JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D1, 8151, doi:10.1029/2001JD000480, 2003

Variability in the emission of carbon-based trace gases from wildfire in the Alaskan boreal forest

Nancy H. F. French
Center for Energy and Environmental Research, Altarum (formerly ERIM), Ann Arbor, Michigan, USA

Eric S. Kasischke and David G. Williams
Department of Geography, University of Maryland, College Park, Maryland, USA

Received 7 February 2001; revised 29 January 2002; accepted 31 January 2002; published 20 December 2002.

[1] A study was carried out to assess the variability in trace gas emission from several factors and to estimate the immediate impact of fire on carbon exchange. Using geospatial data, a model of emission was developed for three carbon-based gases, CO_2, CO, and CH_4, released during fires from 1950 through 1999 in the boreal region of Alaska. The effect of two factors in the model were investigated: the fractions of carbon consumed and the ratio of flaming to smoldering combustion. We chose 4 years with which to investigate the range of outcomes. An average of 4.5 teragrams of carbon (TgC) has been released annually over the past 50 years. Severe fire years can produce emissions as high as 38 TgC. Wide variations in emissions of total carbon and carbon-based gas were seen between years. Variations in the estimates of the fractions of biomass consumed during the burn influenced the amount of total carbon emitted; however, the annual area burned strongly determines total carbon released each year, regardless of fraction consumed. Assumptions regarding flaming versus smoldering fire influenced levels of emissions of CO and CH_4. These estimates show that wildfire in Alaska's boreal region has contributed a substantial amount of carbon-based gas to the atmosphere over the five decades of fire records. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1694 Global Change: Instruments and techniques; 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions

Citation: French, N. H. F., E. S. Kasischke, and D. G. Williams, Variability in the emission of carbon-based trace gases from wildfire in the Alaskan boreal forest, *J. Geophys. Res.*, *107*, 8151, doi:10.1029/2001JD000480, 2002. [printed *108*(D1), 2003]

1. Introduction

[2] Fire is prevalent in the Earth's boreal regions and is very important to the ecology of the forests [*Viereck*, 1973; *Dyrness et al.*, 1986]. Fire also plays a central role in carbon cycling in these forests. Fire initiates succession and thus regulates patterns of carbon accumulation through net primary production. It also influences the soil thermal and moisture regime which, in turn, influence patterns of soil respiration [*O'Neill*, 2000; *Richter et al.*, 2000; *O'Neill et al.*, 2002]. Finally, fire influences the carbon cycle through the direct release of carbon into the atmosphere during biomass burning.

[3] Estimates have been made to assess carbon release from fires in the boreal forest. These estimates include selected years in Russia [*Cahoon et al.*, 1994; *Conard et al.*, 2001], Alaska [*Kasischke et al.*, 1995], and both regions combined [*Kasischke and Bruhwiler*, 2002]. More recently, *French et al.* [2000] and *Amiro et al.* [2001] estimated total carbon release from fires in the North American boreal forest over multiple years. They used large-fire databases, spatially explicit information on the distribution of biomass, and temporally varying combustion efficiency (fraction of biomass consumed) models. These studies show a large interannual variability in total carbon emissions from fires in this region.

[4] In this study, we extended previous studies. We present a modeling approach that estimates emissions of total carbon, carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4) released during fires in the Alaskan boreal forest region (Figure 1). The model uses spatially explicit information about the location of fires and the distribution of aboveground and ground-layer carbon. The model is used to explore how assumptions regarding burn severity influence total carbon emissions and to investigate how assumptions about allocation of burned biomass between flaming and smoldering combustion influence emissions of CO_2, CO, and CH_4.

2. Background

[5] The occurrence of fire in the boreal forest region varies from year to year largely due to variations in climate and weather [*Skinner et al.*, 2000; *Hess et al.*, 2001]. Fire occurs most frequently in dryer continental regions and

0148-0227/02/2001JD000480$09.00

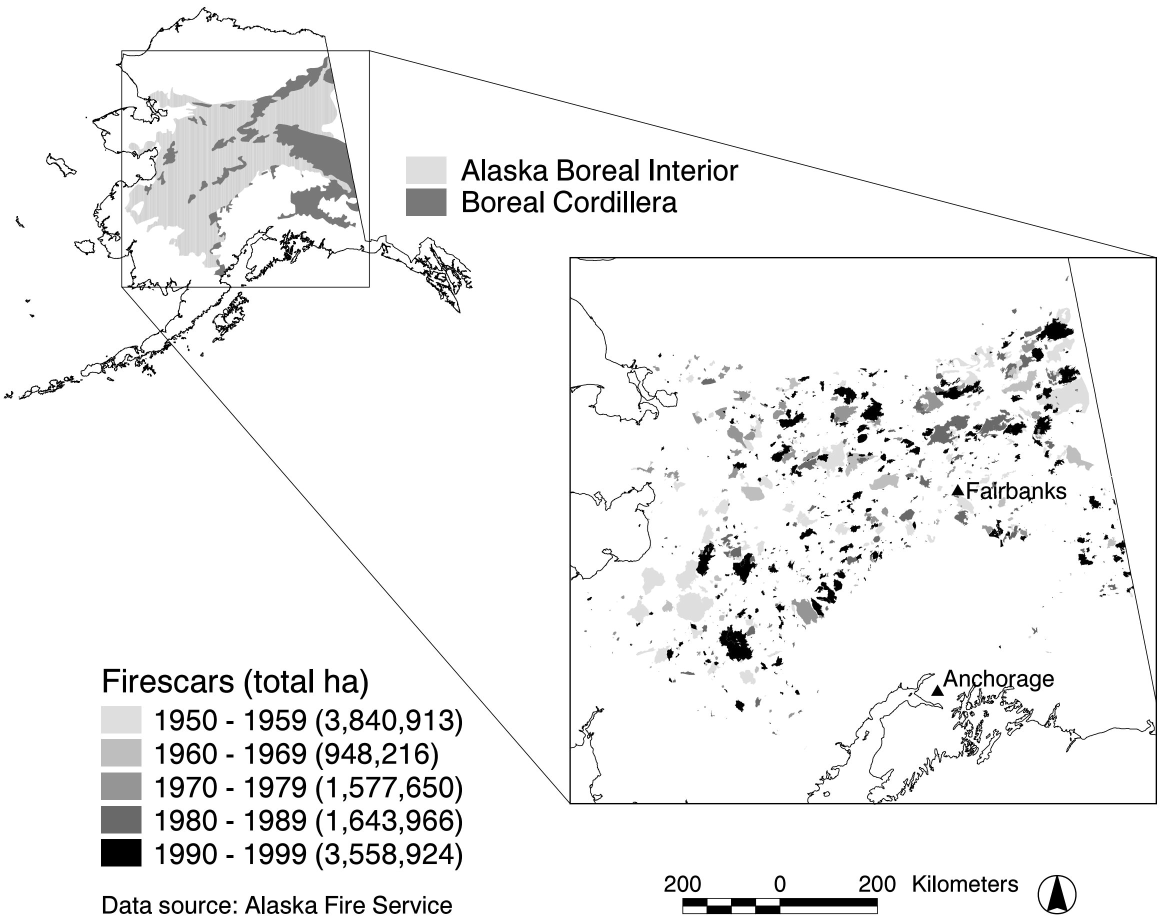

Figure 1. The study region. The inset map shows the location of the study region within the State of Alaska and the boundaries of the two ecozones within the region. The Alaska Boreal Interior covers 40.5 million hectares (Mha) within Alaska, the Boreal Cordillera covers 17.0 Mha and the entire Alaskan boreal region is 58 Mha total. The main map shows the boundaries of the fires in the Alaska boreal region from 1950 to 1999.

during years when precipitation is low and temperatures are warm. The incidence of fire in the Alaskan boreal region over the last 50 years shows the large interannual variability in fire occurrence that is typical for the boreal region (Figure 2). The episodic nature of fire in the boreal region means that a single year does not properly represent the fire regime; therefore, several years are needed to understand fire's impact. Furthermore, speculation about the impact of climate change on boreal fire regimes has led to the hypothesis that fire occurrence will increase in the future due to elevated summer temperatures and longer fire seasons [*Stocks et al.*, 1998; *Wotton and Flannigan*, 1993].

