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# Emissions of carbon dioxide, carbon monoxide, and methane from boreal forest fires in 1998

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[1] The global boreal forest region experienced some 17.9 million ha of fire in 1998, which could be the highest level of the decade. Through the analysis of fire statistics from North America and satellite data from Russia, semimonthly estimates of area burned for five different regions in the boreal forest were generated and used to estimate total carbon release and $CO_2$, CO, and $CH_4$ emissions. Different levels of biomass, as well as different biomass categories, were considered for each of the five different regions (including peatlands in the Russian Far East and steppes in Siberia), as were different levels of fraction of biomass (carbon) consumed during fires. Finally, two levels of flaming versus smoldering combustion were considered in the model. Boreal forest fire emissions for 1998 were estimated to be 290–383 Tg of total carbon, 828–1103 Tg of $CO_2$, 88–128 Tg of CO, and 2.9–4.7 Tg of $CH_4$. The higher estimate represents 8.9% of total global carbon emissions from biomass burning, 13.8% of global fire CO emissions, and 12.4% of global fire $CH_4$ emissions. Russian fires accounted for 71% of the total emissions, with the remainder (29%) from fires in North America. Assumptions regarding the level of smoldering versus flaming generally resulted in small (<4%) variations into the emissions estimates, although in two cases, these variations were higher (6% and 12%). We estimated that peatland fires in the Russian Far East contributed up to 40 Tg of carbon to the atmosphere in the fall of 1998. The combined seasonal CO emissions from forest and peatland fires in Russia are consistent with anomalously high atmospheric CO measurements collected at Point Barrow, Alaska. *INDEX TERMS:* 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 1610 Global Change: Atmosphere (0315, 0325); 1615 Global Change: Biogeochemical processes (4805); *KEYWORDS:* boreal forest fires, peatland fires

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## 1. Introduction

[2] Large areas of the Russian and North American boreal forest burned in 1998. Official government statistics indicate fires affected 4.8 million ha (Mha) in the North American boreal forest region (Alaska and Canada) and 2.7 Mha in Russia. However, a much higher level of fire activity in Russia was detected on satellite imagery collected by the Advanced Very High Resolution Radiometer (AVHRR) system (between 9.5 and 11.5 Mha from estimates of *Conard et al.* [2002] and A. Isaev (Russian Academy of Sciences, personal communication, 2000).

[3] During dry, warm summers, biomass burning in the boreal forest produces large amounts of atmospheric trace gases whose influences on atmospheric chemistry may be quite different from other regions where fires are common, such as the tropics and subtropics [*Cofer et al.*, 1996a]. Studies have shown emissions from boreal forest fires influence atmospheric trace gas measurements at local and regional scales [*Wofsy et al.*, 1992; *Crutzen et al.*, 1998; *Wotawa and Trainer*, 2000; *Fromm et al.*, 2000; *Tanimoto et al.*, 2000; *Dlugokencky et al.*, 2001; *Forster et al.*, 2001]. High levels of emissions from boreal forest fires have been reported [*Amiro et al.*, 2001; *Cahoon et al.*, 1994; *French et al.*, 2000; *Kasischke et al.*, 1995a].

[4] Biomass burning on a global basis emits 3800 to 4300 Tg C $yr^{-1}$ [*Andreae*, 1991; *Andreae and Merlet*, 2001]. *Seiler and Crutzen* [1980] estimated that fires in boreal forest are a relatively minor contributor to global emissions from biomass burning, 23 Tg C $yr^{-1}$, or 0.6% of the global total (based on *Andreae* [1991]). *Bergamaschi et al.* [2000] estimated carbon monoxide emissions from fires in forests above 30°N latitude at 50 Tg $yr^{-1}$ (~6% of the total from biomass burning) while a study by *Galanter et al.* [2000] estimated that 121 Tg of CO are emitted annually from this region. *Hao and Ward* [1993] estimated methane emissions from fires in the boreal forest region are 0.9 Tg C $yr^{-1}$


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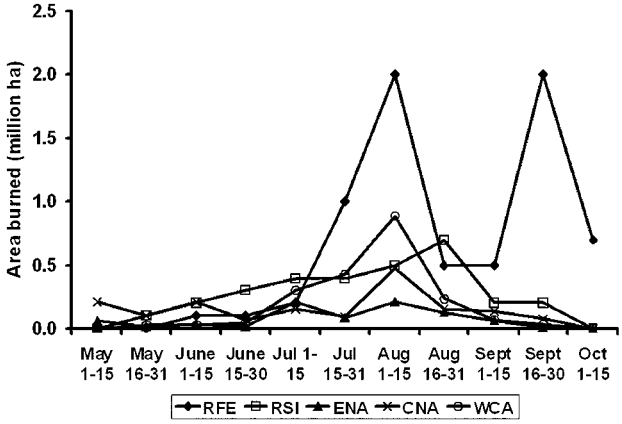


**Figure 1.** Semimonthly estimates of area burned in 1998 for the five different boreal forest regions used in this study (RFE—Russian Far East; RSI—Russian Siberia; ENA—Eastern North America; CNA—Central North America; WNA—Western North America).

(~3% of the all methane emissions from global biomass burning).

[5] Several recent studies have estimated total carbon emissions from fires in Canada and eastern Russia in 1998 [*Amiro et al.*, 2001; *Conard et al.*, 2002]. In this paper, we build on and extend the results of these studies. While we use the same or similar information on area burned as *Amiro et al.* [2001] and *Conard et al.* [2002], we applied these data to produce emissions estimates for specific regions and time periods. In addition, we estimated total carbon emission and emissions of $CO_2$, CO, and $CH_4$. Finally, we considered variable combustion efficiencies [fractions of biomass (carbon) consumed] for different boreal forest regions, and different allocations between flaming and smoldering combustion.

## 2. Methods

[6] Total carbon release through biomass burning ($C_t$) can be estimated after *Seiler and Crutzen* [1980] as:

$$C_t = ABf_c\beta \quad (1)$$

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 $\beta$ is the fraction of biomass consumed (or combustion efficiency) during biomass burning.

[7] Fires in the boreal region differ from those in temperate and tropical areas because there is burning of forest floor fuels (including litter, lichen, live and dead organic soils) [*Chistjakov et al.*, 1983; *Wein*, 1983; *Stocks and Kauffman*, 1997; *Kasischke et al.*, 2000a; *Shvidenko and Nilsson*, 2000b]. To account for this type of burning, equation (1) is modified after *French et al.* [2000] to

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

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 0.45), $\beta_a$ is the fraction of aboveground vegetation consumed during fires, $C_g$ is the carbon density (t $ha^{-1}$) of the organic mat exposed to fire, and $\beta_g$ is the fraction of this organic mat carbon consumed during fires.

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

$$E_s = C_t E_{fs} \quad (3)$$

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

[9] In some cases, the data needed to generate input parameters for equations (2) and (3) are very well defined, whereas in others, they are based on a very limited set of observations or data. The sources of uncertainty in these parameters are more fully discussed in section 4 of this paper. In developing input parameters for equations (2) and (3) presented in the following sections, we divided the global boreal forest into five regions—Russian Far East (RFE), Russian Siberia (RSI), and Eastern, Central and Western North America (ENA, CNA, and WNA, respectively).

### 2.1. Estimates of Area Burned in 1998

[10] Figure 1 presents semimonthly estimates of area burned in 1998 for the Eastern, Central and North American regions using data summarized in weekly fire reports by the Canadian and U.S. governments (for a summary of these data, see http://www.cidi.org/wildfire/index.html).

[11] The Federal Forest Service (FFS) of Russia compiles national statistics on area burned [*Korovin*, 1996]. Analyses of FFS statistics have shown that the methods employed in Russia resulted in a systematic underreporting of annual area burned [*Conard and Ivanova*, 1998; *Shvidenko and Nilsson*, 2000a; *Conard et al.*, 2002], a conclusion supported by analysis of area burned mapped from satellite imagery [*Cahoon et al.*, 1994; *Kasischke et al.*, 1999].

