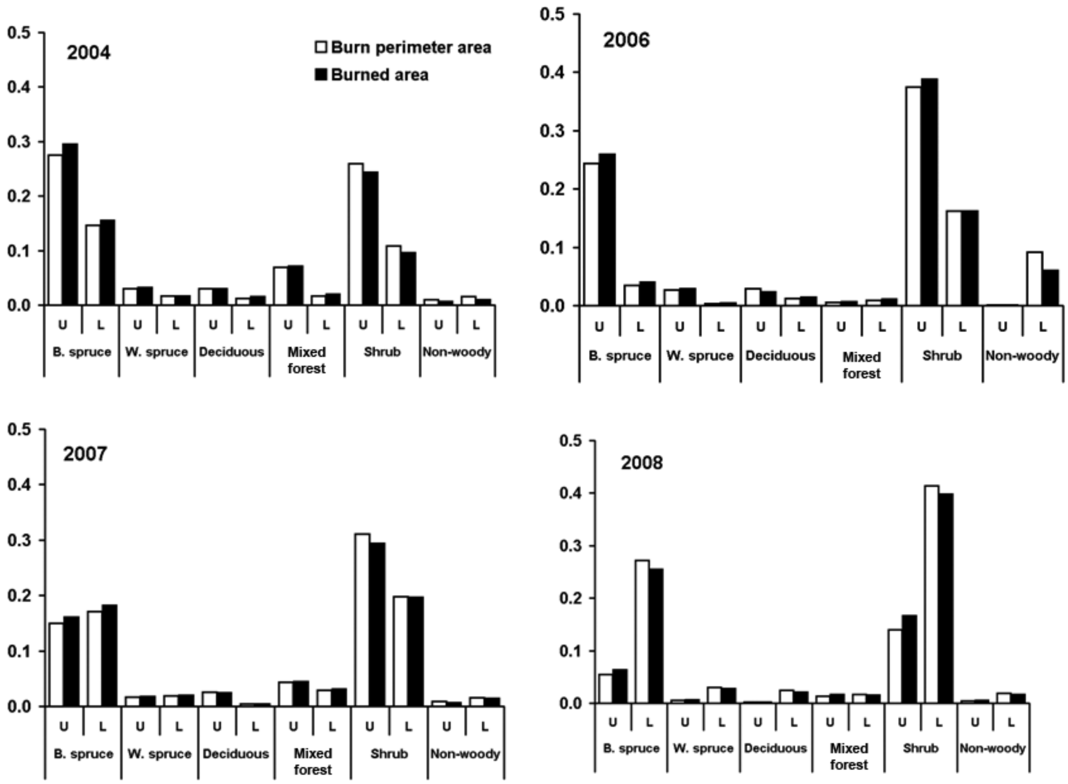

Fig. 5 Fraction of fuel type within burn perimeters and fraction of burned area by fuel type for the 2004 and 2006–2008 fire events in Alaska.

small fire years. Overall, variations in total burned area represented the largest source of uncertainty, followed by uncertainties in the fuel load/fuel consumption of ground layer fuels (Table 7). Because of the large amounts of carbon consumed in the ground layers of black spruce forests in both small and large fire years, the CVs for this component were the largest source of uncertainty (Table 7) within the different fuel categories. Despite the large uncertainties in other fuel categories (CV = 30–50%, Table 4), the uncertainties caused by these other categories were relatively low (Table 7). Because of the lower levels of ground fuel consumption in black spruce forests in small fire years, the contributions from uncertainties from other parameters were higher during small fire years.

Discussion

Previous studies have shown that using finer resolution spatial information products derived from medium-resolution (30 m) satellite data resulted in improved estimates of carbon consumed during wildland fires by providing more reliable sources of data for mapping fuel types and identifying areas experiencing different levels of fire severity (Michalek *et al*., 2000; Campbell *et al*., 2007). In this study, we implemented an approach to use medium resolution geospatial products to estimate carbon consumption for a large region over multiple years. We also developed a new approach for estimating forest floor consumption in sites with deep organic soils that are common to boreal forests based on analysis of an extensive field data set.

