Estimating fire emissions and disparities in boreal Siberia (1998–2002)

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[1] In the biomass, soils, and peatlands of Siberia, boreal Russia holds one of the largest pools of terrestrial carbon. Because Siberia is located where some of the largest temperature increases are expected to occur under current climate change scenarios, stored carbon has the potential to be released with associated changes in fire regimes. Our concentration is on estimating a wide range of current and potential emissions from Siberia on the basis of three modeled scenarios. An area burned product of Siberia is introduced, which spans from 1998 through 2002. Emissions models are spatially explicit; therefore area burned is extracted from associated ecoregions for each year. Carbon consumption estimates are presented for 23 unique ecoregions across Siberia, which range from 3.4 to 75.4 t C ha^{-1} for three classes of severity. Total direct carbon emissions range from the traditional scenario estimate of 116 Tg C in 1999 (6.9 M ha burned) to the extreme scenario estimate of 520 Tg C in 2002 (11.2 M ha burned), which are equivalent to 5 and 20%, respectively, of total global carbon emissions from forest and grassland burning. Our results suggest that disparities in the amount of carbon stored in unique ecosystems and the severity of fire events can affect total direct carbon emissions by as much as 50%. Additionally, in extreme fire years, total direct carbon emissions can be 37–41% greater than in normal fire years, owing to increased soil organic matter consumption. Mean standard scenario estimates of CO_2 (555–1031 Tg), CO (43–80 Tg), CH_4 (2.4–4.5 Tg), TNMHC (2.2–4.1 Tg), and carbonaceous aerosols (4.6–8.6 Tg) represent 10, 15, 19, 12 and 26%, respectively, of the global estimates from forest and grassland burning. Accounting for smoldering combustion in soils and peatlands results in increases in CO, CH_4, and TNMHC and decreases in CO_2 emitted from fire events. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 1640 Global Change: Remote sensing; *KEYWORDS:* AVHRR, area burned, emissions, boreal Siberia

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1. Introduction

[2] The effect of biomass burning on atmospheric chemistry came to the attention of the scientific community with the early work of *Hobbs and Radke* [1969] and *Eagan et al.* [1974], who identified natural fires as a source of cloud condensation nuclei (CCN). Then *Radke et al.* [1978] reported the particles and gases that were the sources of the efficient CCN. Interest continued to grow with pioneering research that linked terrestrial fire emissions to atmospheric pollution [*Crutzen et al.*, 1979; *Seiler and Crutzen*, 1980]. Further studies showed that emissions from fire not only constitute local pollutants but are also transported beyond localities and have the potential to affect global atmospheric chemistry [*Fishman*, 1991; *Levine*, 1996; *Harvey et al.*, 1999; *Rinsland et al.*, 1999; *Schultz et al.*, 1999]. Research has also shown that aerosols from fire directly and indirectly affect radiative forcings [*Konzelmann et al.*, 1996; *Wild*, 1999], and postfire burn scars alter albedo, further influencing the radiation budget [*French*, 2002]. Currently, aerosol-cloud interactions are thought to be one of the most important and uncertain drivers of climate change. Recent research has shown that aerosols from heavy smoke modify cloud droplet size, delaying the

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onset of precipitation, which can lead to intense storms and can slow down or alter the hydrologic cycle [*Ramanathan et al.*, 2001; *Andreae et al.*, 2004]. Feedbacks from fire have the potential to influence regional and global climate by altering atmospheric chemistry and the radiation budget.

[3] Initial fire research focused on the tropics, but the significance of boreal fire emissions has gradually emerged. *Cahoon et al.* [1994] suggested that in 1987 a portion of northeast Asia generated 4% of the annual global emissions of carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4) from biomass burning. Additionally, *Hao and Ward* [1993] estimated that boreal fires contribute 4% of the global CH_4 emissions from biomass burning. *Amiro et al.* [2001] reported that mean fire emissions from Canada represent about 18% of the carbon dioxide emissions from the Canadian energy sector. In a particularly elevated fire year in Russia in 1998, *Conard et al.* [2002] estimated Russian boreal forests accounted for 14–20% of the annual global carbon (C) emissions from forest fires. *Kasischke and Bruhwiler* [2003] estimated that boreal emissions in 1998 represented a sizable portion of total direct global emissions from biomass burning [8.9% C, 13.8% CO, 12.4% CH_4]. Also in 1998, *Tanimoto et al.* [2000] noted anomalous increases of CO in Japan, which were traced to the fires in far east Russia. *Dlugokencky et al.* [2001] found global methane anomalies in 1998 were due, in part, to the severe fire season in Russia. Moreover, *Fromm et al.* [2000] suggested that a substantial amount of smoke from 1998 boreal fires was lofted into the stratosphere where it persisted for several months.

[4] Boreal zones are located in Northern Hemisphere upper latitudes, where temperature increases from climate change are expected to be the largest [*Cubasch et al.*, 2001]. Current research shows that temperatures have been increasing as much as 1°C per decade in Siberia and are, on a global basis, some of the largest temperature increases [*Balling et al.*, 1998; *Folland et al.*, 2001]. Boreal forest fire is largely controlled by weather and climate [*Clark*, 1988; *Stocks and Lynham*, 1996], and warming is predicted to increase area burned, fire season length, and the severity of fire events in boreal regions [*Overpeck et al.*, 1990; *Flannigan and Van Wagner*, 1991; *Wotton and Flannigan*, 1993; *Fosberg et al.*, 1996; *Stocks et al.*, 1998; *Flannigan et al.*, 2001]. Notably, under current climate change scenarios the amount of area predicted to be under extreme fire danger in Siberia during the summer months is three times the area affected in Canada [*Stocks et al.*, 1998].

[5] Wildfire is the dominant disturbance in boreal regions and acts as a catalyst to maintain and alter the mosaic composition of the forest, consequently altering carbon stores. Boreal zones hold the largest reservoir of terrestrial carbon [*Apps et al.*, 1993; *Zoltai and Martikainen*, 1996; *Alexeyev and Birdsey*, 1998] and about 2/3 of the world's boreal forests are located in Russia [*Hare and Ritchie*, 1972]. Northern peatlands have been accumulating peat since the beginning of the Holocene and hold 1/3 of the soil organic matter on Earth [*Gorham*, 1991; *Zoltai and Martikainen*, 1996; *Turetsky et al.*, 2002]. Increased fire in peatlands could result in a substantial loss of carbon to the atmosphere through gaseous emissions and decomposition [*Zoltai et al.*, 1998; *Morrissey et al.*, 2000]. Fire events immediately release carbon and trace gases into the atmosphere but can also continue to affect boreal ecosystems for years after a fire. Postfire biogenic carbon emissions are thought to remain elevated for years to decades following fire events, and it has been reported that postfire biogenic emissions, in any given year, may be up to six times greater than direct carbon emissions from fire [*Van Cleve and Viereck*, 1981; *Dixon and Krankina*, 1993; *Richter et al.*, 2000; *Shvidenko and Nilsson*, 2000b; *O'Neill et al.*, 2003], although this varies significantly with temperature, climate history, and fire severity [*Zhuang et al.*, 2003]. Also, the annual depth of thaw in permafrost (permanently frozen soil) can remain increased for 25–50 years after a fire event [*Mackay*, 1970; *Bliss and Wein*, 1971; *Mackay*, 1977; *Viereck*, 1981]. Models have shown that the transient response to climate change results in increases of atmospheric CO_2 of up to a third of the present level [*Smith and Shugart*, 1993a, 1993b], and the inclusion of fire could further increase this estimate [*Kasischke et al.*, 1995a; *Kurz and Apps*, 1999; *Harden et al.*, 2000]. However, decreases in boreal forest would result in increased albedo, hence cooling, which could extend beyond boreal boundaries [*Bonan et al.*, 1992; *Rizzo and Wilken*, 1992; *Betts*, 2000]. What is certain is that fire strongly influences carbon and energy dynamics in boreal systems, which in turn results in complicated feedbacks with the atmosphere [*Viereck and Schandelmeier*, 1980; *Smith and Shugart*, 1993b; *Kurz et al.*, 1995].

[6] Since the 1970s, efforts to accurately characterize fire emissions and improve on the original work of *Seiler and Crutzen* [1980] have persisted, but Siberia is particularly troublesome. *Cahoon et al.* [1994] used an improved satellite-based area measurement to estimate carbonaceous trace gas emissions from 1987 fires in northern Eurasia. *Kasischke et al.* [1995b] varied fuel consumption estimates in five different land cover types to estimate carbon released from fire in 1990 and 1991 in Alaska. *Conard and Ivanova* [1997] highlighted the significance of surface fires and fire severity in Russia and then, based on fire return intervals, estimated area burned annually, as well as both direct and indirect biogenic emissions of carbon from Russia. *Shvidenko and Nilsson* [2000b] estimated average (1988–1992) direct and indirect biogenic emissions from Russia after assigning area burned to seven ecozones within five ecosystem classes. *French et al.* [2000] modeled carbon emissions from North America with a spatially explicit model that varied fuel consumption in the aboveground and ground layer of each ecosystem, depending on the extent of the area burned annually. Then *Conard et al.* [2002] used satellite-based area burned products and ground-based data to estimate carbon emissions from Russia and the entire boreal zone for the severe fire season in 1998. Subsequently, *Kasischke and Bruhwiler* [2003] incorporated several different ecoregions, fire severity, and aboveground and ground layer carbon to estimate total direct carbon and carbonaceous trace gas emissions for 1998 from Russia and North America. *Amiro et al.* [2001] used a novel approach to estimate emissions from Canada using a fire database, fuel consumption calculations for each ecozone, time of fire, and prevailing weather. This method accounts for the variability of available fuel (fuel that is dry and presently available to burn, not the amount the ecosystem holds) that is problematic in boreal regions. These data

are not available for boreal Siberia; however, a spatially explicit ecosystem map, a spatially and temporally explicit satellite-based fire database, and ecoregion specific carbon density (tons per hectare (t ha^{-1})) maps are available.

[7] One goal of this investigation is to build on previous works to estimate total direct carbon emissions from Siberia for 1998 through 2002. Another major objective of this investigation is to estimate the potential range of emissions from Siberia. Depending on the weather and consequently the amount of fuel that is available to burn at a specific time, the severity of fire events differs tremendously, which can result in large differences in the amount of fuel consumed during a fire [*Conard and Ivanova*, 1997; *French et al.*, 2000; *Amiro et al.*, 2001]. For this reason, three scenarios, which vary the relative severity of fire events, are modeled: traditional, standard, and extreme. Additionally, emissions of CO, CO_2, CH_4, total nonmethane hydrocarbons (TNMHC) and carbonaceous aerosols are estimated. For these estimates, three flaming to smoldering combustion ratios are modeled. This emissions investigation of Siberia extends previous studies in that (1) satellite-based area burned products are introduced for numerous years, (2) carbon consumption estimates are reported for three severity classes in 23 distinct ecoregions, (3) the ecoregion within which the area burned is explicitly identified, (4) each fire event is individually assigned to a severity class within an ecoregion, and (5) numerous years of emissions are estimated. Additionally, in an effort to account for potential elevated fire years, the models explicitly vary the depth of the soil organic matter consumed, exclusive of severity class. The reasons for this are twofold: to attain a wide range of potential total direct carbon emissions and to account for differences in the speciation of carbon products due to increased organic soil consumption.

2. Methods

2.1. Direct Carbon Emissions Estimates

[8] The methodology used to estimate total direct carbon emissions (C_t) is based on the original work of *Seiler and Crutzen* [1980]:

$$C_t = ABf_c\beta, \tag{1}$$

where A is area burned by fire in hectares, B is biomass density in tons per hectare (t ha^{-1}), f_c is the carbon fraction of the biomass, and β is the fraction of biomass consumed during fire events. As previously discussed, this method has evolved in boreal zones to include considerations of various ecosystem categories [*Kasischke et al.*, 1995b], severity classes [*Conard and Ivanova*, 1997], soil organic matter consumption [*French et al.*, 2000], and the effect of weather on fuel consumption [*Amiro et al.*, 2001]. Because weather data for Siberia do not coincide with fire events, an alternative method is devised that allows consideration of the potential range in severity and the associated amount of fuel consumed. The formula is modified to incorporate biomass density data as they are reported for Russian forests [*Alexeyev and Birdsey*, 1998; *Shvidenko et al.*, 1998] and also to allow specific categories (i.e., soil) to be varied:

$$C_t = A[(T\beta_T) + (U\beta_u) + (L\beta_L) + (S\beta_S)], \tag{2}$$

where T is average carbon density of the tree stand vegetation (overstory) in tons of carbon per hectare (t C ha^{-1}), U is average carbon density of the understory in t C ha^{-1}, L is average carbon density of the litter layer in t C ha^{-1}, S is average carbon density of the soil organic matter in t C ha^{-1}, and the T, U, L, and S subscripts refer to the tree, understory, litter, and soil components of biomass, respectively. Biomass or carbon density estimates (dry weight basis) for tree stand vegetation, understory vegetation, litter, and soil organic matter are calculated on the basis of data found in the work of *Alexeyev and Birdsey* [1998]. Carbon fraction of biomass is 0.5, except in cases where *Alexeyev and Birdsey* [1998] used similar or measured values to report density in t C ha^{-1} (i.e., soil organic matter and peatlands). The fraction of biomass consumed (tree, understory, and litter) during a fire is estimated in accordance with levels of fire severity, which is described in detail below. Alternatively, in the soil organic matter category the depth of soil consumed by fire is varied depending on the estimate, standard or extreme, which is also defined below.

[9] Figure 1 shows an overview of the three emissions scenarios that are modeled and compared. The traditional scenario is based on average carbon consumption estimates from low-, medium- and high-severity fires. Standard and extreme scenarios differ in that they vary the depth of soil organic matter consumed during fire events. In the standard and extreme scenarios, three levels of severity are assigned depending on the ecosystem, the size of the fire event, and the month the fire occurred.