[6] The variability and potential for change in boreal fire regimes and the feedback between fire and climate all have important ramifications for global carbon cycle modeling. Wildfire in the boreal region is thought to be an important mechanism for regulating the movement of carbon from the terrestrial biosphere to the atmosphere but its impact has yet to be adequately quantified [*Kasischke and Stocks*, 2000]. Much of the emphasis in terrestrial carbon cycle modeling has been in understanding the biotic controls on carbon cycling. These are net primary production (NPP), the main mechanism for transfer of carbon into the biosphere, and heterotrophic respiration, an important and poorly quantified mechanism for carbon movement out of terrestrial ecosystems.

[7] Fire influences various aspects of the carbon cycle through direct and indirect mechanisms. Carbon stored in the organic soil of boreal forests is particularly vulnerable to fire, since fire is the main mechanism for moving this long-held carbon out of storage. As will be discussed in this paper, the direct consumption of carbon during fire can release large amounts of carbon-based gas directly into the atmosphere. The high energy associated with many boreal fires results in towering convection columns that inject smoke directly into the upper troposphere and lower stratosphere where it can be transported globally [*Fromm et al.*, 2000]. The long distance transport of smoke from boreal fires has important implications for climate change [*Cofer et al.*, 1996]. In addition to the immediate release of carbon from burning, changes in the amount of carbon consumed in the ground-layer play a central role in regulating longer-term (millennium scale) carbon accumulation in organic soil [*Harden et al.*, 2000]. Increased levels of biomass consumption during fire will lower carbon storage potential of boreal forests.

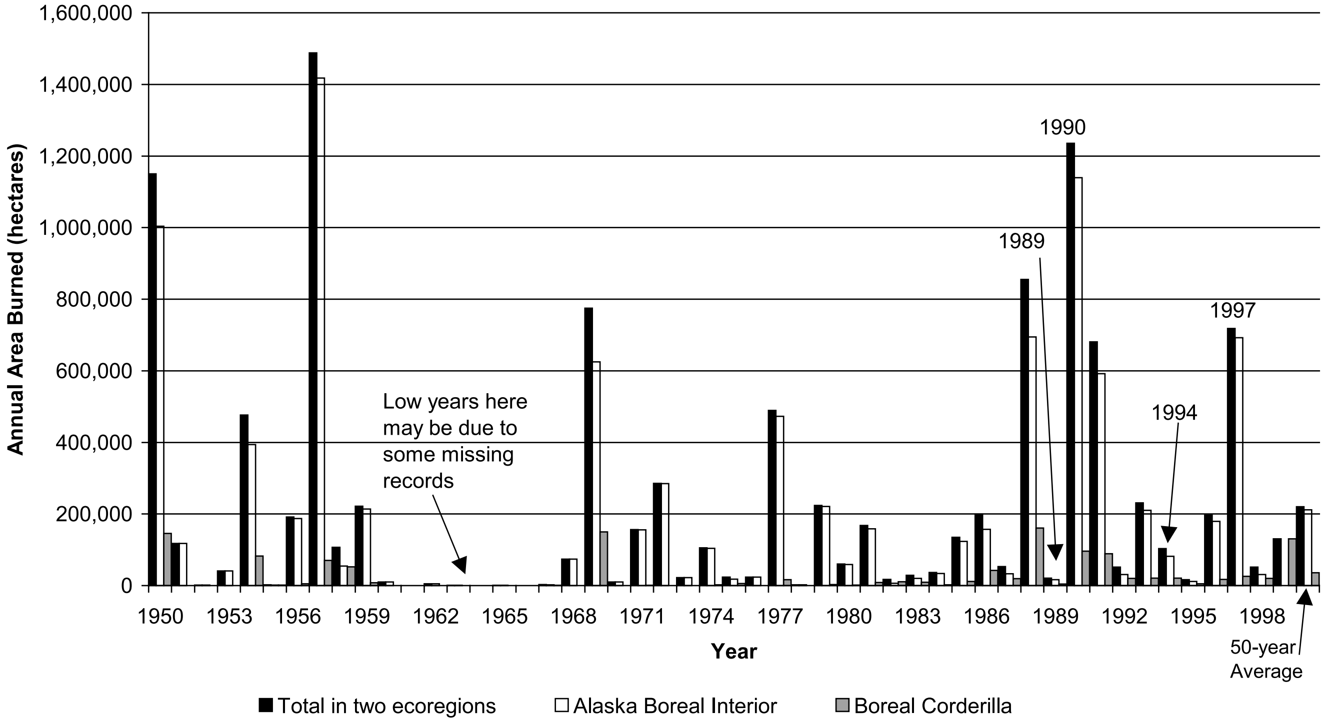

Figure 2. Annual area burned in the two ecozones of Alaska from 1950 to 1999 derived from the Alaska Large Fire Database, compiled from records held by Alaska Fire Service [*Murphy et al.*, 2000]. Note the irregular distribution of area burned and the episodic nature of large fire years.

[8] Fire has important indirect effects on carbon exchange because the depth of organic matter on the forest floor regulates soil moisture and temperature. These two factors play a central role in regulating net ecosystem production, heterotrophic respiration [*Richter et al.*, 2000; *O'Neill et al.*, 2002] and longer-term patterns of forest succession [*Viereck*, 1983; *Kasischke et al.*, 2000b]. One of the questions driving research in this field is the relative impact of these mechanisms on the movement of carbon between the biosphere and atmosphere [*Hinzman et al.*, 2002].

[9] Fire is an important source of direct emissions of such atmospheric trace gases as carbon dioxide, methane, and carbon monoxide. Some early studies as well as recent analyses have concluded that circumpolar boreal forest fires contributed a relatively small portion of global annual emissions of these gases from biomass burning (<1% to 3%) [*Seiler and Crutzen*, 1980; *Hao and Ward*, 1993; *Bergamaschi et al.*, 2000]. These conclusions have been challenged with research showing that during large fire years, boreal forest fire emissions contribute as much as 15% to 20% of total global emissions from biomass burning [*Cahoon et al.*, 1994; *Kasischke and Bruhwiler*, 2002]. During large fire years, boreal forest fires clearly contribute significant amounts of atmospheric trace gases [*Cahoon et al.*, 1994; *French et al.*, 2000; *Amiro et al.*, 2001; *Kasischke and Bruhwiler*, 2002], and contribute to anomalies recorded in the measurements of atmospheric trace gases [*Dlugokencky et al.*, 2001; *Forster et al.*, 2001].

[10] Finally, it has been recently hypothesized that fire plays a major role in regulating long-term carbon dynamics in the boreal forest region. *Harden et al.* [2000] used model-based and field observations to infer long-term soil carbon consumption from fire. They found that 10% to 30% of annual NPP in upland forests of central Canada was likely consumed by fire over the past 6,500 years.

3. Modeling Trace Gas Emissions From Fire

[11] Several approaches have been developed to estimate carbon emissions from fires in boreal regions. *Cahoon et al.* [1994] first estimated total carbon, CO_2, CH_4, and CO emissions from Russian boreal forest fires using a single value for fuel consumption and experimentally derived emission factors for each gas species, an approach also used by *Goode et al.* [2000]. More sophisticated models have been developed to account for the spatial distribution of biomass in different vegetation types and the temporal behavior of fire based on fuel moisture conditions. *Amiro et al.* [2001] used data from the Canadian Large-Fire Database, inventories of forest biomass and soil carbon densities, and Forestry Canada's Fire Behavior Prediction model to estimate total carbon released from burning in Canada. Their approach was based on results of running the fire prediction model retrospectively to estimate biomass consumption and then carbon release for each burn from 1980 to 1994.