Compared to previous research, the approach developed for this study provided more realistic estimates of carbon consumed during Alaskan wildland fires for three reasons. First, the estimates of burned area derived from the analyses of Landsat TM/ETM+ data provide a better source of information than those provided from fire management agencies or estimated from moderate resolution (500–1000 m) satellite data. Area burned data derived from fire perimeter maps provided by land management agencies overestimates actual burned area because they do not provide information on unburned islands present within areas that burn during large fire events. Comparison of the Landsat TM/ETM+ derived estimates of burned area from this study to the burned area derived from MODIS data by Giglio *et al.* (2010) (present in the Global Fire Emissions Dataset, version 3 – GFED3) indicates their approach provided lower estimates of burned area for both large and small fire years used in this study (Table 8). The approach developed by Loboda *et al.*

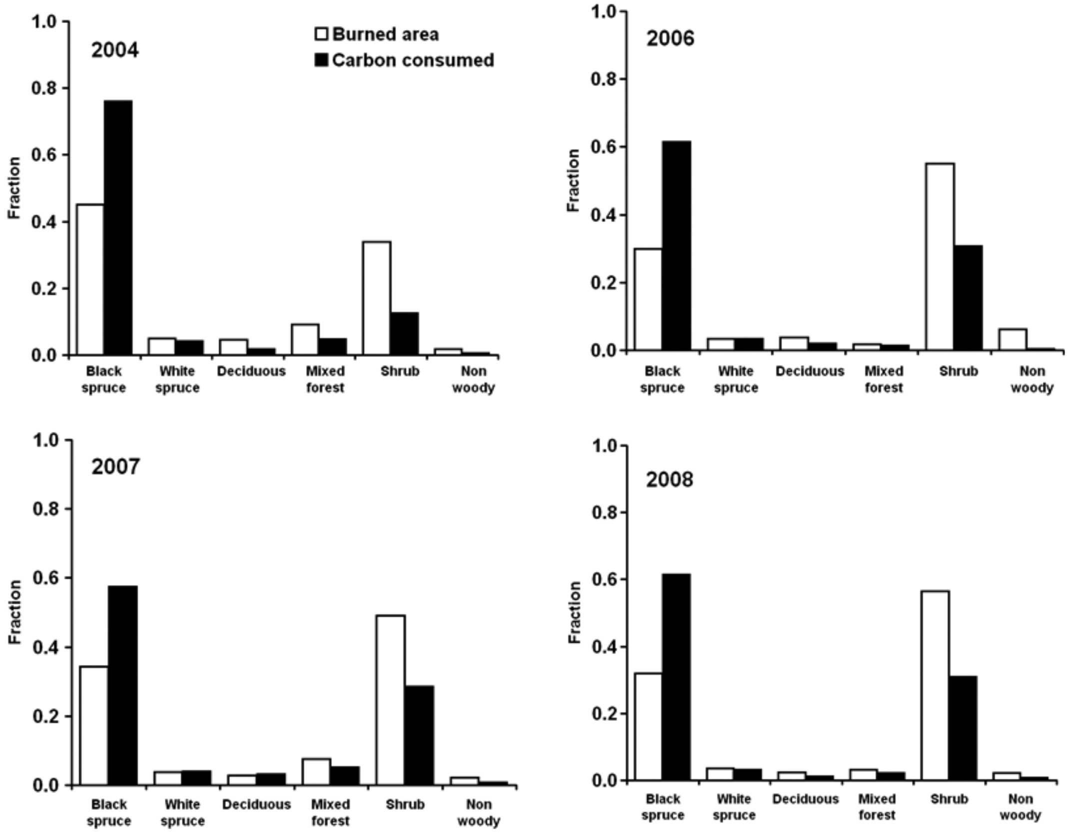

Fig. 6 Fraction of burned fuel type and carbon consumed by fuel types for the 2004 and 2006–2008 fire events in Alaska.