2.2. Area Burned

[10] Area burned is a primary parameter to consider when estimating boreal fire emissions; however, Russian Siberia is vast and remote, and area burned in this region is not easily quantified. About 40% of the Russian Forest Fund area is not protected, meaning that fire is not monitored, controlled, or documented in these regions [*Sofronov et al.*, 1998; *Shvidenko and Nilsson*, 2000a]. Additionally, historical fire records were under-reported before 1988 for economic and political reasons [*Shvidenko and Nilsson*, 2000a]. Currently, Russia lacks the funding to monitor and control fire. Because ground-based fire data are incomplete for Siberia, satellite-based data provide a means to quantify area burned in a cost effective manner. Previous satellite-based studies that have quantified area burned in portions of Siberia or all of Russia have consistently been greater than the Russian estimates for the entire country [*Cahoon et al.*, 1994, 1996; *Kasischke et al.*, 1999; *Conard et al.*, 2002; *Soja et al.*, 2004a].

[11] Two satellite-based products, active fire detection and mapped burn scars, are available from the Sukachev Institute of Forestry [*Soja et al.*, 2004a; A. I. Sukhinin et al., Satellite-based mapping of fires in eastern Russia: A new product for fire management and carbon cycle studies, submitted to *Remote Sensing of the Environment*, 2004, hereinafter referred to as Sukhinin et al., submitted manuscript, 2004]. Advanced very high resolution radiometer (AVHRR) imagery is downloaded, and active fire detections (hot pixels) are processed daily throughout the fire season. However, active fire detection underestimates area burned by large fires in boreal regions [*Li et al.*, 2000a, 2000b; *Soja*, 2004]. For this reason, when a large number of active

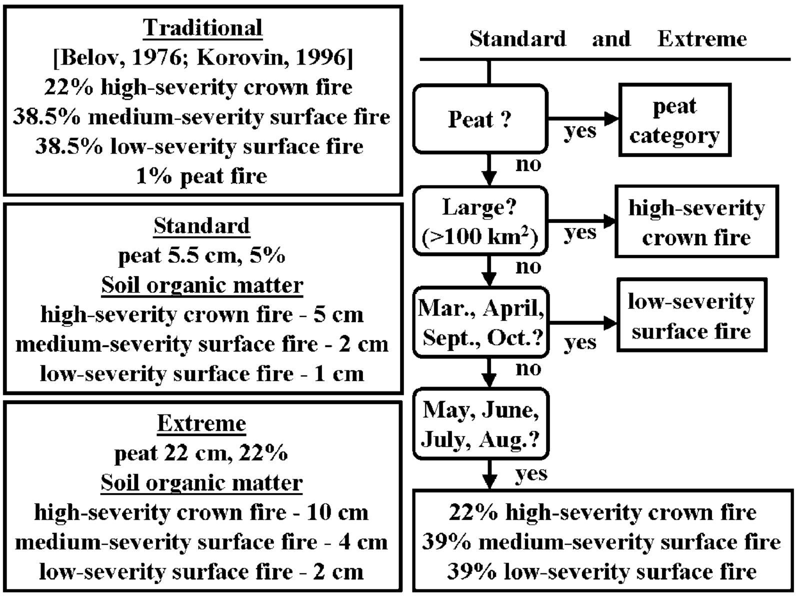

Figure 1. Model decision tree. Overview of the categorization of area burned. The amount of carbon consumed (severity-based) during fire events differs for the three modeled emissions scenarios: traditional, standard, and extreme. Traditional estimates assume traditional percentages of severity and are based on mean carbon consumption estimates calculated using the ecoregions within the standard scenario (includes standard scenario soil organic matter). In the standard and extreme scenarios, area burned is separated by ecosystem, size of fire, and month of fire. Standard and extreme scenarios are modeled with ecoregion-specific carbon consumption estimates (not means), and these scenarios differ from each other in the amount of soil organic matter consumed during fire events.

fire detections (~50) are detected in a short period of time (~2 days), fire scars are mapped.

[12] As part of this research, area burned products are presented for 1998 through 2002. Mapped burn scars are combined with active fire detections that fall outside of burn scars. The coverages are projected to Bonne, which is used for continental mapping at these latitudes and is an equal area projection. Area is calculated using Geographic Information System (GIS) commands.

2.3. Ecoregion Organization

[13] Figure 2 shows five Russian ecozones. The concentration of this study is on the four ecozones found in Siberia. Ten ecoregions (Table 1) span across Siberia, resulting in 23 unique ecoregions. Ecoregions are consistent with those reported in Russian-based literature [*Alexeyev and Birdsey*, 1998; *Shvidenko et al.*, 1998; *Shvidenko and Nilsson*, 2000b] and are spatially displayed in the work of *Alexeyev and Birdsey* [1998].

[14] A detailed ecosystem map of the former Soviet Union, "System of Landscapes for the USSR: Zones, Sectors, and Altitudinal Divisions," was digitized in the University of Virginia GIS laboratory. The original map was developed at the Science Research Institute of Geography, Leningrad State University in 1989 (1:4,000,000 scale). Although the map contains 54 soil attributes and 213 potential altitudinal divisions and ecological sectors, the focus in this study is on the ecological sectors that differentiate vegetation characteristics. The ecosystem map is presented in a condensed format in Figures 3a and 3b. Each ecological sector shares similar floristic and climatic characteristics; however, the variation within each ecological sector is immense. This analysis is based on general averages that must purposely neglect the detail within each sector.

[15] Because the average carbon density of peatlands and forested vegetation differs substantially, fuel consumption estimates are calculated separately for peatlands. Peatlands are defined as sparsely wooded (*P. sylvestris*, *P. siberica*, *Larix siberica*, *Betula* sp.) or nonforested wetlands that contain sphagnum mosses, sedges, mosses, and lichen [*Alexeyev and Birdsey*, 1998]. The ecosystem map classifies bogs and floodlands and deltas. Bogs are considered to be peatlands, and 1/2 of the floodlands and deltas category are considered to be peatlands. The reason for this is that floodlands surround rivers, which are potential regions for false satellite-derived active fire detections. To minimize the potential of false detections, some burned floodlands may be ignored. The area burned products and the ecosystem map are both spatially explicit; therefore the amount of area burned in each ecosystem is accurately assigned to ecoregions within ecozones.

2.4. Derivation of Carbon Consumption Estimates $[(T\beta_T) + (U\beta_u) + (L\beta_L) + (S\beta_S)]$

[16] Accessible biomass is defined as the amount of fuel that is aboveground in a particular ecosystem and could burn during a fire event (i.e., excludes roots). Available biomass is defined as the amount of fuel that would be available to burn in a particular ecosystem under prevailing weather conditions, so in a particular ecosystem, this value could vary considerably depending upon actual burning conditions

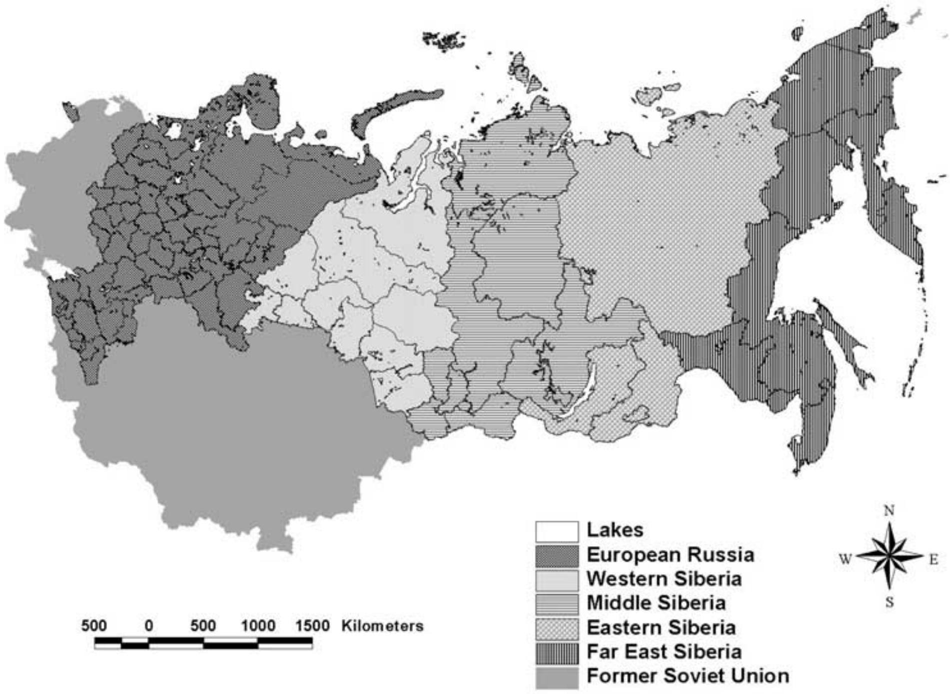

Figure 2. Ecozones of Russia. The concentration of this study is on Siberia, which lies east of the Ural Mountains and is separated into four distinct ecological zones.

[*Quintillio et al.*, 1977; *Canadian Committee on Forest Fire Management* (*CCFFM*), 1987; *Stocks*, 1987; 1989].

2.4.1. Fraction of Biomass Accessible

[17] Biomass or phytomass density (t ha^{-1}) values are found in the work of *Alexeyev and Birdsey* [1998], and these are used to calculate accessible biomass for each ecoregion within each ecozone. *Alexeyev and Birdsey*'s [1998] phytomass values are consistent (±20%) with those reported by *Isaev et al.* [1995], *Shvidenko et al.* [1998], *Moiseev et al.* [2000], *Nilsson et al.* [2000], and *Shvidenko and Nilsson* [2002]. The *Alexeyev and Birdsey* [1998] estimates are conservative, lower than 85% of those reported in the work of *Shvidenko and Nilsson* [2002]. *Alexeyev and Birdsey* [1998] used the forest inventory method, which integrates statistical forest inventory databases and data from research plots located in different ecoregions [*Alexeyev et al.*, 2000]. The forest inventory method considers vegetation composition (age and species) and disturbance (infestation, previously burned forest, and timber harvesting). Stand phytomass is equal to the sum of its constituent parts, which includes stem wood, bark, crown, and roots [*Alexeyev and Birdsey*, 1998]. Understory includes all forest vegetation that is under the canopy of a tree stand: seedlings, bushes, dwarf-shrubs, grasses, mosses, and lichens. For this investigation, to account for portions of the tree stand vegetation that would not likely burn, only 78% of the total stand vegetation is considered accessible [*Alexeyev and Birdsey*, 1998]. To account for roots in the understory, only 33% of the total understory phytomass is assumed to be aboveground and accessible for burning [*Alexeyev and Birdsey*, 1998]. In the subarctic, 17% of the total phytomass is assumed to be aboveground and accessible for burning. In the steppe and subarid regions, 40% of the total phytomass is assumed to be aboveground and accessible for burning.

2.4.2. Fire Severity (Biomass Available)

[18] Fire severity is a general term that can be used in various ways to describe the combined impact of a wildfire. However, in this case, fire severity is directly related to the amount of fuel that is available to burn. On a forest stand scale, severity is related to the type (surface, crown) and intensity of a fire, specific forest ecosystem and site characteristics, as well as current and antecedent weather conditions. The severity-based carbon consumption estimates presented in this paper are landscape-scale estimates that represent a gross aggregation of data across ecosystems.

[19] The fraction of biomass consumed is based on data from numerous field studies across Siberia. *Kurbatsky* [1970] estimated that the maximum amount of aboveground phytomass that can be consumed in a crown fire was 20–30% of the total aboveground phytomass. On the basis of 64 experimental fires in the southern taiga, *Furyaev* [1996b] estimated that on-ground fuels ranged from 6.4 to 34.6 t ha^{-1}, with 73–96% consumption, and in regions where fuels were greater than 21 t ha^{-1}, consumption was greater than 92%. Consumption levels of accessible fuels in larch forests tended to be lower in the spring (50–80%) and higher in the summer and autumn (100%) [*Vasilenko*, 1976]. Litter consumption also tended to be low in the spring (10–15%) [*Shvidenko and Nilsson*, 2000b]. *Shvidenko and Nilsson* [2000b] cited a range of estimates of litter consumed from 20 to 50% during low- and medium-severity fires across Siberia.