[12] Data collected by NOAA's Advanced Very High Resolution Radiometer (AVHRR) system were used to estimate the extent and timing of fires in Russia in 1998 [*Kasischke et al.*, 1999; *Conard et al.*, 2002]. Previous studies have shown that information present in AVHRR imagery can be used to map large burn scars common in the boreal forest region [*Cahoon et al.*, 1992; *Kasischke et al.*, 1993; *Cahoon et al.*, 1994; *Kasischke and French*, 1995; *Cahoon et al.*, 1996]. Another option is to produce fire area estimates from information products created through analysis of the thermal IR channels of the AVHRR sensor [*Dwyer et al.*, 1998; *Stroppiana et al.*, 2000]. However, studies have shown these products underestimate the area of actual burns, and have a large number of false alarms [*Li et al.*, 2000]. The thresholds in the global fire detection algorithms have been adjusted to eliminate the false alarms in the boreal region [*Boles and Verbyla*, 2000; *Li et al.*, 2000].

[13] *Conard et al.* [2002] estimated 11.5 Mha burned in Siberia and the Russian Far East using a combination of burn scars and hot spots detected and mapped on AVHRR imagery. This combination of approaches was used because cloud-free AVHRR imagery was not available at the end of the growing season in all areas where fire occurred. In addition, there were some areas in Russia where AVHRR imagery was not available and/or analyzed. By combining the AVHRR estimates with official fire statistics, and adjust-

ing the fire statistics for the observed bias (underestimation), *Conard et al.* [2002] estimated that 13.3 million ha of fire occurred in Russia in 1998. In this study, we assumed a conservative estimate of 13.1 million ha of area burned in Russia in 1998, with 6 million ha in Siberia and 7.1 in the Russian Far East.

[14] Analysis of AVHRR imagery showed that 3 million ha of fire in Russian Siberia occurred in steppe regions during May, and the remaining 3 million ha occurred in forested areas throughout the summer (A. Sukhinin, personal communication, 2000). For the Siberian portion of Russia, we assumed that 2/3 of the 1998 burning occurred in July and August (Figure 1), a pattern that has been observed during previous years.

[15] The temporal sequence of fire activity in the Russian Far East (Figure 1) was derived through an analysis of the AVHRR imagery and smoke signatures observed on aerosol products from Total Ozone Mapping Spectrometer (TOMS) imagery [*Herman et al.*, 1997; *Hsu et al.*, 1999]. The TOMS instrument is an imaging spectrometer with six 1 nm wide channels between 312.3 and 380.0 nm. A standard aerosol detection/mapping algorithm (which detects both smoke and dust clouds) that uses two channels for mapping total column aerosol (above the atmospheric boundary layer above an elevation of ca. 1 km) has been developed for this system by NASA scientists. Figure 2b presents a standard TOMS aerosol image product from the Russian Far East region in 1998 (additional TOMS fire image products generated by NASA for the RFE region can be viewed at http://jwocky.gsfc.nasa.gov/).

[16] Surface observations of anomalous atmospheric carbon monoxide signatures were used to further check the temporal patterns of fire in Russia. The flask samples and continuous observations of CO in Figure 2c were collected at Point Barrow, Alaska as part of a globally distributed air-sampling network maintained by the NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) [*Novelli et al.*, 1998]. Data from this network were obtained and analyzed to produce Figure 2c, which presents CO anomalies after subtraction of a long-term quadratic trend and an average seasonal cycle (based on data collected between 1991 and 2000) (after procedures described by *Masarie and Tans* [1995]). The CO data in Figure 2c indicate there were elevated CO emissions upwind from Barrow in mid-August and throughout September and October, occurring at the same time as the high fire activity detected on the AVHRR and TOMS imagery.

### 2.2. Carbon Release by Fires

[17] Data are available which document the spatial distribution of aboveground ($B_a f_{ca}$) and organic soil carbon ($C_g$) in both North America [*Tarnocai*, 1997; *Lacelle et al.*, 1997] and Russia [*Stone et al.*, 1997; *Shvidenko et al.*, 1998]. There is still considerable debate on the fraction of carbon consumed terms ($\beta_a$ and $\beta_g$), centering on: (a) the types of fires occurring in Russia; and (b) the degree to which ground-layer organic matter is combusted during fires in North America and Russia [*Stocks and Kauffman*, 1997; *Kasischke et al.*, 1999, 2000a; *Shvidenko et al.*, 2000; *Conard et al.*, 2002]. Because of these uncertainties, we used model inputs representing a range of fuel levels, fire severities and fuel consumptions. Because the vegetation and fire types are closely linked, we discuss the parameters related to each in the same section for the two different boreal forest regions (North America and Russia).

#### 2.2.1. North America

[18] Average carbon density and fraction of biomass (carbon) consumed were based on the different ecozones within each of the three regions [*Bourgeau-Chavez et al.*, 2000]. Eastern North America included the East Boreal Shield, East Taiga Shield, and Hudson Plains ecozones. Central North America included the West Boreal Shield, West Taiga Shield and Boreal Plains ecozones. Western North America included the Taiga Plains, Boreal Cordillera, and Alaska Boreal Interior ecozones.

[19] In the North American boreal forest, most large-scale fires are stand-replacement crown fires that result in high levels of biomass consumption and carbon release. Several studies have estimated carbon release from fires in the North American boreal forest. *Amiro et al.* [2001] used a large-fire database to locate fires throughout Canada from 1959 to 1999 combined with average fuel levels in different ecozones and fire behavior models to estimate levels of fuel consumption for the different fires. *Amiro et al.* [2001] estimated that 13.1 t of carbon is released per hectare burned (ranging from 9 to 16.8 t C $ha^{-1}$ burned for the different years). *French et al.* [2000] used a similar approach for the years 1980 to 1994, and included Alaska. However, the fraction of biomass (carbon) consumed values used by *French et al.* [2000] were based on seasonal patterns of fire, with $\beta_a$ and $\beta_g$ proportional to the area burned in a specific year. *French et al.* [2000] estimated higher carbon emissions (20.5 t C $ha^{-1}$ burned with a range of 9.0 to 37.2 t C $ha^{-1}$ burned) than *Amiro et al.* [2001] because of higher levels of burning of organic soils.

[20] We used an average of the fraction of biomass (carbon) consumed values presented by *French et al.* [2000] based on the ecozones within each region. Three different fire severity categories were assumed (low, medium and high), with each category/region having a different set of fraction of carbon consumed (Table 1). The combination of fire severity categories and carbon densities in Table 1 result in a range of total carbon emissions (9 to 37 t C $ha^{-1}$ burned) that match those reported in the literature [*Stocks and Kauffman*, 1997; *French et al.*, 2000; *Kasischke et al.*, 2000a, 2000b; *Amiro et al.*, 2001].

#### 2.2.2. Russia

[21] For Russia, we considered biomass burning in three vegetation types: forests, steppes, and peatlands. The last type was considered because burn scar locations on satellite imagery collected over Russian Far East showed many fires occurred within a large peatland basin adjacent to the Amur River (1000 km long and 50 to 300 km wide as mapped by *Neustadt* [1984]).

[22] The consensus among Russian scientists is that although large forest fires occur, most burning occurs in surface fires. Crown fires are estimated to account for 10% of fires during average years [*Shvidenko and Nilsson*, 2000a] and up to 50% of fires in severe years [*Conard et al.*, 2002]. *Conard and Ivanova* [1998] and *Conard et al.* [2002] describe three levels of fire severity: (a) low-intensity surface fires where only a small fraction of understory vegetation and litter is consumed; (b) moderate-intensity

Earth Probe TOMS
Smoke over eastern Russia for Sep 24, 1998
NASA
GSFC/916
4.2
3.7
3.2
2.7
2.2
1.7
1.2
0.7
Aerosol Index




1998: Barrow, AK
CO (ppb)
200
150
100
50
0
−50
J F M A M J J A S O N D J

**Table 1.** Summary of Aboveground and Ground-Layer Carbon Density Values and Fraction of Biomass (Carbon) Consumed Values for the North American Boreal Forest Regions

| | Carbon Density, t ha$^{-1}$ | | Fraction of Biomass (Carbon) Consumed (β) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | High Fire Severity | | Moderate Fire Severity | | Low Fire Severity | |
| Region | $B_a f_{ca}$ | $C_g$ | Aboveground | Ground-Layer | Aboveground | Ground-Layer | Aboveground | Ground-Layer |
| Eastern North America | 16.7 | 101.0 | 0.29 | 0.11 | 0.29 | 0.11 | 0.24 | 0.05 |
| Central North America | 19.7 | 84.4 | 0.29 | 0.17 | 0.29 | 0.12 | 0.24 | 0.07 |
| Western North America | 24.0 | 103.7 | 0.25 | 0.30 | 0.25 | 0.20 | 0.20 | 0.12 |

surface fires where 90% of understory vegetation and 50% of the litter is consumed; and (c) high-intensity crown fires, where 40% of aboveground fuels are consumed as well as 100% of combustible fine fuels.