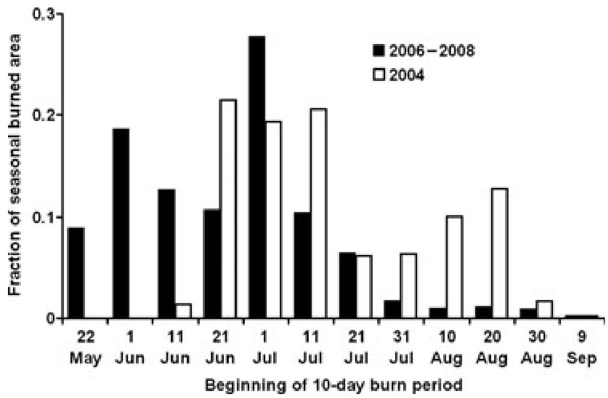

Fig. 7 Seasonal patterns of burned area for the 2004 and 2006–2008 fire events in Alaska.

(2011) using MODIS data appears to provide higher estimates of burned area (Table 8).

The approach implemented for this study also represented an improvement for the accounting of spatial variations in fuel loads. Previous studies in Alaska have relied on average fuel loads for large ecoregions (French *et al.*, 2004; Kasischke *et al.*, 2005) or on moderate-resolution (1 km) land cover products combined with a model to estimate fuel loads through growing biomass over a period of time (van der Werf *et al.*, 2006, 2010). Because it is especially difficult to account for the factors (e.g., site drainage and permafrost) that control the accumulation of surface organic layer fuels using such models, levels of surface fuels are prescribed using soil carbon spatial data sets in other approaches.

Approaches were implemented to account for seasonal variations in burning of ground-layer fuels in order to account for variations in fuel moisture driven by weather (precipitation and temperature) and seasonal thawing in sites underlain by permafrost. Factors other than short-term weather variations, such as local drainage and seasonal thawing of permafrost, control ground layer fuel consumption in sites with deep organic layers. In this study, medium-resolution (60 m) topographic data were used to account for variations in drainage for different fuel types, which in turn, control forest floor fuel levels.

Overall, the estimated uncertainty in carbon consumed from Alaska wildfires ranged between 13% and 22% for both small and large fire years, which is similar to those estimated previously by French *et al.* (2004).

The approach developed for this study resulted in higher average carbon consumption during the large fire year of 2004 (3.01 kg C m^{-2}) compared to the average