[12] The overall modeling approach of these previous efforts, including the work presented in this paper, is based on the standard equation for estimating carbon release from biomass burning (C_t) developed by *Seiler and Crutzen* [1980]:

$$C_t = A B f_c \beta \quad (1)$$

where A is the total area burned (ha), B is the biomass density (t ha^{-1}), f_c is the fraction of the biomass that is carbon, and β is the fraction of carbon consumed during burning.

[13] Fires in boreal regions often burn the organic mat, the moss, lichen, litter and organic soils on the forest floor [*Stocks and Kauffman*, 1997; *Kasischke et al.*, 2000b] and in peatlands [*Chistjakov et al.*, 1983; *Wein and MacLean*, 1983; *Zoltai et al.*, 1998; *Turetsky and Wieder*, 2001], which can hold a high proportion of the carbon present in these ecosystems. To account for burning of the organic mat, the aboveground and ground layer components are estimated separately. Equation (1) is therefore modified as given by *French et al.* [2000] to:

$$C_t = A\left(B_a f_{ca} \beta_a + C_g \beta_g\right) \tag{2}$$

where B_a is the average biomass density of aboveground vegetation (t ha^{-1}), f_{ca} is the carbon fraction of the aboveground vegetation (assumed to be 0.50), β_a is the fraction of aboveground vegetation consumed during fires, C_g is the carbon density (tC ha^{-1}) of the organic mat exposed to fire, and β_g is the fraction of the organic mat consumed during fire.

[14] The amount of a specific trace gas released during fires (E_s) can be estimated as

$$E_s = C_t E_{fs} \tag{3}$$

where E_{fs} is the emission factor (in weight of gas released per weight of carbon burned) for a specific gas species.

[15] Two types of combustion occur during biomass burning: flaming combustion and smoldering combustion. Many studies use a single emission factor that incorporates both of these combustion processes [*Andreae and Merlet*, 2001]. However, since a significant amount of biomass is consumed through smoldering combustion in boreal forest fires, (3) is modified to

$$E_s = C_{t-f}\ E_{fs-f} + C_{t-s}\ E_{fs-s} \tag{4}$$

where the f and s subscripts refer to flaming and smoldering combustion, respectively.

[16] This study extends the results presented by *Kasischke et al.* [1995], who estimated the release of total carbon from fire in Alaska for 2 years (1990 and 1991). First, we selected five cases, one high fire year (1990), a high/moderate fire year (1997), a moderate fire year (1994), a low fire year (1989), and the 50-year average (1950 to 1999) to assess the variability in annual carbon gas released. Second, we estimated emissions of three trace gases, CO_2, CO, and CH_4, in addition to total carbon. And third, we investigated the range of emissions that could be expected under different burning conditions by varying two of the model inputs. The model inputs we varied represent two major sources of uncertainty: (1) the fraction of carbon consumed (β_a and β_g) terms in (2); and (2) the allocation of the biomass burned between flaming and smoldering combustion (C_{t-f} and C_{t-s}) terms in (4).

4. Approach and Model Inputs

[17] The boreal region of Alaska can be divided into two major ecozones, the Alaska Boreal Interior and the Boreal Cordillera. The ecozones differ primarily in their topography (Figure 1) [*Bourgeau-Chavez et al.*, 2000]. Fire statistics show that, on average, 87% of the fire occurs in the Alaska Boreal Interior ecozone, whose topography consists of generally flat terrain with some low rolling hills. The Boreal Cordillera ecozone contains a landscape of high hills and low mountains; 13% of the fires occur there. Both ecozones are dominated by black spruce (*Picea mariana* [Mill.]) ecosystems, which have large soil carbon reserves and are strongly shaped by fire disturbance.

[18] We used a Geographic Information System (GIS)-based modeling approach to generate the emissions estimates using a two-step procedure. In step one, we calculated total carbon released from boreal fires in Alaska for selected years between 1950 and 1999 by merging and analyzing several spatial/temporal data layers based on (2). In step two, we used (4) to estimate the amounts of three carbon-based trace gases released during the burn, carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4), using several different allocations of flaming and smoldering combustion and experimentally derived emission factors.

[19] The origin of each of the inputs used in our models is described below. Our rationale for quantifying the two most uncertain terms, fraction of carbon consumed and the ratio of flaming to smoldering combustion, is also presented here.

4.1. Area Burned

[20] The Alaska large-fire database was used to estimate area burned (A; Figure 2). This database was created by digitizing maps for all fires greater than 400 hectares from 1950 to 1999 as collected by the Alaska Fire Service [*Murphy et al.*, 2000]. Although large fires (>400 ha, or 1000 acres) in the boreal region of North America represent only 2–3% of the fires, they account for about 98% of the area burned and, therefore, most of the carbon released [*Murphy et al.*, 2000]. The fire database is held in ArcInfo coverage format and is available on-line from the U.S. Geological Survey, Alaska Geodata Center (http://agdc.usgs.gov/data/projects/fhm/). The accuracy of the data is very good from the 1980s on, but there are some inaccuracies in the earlier years [*Murphy et al.*, 2000].

4.2. Carbon Reserves

[21] Aboveground biomass (B_a) levels were mapped using data published by *Kasischke et al.* [1995] for different physiographic regions in Alaska. These data are scaled by 0.50, the assumed fraction of carbon in tree biomass (f_{ca}), to estimate aboveground carbon. Ground-layer carbon (C_g) was determined using published GIS-based data [*Lacelle et al.*, 1997]. The carbon density of the surface layer (the top 30 cm) was used since this is the carbon subject to fire. An assessment of data accuracy for the aboveground and ground-layer carbon maps has not been done because information for conducting this validation is not available; this problem is typical for large-scale studies in remote regions. The levels of carbon used in this study are consistent with field observations [*Kasischke et al.*, 2000b] and represent the best available information for Alaska.

4.3. Fraction of Carbon Consumed

[22] A limited number of field observations of consumption of aboveground and ground-layer biomass have been

Table 1. Area Burned and Fraction of Carbon Consumed

Year/Time Period	Area Burned (A),[a] (ha)		Consumption Level[b]	Carbon Fraction Consumed: Aboveground (β_a): Alaska Boreal Interior	Aboveground (β_a): Boreal Cordillera	Organic mat (β_g): Alaska Boreal Interior	Organic mat (β_g): Boreal Cordillera
50-year average	ABI	198,012	High	0.33	0.23	0.25	0.48
	BC	25,208	Avg	0.23	0.13	0.15	0.38
	Total	223,220	Low	0.115	0.065	0.075	0.19
1990 (high fire year)	ABI	1,139,581	Weighted	0.30	0.17	0.22	0.45
	BC	95,844					
1997 (mod/high year)	ABI	692,628	Weighted	0.24	0.10	0.18	0.29
	BC	25,512					
1994 (moderate fire year)	ABI	82,011	Weighted	0.17	0.10	0.11	0.28
	BC	21,044					
1989 (low fire year)	ABI	16,607	Weighted	0.16	0.08	0.10	0.25
	BC	4,467					

[a]ABI, Alaska boreal interior; BC, boreal cordillera.
[b]High, average, and low values are the same for all cases and are listed here for the 50-year average case.

made in the boreal forest region of Alaska [*Kasischke et al.*, 2000b]. For aboveground biomass, these observations show that the fraction of biomass consumed (β) ranges between 0.05 and 0.30, depending on vegetation type. This results in carbon release ranging between 2 and 8 metric tonnes of carbon per hectare of area burned (tC ha-burned^{-1}). This is consistent with observations made in Canadian boreal forests [*Stocks and Kauffman*, 1997].

[23] Studies by *Kasischke et al.* [2000a, 2000b] in a variety of different physiographic settings in Alaska showed that the density of the ground-layer carbon (which is held as litter, lichen, moss, and organic soil) in moderately to poorly drained black spruce forests ranged between 20 and >150 tC ha^{-1}, and the fraction of carbon consumed during fires ranged between 0.10 to 0.90. On average, 44.4 tC ha-burned^{-1}were released from the ground layers of the black spruce sites studied by *Kasischke et al.* [2000b].