[23] Estimates of carbon release from fires are based on a limited amount of data and modeling results. *Shvidenko and Nilsson* [2000b] estimated that 10.0 t C ha$^{-1}$ burned is released from burning of vegetation during surface fires, while 1.0 t C ha$^{-1}$ burned is released from burning of organic soils. For crown fires, *Shvidenko and Nilsson* [2000b] estimated 20.0 t C ha$^{-1}$ burned is released from vegetation, while 1.2 t C ha$^{-1}$ burned is released from burning of organic soils. However, based on field observations, the *FIRESCAN Science Team* [1996] estimated that during crown fires, nearly 11.0 t C ha$^{-1}$ burned was released from burning of organic soils in a forest that contained a relatively shallow (7 cm) organic soil layer. *Conard et al.* [2002] estimate that a total of 2.3 t C ha$^{-1}$ burned are released during low-intensity surface fires, 8.6 t C ha$^{-1}$ burned are released during moderate-intensity surface fires, and 22.5 t C ha$^{-1}$ burned are released during crown fires.

[24] Our assessment of patterns of severity in the 1998 Russian fires is different than that presented by *Conard et al.* [2002]. Based on an analysis of satellite imagery collected over the Russian Far East, we concluded that the majority of fires in this region were crown fires. These fires resulted in very distinct burn scars that were detected on AVHRR imagery collected in 1998 and Landsat 7 satellite imagery collected in 1999. Studies have shown that satellite signatures of surface and crown fires are different [*Michalek et al.*, 2000; *Isaev et al.*, 2002]. Surface fires rarely result in complete mortality of overstory trees, whereas crown fires result in 100% mortality. In the case of surface fires where crowning does not occur, a significant portion of live trees remain, resulting in a different spectral signature when compared to areas where 100% mortality has occurred. The satellite-observed burn scars from the 1998 fires in the Russian Far East were characteristic of crown fires, not surface fires. In addition, the level of atmospheric aerosols mapped by the TOMS satellite indicate that large amounts of smoke were being injected high (>1 km) into the atmosphere by fires in the Russian Far East. This level of smoke injection is the likely result of high-energy crown fires, not lower-energy surface fires (which produce smoke that remains within the atmospheric boundary layer below 1 km elevation and is not detectable by TOMS).

[25] We estimated carbon release for three fire severity categories: low, medium and high. We assumed the amounts of carbon released from burning of vegetation were 10.0, 15.0, and 20.0 t C ha$^{-1}$ burned, for the light, moderate, and severe burn categories, respectively. For burning of organic soils, we assumed 1.0, 6.5, and 12.0 t C ha$^{-1}$ burned, for the light, moderate, and severe burn categories, respectively.

[26] We assumed vegetation in the steppe region of Siberia is similar to grassland savanna ecosystems where much research on biomass burning has taken place. Based on studies by *Hao et al.* [1990], we estimated that steppes had an average aboveground carbon density of 2.0 t ha$^{-1}$ with 83% consumption of this biomass during fire.

[27] While the burning of the organic soil of peatlands is rare, it does occur [*Zoltai et al.*, 1998; *Morrissey et al.*, 2000]. Evidence from both Canada and Russia shows that peatlands can burn later in the growing season (August/September) if the climate patterns permit their drying out [*Wein*, 1983; *Chistjakov et al.*, 1983; *Turetsky and Wieder*, 2001]. *Wein* [1983] presented an example where one meter of organic soil in a Manitoba peatland burned during the exceptionally low rainfall year of 1976. *Turetsky and Wieder* [2001] showed that an average of 22 t C ha-1 burned was released from biomass burning in four different Canadian peatland types within a 1999 fire.

[28] *Gorham* [1991] estimates boreal peatlands have an average depth of 2.5 meters, and a carbon density of 5.8 t C ha$^{-1}$ per cm depth of the peat. For this study, we assumed that 500,000 ha of peatlands burned in the Russian Far East during a one-month period beginning in mid-September 1998. We assumed these peatland fires consumed a total of 40 t C ha$^{-1}$ during each two-week period (7 cm of organic soil). While the total amount of carbon released from the

**Figure 2.** (opposite) Satellite imagery and atmospheric carbon monoxide data showing the high levels of fire activity in the Russian Far East in 1998. (a) A false-color composite image from the visible, near infrared and thermal infrared channels of the Advanced Very High Resolution Radiometer (AVHRR) system collected on 24 September 1998. The red areas in the imagery are burn scars, and the brighter pink areas are active fire fronts. (b) An atmospheric aerosol product generated from the Total Ozone Mapping System (TOMS) on 24 September 1998. The smoke from fires in the Russian Far East regions created the aerosol plume on this image. Many similar smoke plumes were observed during the summer/fall of 1998. (c) Residual CO mixing ratio after subtraction of a quadratic long-term trend and average seasonal cycle from atmospheric samples collected by NOAA's Climate Modeling and Diagnostics Laboratory (CMDL) at Point Barrow, Alaska. Black crosses: hourly average CO from the CMDL continuous analyzer. Red diamonds: flask samples. See color version of this figure at back of this issue.

**Table 2.** Emission Factors[a] for Flaming and Smoldering Combustion in Boreal Forests and for Combined Flaming/Smoldering Combustion in Savannas

| Source | Region | $CO_2$ | CO | $CH_4$ |
|---|---|---|---|---|
| | *Boreal Forest—Flaming* | | | |
| *Goode et al.* [2000] | Alaska | 3320 | 178 | 56 |
| *Cofer et al.* [1996b] | Russia | 3000 | 240 | 42 |
| *Cofer et al.* [1998] | Northwest Territories | 3060 | 200 | 48 |
| *Cofer et al.* [1989] | Canada | 3200 | 140 | 74 |
| | Average | 3145 | 190 | 55 |
| | *Boreal Forest—Smoldering* | | | |
| *Cofer et al.* [1996b] | Russia | 2200 | 700 | 136 |
| *Cofer et al.* [1998] | Northwest Territories | 2689 | 409 | 173 |
| *Cofer et al.* [1989] | Canada | 2880 | 270 | 148 |
| | Average | 2590 | 460 | 152 |
| | *Savanna—Combined* | | | |
| *Lacaux et al.* [1993] | Global | 3220 | 142 | 168 |

[a]Emission factors are expressed in grams of gas released per kilogram of carbon burned.

peatland burning is high (80 t C $ha^{-1}$), it represents a small fraction of the carbon stored in these systems (less than 6% if the peatlands are assumed to have an average depth of 2.5 m).

### 2.3. Emissions of $CO_2$, $CH_4$, and CO

[29] Data collected in laboratory and field studies were used to estimate the amounts of trace gases released during biomass burning in boreal forests [*Cofer et al.*, 1989, 1990; *Nance et al.*, 1993; *Cofer et al.*, 1996b, 1998; *Goode et al.*, 2000]. These data were used to estimate emission factors—the amount of greenhouse gas released per unit of biomass burned.

[30] Two types of combustion were considered when estimating emission factors: flaming and smoldering. Smoldering combustion is less efficient than flaming combustion, and results in lower emissions of carbon dioxide ($CO_2$), but higher emissions of carbon monoxide (CO), methane ($CH_4$), and a variety of nonmethane hydrocarbons. Boreal forest fires may have a higher level of smoldering combustion than other biomes. Organic soils typically have high fuel moisture and bulk density, and lower oxygen contents, all of which result in inefficient combustion.

[31] Table 2 lists the published emission factors for flaming and smoldering combustion in boreal forests, and combined flaming/smoldering combustion for grassland savannas. Note that Table 2 lists the emission factors as a function of the amount of carbon burned, rather than the amount of biomass burned. This approach was adopted because in publishing emission factors, some researchers assumed biomass was 45% carbon, while others assumed the biomass was 50% carbon.