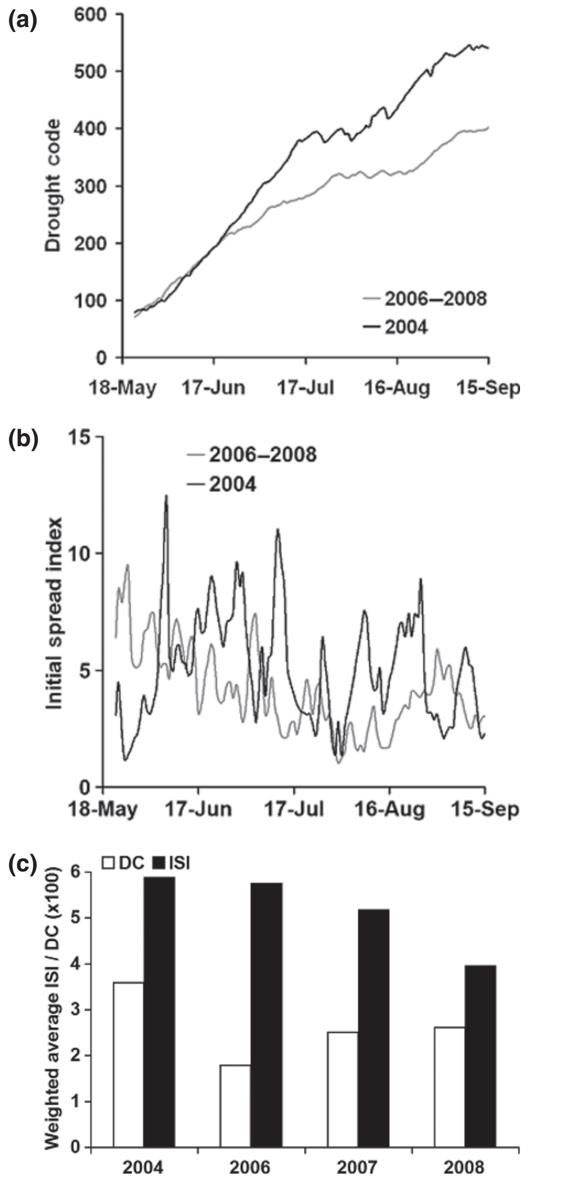

Fig. 8 Variations in fire weather indices for the 2004 and 2006–2008 fire seasons in Alaska. (a) Drought Code; (b) Initial Spread Index; and (c) area weighted average Drought Code and Initial Spread Index.

from large fire years for Alaska of French *et al.* (2004) (2.44 kg C m^{-2}) and the estimate for the 2004 fire season from van der Werf *et al.* (2010) (GFED3, 2.76 kg C m^{-2}). While the estimate of average consumption during small fires years from this study (1.67 kg C m^{-2}) matched those from the small fire years studied by French *et al.* (2004) (1.69 kg C m^{-2}), they were substantially lower than the small fire year estimates for 2006–2008 from van der Werf *et al.* (2010) (2.79 kg C m^{-2}). Assuming that the same average fuel consumption occurred for all small and large fire years

Table 7 Summary of coefficient of variations (CVs) developed from the uncertainty assessment

	Large fire year (%)		Small fire years (%)	
	Low CV	High CV	Low CV	High CV
Total burned area	10.0	15.0	10.0	15.0
Fuel type	0.9	2.0	0.7	1.8
Combined	10.2	15.2	10.2	15.2
FWI (DC, FFMC, BUI, and ISI)	2.8	4.0	5.0	6.9
Fuel loads/fuel consumption				
Black spruce	8.2	14.3	6.2	10.4
All other ground layers	1.5	2.7	2.3	4.0
Total ground layer	8.2	14.5	6.8	11.4
Crown fuels	0.6	1.1	1.1	2.0
Dead woody debris fuels	0.4	0.7	0.5	0.9
Total fuels	8.3	14.6	6.9	11.7
All factors	13.5	21.4	13.0	20.6

All CVs were calculated using the average total carbon consumption, not the carbon consumption for the individual components.

during the 1990s and 2000s for Alaska results in an average ground layer fuel consumption of 2.73 kg C m^{-2}, which is comparable to the average of 2.52 kg C m^{-2} reported for northwestern Canada (taiga plains ecoregion) by Amiro *et al.* (2009).

The estimate of total carbon consumption/emissions of 65.4 Tg is substantially greater than the 45.7 Tg estimate from of van der Werf *et al.* (2010) (based on information obtained from the GFED3 dataset). This higher estimate is the result of a higher estimate of burned area (Table 6) and higher estimates of average carbon consumed. Two studies estimated CO emissions from the 2004 Alaskan fires. Pfister *et al.* (2005) estimated total emissions of 30.0 Tg CO for Alaska and the Yukon

Table 8 Comparison of burned area (10^6 ha) from fire management records compared to those derived from analysis of MODIS data

	AFS adjusted	GFED3	Loboda *et al.*, 2011
2004	2.178	1.655	2.028
2005	1.492		2.665
2006–2008	0.242	0.218	
2006–2007	0.203		0.367

The fire management data are from the Alaska Fire Service (AFS), and have been adjusted by multiplying by 0.8, the fraction of burned area within perimeters derived from this study (AFS-adjusted).
GFED3; Global Fire Emissions Dataset, version 3.