[20] *Conard and Ivanova* [1997] defined three classes of severity: high-severity crown fires consume 40% of total aboveground fuels, which includes 100% of the understory vegetation and litter layer; medium-severity surface fires consume 90% of understory vegetation and 50% of the litter layer; and low-severity surface fires consume 50% of the

Table 1. Standard Scenario Carbon Consumption Estimates[a]

	Western Siberia			Middle Siberia			Eastern Siberia			Far East		
	High-Severity Crown Fire, t C ha^{-1}	Medium-Severity Surface Fire, t C ha^{-1}	Low-Severity Surface Fire, t C ha^{-1}	High-Severity Crown Fire, t C ha^{-1}	Medium-Severity Surface Fire, t C ha^{-1}	Low-Severity Surface Fire, t C ha^{-1}	High-Severity Crown Fire, t C ha^{-1}	Medium-Severity Surface Fire, t C ha^{-1}	Low-Severity Surface Fire, t C ha^{-1}	High-Severity Crown Fire, t C ha^{-1}	Medium-Severity Surface Fire, t C ha^{-1}	Low-Severity Surface Fire, t C ha^{-1}
Plains												
Forest tundra	45.23	20.06	8.69	42.2	18.56	7.99	0	0	0	0	0	0
Northern taiga	45.1	18.45	8.08	29.6	11.75	5.23	0	0	0	0	0	0
Middle taiga	41.65	15.85	7.06	40.12	15.05	6.66	35.62	14.05	6.26	0	0	0
Southern taiga	43.81	16.2	7.24	45.93	16.4	7.29	0	0	0	0	0	0
Forest steppe	47.37	17.44	7.93	48.02	18.04	8.28	0	0	0	50.12	19.94	8.98
Steppe	20.2	7.5	3.4	0	0	0	0	0	0	0	0	0
Mountains												
Subarctic	0	0	0	30.21	13.86	5.94	34.02	15.66	6.69	25.92	11.66	5.09
Boreal	0	0	0	37.26	14.25	6.27	35.55	14.35	6.27	39.2	15.55	6.72
Subboreal	0	0	0	37.14	13.4	5.9	36.55	13.6	6	39.99	14.9	6.5
Subarid	0	0	0	28.12	11	5	0	0	0	0	0	0
Mean column	40.56	15.92	7.07	37.62	14.7	6.51	35.44	14.42	6.31	38.81	15.51	6.82
Mean group	21.18			19.61			18.72			20.38		
Standard Mean Carbon Consumption Estimates for Peatlands, t C ha^{-1}												
Peatlands		20.88			22.13			20.49			17.89	

[a]Here $(T\beta_T) + (U\beta_L) + (L\beta_L) + (S\beta_S)$. Estimates are based on biomass and carbon data reported in the work of *Alexeyev and Birdsey* [1998]. Carbon consumption is reported in tons of carbon per hectare (t C ha^{-1}). Zeros are present when no data values are reported by *Alexeyev and Birdsey* [1998].

understory vegetation and 10% of the litter layer. On the basis of the experimental data and the theoretical model described above, three levels of fire severity are represented in this study, high-severity crown fire, medium-severity surface fire, and low-severity surface fire. In high-severity crown fires, 20% of the accessible tree stand vegetation is consumed and 100% of the accessible understory and litter layer are consumed; medium-severity surface fires consume 50% of the accessible understory and litter layer; and low-severity surface fires consume 20% of the accessible understory and litter layer.

2.4.3. Soil Organic Matter Consumption

[21] Seventy-five percent of the terrestrial carbon accumulated in Russia is stored in peat and soils [*Alexeyev and Birdsey*, 1998]. Direct losses of carbon from the deep organic soils that are typical of boreal ecosystems are large; however, they are difficult to impossible to quantify [*Alexeyev et al.*, 2000; *Shvidenko and Nilsson*, 2000b]. Following wildfire events, the original depth of the soil organic matter can only be surmised by examining the depth of the soil organic matter in forests outside of the fire area that are similar in structure and age [*Kasischke et al.*, 1995b]. The idea here is to model a range of potential scenarios, which include minimal fire years and elevated fire years.

[22] Experimental fires have been useful for determining the approximate depth of a burn following fire events; however, terminology differences among scientists working in different biomes, different countries, and different fields of expertise are often confusing. In this paper, duff is defined as the fermentation (*F*) and humus (*H*) layers of the forest floor, which correspond to the layers of partially and well-decomposed organic materials that lie below the litter and immediately above the mineral soil [*Johnson*, 1992]. Depth of burn, for the experimental burns described in the next paragraph, is defined as the reduction in forest floor thickness due to consumption by the fire process and includes the litter, *F*, and *H* layers of the forest floor [*CCFFM*, 1987]. Soil organic matter is a Russian term, which excludes living biomass (i.e., lichen, moss) and the litter layer. This investigation relies on carbon data as reported by Russian scientists, so for consistency, litter and soil organic matter are modeled separately.

[23] During the *Fire Research Campaign Asia-North* (*FIRESCAN*) [1996] experimental crown fire on Bor Island in Siberia, the average depth of burn was 8.36 cm in a forest with relatively shallow soils (prefire depth 10.9 cm). The ground fuels (37.5% lichen and 28% duff) represented 65.7% of the total fuel consumed (22% surface, 12.3% aerial). During the Fire Effects in the Boreal Eurasian Forests (FIRE BEAR) experiments, which were conducted in a similar forest (*P. sylvestris* with shallow forest floor), the depth of burn for 12 experimental surface fires ranged depending on burning conditions from 3.5 to 6.4 cm [*McRae et al.*, 2004]. The ground fuels (litter and duff) accounted for 79% of the average total fuel consumed (21% surface). Data from one crown fire revealed the contribution to average total fuel consumption was 18, 13, and 69% from crown, surface, and ground fuels, respectively. Studies from boreal Canada also demonstrate the significance of ground fuel (litter and duff) consumption, which was 28–74% in jack pine forests [*Stocks*, 1987, 1989]. In several fires in

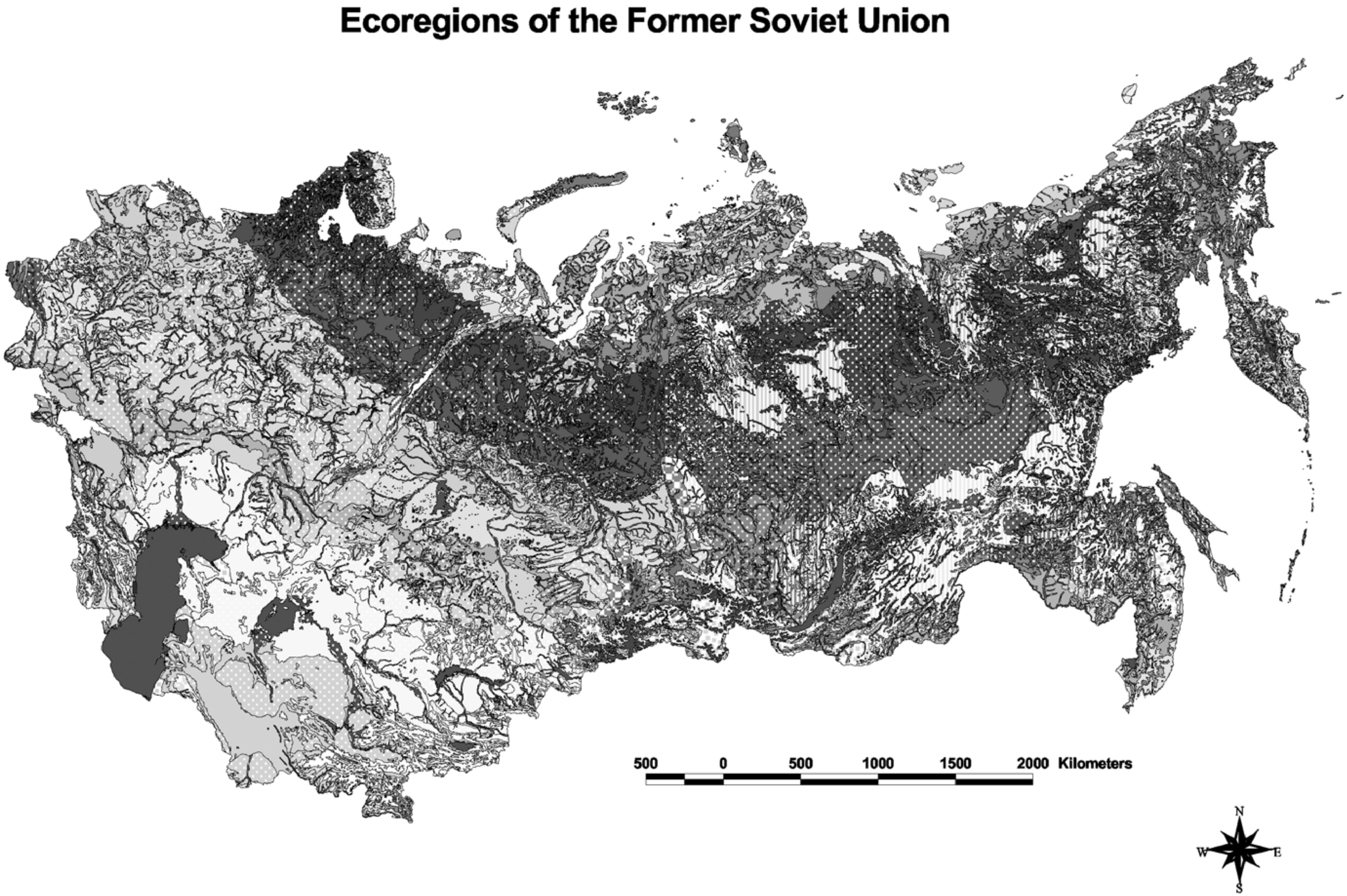

Figure 3a. Ecosystems of the former Soviet Union. This map is a subset of the original map, "System of Landscapes for the USSR: Zones, Sectors, and Altitudinal Divisions," developed at the Science Research Institute of Geography, Leningrad State University in 1989 (scale 1:4,000,000). See color version of this figure at back of this issue.

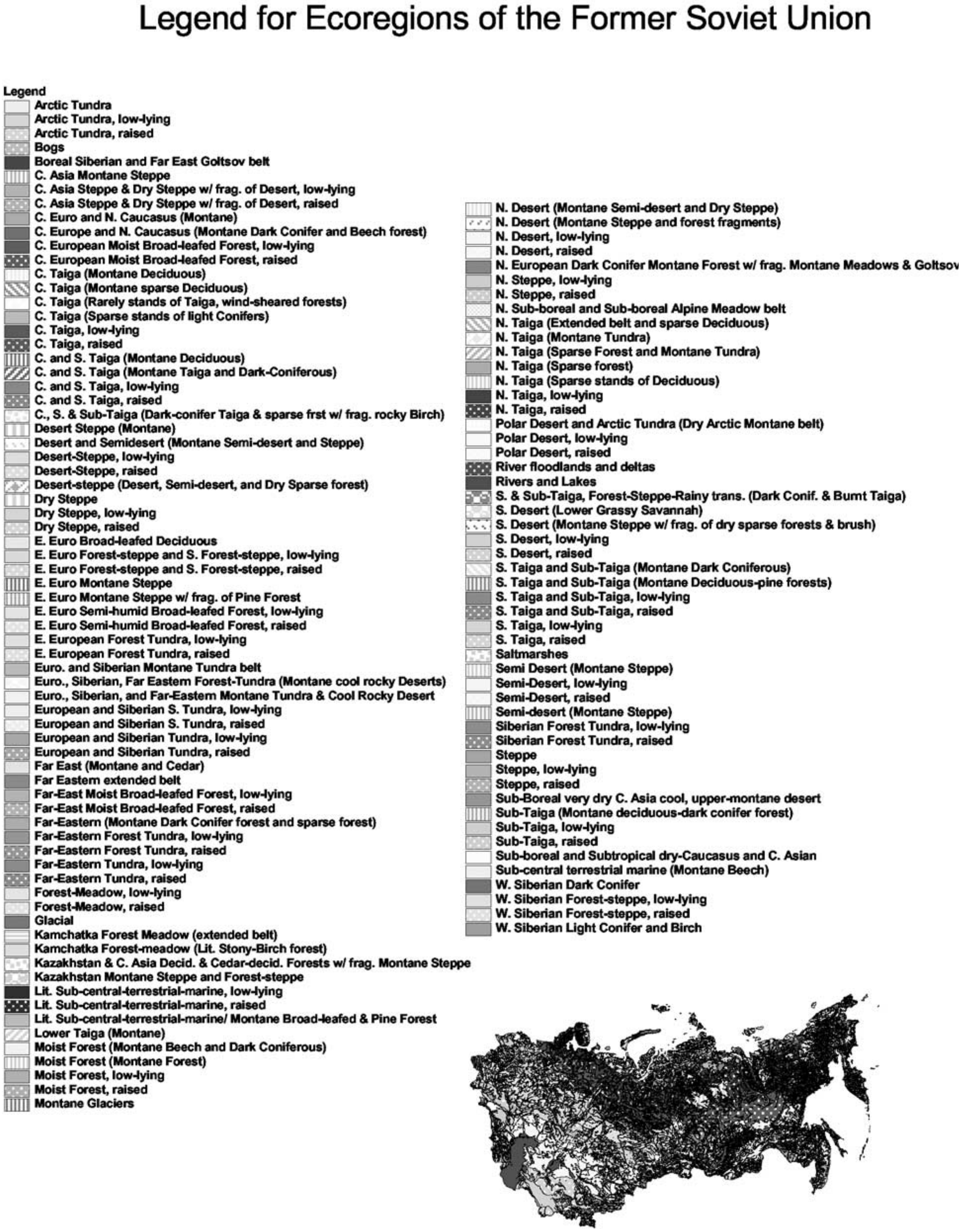

Figure 3b. Legend for the map shown in Figure 3a. See color version of this figure at back of this issue.

Alaska, burning was reported to extend to the mineral soil [*French*, 2002]. These reports show the significance of soil organic matter consumption, even when considering surface fires in park-like open forests.

[24] On the basis of these data, for the standard scenario, 5 cm of the soil organic matter is consumed during high-severity crown fires; 2 cm of soil organic matter is consumed during medium-severity surface fires; and low-

severity surface fires consume 1 cm of the soil organic matter. Under the extreme scenario, 10, 4, and 2 cm of the soil organic matter is consumed during high-, medium-, and low-severity fire events, respectively. *Alexeyev and Birdsey* [1998] report values of average soil carbon density between depths of 0 and 20 cm in t C ha^{-1} for each ecoregion. Even though we realize a nonlinear relationship exists between soil carbon and depth (increasing C with depth), we assume the amount of carbon in each cm layer is equivalent. Nonlinear curves have been established for some sites, but the *Alexeyev and Birdsey* [1998] soil data are based on ecoregion averages.