[32] To estimate greenhouse gas emissions using the levels of carbon released estimated by equation (3), it is necessary to allocate the biomass burned between flaming combustion and smoldering combustion. Studies have not been carried out in boreal forests to quantify the fractions of biomass consumed during the two combustion phases. Observations of fires indicate that a high percentage (60 to 80%) of aboveground biomass is consumed during flaming combustion, while more organic soil biomass (e.g., duff) is consumed by smoldering combustion [*Johnson*, 1992].

[33] Two sets of assumptions were used in this study. First, based on previous studies [*Cahoon et al.*, 1994], we assumed 50% flaming combustion and 50% smoldering combustion. Second, because of the differences in combustion in aboveground and ground-layer biomass observed for boreal forests, we assumed: (1) 80% of the aboveground vegetation was consumed by flaming combustion, and 20% by smoldering combustion; and (2) 20% of the organic mat carbon was consumed by flaming combustion, and 80% by smoldering combustion.

[34] We assumed that 100% of the peat in the Russian Far East was consumed by smoldering combustion because we felt the higher moisture content and high bulk density of peat does not support flaming combustion.

### 2.4. Biomass Burning Scenarios

[35] For exercising the emissions model, we assumed there were seasonal variations in the patterns of biomass consumption during fires, with lower levels in the spring and early summer and higher levels in late summer and fall (Table 3). The differences in fire severity were quantified as variations in fraction of biomass (carbon) consumed in Table 1.

## 3. Results

[36] Table 4 summarizes the average level of carbon release from biomass burning in the different boreal forest regions. These estimates do not include the burning of steppes or peatlands in Russia, and are weighted according to the area burned in the specific region over the entire growing season.

[37] The average total carbon emissions for Scenarios 1 and 2 agree with those estimated for North America by *Amiro et al.* [2001], while the values for Scenario 3 are closer to the values reported by *French et al.* [2000]. The values for Russian Siberia for all scenarios match those estimated by *Shvidenko and Nilsson* [2000b], while the values for the Russian Far East are slightly higher. The Russian estimates are higher than those of *Conard et al.* [2002].

[38] The variability of carbon loading in different vegetation types combined with the spatial/temporal patterns of

**Table 3.** Seasonal Patterns of Burn Severity Assumed in This Study for the Five Different Boreal Forest Regions[a]

| | RFE | RSI | ENA | CNA | WNA |
|---|---|---|---|---|---|
| | | | *Scenario 1* | | |
| May | Low | Low | Low | Low | Low |
| June | Low | Low | Low | Low | Low |
| July | Low | Low | Moderate | Moderate | Moderate |
| August | Low | Low | Moderate | Moderate | Moderate |
| September | Moderate | Moderate | Moderate | Moderate | Moderate |
| October | Moderate | Moderate | | | |
| | | | *Scenario 2* | | |
| May | Low | Low | Low | Low | Low |
| June | Low | Low | Low | Low | Low |
| July | Moderate | Moderate | Moderate | Moderate | Moderate |
| August | Moderate | Moderate | Moderate | Moderate | Moderate |
| September | Moderate | Moderate | High | High | High |
| October | Moderate | Moderate | | | |
| | | | *Scenario 3* | | |
| May | Low | Low | Low | Low | Low |
| June | Low | Low | Low | Low | Low |
| July | Moderate | Moderate | Moderate | Moderate | Moderate |
| August | High | High | High | High | High |
| September | High | High | High | High | High |
| October | High | High | | | |

[a]RFE—Russian Far East; RSI—Russian Siberia; ENA—Eastern North America; CNA—Central North America; and WNA—Western North America.

the fraction of biomass consumed during fires leads to several orders of magnitude in variation in the trace gas emission estimates per unit area burned (Figure 3). Across all fuel types, carbon release and $CO_2$ emissions vary by a factor of 44 while $CH_4$ and CO emissions vary by a factor of 187 and 145, respectively. Within the different forest types and fire severities, this variation is much less but still considerable—a factor of 3.1 to 5.2 for total carbon and $CO_2$, $CH_4$ and CO emissions.

[39] A significant fraction of the carbon released during fires in different boreal forest regions derives from burning of biomass present in the organic mat (e.g., moss, litter, lichen and organic soils). The percent of total carbon release coming from burning of organic mat material is higher in North America (54 to 84%) than in Russia (9 to 38%).

[40] Table 5 summarizes the estimates of total carbon release, average carbon release, and total emissions of $CO_2$, CO and $CH_4$ for the different burn severity cases. The results show that the assumptions defining the degree of flaming versus smoldering combustion produced small differences in emission estimates, less than 4%, with two exceptions [the low burning scenario for CO emissions (12%) and $CH_4$ (6%)].

[41] Because of the severity of fires observed on satellite imagery collected over Russia and from our observations of fire in North America, we feel that the emissions estimates from Scenarios 2 and 3 match the conditions that most likely occurred in 1998. We also feel that peatland burning occurred in the Russian Far East. These assumptions result in a range of emission estimates from boreal forest fires in 1998: 290 to 383 Tg of total carbon, 828 to 1103 Tg of $CO_2$, 88 to 128 Tg of CO, and 2.9 to 4.7 Tg of $CH_4$.

[42] The data in Table 5 show total emissions for the moderate severity case and scenario 3 are similar. Figure 4a presents a plot of seasonal emissions of CO from all boreal forest fires based on these two cases. Plots for total carbon, $CO_2$ and $CH_4$ exhibit the same seasonal pattern. Both cases show peaks in CO emissions in early August and late

**Table 4.** Summary of Average Levels of Carbon Release[a] as a Function of Fire Severity During Biomass Burning for the Five Boreal Forest Regions[b]

| | RFE | RSI | ENA | CNA | WNA | North America | Russia | Total |
|---|---|---|---|---|---|---|---|---|
| Low | 11.0 | 11.0 | 9.9 | 10.9 | 17.7 | 13.8 | 11.0 | 11.9 |
| Moderate | 21.5 | 21.5 | 16.2 | 16.0 | 26.8 | 20.9 | 21.5 | 21.3 |
| High | 32.0 | 32.0 | 16.2 | 20.1 | 37.2 | 27.1 | 32.0 | 30.4 |
| Scenario 1 | 15.7 | 12.4 | 15.2 | 14.2 | 26.3 | 19.8 | 14.7 | 16.4 |
| Scenario 2 | 21.2 | 12.4 | 15.2 | 14.7 | 26.9 | 20.3 | 18.6 | 19.1 |
| Scenario 3 | 25.9 | 13.8 | 15.2 | 16.2 | 32.5 | 23.4 | 22.3 | 22.7 |

Weighted average value does not include nonforested areas of steppes and peatlands in Russia. Values were weighted for each scenario by the level of burning during the entire fire season.

[a]Carbon release is measured in t $ha^{-1}$ burned.

[b]RFE—Russian Far East; RSI—Russian Siberia; ENA—Eastern North America; CNA—Central North America; and WNA—Western North America.