[24] The major difference between levels of ground fuel consumption observed in Alaska and those observed elsewhere were in the burning of deep organic soils found in the black spruce forests that are a predominant feature of this region. Relatively high levels of ground-layer fuel consumption were also observed in forests found on drier sites (60 to 90%), but, because of the low ground-layer carbon densities found in these sites, levels of total carbon release were 5 to 10 tC ha-burned^{-1}; again, this is consistent with levels observed in Canadian boreal forests by *Stocks and Kauffman* [1997].

[25] Two studies have been carried out in Alaska to estimate the average carbon release from forested landscapes typical in this region, e.g., fire-disturbed sites that contain a range of forest types and burning severities. In a midseason fire, *Kasischke et al.* [2000b] showed that the average carbon release was 21.4 tC ha-burned^{-1}. For a late season fire with severe ground-layer burning, *Kasischke et al.* [2000a] showed that the average carbon release was 30.0 tC ha-burned^{-1}.

[26] Given the limited number of observations, we developed a set of fraction of carbon consumed (β) values for this study which represent the range of burning conditions that are expected for the Alaskan boreal forest region (Table 1). For the Alaska Boreal Interior ecozone, we assumed three baseline levels of fraction consumed: low, average, and high. Using these values results in a carbon release range that is consistent with field observations at two sites within the ecozone. The average fraction of carbon consumed values we used for the two layers (aboveground and ground layer), when combined with the average biomass/carbon levels for the ecozone, result in a carbon release of 18.8 tC ha-burned^{-1}, which is consistent with the estimate of *Kasischke et al.* [2000b] for a midseason fire (21.4 tC ha-burned^{-1}). Using the high fraction of carbon consumed levels in Table 1 with the average carbon level results in a carbon release of 30.1 tC ha-burned^{-1}, which is consistent with the estimate of *Kasischke et al.* [2000a] for a severe, late-season fire (30.0 tC ha-burned^{-1}). The low levels of carbon consumption were set at 50% of the average level and result in a carbon release of 9.4 tC ha-burned^{-1}, which is consistent with the levels of burning observed in Canadian boreal forests with lesser levels of organic soil burning (12.2 t C ha-burned^{-1} as observed by *Stocks and Kauffman* [1997]).

[27] The average levels of fraction of carbon consumed for the Boreal Cordillera ecozone were provided by a Canadian fire scientist (B. Stocks, personal communication). We determined the high and low fraction consumed values for this region the same as for the Alaska Boreal Interior ecozone; high levels were set 10% above the average, and low levels were set at one-half of average for both layers (see Table 1).

[28] We calculated an additional fraction consumed value for each of the 4 years studied, based on the weighting method developed by *French et al.* [2000]. The average values of β_a and β_g for each ecozone described in the previous paragraph were used as a starting point for determining the weighted fraction consumed for each year. Weighting factors were derived by assuming that larger areas are burned and higher levels of biomass are consumed during warmer, drier years, whereas total area burned and fraction of biomass consumed are lower during cooler, wetter years.

[29] A regression equation of fraction consumed as a function of annual area burned was developed for each ecozone based on the low, average, and high values (Table 1; Figure 3). Using the regression equation, the expected fraction consumed was determined separately for each year,

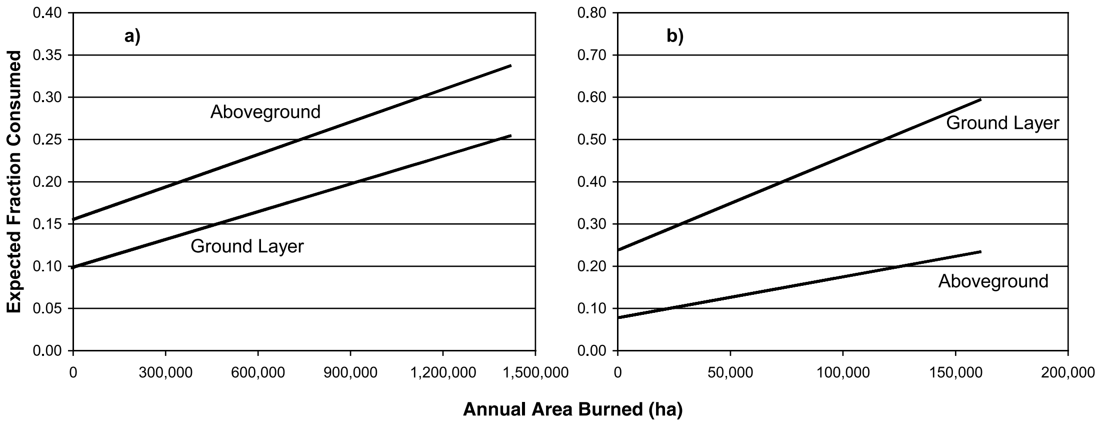

Figure 3. Regression plots used in assigning weighted fraction consumed values (β) for the Alaska Boreal Interior (a) and Boreal Cordillera (b) ecozones. The weighting method is based on the assumption that larger areas are burned and higher levels of biomass are consumed during warmer, drier years, whereas total area burned and fraction of biomass consumed are lower during cooler, wetter years. The fraction consumed is then assigned from the regression result, based on the area burned in a given year.

ecozone, and carbon layer, based on annual area burned within the ecozone. Based on this basic relationship, the weighted fraction of biomass consumed is proportional to the annual area burned, so larger fire years receive larger fraction consumed values.

[30] The analysis conducted uses the high, average, low, and weighted fraction consumed values for each case to generate a range of carbon release estimates. The average values are used for the 50-year average and the weighted values are used for the four individual years as our basic assumptions in calculating total carbon released.

4.4. Emission Factors

[31] The emission factors (E_{fs}) for the boreal region have been determined from airborne sampling of smoke plumes generated from fires in several locations. The E_{fs} for a particular gas is determined either through laboratory measurement of the contents of smoke collected in flasks [*Cofer et al.*, 1998] or by using aircraft-mounted gas-sensor equipment [*Goode et al.*, 2000]. In addition, measurements are based on laboratory combustion of biomass from boreal forests [*Yokelson et al.*, 1997].

[32] Using these approaches, emission factors have been measured for both the flaming and smoldering phases of fires in a variety of boreal forest types [*Cofer et al.*, 1989, 1990, 1996, 1998] and for flaming fires in Alaska [*Goode et al.*, 2000]. While the data of *Goode et al.* [2000] are from forests in the study region, they did not differentiate between the flaming and smoldering phases of fires; in this study, therefore, we used averages of values published by *Cofer et al.* [1989, 1990, 1996, 1998], *Goode et al.* [2000], and *Yokelson et al.* [1997] (Table 2).

4.5. Ratio of Flaming to Smoldering Combustion

[33] In previous studies of trace gas emissions from the boreal forest region, *Cahoon et al.* [1994] assumed that one-half of all carbon release originated from aboveground vegetation and one-half from ground-layer biomass. They assumed that 50% of all biomass was consumed during flaming combustion, and 50% during smoldering combustion. However, for several reasons, we have concluded that this assumption may not be valid for boreal forest regions, where fire consumes large levels of organic soil carbon. First, flaming combustion is the result of the presence of plant material (e.g., terpenes and other plant extracts) that can be volatilized to produce gases that burn efficiently in a high oxygen environment. The plant substances required to support flaming fires do not exist in much of the decomposed plant material found in dead organic matter in forest floors. Both *Johnson* [1992] and *Yokelson et al.* [1997] observe that the primary means of consumption of organic soil is through smoldering combustion. Furthermore, the average of the emission factors produced in the laboratory by *Yokelson et al.* [1997] for a variety of plant materials common to Interior Alaska are very similar to the average smoldering emission factors observed by *Cofer et al.* [1989, 1990, 1996, 1998]. Based on these observations, *Kasischke and Bruhwiler* [2002] assumed that 80% of the aboveground carbon is consumed in flaming combustion and 20% in smoldering combustion, whereas 20% of the ground-layer carbon is consumed in flaming fires and 80% in smoldering fires.