2.4.4. Peatlands

[25] Specific data for peatland burning in Siberia are limited and therefore difficult to assess. Our calculations are based on data found in the work of *Efremov et al.* [1998], who first estimated organic matter stored and carbon density in peatlands for every administrative territory and ecoregion in Russia. *Efremov et al.*'s [1998] carbon density data are reported in t C ha^{-1} (not biomass). We assume average depths and average peat density values for each ecozone. *Zoltai et al.* [1998] reported that shallow peat fires consumed between 4 and 20 cm in thickness and deep peat fires could consume as much as 50 cm to 1 m in North America. Medium-depth peatlands in Siberia are classified as those less than 1.5 m in depth, and their midrange is 1.1 m. Therefore, in the standard scenario, 5.5 cm (5%) of peat is consumed, and in the extreme scenario, 22 cm (20%) is consumed.

2.5. Models

2.5.1. Traditional Scenario

[26] During a normal fire year in Russia, surface fires consume approximately 80% of the area burned and about 20% is consumed by crown fires [*Belov*, 1976; *Korovin*, 1996]. Specifically, Korovin estimates that 77% of the area burned by wildfire in Russia is by surface fires, 22% by crown fires, and 1% by ground fires (peat). The traditional approach accepts the percentages of area burned according to *Korovin* [1996] and calculates total carbon emissions using the mean amount of carbon released from ecoregions within the standard scenario (includes standard soil organic matter). The traditional estimate differs from the standard and extreme estimates in that it uses the mean amount of carbon released from each severity class in each ecozone, as opposed to defining carbon released by ecosystem, temporally, or by the extent of area burned. For the traditional estimate, 22% of the area burned is consumed by high-severity crown fires, 38.5% is by medium-severity surface fires, 38.5% is by low-severity surface fires, and the remaining 1% is by peat fires.

2.5.2. Standard and Extreme Scenarios

[27] These two scenarios are equivalent, except in terms of the amount of soil organic matter consumed. Figure 1 diagrams the separation of area burned in hierarchical order of importance. Peat fires are first segregated, then large fires (>100 km^2), and lastly by the month the fire occurred. In other words, if a peat fire is a large fire, it is included in the peat category, not the large fire category.

[28] The variety of fire behavior that occurs naturally across boreal Siberia can be more realistically portrayed by classifying the severity of fire in terms of ecosystems, extent of area burned, and the month fire events occur. Peatland fires are analyzed separately because the amount of carbon stored in peatlands is typically higher than that held in forested zones. In addition, any single fire event that consumes more that 100 km^2 is assumed to be a large and severe fire. This is similar to the *French et al.* [2000] model, where the fraction of biomass consumed was based on the extent of the area burned annually. Fires that occur at the extremities of the fire season (March, April, September, October (MASO)), when temperatures are cooler and less conducive for drying fuels, are assumed to be of low severity. Intense fires that may occur in MASO should be sufficiently large to be included in the large fire category.

[29] The months of severe fire events are somewhat confounded by competing arguments. Generally, over half of the annual precipitation that falls in Siberia falls during June, July, and August, accounting for 62 and 57% of the total annual precipitation in Irkutsk and Verkhoyansk, respectively, which results in relatively dryer fuels in May [*Lydolph*, 1985]. However, peak temperatures concurrently occur in June, July, and August, and the peak growing season also occurs during this time, providing the greatest potential for evapotranspiration, also resulting in dryer fuels. Furthermore, high-severity fire events are more likely to be under the control of regional-scale weather patterns [*Stocks and Street*, 1982; *Pastor and Mladenoff*, 1992; *Stocks et al.*, 1998], and these data are not available at the current time. Additionally, it has been our experience in Krasnojarsk that fires are possible during any month of the fire season. For instance, several experimental burns conducted in July and August burned well following precipitation events that occurred earlier in the day. For these reasons, fires that occur in May, June, July, or August (MJJA) (excluding large and peat) are modeled strictly on the basis of *Korovin* [1996] averages, 22% high-severity crown fires, 39% medium-severity surface fires, and 39% low-severity surface fires.

2.6. Emissions of CO_2, CO, CH_4, TNMHC, and Carbonaceous Aerosols

[30] Carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), total nonmethane hydrocarbons (TNMHC), and carbonaceous aerosols are calculated using mean emissions ratios taken from prescribed boreal fires [*Cofer et al.*, 1991]. While there is currently a large amount of activity in determining emission ratios (particularly with regard to oxygenated hydrocarbons), these efforts are more critical to atmospheric chemistry processes and should only minimally affect total carbon species emissions calculations. TNMHC are hydrocarbons lumped together and measured as equivalent methane response. Carbonaceous aerosols (organic carbon and black carbon) are assumed to be 2%, even though the concentration in the initial plume may be higher (larger particles settle quickly). The production of black carbon and organic carbon are different in the smoldering and flaming phases of a fire; however, total carbonaceous aerosols are assumed to remain constant. Emissions of each species are calculated using the following formula for both the standard and extreme scenarios.

$$E_s = C_t ER_s \frac{MW_s}{MW_c}, \tag{3}$$

where E_s is emissions of the species, ER_s is the emissions ratio of the species, MW_s is molecular weight of the species, and MW_c is the molecular weight of carbon.

[31] The fractions of flaming versus smoldering combustion are difficult to partition because no quantitative method exists in boreal systems. For this reason, aboveground vegetation is partitioned equally (50% flaming, 50% smoldering). Soil organic matter is partitioned as 100% smoldering on the basis of the work of *Johnson* [1992] and *Yokelson et al.* [1996], who suggested that ground fire consumption is dominated by smoldering combustion. Specific product emissions calculated and tabulated for the peat category have the highest uncertainty because they have been so poorly characterized. *Zoltai et al.* [1998] report that smoldering combustion characterizes peatlands; however, herbaceous overstory tends to burn in fens (a peatland category). Even though one might think that peat fires are less efficient, producing more partially oxidized carbon products, that thought cannot be substantiated. Consequently, emissions from peat fires are calculated as 90% smoldering and 10% flaming.

3. Results

3.1. Carbon Consumption Estimates

[32] The derived fuel consumption estimates are reported for each ecoregion in terms of carbon for each severity class in Tables 1 and 2. Ecozone mean carbon consumption estimates for peatlands are also shown in Tables 1 and 2. Differences between carbon consumption estimates exemplify the importance of fire severity and ecoregion specifics. The difference between low- and high-severity carbon consumption estimates ranges from 80 to 84%, and the difference between standard and extreme scenario estimates ranges from 22 to 38%. The difference in carbon consumption estimates between the west Siberian forest tundra and the northern taiga is less than 1%; however, the difference between the west Siberian steppe and the Far East forest steppe is 60%. These differences highlight the potential for the severity of fire events and the ecoregion burned to influence estimates of total direct carbon emitted.

[33] Biomass is typically higher in boreal ecoregions than in similar vegetation zones in warmer regions of the world. For example, the steppe zone includes forest forming species (*Betula pendula*, *Pinus sylvestris*), as well as forbs, herbs, and bunchgrass [*Alexeyev and Birdsey*, 1998]. In terms of carbon stored, Siberian steppe regions are not similar to grassland savannas. In forest-steppe regions in Siberia, soil carbon density reaches a maximum. These effects are produced by relatively high productivity in the regions and the equilibrated processes of mineralization and humification of incoming organic matter [*Alexeyev and Birdsey*, 1998]. Additionally, negligible winter precipitation results in deep freezing of the soils followed by spring precipitation that delays litterfall decomposition, resulting in deep humic profiles.

[34] Comparisons between estimates from this study and previously published estimates from Russia are shown in Figure 4 and described in the following paragraphs. Mean carbon consumption estimates are 19.97 t C ha^{-1} in the standard scenario and 28.27 t C ha^{-1} in the extreme scenario. Early published estimates of mean carbon emissions for

Table 2. Extreme Scenario Carbon Consumption Estimates[a]

	Western Siberia			Middle Siberia			Eastern Siberia			Far East		
	High-Severity Crown Fire, t C ha^{-1}	Medium-Severity Surface Fire, t C ha^{-1}	Low-Severity Surface Fire, t C ha^{-1}	High-Severity Crown Fire, t C ha^{-1}	Medium-Severity Surface Fire, t C ha^{-1}	Low-Severity Surface Fire, t C ha^{-1}	High-Severity Crown Fire, t C ha^{-1}	Medium-Severity Surface Fire, t C ha^{-1}	Low-Severity Surface Fire, t C ha^{-1}	High-Severity Crown Fire, t C ha^{-1}	Medium-Severity Surface Fire, t C ha^{-1}	Low-Severity Surface Fire, t C ha^{-1}
						Plains						
Forest tundra	61.98	26.76	12.04	56.45	24.26	10.84	0	0	0	0	0	0
Northern taiga	62.6	25.45	11.58	42.85	17.05	7.88	0	0	0	0	0	0
Middle taiga	59.65	23.05	10.66	56.12	21.45	9.86	51.62	20.45	9.46	0	0	0
Southern taiga	62.81	23.8	11.04	64.18	23.7	10.94	0	0	0	0	0	0
Forest steppe	71.37	27.04	12.73	74.77	28.74	13.63	0	0	0	75.37	30.04	14.03
Steppe	30.2	11.5	5.4	0	0	0	0	0	0	0	0	0
						Mountains						
Subarctic	0	0	0	40.21	17.86	7.94	44.77	19.96	8.84	36.67	15.96	7.24
Boreal	0	0	0	51.51	19.95	9.12	48.8	19.65	8.92	51.7	20.55	9.22
Subboreal	0	0	0	50.64	18.8	8.6	50.55	19.2	8.8	53.49	20.3	9.2
Subarid	0	0	0	41.56	17	8	0	0	0	0	0	0
Mean column	58.1	22.93	10.58	53.14	20.98	9.65	48.94	19.82	9.01	54.31	21.71	9.92
Mean group	30.54			27.92			25.92			28.65		
					Extreme Mean Carbon Consumption Estimates for Peatlands, t C ha^{-1}							
Peatlands		83.53			88.51			81.95			71.55	

[a]Here $(T\beta_T) + (U\beta_U) + (L\beta_L) + (S\beta_S)$. Estimates are based on biomass and carbon data reported in the work of *Alexeyev and Birdsey* [1998]. Carbon consumption is reported in tons of carbon per hectare (t C ha^{-1}). Zeros are present when no data values are reported by *Alexeyev and Birdsey* [1998].

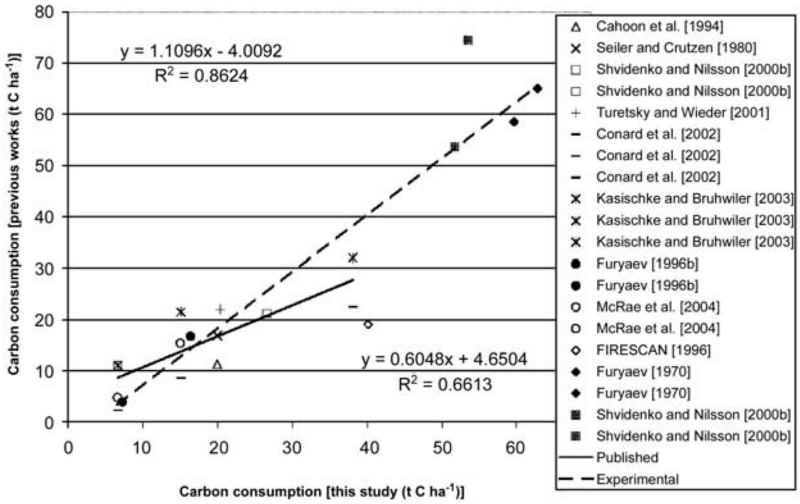

Figure 4. Carbon consumption comparison. Estimates from this study are compared with estimates from (1) previously published works (published) and (2) experimental fires (experimental). The formula on the top of the graph refers to experimental data, and the formula on the bottom of the graph refers to previously published works. Only Russian data values are included, and these are reported in tons of carbon per hectare (t C ha^{-1}). Each value is discussed in detail in the text.

boreal Siberia ranged from 11.25 [*Cahoon et al.*, 1994] to 16.9 t C ha^{-1} [*Seiler and Crutzen*, 1980]. *Stocks and Kaufman* [1997] estimated from 9 to 17 t C ha^{-1} (f_c = 0.50) for boreal regions, and *Shvidenko and Nilsson* [2000b] estimated from 11 to 21.2 t C ha^{-1} for Russia. The mean standard scenario estimate of carbon released from peatlands is 20.35 t C ha^{-1}, which is consistent with the *Turetsky and Wieder* [2001] average estimate of 22 t C ha^{-1}; however, the extreme scenario average estimate of 81.39 t C ha^{-1} is much greater than reported means. The mean estimates from this investigation are generally higher than previous mean estimates but are comparable, even though a substantial amount of soil organic matter is explicitly included in the estimates from this investigation, particularly in the extreme scenario.

[35] Several works have realized the importance of estimating ecoregion-specific carbon consumption because of the significant differences in carbon stored in varying ecoregions. *Kasischke et al.* [1995b] modeled biomass accumulation and reported between 25.4 and 30.0 t C ha^{-1} released from fire in boreal Alaska. *Amiro et al.* [2001] estimated ecozone-based carbon consumption estimates for boreal Canada, which ranged from 9 to 19.5 t C ha^{-1}. *French et al.* [2000] calculated ecosystem-based carbon consumption estimates for North America in "low-" and "high-" severity fire years, which ranged from 2.43 to 18.86 t C ha^{-1} in low fire years and from 17.05 to 57.99 t C ha^{-1} in high-severity fire years. Carbon consumption estimates from this study range from 3.40 to 50.12 t C ha^{-1} in the standard scenario and from 5.40 to 75.37 t C ha^{-1} in the extreme scenario. The carbon consumption estimates reported here are most similar to the *French et al.* [2000] estimates because both studies incorporate ecoregion specific anomalies and varying depths of soil organic matter consumed. The range of estimates reported in the extreme scenario is larger than those reported in the literature; however, Siberian ecosystems are unique and it is our intent to include extreme estimates.