Territories by inversion of MOPPITT estimates of atmospheric CO concentration. We estimate that 18.0 Tg CO came from Alaskan fires since 60% of the burned area in the region occurred in Alaska in 2004. Turquety *et al.* (2007) estimated emissions of 16.3 Tg CO using burned area coupled to average fuel consumptions for the major ecoregions in interior Alaska. Using the same emission factors and assumptions concerning smoldering vs. flaming combustion as Turquety *et al.* (2007) resulted in an estimate of 30.0 Tg CO emissions from the total of 65.4 Tg C for the 2004 fires, which is much greater than the estimates from previous studies.

The approach of van der Werf *et al.* (2010) produced a carbon consumption of 6.1 Tg C for the three small years of 2006–2008, compared to 3.9 Tg C from this study. The higher estimates for the small fire years are the result of the higher average carbon consumptions produced by van der Werf *et al.* (2010). This result suggests that the higher estimate of fuel consumption by van der Werf *et al.* (2010) most likely resulted from an approach that resulted in deeper burning of surface organic layers than is realistic for Alaskan ecosystems during small fire years.

Conclusions

To date, approaches to estimate carbon consumed during fires at regional and larger scales have been based on using moderate to coarse-resolution data sets, both in space (1 by 1 km cell size or greater) and time (1 month or annual scales), which in turn, can introduce significant sources of uncertainty into quantifying carbon consumption that are difficult to identify and quantify. In contrast, using finer-spatial scale data (100 by 100 m cell size) with finer temporal scales (weekly or shorter) can result in lower levels of uncertainties; however, to date, the availability of these data sets have limited application of these higher resolution information products to individual fire events.

For the first time, in this study medium-resolution (60 m pixel) information products were used to estimate carbon consumption for multiple fire events spanning four different fire seasons over a large geographic region, providing improved information on burned area, fuel type, site drainage characteristics, and daily patterns of burning. When combined with models of fuel consumption based on field observations, this approach is the basis for understanding factors controlling carbon consumption during fires, including the roles of variations in fuel type, topography, and seasonal differences in weather.

Previous studies identified depth of burning of surface organic layers as being a primary area of uncertainty in biomass consumption during wildland fires in boreal regions (French *et al.*, 2004; Kasischke *et al.*, 2005; Turquety *et al.*, 2007; Amiro *et al.*, 2009). The approach implemented for this study built on research quantifying the factors controlling burning of surface organic layers in black spruce forests (the dominant forest cover in Alaska), and implemented approaches to account for the three factors that were most responsible for causing variations in the burning of these layers (topography, timing of the fire during the growing season, and seasonal burned area).

While the approach developed for this paper accounts for the primary factors that drive burning of surface organic layers in black spruce forests (e.g., variations in site moisture controlled by topography and seasonal thawing of permafrost), it only crudely accounts for the impacts of seasonal variations in temperature and precipitation on surface fuel moisture. Additional research is needed to understand how topography, permafrost thaw, organic layer depth and seasonal weather interact to control ground-layer fuel moisture. Such research should include the collection of soil and surface organic layer moisture data along with weather data at multiple sites located on different topographic positions.

The large fire years in Alaska that have become more frequent in Alaska over the past 25 years (Kasischke *et al.*, 2010) have had major impacts on trace gas emissions to the atmosphere (Pfister *et al.*, 2005; Turquety *et al.*, 2007) as well as on terrestrial carbon storage (Turetsky *et al.*, 2011). The 65.4 Tg C emissions from Alaskan fires in 2004 were equal to all emissions estimated for domestic airlines and railroads for 2003 for North America (63.9 Tg C) (King *et al.*, 2007). On a daily basis, there were 12 days when the emissions from the 2004 fires were greater than the average daily emissions for the entire transportation sector (1.38 Tg day^{-1}; Fig. 4) (King *et al.*, 2007). The results from this study provide the basis for making improvements to both the trace gas emission and carbon cycle models needed to understand the impacts of not only individual fire events, but also the effects of longer term changes in the fire regime in boreal regions.

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