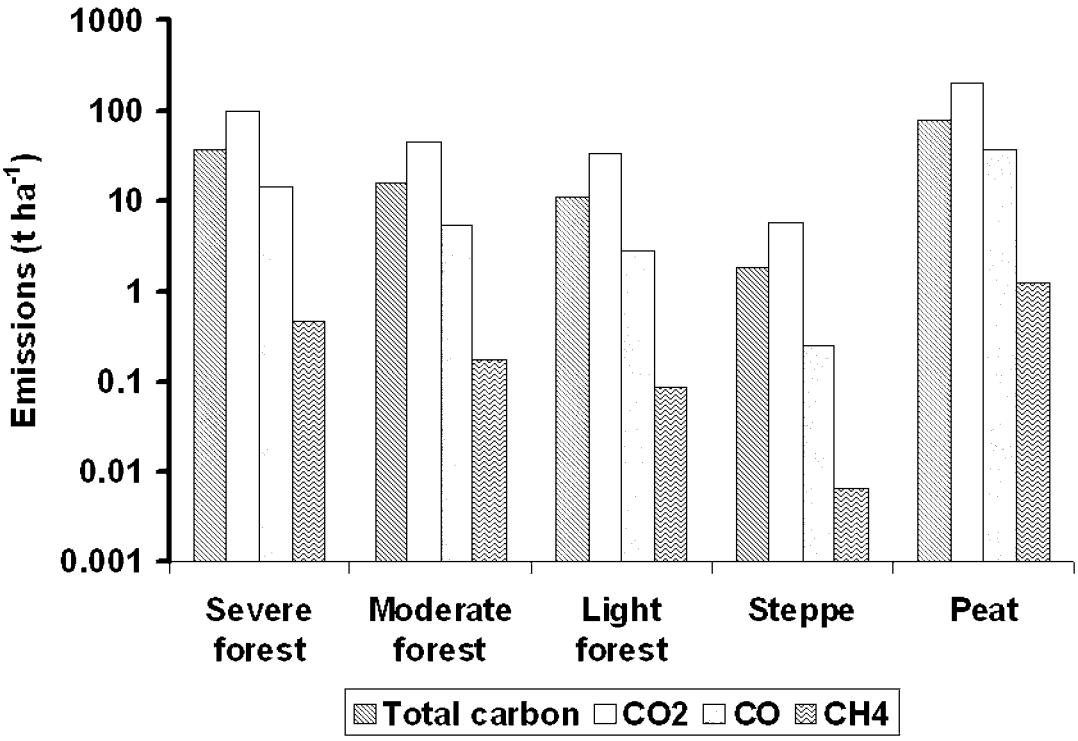


**Figure 3.** Estimates of carbon release and $CO_2$, $CH_4$ and CO emissions as a function of fuel type (steppe, forest, and peatland) and burn severity based on fraction of biomass (carbon consumed). Examples include the severe case for the WNA region, the moderate case for the CNA region, and the light case for the RFE region. Uncertainties in these estimates are ±50%.

September. However, the different burn severities in the two cases result in a pattern where the scenario 3 emissions were lower than the moderate case during the early part of the fire season and higher during the later part.

[43] The seasonal differences between these two cases are more pronounced at a regional scale, as illustrated in Figure 4b for Russia. While the two CO emission peaks (in early August and late September) are still present in Figure 4b, in the moderate case, the August peak is greater than the September peak, while for scenario 3, the opposite pattern is observed. Finally, assuming peatland burning in the Russian Far East greatly increases the late-season CO emissions.

[44] The NOAA CMDL operated sampling station at Point Barrow, Alaska where the CO samples presented in Figure 2c were collected is immediately downwind from the Russian Far East. Large CO emissions originating from fires in Russia are likely to influence the atmospheric measurements collected at this station. It can be seen that the estimated CO peaks presented in Figure 4b during early August and late September correlate well with spikes observed at the same time in the CO data in Figure 2c. The high CO emissions from fires in September and October from Russia are thought to be the primary source of the elevated CO levels observed at Barrow during September through December.

[45] The correlation between the CO emissions in Figure 4b and the CO observations in Figure 2c are consistent with previous research. At local scales, *Crutzen et al.* [1998], *Tanimoto et al.* [2000], and *Wofsy et al.* [1992] have all noted that the likely source for elevated atmospheric CO measurements in high northern latitude regions is boreal forest fires. *Wotawa and Trainer* [2000] concluded that large fires in Canada contributed to elevated CO levels

**Table 5.** Summary of Total Carbon, Carbon Dioxide, Carbon Monoxide, and Methane Emissions[a] From Boreal Forest Fires in 1998 Based on Different Fire Severity and Peatland Burning Scenarios

| Fire Scenario | Total Carbon | $CO_2$ | CO | $CH_4$ |
|---|---|---|---|---|
| Low | 183 | 523 | 58 | 1.5 |
| | | ***532*** | ***52*** | ***1.6*** |
| Moderate | 323 | 927 | 104 | 3.3 |
| | | ***945*** | ***102*** | ***3.2*** |
| High | 458 | 1316 | 148 | 4.7 |
| | | ***1328*** | ***149*** | ***4.7*** |
| Scenario 1 | 250 | 717 | 80 | 2.3 |
| | | ***734*** | ***78*** | ***2.4*** |
| Scenario 2 | 290 | 828 | 91 | 2.9 |
| | | ***845*** | ***88*** | ***2.9*** |
| Scenario 3 | 343 | 985 | 110 | 4.1 |
| | | ***998*** | ***110*** | ***4.1*** |
| Peatland burning | 40 | 105 | 18 | 0.6 |

For $CO_2$, CO, and $CH_4$, two values are presented. The top value is based on the assumption that 50% of all biomass consumption burning occurred in flaming fires and 50% in smoldering fires. The bottom values (in bold italics) were based on the assumption that 80% of aboveground biomass was consumed in flaming fires and 20% in smoldering fires, while 20% of organic mat biomass was consumed in flaming fires and 80% in smoldering fires.

[a]Emissions are expressed in Tg or $10^{12}$ g.

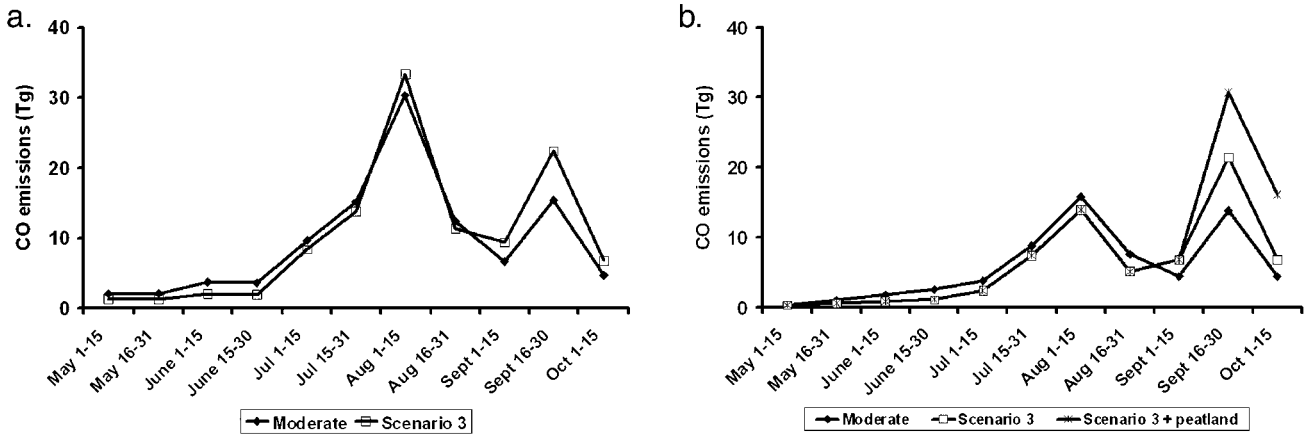


**Figure 4.** Semimonthly CO emission estimates from boreal forest fires in 1998: (a) global CO emissions based on the moderate severity case and scenario 3; (b) Russian (Russian Far East plus Russian Siberia) CO emissions based on the moderate severity case, scenario 3, and scenario 3 plus peatland burning. Uncertainties in these estimates are ±50%.

observed in eastern U.S. metropolitan regions in the summer of 1995. Finally, *Forster et al.* [2001] argue that anomalous CO signatures observed at Macehead, Ireland in mid- to late August of 1998 originated from fires in Canada.

## 4. Sources of Uncertainty

[46] The range in emission estimates in Table 5 is the result of uncertainties in measuring and modeling the input parameters for equations (2) and (3). The overall uncertainty can be estimated by comparing the minimum and maximum values in Table 5 with the average value. Comparing the low and high severity plus peatland burning cases in Table 5 results in uncertainties of ±35 to 51%, which are consistent with the ±50% uncertainty of *Andreae and Merlet* [2001].

[47] Table 6 presents a summary of the uncertainty levels that are thought to exist in the different parameters in equations (2) and (3). In some cases, these uncertainties are based on detailed analysis, while in others, they represent an assessment of the current state of knowledge.

[48] The uncertainties in the parameters in Table 6 can be divided into two broad categories. First, there are uncertainties in characteristics that can be directly measured or observed for different forest types or for broad regions. These characteristics include the location, extent and types of fire and aboveground and ground-layer biomass/carbon densities. Second, there are uncertainties in those parameters which can be measured from or during individual fire events, but whose extrapolation over large areas and different time periods is challenging. These include determining the level of flaming versus smoldering combustion, measuring fire severity in different vegetation or forest types and under different moisture conditions, and measuring or estimating emissions of different trace gas species in different forest types. In the following sections, we briefly review the sources of uncertainties in the parameters required to estimate emissions from fires in the boreal forest.