[36] *Conard et al.* [2002] and *Kasischke and Bruhwiler* [2003] considered fire severity in their fuel consumption estimates. *Conard et al.* [2002] reported 2.3 t C ha^{-1} consumed in low-severity surface fires, 8.6 t C ha^{-1} in medium-severity surface fires, and 22.5 t C ha^{-1} in high-severity crown fires in Russia. *Kasischke and Bruhwiler* [2003] estimated carbon consumption of 2, 11, 21.5, and 32 t C ha^{-1} in steppe, light, moderate, and severe burn categories, respectively, for Russia. In the standard scenario the average estimates of fuel consumed are 6.68, 15.14, and 38.11 t C ha^{-1} for low-severity surface fires, medium-severity surface fires, and high-severity crown fires, respectively, and 9.79, 21.36, and 53.62 t C ha^{-1} for the extreme scenario. The *Conard et al.* [2002] estimates are consistently lower than the estimates reported here; however, they did not explicitly include consumption of soil organic matter. Except in the extreme high-severity case, the estimates reported in this study are consistent with the *Kasischke and Bruhwiler* [2003] estimates. However, the lowest value of 2 t C ha^{-1} was taken from grassland savanna ecosystems, which are not similar to Siberia steppe ecosystems.

[37] Several experimentally based fuel consumption estimates are available for regions in Siberia [*Shvidenko and Nilsson*, 2000b]. *Furyaev* [1996b] estimated carbon consumption of on-ground fuels in pine stands in the southern taiga ranged from 3.93 to 16.71 t C ha^{-1} (f_c = 0.50). The standard scenario surface fire estimates from this study for the southern taiga in this zone range from 7.29 to 16.40 t C ha^{-1}, which are within the range of the *Furyaev* [1996b] estimates. The FIRE BEAR [*McRae et al.*, 2004] project reported the range of estimates in dry pine stands were 4.8–15.4 t C ha^{-1}, which is remarkably similar to comparable estimates from this study of 6.66–15.05 t C ha^{-1}. On a similar forest site, the *FIRESCAN* [1996] team estimated 19.06 t C ha^{-1} (f_c = 0.50) released from a crown fire. The comparable standard scenario estimate for this forest type is substantially larger, 40.12 t C ha^{-1}.

However, the FIRESCAN experimental fire transpired on an island in a forest type that does not typically support crown fires, and in order to support the high-intensity fire, a convection style perimeter ignition was required. Because this was a forest type that does not typically support crown fire, the experimental estimate may be low when compared to the entire ecoregion that does contain areas that support crown fires (i.e., have ladder fuels). *Furyaev* [1970] reported average carbon consumption estimates that ranged from 58.5 to 65 t C ha^{-1} (f_c = 0.50) in a west Siberian dark coniferous forest affected by infestation. The comparable extreme scenario high-severity estimates from this study are 59.65 and 62.81 t C ha^{-1}, which are both within the range of the ground-based data. Lastly, in a wind-damaged dark coniferous forest on Sakhalin Island, *Shvidenko and Nilsson* [2000b] estimated carbon released during a severe fire of between 53.6 and 74.4 t C ha^{-1} (f_c = 0.50). The comparable extreme scenario high-severity estimates from this study are 51.70 and 53.49 t C ha^{-1} in this region, which are both lower than the empirical estimates.

[38] In general, the estimates of carbon consumption reported in this study compare well to both published and ground-based data in both the standard and extreme scenarios. Figure 4 shows the carbon consumption estimates derived in this study are in better agreement with the experimental data than the published data, which illustrates derived carbon consumption estimates explain ecoregion and severity differences better than previously published averages. The derived estimates reported in this investigation are for a wide range of ecoregion-specific sites, which provide for a more accurate quantification of emissions. Additionally the extreme scenario, while admittedly high, provides for comparison of potential extreme fire years.

3.2. Annual and Interannual Variability of Fire

[39] Even though fire progresses northward in a regular pattern during a fire season, a tremendous amount of annual and interannual variability exists longitudinally and in the amount of area burned [*Korovin*, 1996; *Soja et al.*, 2004a]. Area burned in greater Siberia is pictured from 1998 through 2003 in Figures 5a–5f and area burned in Siberia is reported in Table 3. Annual area burned estimates vary by 62%. Estimates reported in this study for Siberia are greater than those reported by the Russia Forest Service for Russia because (1) unprotected territory is not monitored by the Aviallesookrana (Russian aerial fire fighters) and (2) the ability of the Aviallesookrana has been severely hampered in recent years owing to lack of funding for equipment and personnel [*Sofronov et al.*, 1998; *Conard et al.*, 2002; *Davidenko and Eritsov*, 2003; *Soja et al.*, 2004a, 2004b].

[40] Previous versions of the Sukachev fire products were used as the basis of area burned in two previous studies, *Conard et al.* [2002] and *Kasischke and Bruhwiler* [2003]. These studies estimate 13.3 and 13.1 million hectares (M ha) burned, respectively, in Russia in 1998, and this study reports that 10.34 M ha burned in Siberia. The reasons for these differences are the *Conard et al.* [2002] analysis included data from European Russia and was scaled to include regions where scars were not analyzed. Additionally in 1998, large fires occurred in the Far East, at the limits of the Sukachev detection mask. Further versions of the products may yield larger amounts of area burned (Sukhinin et al., submitted manuscript, 2004). Area burned data presented here are based on the Sukhinin et al. (submitted manuscript, 2004) data set and as such, are consistent with those estimates. One additional study used satellite data to estimate area burned in 1998 in Siberia and northern Mongolia, resulting in 11 M ha burned [*Kajii et al.*, 2002], which is consistent with the estimate provided in this study for Siberia.

[41] According to published reports, high-severity crown fires in elevated fire years represent up to 50% of the total area burned annually in Russia [*Belov*, 1976] and about 22% during normal fire years [*Korovin*, 1996]. This study finds high-severity crown fires represent 51% of the total area burned in 1998, 24% in 1999, 49% in 2000, 47% in 2001, and 59% in 2002, which is not consistent with Russian reports unless most of these are elevated fire years. Perhaps this is evidence of increased severity in fire seasons, which has been predicted, will occur under warmer climate change scenarios [*Stocks and Lynham*, 1996]. Alternatively, it could be evidence of an altered fire regime owing to lack of funding for the Aviallesookrana.

[42] Area burned is reported by ecoregion in Figure 6. Ecoregions span ecozones, and most of the area burned in boreal regions is by large fire events [*Stocks*, 1991; *Alaska Fire Service* (*AFS*), 1992; *Valendik*, 1996; *Soja et al.*, 2004a], so this figure also identifies the ecoregions where large fire events occurred (middle taiga and montane subboreal). Area burned is presented in each category in Figure 7, which shows that area burned in every year is dominated by large fire events.

[43] Two severe fire years are included in this study, 1998 and 2002. The well-documented 1998 fires burned 3.9 M ha in Khabarovsk and 3.5 M ha in the area surrounding Chita (Figures 5a and 5e). Over 4.7 M ha burned in the montane subboreal ecoregion and almost 2 M ha in the montane boreal ecoregion (Figure 6). Also notable in 1998 is 0.9 M ha burned in the steppe ecoregion, which is about six times greater than in any other reported year.

[44] A severe fire season also occurred in 2002, burning over 5 M ha in Yakutia and 1.8 M ha in Amurskia (Figure 5e). Unlike the 1998 fires, these fires are not well documented. The fires in Yakutia began in April of 2002 and continued through early October. When the fires peaked in mid to late August, a dark pall of smoke covered hundreds of kilometers (Figure 8). Notably, over 4.3 M ha burned in the middle taiga ecoregion of east Siberia (Figures 5 and 6), which accounts for almost half of the total carbon emissions from 2002 (148 Tg (teragrams – 10^{12})).

3.3. Total Direct Carbon Emissions

[45] Direct carbon emissions estimates are reported by category within each ecozone in Table 4, and Figure 9 shows direct carbon emissions by ecozone. Table 4 and Figures 5–9 provide a sense of the temporal, spatial, and interannual variability of fire in Siberia. For instance, the largest contribution to emissions in 1999 is from large fires (>100 km^2) in middle Siberia. In contrast, the largest contribution to emissions in 1998, 2000, and 2001 is from large fires in the Far East, and the largest contribution to emissions in 2002 is from large fires in east Siberia. Area burned in the MJJA category is largest in 1999, which is considered to be a less severe fire year. And in the elevated

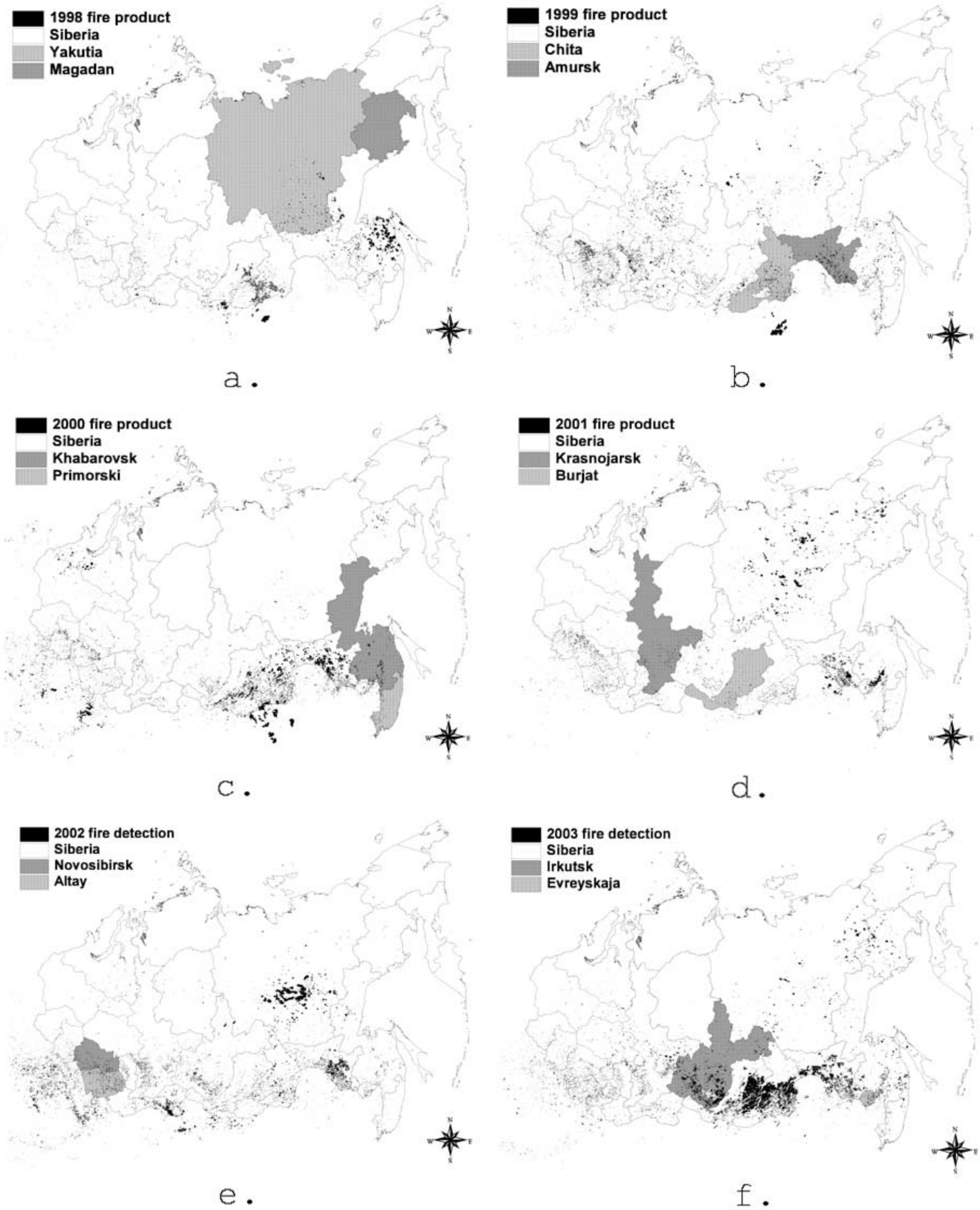

Figure 5. (a–f) Area burned annually in Siberia (1998–2003). Unique states are shown in each map. Although emissions from 2003 are not included in this study, 2003 is another severe fire year resulting in area burned of greater than 13.7 M ha (fire detections calculated only).

fire years of 1998 and 2002, area burned by large fires is greatest, which is expected in elevated fire years. The zone or ecoregion burned is not consistent, but large fire events consistently dominate emissions.

[46] Area burned in peatlands is largest for any year in 1998. The *Kasischke and Bruhwiler* [2003] estimates of 40–80 Tg C consumed in peatland burning in 1998 is based on 0.5 M ha burned. The 1998 estimates reported in this study are based on 1.3 M ha burned; however, the *Kasischke and Bruhwiler* [2003] emissions estimates lie between the standard (25 Tg C) and extreme (101 Tg C) scenario estimates reported in this study for 1998.

Table 3. Area Burned Comparison

	Region					
Year	Siberia,[a] M ha	Siberia and Northern Mongolia,[b] M ha	Russia,[c] M ha	Russia,[d] M ha	Russia,[e] M ha	Russia,[f] M ha
1998	10.34	11	13.3	13.1	11.49	5.34
1999	6.88				5.43	1.05
2000	9.00				9.71	1.64
2001	8.10			5.2[g]	7.56	1.23
2002	11.17				12.1	1.83

[a]From this study.
[b]From *Kajii et al.* [2002].
[c]From *Conard et al.* [2002].
[d]From *Kasischke and Bruhwiler* [2003].
[e]From Sukhinin et al. (submitted manuscript, 2004).
[f]From Russian Federal Forest Service; see also *Shvidenko and Goldammer* [2001] and *Goldammer* [2003].
[g]From *Zhang et al.* [2003].