[34] In this study, we estimated trace gas emissions using three different scenarios for dividing biomass between flaming and smoldering combustion. The first scenario follows the assumptions of *Kasischke and Bruhwiler* [2002] outlined above; it is used as our basic assumption in reporting our final estimates. Scenario 2 follows *Cahoon et al.* [1994] by assigning 50% of biomass consumption by flaming combustion and 50% by smoldering for both the aboveground and ground layer. Scenario 3 is set at the opposite extreme from the first case with flaming:smolder-

Table 2. Emission Factors[a] for Three Carbon-Based Gases

	Emission Factor, g gas/kg total carbon		
Combustion Type	CO_2	CO	CH_4
Flaming	3,145 (108)	190 (49)	5.5 (1.6)
Smoldering	2,590 (400)	460 (225)	15.2 (1.8)

[a]Mean (standard deviation of estimates used).

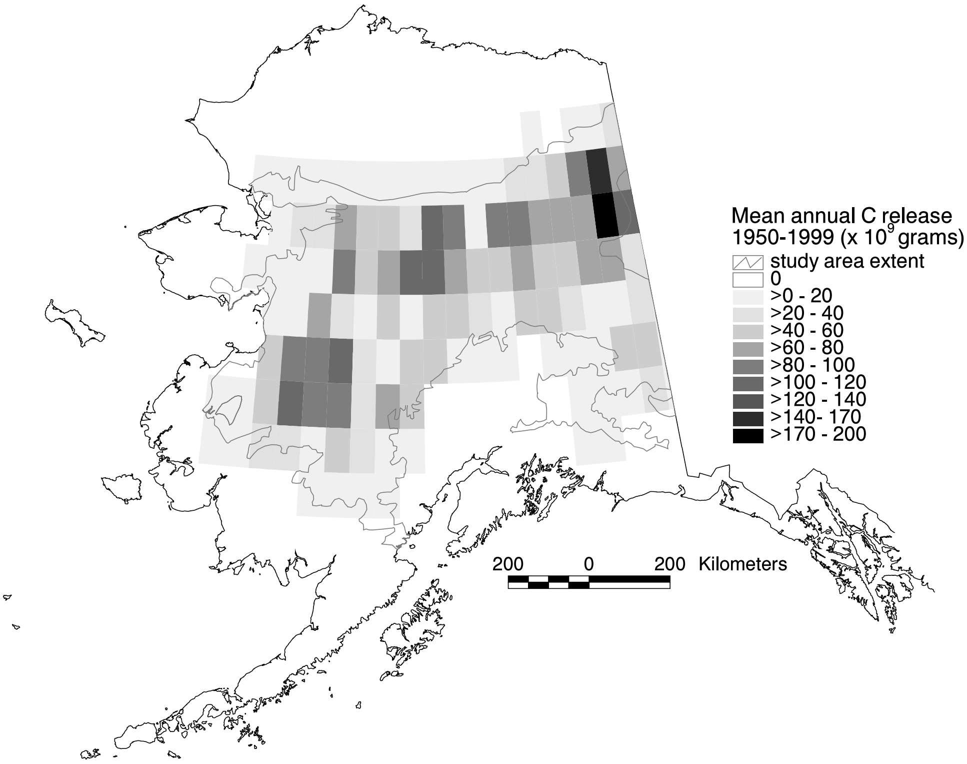

Figure 4. Carbon released from Alaskan boreal fires averaged for 50 years (1950 to 1999). Each grid cell represents 1° of latitude by 1° of longitude. Values shown are the sum of the average annual carbon released for each of the grid cells (in 1×10^9 grams). A spatially aggregated estimate of the mean annual carbon released for the 50-year period as well as for four individual years is given in Table 3.

ing assumptions of 80:20 for the aboveground and 20:80 for the ground layer.

5. Results

[35] Carbon released from biomass burning in the Alaskan boreal forest varies spatially based on two dominant factors, resident carbon and area burned. Both of these data sources are represented spatially in the input data set, so the results can be viewed as a map (Figure 4). We display the average carbon released on a 1° latitude by 1° longitude grid because many global-scale models operate on this scale, simplifying comparisons with other information. Also, the various input data layers are held at different spatial scales; the one-degree grid display helps to integrate the various data sources visually at a convenient scale.

[36] Using the average values for fraction of carbon consumed (β), an average of 4.5 teragrams (Tg = 10^{12} g) of carbon per year was released from biomass burning in the boreal regions of Alaska over the past 50 years (Table 3). Of great importance is the annual variability in area burned, which results in high variability in carbon emissions from year to year. Using the weighted fraction of carbon consumed value, we estimate that 8 times the average amount of carbon (36 Tg) was released in a high fire year (1990), while a low year (1989) showed relatively little carbon released (0.36 Tg when 21,074 ha burned).

[37] Varying the four fraction consumed values (β), from high to low estimates, strongly influences the total amount of carbon emitted (Table 4). For example, 23 Tg more carbon was released during the highest year studied (1990), if high versus low consumption is assumed. The results of varying the fraction consumed reveal, however, that the area burned in a given year strongly affects the total carbon released regardless of the fraction consumed values used.

Table 3. Estimated Amounts of Carbon-Based Gas Released From Alaskan Fires

Year/Time Period	Total C, Tg	Gas Released, Tg gas/Tg C		
		CO_2	CO	CH_4
50-year average	4.49	12.5/3.4	1.65/0.71	0.014/0.011
1990 (high fire year)	35.8	99.9/27.3	13.1/5.63	0.11/0.085
1997 (mod/high year)	14.9	41.6/11.3	5.54/2.38	0.046/0.035
1994 (moderate fire year)	1.65	4.60/1.25	0.61/0.26	0.0052/0.0039
1989 (low fire year)	0.36	0.99/0.27	0.13/0.057	0.0011/0.00082
1997 [*Goode et al.*, 2000]		45.9 Tg gas	2.46	0.077

Table 4. Results of Total Carbon Released for a Range of Fraction Consumed Values (β)[a]

Fraction Consumed[b]	50-Year Average	1990 (High Fire Year)	1997 (Moderate/High Fire Year)	1994 (Moderate Fire Year)	1989 (Low Fire Year)
high	7.00	39.81	21.27	3.42	0.81
average	**4.49**	25.33	13.30	2.26	0.53
low	2.24	12.62	6.60	1.13	0.27
weighted	–	**35.83**	**14.93**	**1.65**	**0.36**

[a]Total carbon released in TgC. Results in bold are also reported as final estimates in Table 3.
[b]See Table 1.

Table 5. Effect of Modifying the Ratio of Flaming to Smoldering Combustion in the Aboveground and Ground Layers for the 50-Year Average Estimate[a]

CO_2					
			F_g:S_g[b]		
			20:80	50:50	80:20
	F_a:S_a[c]	80:20	1.00	1.05	1.09
		50:50	0.99	1.03	1.08
		20:80	0.97	1.02	1.06
CO_2					
			F_g:S_g		
			20:80	50:50	80:20
	F_a:S_a	80:20	1.00	0.83	0.67
		50:50	1.05	0.89	0.72
		20:80	1.11	0.94	0.77
CH_4					
			F_g:S_g		
			20:80	50:50	80:20
	F_a:S_a	80:20	1.00	0.81	0.63
		50:50	1.06	0.87	0.68
		20:80	1.12	0.93	0.75

[a]The results are normalized to a basic assumption of 80:20 in the aboveground and 20:80 in the ground layer (upper left value).
[b]Ground layer flaming:smoldering.
[c]Aboveground flaming:smoldering.

[38] In estimating emission of trace gases, we found that 100 Tg of CO_2 was released during the highest year, while 1 Tg was released in the low year, assuming a flaming to smoldering ratio of 80:20 in the aboveground and 20:80 in the ground layer. The other gases show proportionally the same results, based on total area burned, with 13 Tg CO and 0.11 Tg CH_4 released in the high year (see Table 3).