### 4.1. Area Burned

[49] The sources for uncertainties in area burned are different for North America and Russia. In North America, areas of fires are based on compilation of statistics for individual fire events whose locations and sizes are known. In many cases, fire perimeters have been digitized. In Russia, longer-term estimates of area burned are based on compilation of records from different districts. Information on individual fire events is not available from this source [*Korovin*, 1996]. More recently, area-burned information in Russia has been produced through analysis of satellite imagery.

[50] Data on the location and size of large fires in the North American boreal region are based on hand-drawn maps of fire perimeters created through ground-surveys or

**Table 6.** Summary of Levels of Uncertainty in Parameters Required to Estimate Emissions From Fires in the Boreal Forest

| Parameter | North America | Russia |
|---|---|---|
| Area burned—$A$ | ±10% | ±30% for satellite imagery, − 300% for official government statistics |
| Aboveground carbon density—$B_a f_{ca}$ | ±25% | ±25% |
| Ground-layer carbon density—$C_g$ | ±50% | ±50% |
| Fraction of carbon consumed in aboveground vegetation—$\beta_a$ | ±25% | ±30% |
| Fraction of carbon consumed in ground-layer biomass—$\beta_g$ | ±75% | ±100% |
| Emission factor—$E_{fs}$ | ±20 to 50% | ±20 to 50% |

airborne reconnaissance flights, with the exception of the Northwest Territories, where high-resolution (25 m) Landsat imagery is used to map burned areas [*Epp and Lanoville*, 1996]. The accuracy of hand-drawn maps has improved dramatically with the use of global positioning systems. These maps do not usually contain the locations of unburned forest areas within a fire perimeter, and therefore overestimate total area burned. After 1970, the accuracy of fire area information provided through the large fire databases for Alaska and Canada are thought to be ±10% [*Amiro et al.*, 2001].

[51] For Russia, it is known that the official government statistics on forest area burned are off by a factor of 1.5 to 10, with an average of 3.5 when compared to satellite estimates [*Kasischke et al.*, 1999; *Shvidenko and Nilsson*, 2000a; *Conard et al.*, 2002]. For example, the area burned reported for Russia in 1998 was initially reported at 2.6 Mha in official government statistics, where analysis of satellite imagery showed there was > 13 Mha. In 1987, official fire statistics reported 1.27 Mha of fire, while analysis of satellite imagery showed > 11.7 Mha of fire activity in eastern Russia [*Cahoon et al.*, 1994].

[52] Efforts are underway to map burn scar boundaries in Russia back to 1980 using archived satellite (AVHRR) imagery. To date, area-burned information for Russia has been generated for eastern Russia for 1987, 1992, and 1998 to 2001. It is known that while AVHRR data are accurate for large fires [*Cahoon et al.*, 1992], they miss smaller fires, and tend to underestimate total area of large fires based on their perimeters [*Kasischke and French*, 1995]. On the whole we feel that the area-burned estimates for 1998 used in this study are low because the entire country of Russia was not mapped using AVHRR imagery. Finally, the area burned of steppes has not been considered until recently.

### 4.2. Vegetation and Ground Biomass (Carbon) Distribution

[53] The issue of using information on the spatial distribution of the aboveground and ground-layer biomass that burns during fires must be looked at from several perspectives, including: (a) estimating the biomass/carbon densities at regional scales; and (b) understanding temporal variations in fuel conditions.

[54] At large scales, forest biomass and soil inventories provide information for mapping the spatial variability in biomass in the North American and Russian boreal forests [*Tarnocai*, 1997; *Lacelle et al.*, 1997; *Stone et al.*, 1997b; *Shvidenko et al.*, 1998]. Such information has been used in North America to estimate total and regional-scale carbon emissions from fires based on data aggregated for different ecozones [*Amiro et al.*, 2001] and 1° by 1° grid cell [*French et al.*, 2000]. Similar efforts are currently being carried out in Russia to combine area-burned maps produced from satellite data with carbon density maps.

[55] One critical area of uncertainty in both North America and Russia is burning in areas damaged by insects, previous fires, and in areas that have been logged. While the biomass densities of such disturbed forests have been documented, the fraction of biomass (carbon) consumed has not.

[56] One point of debate in providing input parameters for estimating emissions in boreal forests is the level of biomass present in the organic mat in different regions. While high levels of organic mat material have been measured in Alaskan black spruce forests (80 t C $ha^{-1}$) [*Kasischke et al.*, 2000a], it has been argued that these high levels are not found in the boreal forest regions of Canada and Russia [*Stocks and Kauffman*, 1997; *Shvidenko and Nilsson*, 2000b]. However, field measurements show much higher levels of organic soil carbon in some Canadian black spruce forests than are found in Alaskan black spruce forests [*Trumbore and Harden*, 1997; *Harden et al.*, 1997]. In addition, examination of the database provided by *Lacelle et al.* [1997] shows that the average carbon density in the upper 30 cm of soil throughout much of Canada in areas that burned between 1980 and 1994 is higher than that for the boreal forest region of Alaska [*French et al.*, 2000]. Finally, the soil databases for Russia presented by *Shvidenko et al.* [1998] show that the vast Siberian boreal forests in the Middle and Northern Taiga ecoregions have significant levels of organic soil and litter in the top 20 cm of soil (58 and 76 t C $ha^{-1}$, respectively).

[57] Another source of uncertainty is the spatial distribution of carbon stored in the organic soils of peatlands found in both Russia and North America. While the location of these peatlands are known in general [*Neustadt*, 1984; *Zoltai et al.*, 1998], the spatial distribution of soil carbon densities within different peatland types is not well defined.

[58] Several of the model parameters in equations (2) and (3) are not independent variables. Both the fraction of carbon consumed as well as the division of biomass between flaming/smoldering combustion are not only dependent on the vegetation-cover type and the type of dead organic matter being burned, but are also dependent on the moisture content of the biomass at the time of the fire. Different factors influence the moisture content of the biomass that burns during fires. For aboveground vegetation and ground-layer biomass, there are phenologic as well as climatic considerations. Models are now being developed and evaluated that incorporate seasonal phenologic and climatic variations into estimates of burn severity and total carbon emissions [*Amiro et al.*, 2001].

[59] For burning of ground-layer organic matter, a third factor must also be considered. In the case of forests or peatlands underlain by permafrost, soil moisture is also controlled by the seasonal patterns of soil thawing. While the influence of seasonal variations in thaw depth on the burning of organic soil in black spruce forests in Alaska has been documented [*Kasischke et al.*, 2000a], this process has yet to be completely incorporated into developing input parameters for emissions models. The temporal dynamics of fuel condition (moisture) leads to considerable uncertainties in estimating emissions from fires in the boreal region.

### 4.3. Fraction of Biomass (Carbon) Consumed

[60] Uncertainties in estimating fraction of biomass (carbon) consumed during fires can be divided into three categories: (a) determining the severity of fires that occur over the landscape; (b) determining the fraction of aboveground biomass that is consumed; and (c) determining the fraction of ground-layer organic matter that is consumed by fires.

[61] As noted previously in this paper, while the types of fires that can occur in the North American and Russian

boreal forests are well known, there is great deal of variability in terms of the spatial patterns of fire severity. Determining the patterns of fire severity is the first step in reducing uncertainties in the fraction of biomass (carbon) consumed term. The overall patterns of severity can be estimated based on forest type and climate conditions at the time of fire [*Amiro et al.*, 2001], or through assessment made with satellite observations [*Michalek et al.*, 2000; *Isaev et al.*, 2002]. However, a systematic approach to quantifying fire severity has yet to be implemented, and uncertainties in this area remain significant.

[62] A great deal of research has been conducted to quantify the patterns of aboveground fuel consumption during fires in different boreal forest types throughout North America and Russia [*Stocks and Kauffman*, 1997; *Kasischke et al.*, 2000a; *Shvidenko and Nilsson*, 2000b]. Data exist to model levels of aboveground biomass consumption as a function of fire type with a relatively high degree of accuracy, including the effects of variable fuel moisture conditions.