[47] Table 5 provides total direct carbon emissions estimates for the traditional, standard, and extreme scenarios. Traditional scenario emissions estimates are lower than the standard scenario estimates, corresponding to 59, 67, 59, 64, and 57% of the standard estimates for 1998 through 2002, respectively. Because the traditional estimates are based on averages, this highlights the significance of using area-weighted ecoregions, fire size, and the month of the fire occurrence when estimating emissions. Standard scenario estimates are 63, 60, 61, 59, and 62% of extreme scenario estimates for 1998 through 2002, respectively. These differences emphasize one of the most significant aspects of estimating total carbon emissions, which resides in determining and or selecting the amount of burning in the partially decomposed soil organic matter. These considerations can realistically affect total carbon emissions estimates.

[48] Table 6 compares the total direct carbon emissions estimates determined in this study to those resolved in other investigates. In the last column, other studies are scaled to the amount of area burned in this study so that they can be easily compared. Traditional scenario estimates are well within the range of estimates from other studies. Two of the standard scenario estimates are within the range of other studies. The largest standard estimate is 18% greater than the largest previously published estimate. The major contribution to these differences is the ecoregion-specific carbon consumption estimates. All of the extreme scenario estimates are greater than published estimates, ranging from 8 to 49% greater than the largest previous estimate. The depth of soil organic matter consumed during fire events is the primary contribution to these disparities. Taking into

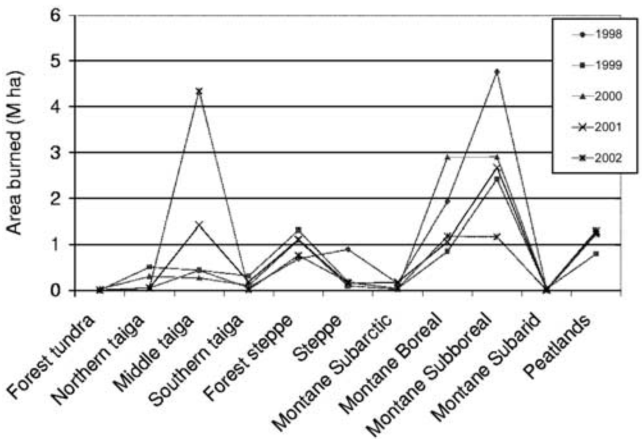

Figure 6. Area burned by ecoregion. Ecoregions span ecozones. Area burned is reported in millions of hectares (M ha).

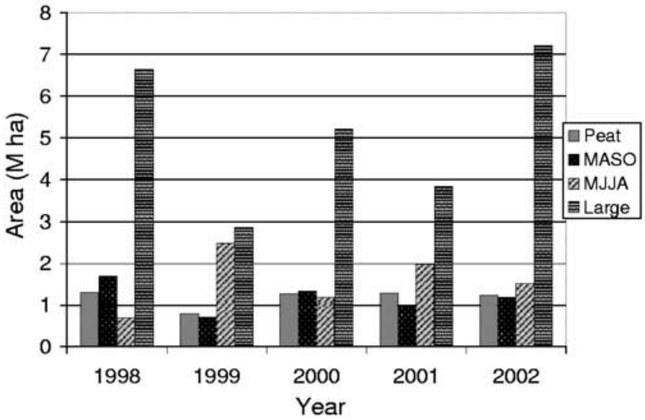

Figure 7. Area burned in each category. Categories are only delineated in the standard and extreme model scenarios. These include: peatlands (peat); low-severity surface fires (March, April, September, or October (MASO)); fires that occur in May, June, July, or August (MJJA); and high-severity crown fires (large fires >100 km^2). Area burned is reported in millions of hectares (M ha).

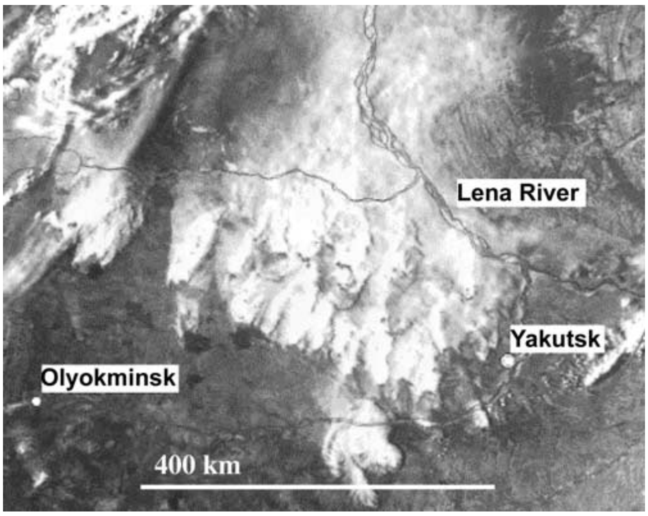

Figure 8. Smoke covering Yakutia during the 2002 fire season. The image displayed above is an AVHRR image from 14 August 2002. Active fires are highlighted in red; smoke is shown in yellowish white, rivers are overlaid in blue, scars are dark brown, clouds are bright white, and vegetation is green. See color version of this figure at back of this issue.

Table 4. Summary of Direct Carbon Emissions for Each Ecozone by Category[a]

Year	West Siberia Standard Estimate				West Siberia Extreme Estimate			
	Peat, Tg C	MASO, Tg C	MJJA, Tg C	Large, Tg C	Peat, Tg C	MASO, Tg C	MJJA, Tg C	Large, Tg C
1998	4.53	7.38	2.3	2.91	18.11	11.79	3.5	4.27
1999	3.45	1.28	11.9	18.14	13.82	2.04	18.19	27.27
2000	6.78	2.25	3.19	22.38	27.13	3.61	4.64	32.38
2001	1.99	1.62	6.37	7.65	7.96	2.58	9.73	11.51
2002	1.45	1.6	5.26	5.21	5.78	2.55	7.99	7.63
	Middle Siberia Standard Estimate				Middle Siberia Extreme Estimate			
	Peat, Tg C	MASO, Tg C	MJJA, Tg C	Large, Tg C	Peat, Tg C	MASO, Tg C	MJJA, Tg C	Large, Tg C
1998	4.31	0.18	3.63	5.91	17.24	0.27	5.1	8.2
1999	3.47	0.37	19.95	41.76	13.9	0.54	28.27	58.04
2000	0.6	0.73	2.24	3.13	2.41	1.08	3.16	4.34
2001	0.97	0.38	4.91	6.97	3.86	0.55	6.93	9.66
2002	2.97	1.57	10.51	47.52	11.89	2.3	14.77	65.4
	East Siberia Standard Estimate				East Siberia Extreme Estimate			
	Peat, Tg C	MASO, Tg C	MJJA, Tg C	Large, Tg C	Peat, Tg C	MASO, Tg C	MJJA, Tg C	Large, Tg C
1998	3.74	1.4	3.73	105.74	14.95	2.03	5.24	146.92
1999	5.16	1.41	5.48	26.98	20.62	2.05	7.72	37.69
2000	4.13	3.77	7.95	84.35	16.5	5.49	11.11	116.52
2001	7.55	1.61	19.53	66.35	30.18	2.35	27.72	93.7
2002	10.15	5.05	2.18	169.62	40.59	3.17	7.24	244.68
	Far East Standard Estimate				Far East Extreme Estimate			
	Peat, Tg C	MASO, Tg C	MJJA, Tg C	Large, Tg C	Peat, Tg C	MASO, Tg C	MJJA, Tg C	Large, Tg C
1998	12.62	0.07	1.98	136.61	50.48	0.1	2.69	182.5
1999	3.93	1.99	4.03	24.13	15.71	3.01	5.48	33.07
2000	12.75	2.12	7.01	94.02	50.99	3.12	9.76	128.33
2001	13.95	3.32	1.74	67.76	55.81	4.96	2.38	92.66
2002	9.52	2.66	4.33	42.56	38.07	3.91	5.97	57.97

[a]Categories include peatlands (March, April, September, October (MASO); May, June, July, August (MJJA)) and large fire events (>100 km^2). Emissions are reported for the standard and extreme scenarios for 1998 through 2002. Carbon (C) is reported in teragrams (Tg (10^{12})).

account predicted changes in fire season severity, extreme estimates may represent a future reality.

3.4. Emissions of CO_2, CO, CH_4, TNMHC, and Carbonaceous Aerosols

[49] Table 7 shows emissions of primary carbon products, separated by year and combustion category (peat, aboveground, and soil organic matter). Standard scenario estimates of CO_2, CO, CH_4, TNMHC, and carbonaceous aerosols are between 58 and 63% of the extreme scenario estimates. The differences in these scenarios suggest that the amount of soil organic matter available during a fire is significant to estimating trace gases emitted to the atmosphere.

[50] *Goode et al.* [2000] estimated boreal emissions of CO_2, CO, CH_4, and TNMHC, and these are consistent with those reported in this investigation, even though peatland and flaming to smoldering combustion were not differentiated in the *Goode et al.* [2000] investigation. Table 6 compares estimates from this investigation with *Goode et al.* [2000] estimates, scaled to 11.17 M ha (this study, year 2002). With the exception of CH_4, the standard scenario estimates are within the range of *Goode et al.* [2000] estimates. Extreme scenario estimates are 33, 9, and 36% greater than the *Goode et al.* [2000] estimates for CO_2, CO, and TNMHC, respectively. The standard scenario CH_4 estimate is 11% greater than the largest *Goode et al.* [2000] estimate.

[51] Primary carbon product estimates from this study are compared with global estimates published in the work of *Andreae and Merlet* [2001]. Estimates of CO_2 from Siberian fires in 1998 through 2002 in the standard scenario range between 6 and 13% of the total global estimate from forest and grassland burning and up to 20% in the extreme scenario; estimates of CO from the standard scenario range between 10 and 19% of the total global estimate from forest and grassland burning and up to 32% in the extreme scenario; estimates of CH_4 from the standard scenario range between 13 and 23% of the total global estimate from forest and grassland burning and up to 38% in the extreme scenario; estimates of TNMHC from the standard scenario

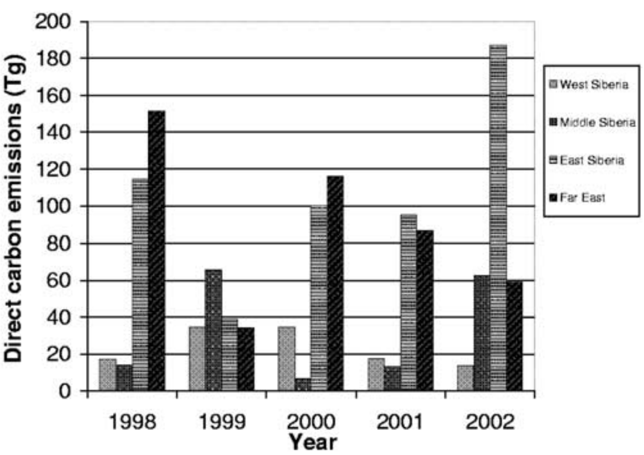

Figure 9. Direct carbon emissions by ecozone. Emissions are reported in teragrams (Tg (10^{12})) of carbon (C).

Table 5. Summary of Total Direct Carbon Emissions From Siberia for 1998 Through 2002[a]

		Total Direct Carbon Emissions		
Year	Area, M ha	Traditional, Tg C	Standard, Tg C	Extreme, Tg C
1998	10.34	175.10	297.03	473.37
1999	6.88	116.19	173.42	287.42
2000	9.00	151.57	257.40	420.56
2001	8.10	135.52	212.67	362.55
2002	11.17	184.37	322.15	519.93

[a]Three scenarios are reported that vary the severity of fire events and the associated amount of soil organic matter consumed. Area burned is reported in millions of hectares (M ha) and carbon (C) is reported in teragrams (Tg (10^{12})).

range between 9 and 17% of the total global estimate from forest and grassland burning and up to 27% in the extreme scenario; and estimates of carbonaceous aerosols from the standard scenario range between 18 and 33% of the total global estimate from forest and grassland burning and up to 53% in the extreme scenario. These results suggest that Siberia is indeed a substantial source of global biomass burning emissions.

[52] The three categories of flaming to smoldering combustion presented in this study are compared to the typical 50:50 ratio. Figure 10 shows an example of the difference in CH_4. Accounting for smoldering combustion in the soil organic matter resulted in increases of about 11–12% in CO, 13–14% in CH_4, 10–11% in TNMHC, and decreases of 1–2% in CO_2. Higher emissions of CO and CH_4 and lower emissions of CO_2 are consistent with *French et al.* [2003] findings. The results demonstrate that the portion of flaming to smoldering combustion is significant to determining quantities of trace gas species. The model highlights the potential for error caused by inaccurate flaming to smoldering combustion ratios, which suggests that empirical quantification of flaming to smoldering combustion is warranted, particularly in boreal regions where most of the carbon is stored in the soils and peats, where smoldering combustion typically dominates [*Johnson*, 1992; *Alexeyev and Birdsey*, 1998; *Zoltai et al.*, 1998]. *Yokelson et al.* [1996] suggested that three processes should be considered to characterize the temporal behavior of emissions: flaming, smoldering, and pyrolysis/distillation. Furthermore, a recent paper by *Bertschi et al.* [2003] highlighted residual smoldering combustion, which can be emitted for several weeks after a flame front passes. *Bertschi et al.* [2003] suggested that emission factors for these emissions are markedly different from previously reported emissions factors, which are typically based on aboveground fine fuels.