[39] Table 5 presents the relative variation in trace gas emissions, assuming different splits between flaming and smoldering combustion. The table shows that, compared with a 50:50 split of flaming to smoldering in both layers, our assumptions of 80:20 in the aboveground and 20:80 in the ground-layer result in lower emissions of CO_2 but higher emissions of CH_4 and CO due to differences in combustion efficiency between flaming and smoldering burn types. The most dramatic effect of varying the flaming to smoldering ratios comes in variations in the below-ground component.

6. Discussion

[40] Two unique conditions contribute to the potential impact of biomass burning in the Alaskan boreal region on the carbon balance of the atmosphere. The first is the high frequency of large and intense stand replacement fires, and the second is the large amount of stored carbon, especially in the organic mat. These two factors combine to make a system where potential carbon conversion from the biomass pool to the atmosphere during fire is significant. Although the biomass pool dictates how much carbon could be released during burning, it is fire which regulates this release. The location of the burn and factors which contribute to burn severity, such as time of year, fire intensity, fuel condition, soil drainage, and fire danger condition (which integrates current and antecedent weather conditions), are key in determining the amount of carbon consumed and the relative amounts of carbon-based gases released.

[41] Our results show that fire-induced carbon emissions are highly variable from year to year due to the high interannual variability in area burned. This result underscores the need for investigating more than one or two fire seasons when assessing the impact of boreal forest fires on carbon cycling. Using average fire statistics may also be misleading, since the distribution of annual area burned is irregular and regionally variable (see Figure 2). A proper assessment of the impact of boreal fire can only be done if multiple years are used, as in this analysis. Even then, the fire record for Alaska is only 50 years in length, so our analysis is valid for the last half century, but may not represent conditions over longer time frames.

[42] Our study and others [*Harden et al.*, 2000] indicate that fire can cause an immediate, substantial release of carbon when compared with some estimates of NPP, the main process controlling the transfer of carbon from the atmosphere to the biosphere. *Harden et al.* [2000] use an estimate of NPP of 170 to 330 gC m^{-2} yr^{-1} for the boreal region as a whole and 180 to 430 gC m^{-2} yr^{-1} for black spruce types, which predominate in Alaska. This translates to 104 to 247 TgC yr^{-1} transferred from the atmosphere to the ecosystems of the Alaskan boreal regions from plant production. Our results show that one year of burning in the boreal region of Alaska can transfer as much as 36 TgC, or 62 gC m^{-2}, into the atmosphere in a big fire year, which is as much as 35% of estimated annual NPP.

[43] Estimates of net ecosystem production (NEP), the balance of biotic carbon exchange, for the boreal region range from -8 gC m^{-2} yr^{-1}, a small net source, to 130 gC m^{-2} yr^{-1}, a net sink. General estimates of about 40g C m^{-2} yr^{-1} for the black spruce dominated region of western North America [*Black et al.*, 1996; *Frolking*, 1997; *Goulden et al.*, 1998; *French et al.*, 2000]. Subtracting the amount of carbon released from burning during the high year of 1990 (62 gC m^{-2}) from an NEP of 40 gC m^{-2} yr^{-1} means that Alaskan boreal region could have been a considerable net source of carbon (-22 gC m^{-2} yr^{-1}) to the atmosphere, depending on proper quantification of NEP for Alaska that year. It is important to realize, however, that because of the large interannual variation in area burned and the current uncertainty in estimates of carbon release from fire as well as estimates of biotic carbon exchange [see, e.g., *Randerson et al.*, 1997], only rough comparisons of these carbon exchange mechanisms can be made.

[44] Our estimates of carbon released during burning in Alaska translate to 2.01 kgC m^{-2} yr^{-1} consumed by fire, on average, per unit area burned. For the high year, 2.43 kgC m^{-2} per unit area burned was released, and 1.71 kgC m^{-2} was released during the low year (or 20.1, 24.3, and 17.1 tC ha^{-1}, respectively). These results are generally higher than previous estimates of fuel consumption in boreal regions, such as an average of 1.46 k C m^{-2} yr^{-1} for Russia [*Dixon and Krankina*, 1993] and 1.23 to 2.75 kgC m^{-2} yr^{-1} globally [*Seiler and Crutzen*, 1980], but they compare well. These estimates are lower than the results found for Alaska as shown by *French et al.* [2000] because of differences in soil carbon fraction consumed values (β_g) used for the Alaska Boreal Interior.

[45] It well understood from field observations that fire's impact varies widely. Understanding the variability possible in the fraction of the organic mat consumed in fires across Alaska is an important issue, since large amounts of carbon are held in the soils of these ecosystems. Soil carbon is a long-term storage pool, so as fire regimes modify due to climate changes, soil carbon reserves will figure strongly in the carbon cycle [*Goulden et al.*, 1998; *Harden et al.*, 2000]. A good understanding of the impact of fire on these long-held carbon reserves is very important.

[46] In reporting our final estimates (Table 3), we assumed that fires in the 50-year average burned in average severity conditions (as measured from the field-based studies discussed earlier). We assumed higher-than-average consumption at all sites in high fire years and lower-than-average consumption at all sites in low fire years, using the weighting method presented. The fraction consumed variation analysis (Table 4) shows how carbon release results would vary if our assumption of burn severity were different; that is, if we assume only high, average, or low consumption across the ecozone. Since we have no direct measure of the variability in consumption for any particular year, the exercise allows us to estimate the extreme possibilities of the various scenarios. If we use the average values to compute carbon released, we are assuming that the fraction of carbon consumed is average at all sites within the ecozone for that year. Using the high case assumes that all sites in the region burned severely for that year, while the low value implies an assumption that all fires burned with low severity. The likely reality is that fire severity varies from low to high across a region within 1 year, although presumably high fire years will have proportionally more severe fires than low fire years.

[47] As the results show, regardless of the fraction consumed values used, the amount of area burned plays strongly in determining total carbon released in a particular year; large fire years always give relatively higher total carbon emissions than low fire years, and vice versa. Providing unique consumption estimates for each ecozone also makes an important difference in the outcome. An increase in the values used for the Alaska Boreal Interior comparable to the adjacent Boreal Cordillera ecozone, gives a result of about 80 Tg C produced in 1990, more than twice as much as our estimate for that year.

[48] We have compared our estimates of trace gas emissions with those of *Goode et al.* [2000] who produced estimates of trace gas emissions from the 1997 fire season in Alaska (see Table 3). The CO_2 estimates are fairly similar for the two studies (46 Tg CO_2 from *Goode et al.* [2000] and 42 Tg CO_2 from this study). Our estimations, however, result in 3 Tg more of CO and 0.03 Tg less of CH_4 released than estimated by *Goode et al.* [2000]. Their values vary from those presented in this study for several reasons. First, *Goode et al.* [2000] assumed a constant biomass for the entire state, as well as a constant fraction of carbon consumed. In addition, they did not differentiate combustion type between flaming and smoldering. As our analysis of varying the assumptions of flaming and smoldering (Table 5) shows, the gas release estimates are different as assumptions of flaming versus smoldering combustion are changed. This is primarily because of the impact of non-efficient smoldering combustion on creation of non-CO_2 gases. Further investigation into how much smoldering versus flaming actually occurs in boreal fires would be helpful in refining estimates of the various gases emitted.

[49] The comparison of our estimate with *Goode et al.*'s [2000] emphasizes a key feature of our analysis: the use of geospatially explicit data sets. This is important when input data varies in space, since spatially averaged data may not properly quantify the variable at the location of interest. Our technique allows more accurate input data to the model. For example, rather than using an average value for carbon present in the region, we use a carbon value that is estimated for the location that burned. GIS-based analysis also allows a geospatial interpretation of the results (Figure 3). Displaying our results as a map helps to depict the interaction of fire events and carbon pools to see where fire effects are the most important from the standpoint of carbon cycling (see also *French et al.* [2000] for results for North America.)