[63] The level of biomass consumption in the organic mat layer is largely controlled by soil moisture conditions, which in turn are related to both the bulk density of the organic material and the underlying drainage conditions. In general, higher values for fraction of carbon consumed occur in the floors of forests found on warm, dry sites and lower values for fraction of carbon consumed occur in forests found on cold, wet sites. Therefore, if the distribution of forest types in a region is known, then a composite fraction of carbon consumed can be estimated [see *Kasischke et al.*, 2000a, 2000b].

[64] The uncertainties in the ground-layer fraction of biomass (carbon) consumed term stem from the lack of field observations from a wide-range of forest ecosystems and peatlands where fire occurs. Most fire behavior studies have taken place in forests located on well-drained sites that have shallow organic soils [*Stocks*, 1987, 1989; *FIRESCAN Science Team*, 1996]. Only a limited number of studies have been conducted in forest types that contain deep organic soils [*Kasischke et al.*, 2000a, 2000c] or in peatlands [*Wein*, 1983; *Chistjakov et al.*, 1983; *Turetsky and Wieder*, 2001].

### 4.4. Emission Factors

[65] There are two sources of uncertainty to consider in the emission factor term in equation (3). First, there are uncertainties associated with the estimation of the emission factors (Table 2). If expressed as a coefficient of variation (e.g., the standard deviation divided by the mean as percent), then the uncertainties based on the data presented in Table 2 for flaming fires are ±5% for $CO_2$ and ±25% for CO and $CH_4$. For smoldering fires, the uncertainties are ±14% for $CO_2$ and $CH_4$, and ±50% for CO. It should be noted these values are based on samples collected in a very limited number of forest types and fuel moisture conditions. In addition, no attempt was made to differentiate between emission factors for different fuel types (e.g., aboveground and ground-layer) in most studies.

[66] The second source of uncertainty in the emission factors is associated with allocating the biomass (carbon) consumed during fires between flaming and smoldering combustion. The results from this study show that varying the assumption of the amount of biomass consumed during flaming and smoldering combustions results in ±4% variation in the emissions estimates in most cases. However, these results are from forests ecosystems in one region (Russia) where it was assumed there was a high level of aboveground biomass consumed and a second region (North America) where it was assumed there was a high level of ground-layer biomass consumed. These assumptions tend to cancel one another out when changing the levels of flaming versus smoldering combustion. A sensitivity study by *French et al.* [2002] showed that in forests where organic-soil burning occurs, varying the level of flaming/smoldering combustion as assumed in this study leads to uncertainties on the order of ±15%.

## 5. Discussion

[67] Since *Seiler and Crutzen* [1980] identified biomass burning as a significant source of atmospheric trace gases, researchers have developed approaches to incorporate more spatially refined information to improve the accuracy of estimates of carbon and trace gas emissions from fires [*Hao et al.*, 1990; *Hao and Ward*, 1993; *Kasischke et al.*, 1995a; *French et al.*, 2000; *Amiro et al.*, 2001]. *Seiler and Crutzen* [1980] influenced the direction for research in this area by identifying the tropical and subtropical regions as the primary source of emissions from biomass burning. The original *Seiler and Crutzen* [1980] research relegated the boreal forest to a minor role in terms of global emissions from biomass burning, primarily because of a lack of accurate information on the area burned in this region, as well as levels of carbon released. The extent of fire in this region has been updated in recent studies of trace gas emissions [*Hao and Ward*, 1993; *Lobert et al.*, 1999; *Bergamaschi et al.*, 2000; *Galanter et al.*, 2000; *Lavoue et al.*, 2000], but not to the degree necessary to depict the actual fire regime in the boreal forest because of lack of information on area burned in Russia. The use of area-burned estimates derived from satellite imagery addresses this critical information need [*Cahoon et al.*, 1994; *Conard et al.*, 2002].

[68] In this study we examined emissions from the boreal forest fires in 1998, when some 17.9 million ha of forest, steppe and probably peatland burned in Russia, Canada, and Alaska. While other boreal forests exist in Fennoscandia, fire suppression activities result in less than 2,000 ha $yr^{-1}$ of fire in this region [*Stocks*, 1991]. Thus, fire in Russia, Canada, and Alaska are the primary boreal forest contributors to global biomass burning emissions.

[69] While a range of trace gas emission estimates are presented in Table 5, we believe there are reasons that scenario 2 or scenario 3 plus peatland burning represents the actual level. First, the area burned for Russia is probably low because satellite imagery for the entire country was not analyzed. Second, arguments can be made that high levels of organic soil consumption occur during fires in the North American boreal forest region based on field observations [*Kasischke et al.*, 2000a] and modeling studies [*Harden et al.*, 2000]. In particular, *Harden et al.* [2000] showed that substantial levels of organic soil burning (20 to 40 t $ha^{-1}$) during each fire event were required to balance soil carbon budgets over the longer term in a Canadian boreal forest system. And third, satellite imagery shows that in the

Russian Far East, the 1998 fires were most likely crown fires and that areas with peatlands burned.

[70] The emissions based on scenario 3 plus peatland burning represent 8.9% of total global fire carbon emissions [*Andreae and Merlet*, 2001], 13.8% of global fire CO emissions [*Bergamaschi et al.*, 2000], and 12.4% of global fire $CH_4$ emissions [*Hao and Ward*, 1993]. Thus, during a peak fire year such as 1998, fires in the boreal forest represent a more significant source of trace gases and carbon emissions than previously estimated.

[71] *Conard et al.* [2002] estimate that between 188 to 228 Tg of carbon were emitted from the 1998 fires in the boreal forest. While this estimate matches the low severity case in Table 5 (182 Tg C), it is significantly lower than the values in this study produced using variable burn severities during the growing season (290 to 383 Tg C). However, *Conard et al.* [2002] also acknowledged that their emissions estimates are quite conservative.

[72] *Amiro et al.* [2001] estimate that 61.2 Tg C were released from fires in Canada in 1998, which matches quite well with the estimate produced by the low fire severity case for this study (63.3 Tg C for North America), but is lower than the estimates produced by scenarios 2 and 3 (93.3 and 107.5 Tg C, respectively).

[73] The lower end of the range of biomass burning emissions for the boreal forest region can be calculated by considering 1992, when 1.5 million ha of fire occurred in Russia [*Cahoon et al.*, 1996] and 0.88 million ha in North America [*Murphy et al.*, 2000]. Based on the low emissions case in Table 4, we estimate that during 1992, 28.6 Tg of total carbon, 73.4 Tg of $CO_2$, 7.5 Tg of CO, and 0.24 Tg of $CH_4$ were released from boreal forest fires.

[74] Comparison of the estimates from 1992 to 1998 shows that there is an order of magnitude inter-annual variation in emissions from fires in the boreal forest. This variability undoubtedly influences the atmospheric carbon observations, but has yet to be accounted for in models that consider spatial/temporal gradients in $CO_2$ as a means to analyze terrestrial carbon source/sink relationships [e.g., *Bousquet et al.*, 2000].

[75] Comparison of Figure 4 with Figure 2c indicates that during high fire years, emissions from boreal forest fires may influence atmospheric concentration of carbon monoxide. In addition, *Dlugokencky et al.* [2001] concluded that the high methane emissions from boreal forest fires in 1998 contributed to the anomalously high atmospheric concentrations observed in extra-tropical northern regions in this year. However, the 2.9 to 4.7 Tg of $CH_4$ emitted from fires in 1998 represent a significant portion of the 11.6 Tg anomaly observed in high northern latitudes during that year.

## 6. Conclusions

[76] This study indicates that biomass burning in the boreal forest region may result in higher levels of trace gas emissions to the atmosphere than previously estimated. However, the results show that the most significant impacts of this burning occur during episodic fires years, such as 1998. During most years (4 out of 5), the levels of trace gas emissions are much lower, resulting in substantial inter-annual variation in emissions associated with biomass burning. It remains to be determined how much of the inter-annual variations in trace gases in high northern latitudes are explained by patterns of emissions from biomass burning in boreal forests.