4. Discussion

[53] A range of total direct carbon emissions from Siberia is presented, which represents a substantial amount of global carbon emissions from biomass burning. The lowest standard scenario estimate represents 7% of total global carbon emissions from forest and grassland burning, and the largest extreme scenario estimate represents 20% of the total global carbon emissions from forest and grassland burning [*Andreae and Merlet*, 2001]. These estimates include improvements in accounting for ecoregion-specific biomass differences. Additionally, the spatially explicit nature of the models improves on previous models by accurately assigning area burned to specific ecoregions. The extreme scenario values are higher than those previously reported and this is primarily due to including a larger amount of soil organic matter consumed during fire events.

[54] In this investigation, area burned and aboveground biomass density values are conservative estimates. Soil organic matter consumed, particularly in the extreme scenario has the highest level of uncertainty. However, when comparing the limited empirical carbon consumption estimates from extreme fire events to the high-severity extreme scenario reported in this study, the estimates reported here are within range and comparatively low. The extreme scenario estimates are most likely representative of elevated fire years that may occur under predicted climate change

Table 6. Comparison of Emissions Estimates[a]

Study	Area Burned, M ha	Region Considered in Study	TDCE, Tg C yr^{-1}	Total Postfire Biogenic Emissions, Tg C yr^{-1}	TDCE Scaled to 6.88 and 11.17 M ha, Tg C yr^{-1}
Crutzen et al. [1979]	1.3	boreal zone	18–27		95–232
Dixon and Krankina [1993]	2.9	Russia	47	117–281	112–181
Conard and Ivanova [1997]	12	Russia	194	484–1162	111–181
French et al. [2000]	2.59	boreal North America	53	-	14–229
Shvidenko and Nilsson [2000b]	3.5	Russia	58	64	114–185
Conard et al. [2002] (excludes peat)	13.3	Russia	135–190	-	70–160
Kajii et al. [2002]	11	Siberia, northern Mongolia	176	-	110–179
Kasischke and Bruhwiler [2003]	17.9	boreal zone	290–423	-	112–264
This study	6.88–11.17	Siberia	116–520	-	116–520

Comparison of Trace Gas Emission Estimates

	Estimate Range Scaled to 11.17 M ha, This Study, 2002				
Study	Compound	CO_2, Tg yr^{-1}	CO, Tg yr^{-1}	CH_4, Tg yr^{-1}	TNMHC, Tg yr^{-1}
Goode et al. [2000]		680–1113	36–119	1.1–3.7	1.3–4.3
This study		1031–1662	80–130	4.5–7.4	4.1–6.8

[a]Comparisons include the entire range of total direct carbon emissions (TDCE) and a standard and extreme scenario estimate of trace gas emissions for 2002. Estimates from published data are scaled to the amount of area burned in this study in order to exclude differences caused by varying amounts of area burned. Carbon (C) is reported in teragrams per year (Tg C yr^{-1}).

Table 7. Summary of Carbon Monoxide (CO), Carbon Dioxide (CO_2), Methane (CH_4), Total Nonmethane Hydrocarbons (TNMHC), and Carbonaceous Aerosol Emissions[a]

	CO Standard				CO Extreme			
Year	Peatlands, Tg	Above, Tg	Soil, Tg	Total, Tg	Peatlands, Tg	Above, Tg	Soil, Tg	Total, Tg
1998	6.80	34.58	32.23	73.61	27.18	47.40	44.18	118.76
1999	4.32	20.02	18.67	43.01	17.28	28.42	26.49	72.18
2000	6.54	29.66	27.65	63.85	26.17	41.16	38.36	105.69
2001	6.60	23.94	22.32	52.86	26.39	33.68	31.39	91.45
2002	6.50	37.92	35.34	79.76	25.99	53.89	50.23	130.10
	CO_2 Standard				CO_2 Extreme			
Year	Peatlands, Tg	Above, Tg	Soil, Tg	Total, Tg	Peatlands, Tg	Above, Tg	Soil, Tg	Total, Tg
1998	79.83	511.13	359.68	950.64	319.31	700.60	493.02	1512.93
1999	50.74	295.98	208.28	555.00	202.95	420.00	295.56	918.51
2000	76.86	438.38	308.49	823.72	307.44	608.34	428.09	1343.86
2001	77.49	353.89	249.04	680.42	309.97	497.77	350.28	1158.02
2002	76.32	560.45	394.39	1031.16	305.28	796.47	560.48	1662.23
	CH_4 Standard				CH_4 Extreme			
Year	Peatlands, Tg	Above, Tg	Soil, Tg	Total, Tg	Peatlands, Tg	Above, Tg	Soil, Tg	Total, Tg
1998	0.39	1.94	1.84	4.17	1.55	2.67	2.52	6.74
1999	0.25	1.13	1.07	2.44	0.98	1.60	1.51	4.10
2000	0.37	1.67	1.58	3.62	1.49	2.31	2.19	6.00
2001	0.38	1.35	1.28	3.00	1.50	1.89	1.79	5.19
2002	0.37	2.13	2.02	4.52	1.48	3.03	2.87	7.38
	TNMHC Standard				TNMHC Extreme			
Year	Peatlands, Tg	Above, Tg	Soil, Tg	Total, Tg	Peatlands, Tg	Above, Tg	Soil, Tg	Total, Tg
1998	0.35	1.83	1.64	3.82	1.39	2.51	2.25	6.16
1999	0.22	1.06	0.95	2.23	0.89	1.50	1.35	3.74
2000	0.34	1.57	1.41	3.31	1.34	2.18	1.96	5.48
2001	0.34	1.27	1.14	2.74	1.35	1.78	1.60	4.74
2002	0.33	2.01	1.80	4.14	1.33	2.85	2.56	6.75
	Aerosols Standard				Aerosols Extreme			
Year	Peatlands, Tg	Above, Tg	Soil, Tg	Total, Tg	Peatlands, Tg	Above, Tg	Soil, Tg	Total, Tg
1998	0.67	4.20	3.04	7.92	2.69	5.76	4.17	12.62
1999	0.43	2.43	1.76	4.62	1.71	3.45	2.50	7.66
2000	0.65	3.61	2.61	6.86	2.59	5.00	3.62	11.21
2001	0.65	2.91	2.11	5.67	2.61	4.09	2.96	9.67
2002	0.64	4.61	3.34	8.59	2.57	6.55	4.74	13.86

[a]Shown are species-specific emissions estimates. Total emissions are reported for three categories (peatlands, aboveground biomass, and soil organic matter), which are modeled using three unique flaming to smoldering combustion ratios. Emissions are presented for both the standard and extreme scenarios.

scenarios; however, the extreme scenarios reported here do not include potential increases in area burned.

[55] Uncertainties stem from the parameters that are used to estimate boreal fire emissions and also from the terminology that is used to describe the parameters. For instance, available fuel is a seemingly simplistic term that does not mean the amount of fuel that resides in an ecosystem. As previously defined, available fuel is the amount of fuel that is available to burn in a particular ecosystem under prevailing weather conditions [*Quintillio et al.*, 1977; *CCFFM*, 1987; *Stocks*, 1987, 1989]. Considering that quantifying emissions often includes scientists from different nations and fields of expertise, emissions could be improved by a combined endeavor whose goal is to define and standardize terminology.

[56] Emissions parameters include area burned, carbon fraction, emission ratios (or factors), biomass density, and biomass consumed. Emissions errors and the potential for error to be propagated through emissions models are the subject of *French et al.* [2004]. *Kasischke and Bruhwiler* [2003] described uncertainty and assigned levels of uncertainty to the parameters required to estimate boreal forest fire emissions. They found the largest of these errors were for the Russian parameters, ranging from ±20 to ±100% (area burned −300%). Previously, area burned was considered to be the largest source of error in Russian investigations. *Conard et al.* [2002] observed the difference between AVHRR-based and local area burned estimates varied greatly between administrative regions. *Soja et al.* [2004a] reported that area burned in Russia was commonly underestimated by an average of 213% annually. The satellite-based product presented here, which combines active fire detection and mapped burn scars, provides a considerable improvement in area burned. *Fraser et al.* [2000] determined that combining active fire detection with burn scar mapping in boreal Canada resulted in errors of ±5%. Improvements in area burned before 2001 could be accomplished by visiting individual Aviallesookrana bases, which have been helpful in the past. After 2001, Moderate-Resolution Imaging Spectroradiometer (MODIS) data products offer the potential to improve area burned estimates for Russia. Carbon fraction varies by species from about 0.45 to 0.53, and considering the size of the problem, carbon fraction is a minimal source or error. Similarly, emission

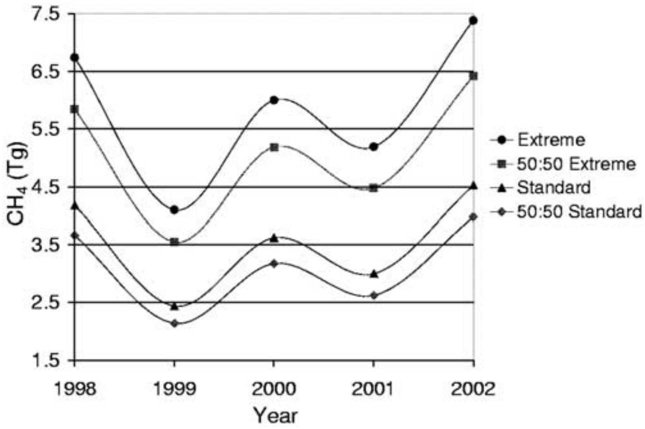

Figure 10. Comparison of flaming to smoldering ratios. Emissions of methane are modeled for standard and extreme scenarios in accordance with the three flaming to smoldering ratios defined in this study (aboveground 50:50, soil organic matter 100% smoldering, and peat 10:90). These estimates are compared to the ratio that is typically modeled, 50:50. Using the ratios defined in this investigation, emissions of CO and TNMHC also increase, and CO_2 increases.

ratios are a minimal source of error in relation to the size of the problem.

[57] Currently, the largest source of emissions error for Siberia is found in quantifying the amount of fuel or carbon consumed during fire events. The amount of total biomass varies between ecosystems, and the amount of biomass consumed varies significantly within an ecosystem, depending on the prevailing and antecedent weather conditions [*Amiro et al.*, 2001]. Total biomass reported for Russia varies by ±20% [*Alexeyev and Birdsey*, 1998; *Shvidenko et al.*, 1998; *Alexeyev et al.*, 2000]. Ecosystem specific details, as opposed to ecoregion, could improve the fuel consumption estimates; however, further refinement may not be viable at the continental scale. The digital ecosystem map is based on a 1989 ecosystem map and does not include changes in ecosystems, which is also a source of error, albeit minor, considering that the models are based on larger-scale ecoregions. Owing to their spatial domain, the models presented here are a gross improvement in accounting for fuel differences between ecoregions. Although severity-based percentages of fuel consumed and depth of soil organic matter consumed are based on experimental and published data, the potential for error in these estimates is substantial. The average difference in total direct carbon emissions between the standard and extreme scenarios is 39%, which is both indicative of minimal and elevated fire years and also of the uncertainties in fuel consumption. Modeling several severity levels is essential to mimic the patterns of fire that exist across boreal Siberia, but further ground-based validation of carbon consumed during fire events would greatly enhance these estimates. For example, not one realistic crown fire experiment has been conducted in the ecoregions that typically sustain crown fires in Siberia. Particular need exists in the unique ecosystems of Siberia and in peatlands, where large quantities of carbon are stored and minimal data exist.

[58] Siberia is a keystone region that has the size necessary to affect global change. First, Siberian ecosystems are unique and relatively unknown to western scientists. Larch (*Larix sukaczewii*, *L. siberica*, and *L. gmellini*) forests span across Siberia, traversing over 130 degrees of longitude and 20 degrees of latitude, forming pure and open stands in the north and east. *L. gmellini* (syn. *L. cajanderi*), a deciduous needleleafed species, is the only forest forming species that exists under the extreme climatic conditions in eastern Siberia on continuous permafrost, which can reach depths of greater than 500 m. On the western bank of the Yenisey River, *P. sylvestris* forests form park-like open stands that experience surface fires approximately every 15–40 years [*Furyaev*, 1996a; *Swetnam*, 1996]. It is not uncommon to find living *P. sylvestris* with two to five visible fire scars from previous fires. In North America, these particular forest-forming species do not naturally exist, and larch, of any species, does not form pure stands. Additionally, the west Siberian lowlands are the largest bog region on Earth, and they hold 40% of the Earth's peat [*Walter*, 1979; *Zoltai and Martikainen*, 1996]. Furthermore, atmosphere-ocean general circulation models (AOGCM) are in agreement concerning northern Asia, and these models estimate that warming in northern Asia could be in excess of 40% of the global warming mean [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. Consequently, fire severity and area burned are expected to increase [*Overpeck et al.*, 1990; *Flannigan and Van Wagner*, 1991; *Wotton and Flannigan*, 1993; *Stocks et al.*, 1998; *Flannigan et al.*, 2001]. Increased fire has the potential to affect global atmospheric chemistry and alter albedo, thus influencing the radiation budget [*Betts and Ball*, 1997; *French*, 2002]. The point here is Siberia is a unique and significant region that warrants increased investigation.

[59] The immediate effects of fire on soil are minimal; however, following fire events, soil temperatures can increase by as much as 2–6°C for up to 15 years after a fire, which also increases the depth of permafrost thaw, thus increasing moisture and decomposition [*Lutz*, 1956; *Kershaw et al.*, 1975; *Mackay*, 1977; *Viereck and Dyrness*, 1979; *Van Cleve and Viereck*, 1981, 1983; *O'Neill et al.*, 2003]. Several studies estimate that annual postfire biogenic carbon emissions are as much as six times greater than direct carbon emissions in boreal regions [*Dixon and Krankina*, 1993; *Conard and Ivanova*, 1997; *Shvidenko and Nilsson*, 2000b; *O'Neill et al.*, 2003]. By increasing the mean standard scenario estimate (1998–2002) by two and six times, the total mean carbon emissions (biogenic and direct) estimates are 505 and 1515 Tg C per year from Siberia. Further studies of biogenic emissions from Siberia are necessary to elucidate these quantities and the species emitted.