[50] Our analysis uses existing data sets to estimate carbon release during burning. Although these results are a first-order estimate, they show that the direct release of carbon during burning, particularly in high fire years, is substantial enough to warrant further refinement of input data. Under current research programs, we are working on improving the estimates of aboveground carbon and the fraction of carbon consumed so we can generate a more accurate, spatially defined set of input variables for our model. Improvements in fraction consumed will be made by mapping fire severity at recently burned sites using fine resolution (Landsat-scale) remote sensing data. Most of the uncertainty in quantifying carbon release from fire stems from the high variability in fraction consumed estimates, so understanding this variable is critical. In the future we hope to use more spatially explicit estimates of fraction consumed from these remote sensing measurements. Development of an uncertainty model, which propagates the uncertainty through the model, is also underway. The result will be an estimate of carbon released with confidence intervals, which provide useful information on the error associated with the result and for making predictions.

7. Conclusions

[51] We have used fire location information for a half-century (1950 to 1999) to examine the amount of carbon and carbon-based gas released during fire in the Alaskan boreal region, a region whose ecosystems are strongly affected by fire. We estimated that, on average, approximately 4.5 Tg of carbon is released annually from biomass burning in the boreal interior of Alaska, with an average area burned of 223,220 ha. The variability in the area burned from year to year is of great importance. In a high fire year (for example, in 1990, when 1.2 million hectares burned) 8 times the average (36 TgC) is released, while low years show relatively little carbon released (0.36 TgC in 1989, when 21,074 ha burned).

[52] We conclude that fire can cause an immediate release of carbon that is substantial when compared with NPP, and the amount varies widely from year to year, based on the location and amount of area burned. Our results show that it is not possible to understand the impact of fire on the atmosphere if average values are used because the year-to-year variation is so great. Moreover, the importance of fire

can be underestimated if a low fire year is used to represent the ‘‘normal’’ condition or overestimated if a high fire year is used.

[53] The interannual variations in trace gas emissions produced from this study parallel those discussed for total carbon emissions. Our estimates for trace gas emissions differ from previous studies, however, because we assume that a higher fraction of ground-layer biomass is consumed during smoldering fires than during flaming fires. This assumption results in a slightly lower level of CO_2 emissions and higher CO and CH_4 emissions.

[54] Using geospatial information we can analyze data and visualize results across the region. We can use more accurate input and gain a better appreciation for local variation in carbon release from burning than if nonspatially defined estimates are used. It is the combination of knowing where the carbon is, where the fire is, and how much is consumed during burning that allows us to map the release of carbon and carbon-based gases from fire in the boreal region of Alaska. Refinements in our input variables in both absolute values and in spatial pattern, will improve our estimates. The current study underscores the need to refine input variables since boreal fires may be a considerable source of carbon to the atmosphere and could play a critical role in the distribution of carbon and trace gases within the Earth system.

[55] **Acknowledgments.** The authors would like to thank Ed Hyer of the University of Maryland for helping to finalize the analysis, Mary Joscelyn for her help in editing the manuscript, and an anonymous reviewer for suggestions in revising an earlier version of the manuscript. The research presented in this paper was supported by NASA grant NAG59440 to the University of Maryland and ERIM. N.H.F.F. was partially supported by a NASA Earth System Science Fellowship.

References

Amiro, B. D., J. B. Todd, B. M. Wotton, K. A. Logan, M. D. Flannigan, B. J. Stocks, J. A. Mason, D. L. Martell, and K. G. Hirsch, Direct carbon emissions from Canadian forest fires, 1959 to 1999, *Can. J. For. Res.*, 2001.

Andreae, M. O., and P. Merlet, Emissions of trace gases and aerosols from biomass burning, *Global Biogeochem. Cycles*, *15*, 955–966, 2001.

Bergamaschi, P., R. Hein, C. A. Brenninkmeijer, and P. J. Crutzen, Inverse modeling of the global CO cycle, 2, Inversion of $^{13}C/^{12}C$ and $^{18}O/^{16}O$ isotope ratios, *J. Geophys. Res.*, *105*, 1929–1945, 2000.

Black, T. A., et al., Annual cycles of water vapour and carbon dioxide fluxes in and above boreal aspen forest, *Global Change Biol.*, *2*, 219–229, 1996.

Bourgeau-Chavez, L. L., E. S. Kasischke, J. P. Mudd, and N. H. F. French, Characteristics of forest ecozones in the North American boreal region, in *Fire, Climate Change, and Carbon Cycling in the North American Boreal Forest*, edited by E. S. Kasischke and B. J. Stocks, pp. 258–273, Springer-Verlag, New York, 2000.

Cahoon, D. R.,, Jr., B. J. Stocks, J. S. Levine, W. R. Cofer III, and J. M. Pierson, Satellite analysis of the severe 1987 forest fires in northern China and southeastern Siberia, *J. Geophys. Res.*, *99*, 18,627–18,638, 1994.

Chistjakov, V. I., A. I. Kuprijanov, V. V. Gorshkov, and E. S. Artsybashev, Measures for fire prevention on peat deposits, in *The Role of Fire in Northern Circumpolar Ecosystems*, edited by R. W. Wein and D. A. MacLean, pp. 259–271, John Wiley, New York, 1983.

Cofer, W. R., III, J. S. Levine, D. I. Sebacher, E. L. Winstead, P. J. Riggan, B. J. Stocks, J. A. Brass, V. G. Ambrosia, and V. J. Boston, Trace gas emissions from chaparral and boreal forest fires, *J. Geophys. Res.*, *94*, 2255–2259, 1989.

Cofer, W. R., III, J. S. Levine, E. L. Winstead, and B. J. Stocks, Gaseous emissions from Canadian boreal forest fires, *Atmos. Environ., Part A*, *24*(7), 1653–1659, 1990.

Cofer, W. R.,, III, E. L. Winstead, B. J. Stocks, L. W. Overbay, J. G. Goldammer, D. R. Cahoon, and J. S. Levine, Emissions from boreal forest fires: Are the atmospheric impacts underestimated?, in *Biomass Burning and Climate Change*, vol. 2, *Biomass Burning in South America, Southeast Asia, and Temperate and Boreal Ecosystems, and the Oil Fires of Kuwait*, edited by J. S. Levine, pp. 834–839, MIT Press, Cambridge, Mass., 1996.

Cofer, W. R., III, E. L. Winstead, B. J. Stocks, J. G. Goldammer, and D. R. Cahoon Jr., Crown fire emissions of CO_2, CO, H_2, CH_4 and TNMHC from a dense jack pine boreal forest fire, *Geophys. Res. Lett.*, *25*, 3919–3922, 1998.

Conard, S. G., A. L. Sukhinin, B. J. Stocks, D. R. Cahoon, D. P. Davidenko, and G. A. Ivanova, Determining effects of area burned and fire severity on carbon cycling and emissions in Siberia., *Clim. Change*, in press, 2001.

Dixon, R. K., and O. N. Krankina, Forest fires in Russia: carbon dioxide emissions to the atmosphere, *Can. J. For. Res.*, *23*, 700–705, 1993.

Dlugokencky, E. J., B. P. Walter, K. A. Masarie, P. M. Lang, and E. S. Kasischke, Measurements of an anomalous global methane increase during 1998, *Geophys. Res. Lett.*, *28*, 499–502, 1998.

Dyrness, C. T., L. A. Viereck, and K. VanCleve, Fire in taiga communities of interior Alaska, in *Ecological series*, vol. 57, *Forest Ecosystems in the Alaskan Taiga*, edited by K. VanCleve et al., Springer-Verlag, New York, 1986.

Forster, C., et al., Transport of boreal forest fire emissions from Canada to Europe, *J. Geophys. Res.*, *106*(D9), 22,887–22,906, 2001.

French, N. H. F., E. S. Kasischke, B. J. Stocks, J. P. Mudd, D. L. Martell, and B. S. Lee, Carbon release from fires in the North American boreal forest, in *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*, edited by E. S. Kasischke and B. J. Stocks, pp. 377–388, Springer-Verlag, New York, 2000.

Frolking, S., Sensitivity of spruce/moss boreal forest net ecosystem productivity to seasonal anomalies in weather, *J. Geophys. Res.*, *102*(D24), 29,053–29,064, 1997.