[77] The trend for fire in the North American boreal forest clearly shows that annual area burned has been increasing over the last three decades [*Kasischke et al.*, 1999]. Modeling studies show the potential for severe fire years is tightly linked to patterns of temperature, and that future climate warming will increase the probability of severe fire years throughout the boreal region [*Stocks et al.*, 1998, 2000]. The linkage between climate and fire activity is consistent with the patterns of fire activity in the North American boreal forest, which has experienced a significant warming over the past three decades.

[78] An important question arising from these observations is: what pattern will future trace gas emissions from boreal forest fires follow in a warming climate? (1) Will the expected increases in fire activity manifest themselves through increases in annual area burned in both high and low fire years? (2) Will the expected increases in fire activity manifest themselves through increases in the frequency of high fire years? Or (3) Will the expected increases in fire activity manifest themselves through a combination of (1) and (2)?

[79] Finally, another important issue with respect to fire and carbon emissions in the boreal forests is the indirect effect of fire on soil respiration [*Kasischke et al.*, 1995b]. Areas underlain by permafrost contain deep, carbon-rich organic soils. Changes in the surface/atmosphere energy budget as a result of fire causes dramatic increases in soil temperature in these areas (up to 10°C to a meter depth in soils that were previously frozen below 30 cm depth [*Kasischke et al.*, 2000d]). This warming enhances soil respiration, and results in even higher $CO_2$ emissions, for up to a decade after the fire has occurred [*Richter et al.*, 2000; *O'Neill et al.*, 2002]. This indirect relationship between fire, soil temperature and heterotrophic $CO_2$ emissions will result in even higher levels of variability in emissions of carbon to the atmosphere.

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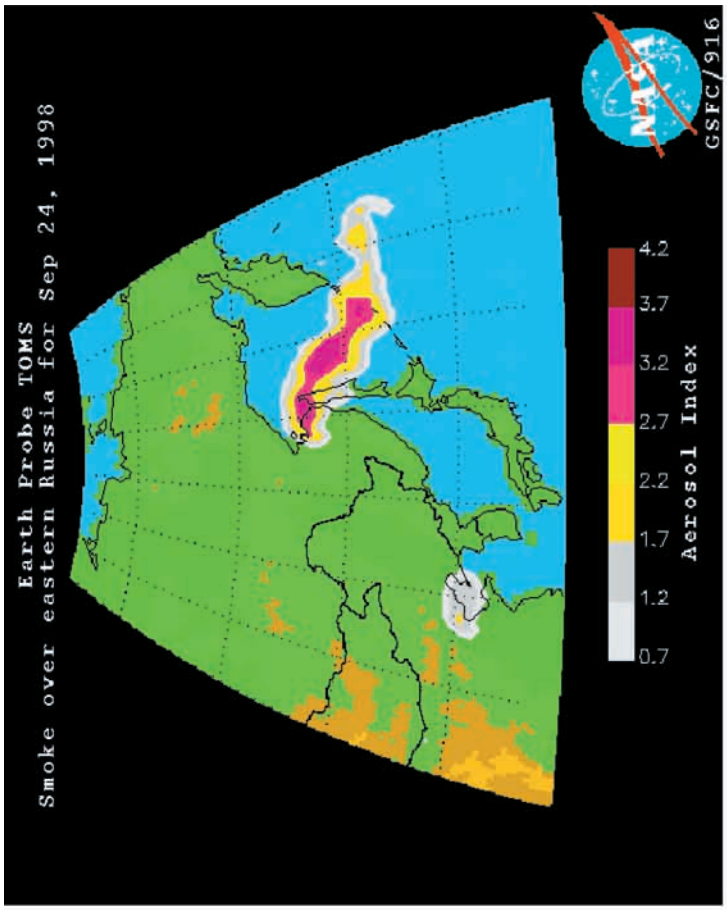
Earth Probe TOMS
Smoke over eastern Russia for Sep 24, 1998
Aerosol Index
4.2
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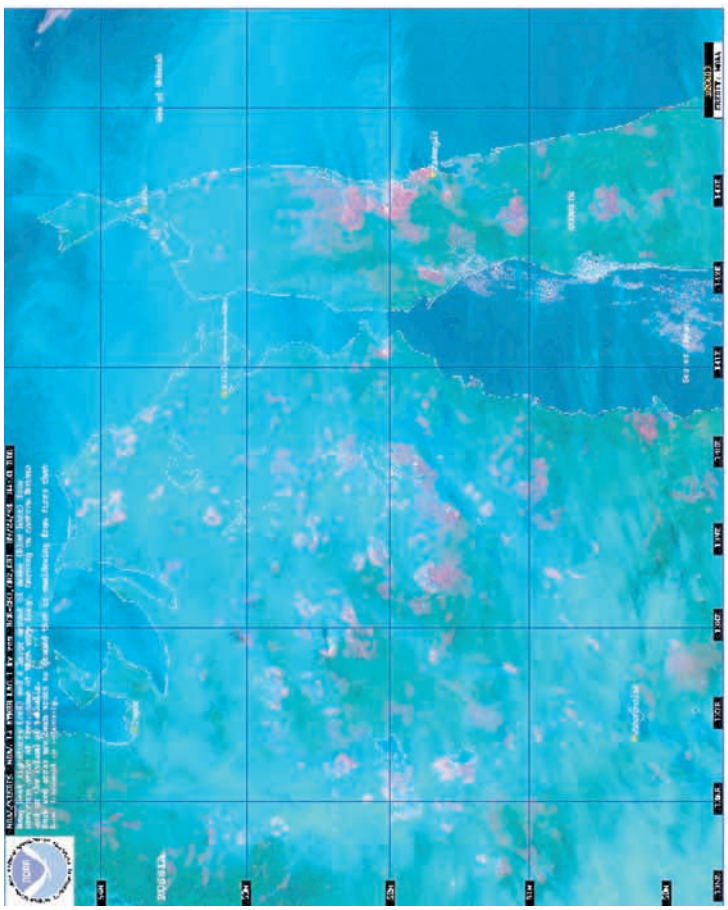

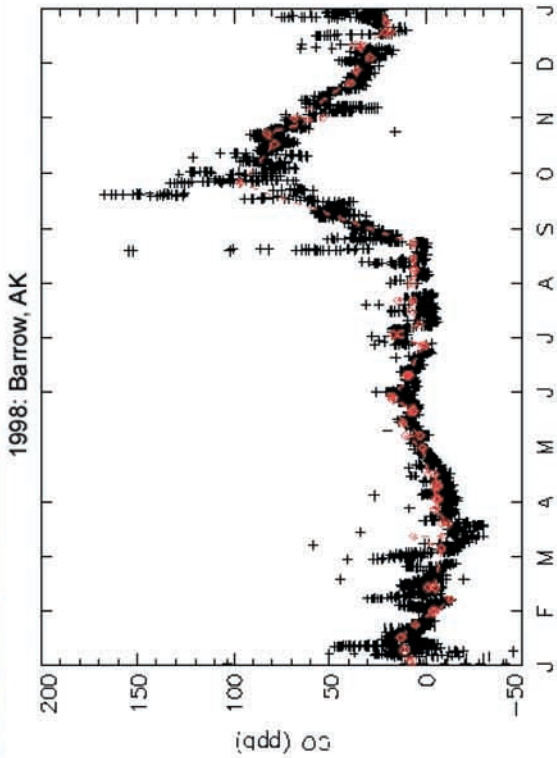
1998: Barrow, AK
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**Figure 2.** (opposite) Satellite imagery and atmospheric carbon monoxide data showing the high levels of fire activity in the Russian Far East in 1998. (a) A false-color composite image from the visible, near infrared and thermal infrared channels of the Advanced Very High Resolution Radiometer (AVHRR) system collected on 24 September 1998. The red areas in the imagery are burn scars, and the brighter pink areas are active fire fronts. (b) An atmospheric aerosol product generated from the Total Ozone Mapping System (TOMS) on 24 September 1998. The smoke from fires in the Russian Far East regions created the aerosol plume on this image. Many similar smoke plumes were observed during the summer/fall of 1998. (c) Residual CO mixing ratio after subtraction of a quadratic long-term trend and average seasonal cycle from atmospheric samples collected by NOAA's Climate Modeling and Diagnostics Laboratory (CMDL) at Point Barrow, Alaska. Black crosses: hourly average CO from the CMDL continuous analyzer. Red diamonds: flask samples.