[60] Fire in Siberia is a dynamic process and a tremendous amount of annual and interannual variability exists [*Korovin*, 1996; *Valendik*, 1996; *Soja et al.*, 2004b]. In minimal fire years, surface fires dominate and the amount of area burned annually is small, and in elevated fire years, large extreme crown fire events burn a large amount of area annually. On the basis of the traditional and extreme scenarios presented in this investigation, total annual direct carbon emissions could be 25 Tg C in a low-severity fire year (1.5 M ha burned), and in an elevated fire year, total

annual direct carbon emissions could be as high as 929 Tg C (20 M ha burned), which amounts to 0.96 and 36% of the total global carbon emissions from forest and grassland burning [*Andreae and Merlet*, 2001]. We believe these extremes in estimates represent the potential total range of direct carbon emissions from Siberia.

5. Conclusions

[61] In earlier years, boreal fire emissions had been relegated to a minor position in terms of global fire emissions. This was largely due to incomplete knowledge of the area burned in boreal regions, particularly Russia, and also the exclusion of stored carbon that is released from soil organic matter during fire events. Boreal systems are unique in that the temperatures are relatively cool, inhibiting decomposition processes that typically release carbon to the atmosphere. The result is a large pool of stored carbon that is held in the soils and peatlands of boreal regions. Boreal fire is indeed significant to the global carbon budget and to global estimates of trace gases and aerosols emitted to the atmosphere from biomass burning and this is increasingly supported by this and other studies [*Hao and Ward*, 1993; *Cahoon et al.*, 1994; *Conard and Ivanova*, 1997; *French et al.*, 2000; *Amiro et al.*, 2001; *Conard et al.*, 2002; *Kasischke and Bruhwiler*, 2003].

[62] This investigation derives ecoregion-specific carbon consumption estimates for several classes of severity, and on the basis of these data a range of total direct carbon emissions estimates is calculated for Siberia from 1998 through 2002. Our primary conclusions are:

[63] 1. Derived ecoregion-specific carbon consumption estimates provide a range of estimates that capture the variability of carbon stored in ecoregions across Siberia and this variability is in agreement with experimental data (Figure 4).

[64] 2. The location of fire events differs tremendously, annually and interannually, thus accurately assigning fire events to severity classes and the ecoregions that burned is significant to accurately quantifying emissions (total of 69 potential categories in this study (excludes scenarios)).

[65] 3. Difference in the amount of carbon stored in individual ecoregions and the severity of fire events can realistically impact total direct carbon emissions by as much as 50% (within the standard scenario).

[66] 4. In potential extreme fire seasons (extreme scenario), which result in increased soil organic matter consumption, total direct carbon emissions are 37–41% greater than standard scenario estimates.

[67] 5. Because Siberia holds a large amount of terrestrial carbon, increases in area burned and the severity of fire events have the potential to release large amounts of carbon, at least in the short term (10–50 years). The extreme scenario results in emissions of 20% of the total global carbon emissions from forest and grassland burning (2002) and a potential of 36% in an extreme fire year (20 M ha burned). This excludes postfire biogenic emissions, which are significant.

[68] 6. Accurately accounting for smoldering combustion in soils and peatlands would result in increases of CO, CH_4, and TNMHC and decreases in CO_2 emitted from fires.

[69] Boreal forests are located in regions that are predicted to experience some of the largest temperature increases from climate change, and they hold the largest pool of global terrestrial carbon. Boreal regions are noteworthy regions to monitor and investigate because fire, which is largely under the control of weather and climate [*Payette and Gagnon*, 1985; *Clark*, 1988; *Flannigan and Harrington*, 1988; *Stocks et al.*, 1998], holds the key to unlocking carbon stores, which could result in large short-term fluxes of carbon to the atmosphere. Siberia is an understudied region that houses vast unique ecosystems and immense peatlands. Uncertainties in emissions estimates could be reduced by associating burning conditions (i.e., weather) to actual fire events and by quantifying ecosystem-specific fuel consumption estimates via experimental burns that are typical of the ecosystem under study.

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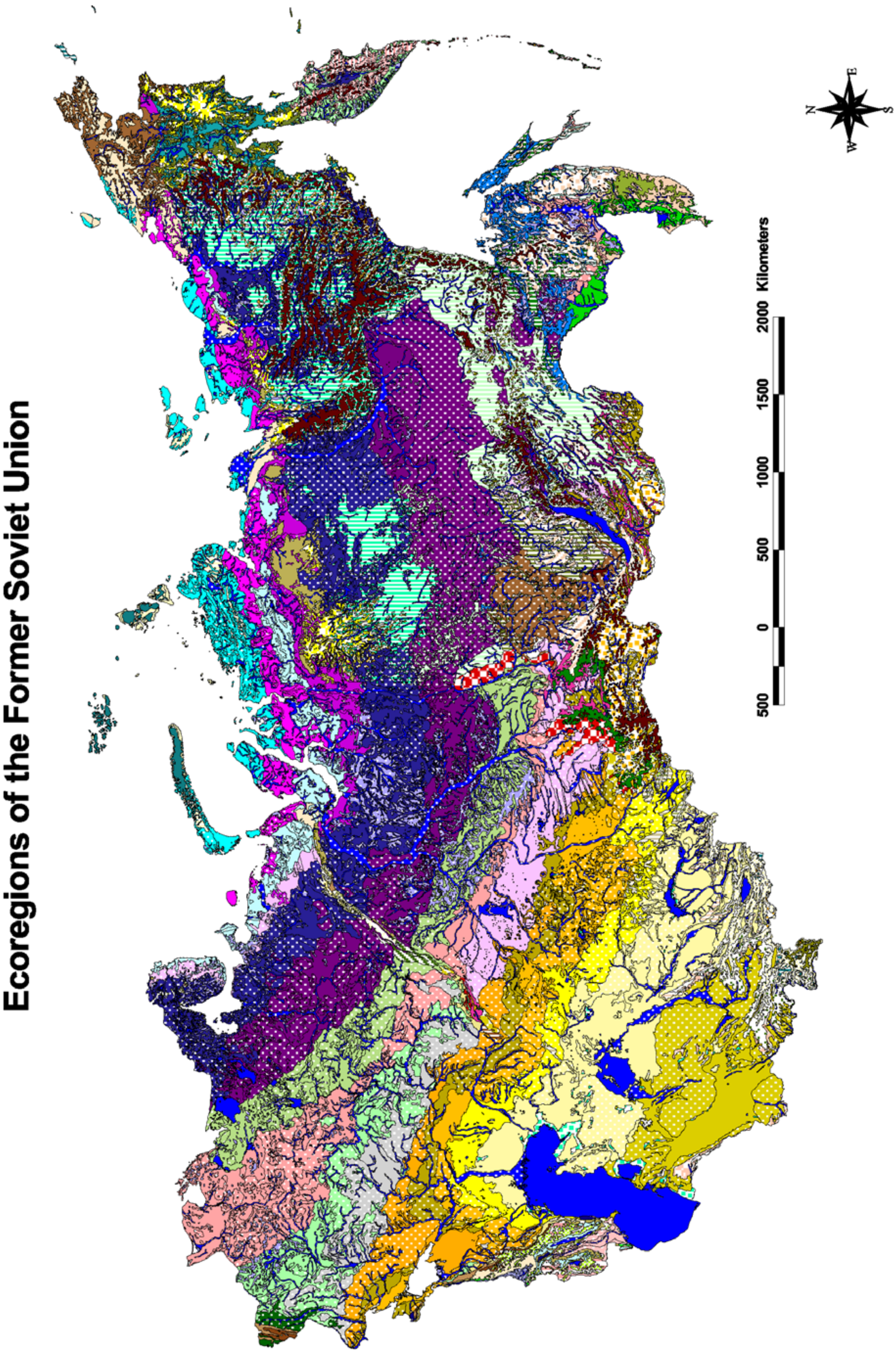

Figure 3a. Ecosystems of the former Soviet Union. This map is a subset of the original map, "System of Landscapes for the USSR: Zones, Sectors, and Altitudinal Divisions," developed at the Science Research Institute of Geography, Leningrad State University in 1989 (scale 1:4,000,000).

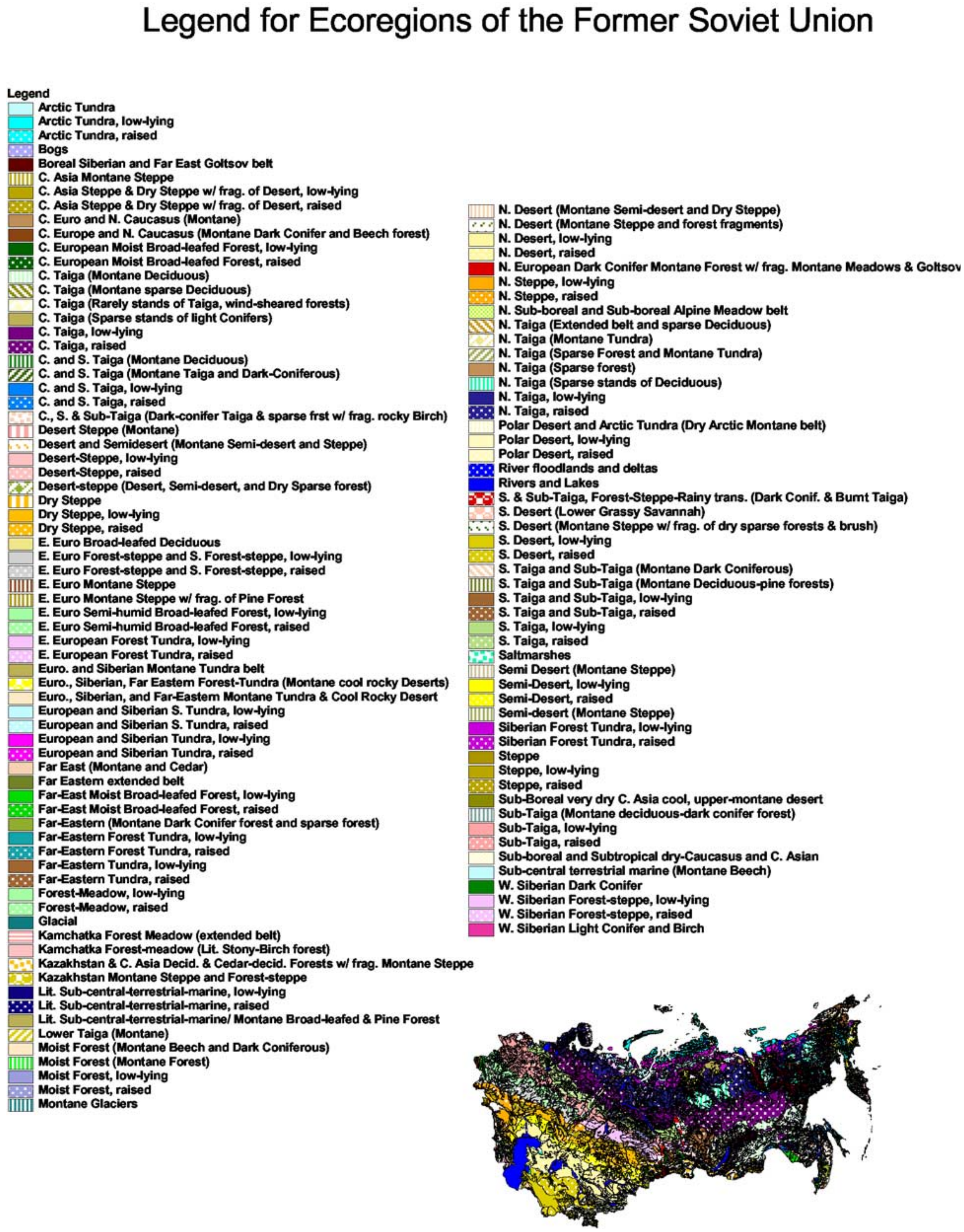

Figure 3b. Legend for the map shown in Figure 3a.

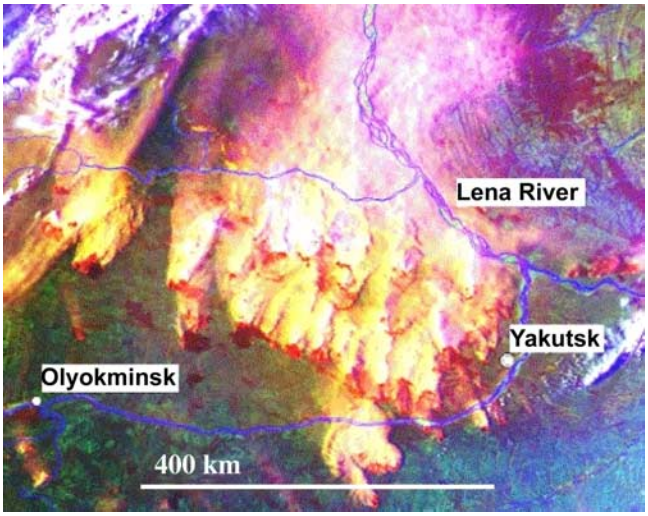

Figure 8. Smoke covering Yakutia during the 2002 fire season. The image displayed above is an AVHRR image from 14 August 2002. Active fires are highlighted in red; smoke is shown in yellowish white, rivers are overlaid in blue, scars are dark brown, clouds are bright white, and vegetation is green.