Fromm, M., J. Alfred, K. Hoppel, J. Hornstein, R. Bevilacqua, E. Shettle, R. Servranckx, Z. Li, and B. Stocks, Observations of boreal forest fire smoke in the stratosphere by POAM III, SAGE II, and lidar in 1998, *Geophys. Res. Lett.*, *27*(9), 1407–1410, 2000.

Goode, J. G., R. J. Yokelson, D. E. Ward, R. A. Susott, R. E. Babbitt, M. A. Davies, and W. M. Hao, Measurements of excess O_3, CO_2, CO, CH_4, C_2H_4, C_2H_2, HCN, NO, NH_3, HCOOH, CH_3COOH, HCHO, and CH_3OH in 1997 Alaska biomass burning plumes by airborne Fourier transform infrared spectroscopy (AFTIR), *J. Geophys. Res.*, *105*, 22,147–22,166, 2000.

Goulden, M. L., et al., Sensitivity of boreal forest carbon balance to soil thaw, *Science*, *279*, 214–217, 1998.

Hao, W. M., and D. E. Ward, Methane production from global biomass burning, *J. Geophys. Res.*, *98*, 20,657–20,661, 1993.

Harden, J. W., S. E. Trumbore, B. J. Stocks, A. Hirsch, S. T. Gower, K. P. O'Neill, and E. S. Kasischke, The role of fire in the boreal carbon budget, *Global Change Biol.*, *6*, 174–184, 2000.

Hess, J. C., C. A. Scott, G. L. Hufford, and M. D. Fleming, El Nino and its impact on fire weather conditions in Alaska, *Int J. Wildland Fire*, *10*, 1–13, 2001.

Hinzman, L. D., M. Fukuda, D. V. Sandberg, F. S. Chapin III, and D. Dash, FROSTFIRE: An experimental approach to predicting the climate feedbacks from the changing boreal fire regime, *J. Geophys. Res.*, *107*, doi:10.1029/2001JD000415, in press, 2002.

Johnson, E. A., *Fire and Vegetation Dynamics: Studies from the North American Boreal Forest*, Cambridge Univ. Press, New York, 1992.

Kasischke, E. S., and L. M. Bruhwiler, Emissions of carbon dioxide, carbon monoxide and methane from boreal forest fires in 1998, *J. Geophys. Res.*, *107*, doi:10.1029/2001JD000461, in press, 2002.

Kasischke, E. S., and B. J. Stocks (Eds.), *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*, 461 pp., Springer-Verlag, New York, 2000.

Kasischke, E. S., N. H. F. French, L. L. Bourgeau-Chavez, and N. L. Christensen Jr., Estimating release of carbon from 1990 and 1991 forest fires in Alaska, *J. Geophys. Res.*, *100*(D2), 2941–2951, 1995.

Kasischke, E. S., N. H. F. French, L. L. Bourgeau-Chavez, and J. L. Michalek, Using satellite data to monitor fire-related processes in boreal forests, in *Fire, Climate Change, and Carbon Cycling in the North American Boreal Forest*, edited by E. S. Kasischke and B. J. Stocks, pp. 406–422, Springer-Verlag, New York, 2000a.

Kasischke, E. S., K. P. O'Neill, N. H. F. French, and L. L. Bourgeau-Chavez, Controls on patterns of biomass burning in Alaskan boreal forests, in *Fire, Climate Change, and Carbon Cycling in the North American Boreal Forest*, edited by E. S. Kasischke and B. J. Stocks, pp. 173–196, Springer-Verlag, New York, 2000b.

Lacelle, B., C. Tarnocai, S. Waltman, J. Kimble, F. Orozco-Chavez, and B. Jakobsen, North American Soil Carbon Map, Agriculture and Agri-Food Canada, USDA, INEGI, Inst. of Geography, Univ. of Copenhagen, 1997.

Murphy, P. J., B. J. Stocks, E. S. Kasischke, D. Barry, M. E. Alexander, N. H. F. French, and J. P. Mudd, Historical fire records in the North American boreal forest, in *Fire, Climate Change, and Carbon Cycling in the North American Boreal Forest*, edited by E. S. Kasischke and B. J. Stocks, pp. 274–288, Springer-Verlag, New York, 2000.
O'Neill, K. P., Changes in carbon dynamics following wildfire in soils of interior Alaska, Ph.D. dissertation, Duke Univ., Durham, N. C., 2000.
O'Neill, K. P., E. S. Kasischke, and D. D. Richter, Seasonal and decadal patterns of soil carbon uptake and emission along an age-sequence of burned black spruce stands in interior Alaska, *J. Geophys. Res.*, *107*, doi:10.1029/2001JD000443, in press, 2002.
Randerson, J. T., M. V. Thompson, T. J. Conway, I. Y. Fung, and C. B. Field, The contributions of terrestrial sources and sinks to trends in the seasonal cycle of atmospheric carbon dioxide, *Global Biogeochem. Cycles*, *11*(4), 535–560, 1997.
Richter, D., E. S. Kasischke, and K. P. O'Neill, Postfire stimulation of microbial decomposition in black spruce (*Picea mariana* L.) forest soils: A hypothesis, in *Fire, Climate Change, and Carbon Cycling in the North American Boreal Forest*, edited by E. S. Kasischke and B. J. Stocks, pp. 197–213, Springer-Verlag, New York, 2000.
Seiler, W., and P. J. Crutzen, Estimates of gross and net fluxes of carbon between the biosphere and atmosphere, *Clim. Change*, *2*, 207–247, 1980.
Skinner, W. R., B. J. Stocks, D. L. Martell, B. Bonsal, and A. Shabbar, The relationship between area burned by wildland fire in Canada and circulation anomalies in the mid-troposphere, in *Biomass Burning and Its Inter-Relationship With the Climate System*, edited by J. L. Innes, M. Beniston, and M. M. Verstraete, pp. 101–125, Kluwer Acad., Norwell, Mass., 2000.
Stocks, B. J., and J. B. Kauffman, Biomass consumption and behavior of wildland fires in boreal, temperate, and tropical ecosystems: Parameters necessary to interpret historic fire regimes and future fire scenarios, in *Sediment Records of Biomass Burning and Global Change*, edited by J. S. Clark et al., pp. 169–188, Springer-Verlag, New York, 1997.
Stocks, B. J., et al., Climate change and forest fire potential in Russian and Canadian boreal forests, *Clim. Change*, *38*, 1–13, 1998.
Turetsky, M. R., and R. K. Wieder, A direct approach to quantifying organic matter lost as a result of peatland wildfire, *Can. J. For. Res.*, *31*, 363–366, 2001.
Viereck, L. A., Wildfire in the taiga of Alaska, *Quat. Res.*, *3*, 465–495, 1973.
Viereck, L. A., The Effects of Fire in Black Spruce Ecosystems of Alaska and Northern Canada, in *The Role of Fire in Northern Circumpolar Ecosystems*, edited by R. W. Wein and D. A. MacLean, pp. 201–220, John Wiley, New York, 1983.
Wein, R. W., and D. A. MacLean, *The Role of Fire in Northern Circumpolar Ecosystems*, John Wiley, New York, 1983.
Wotton, B. M., and M. D. Flannigan, Length of the fire season in a changing climate, *For. Chron.*, *69*, 187–192, 1993.
Yokelson, R. J., and R. Susott, et al., Emissions from smoldering combustion of biomass measured by open-path Fourier transform infrared spectroscopy, *J. Geophys. Res.*, *102*, 18,865–18,877, 1997.
Zoltai, S. C., L. A. Morrissey, G. P. Livingstone, and W. J. de Groot, Effects of fires on carbon cycling in North American peatlands, *Environ. Rev. (Ottawa)*, *6*, 13–24, 1998.

N. H. F. French, Center for Energy and Environmental Research, Altarum (formerly ERIM), PO Box 134001, Ann Arbor, MI 48113-4001, USA. (nancy.french@altarum.org)

E. S. Kasischke and D. G. Williams, Department of Geography, University of Maryland, 2181 LeFrak Hall, College Park, MD 20742, USA.