Fire in Siberian Boreal Forests — Implications for Global Climate and Air Quality[1]

Susan G. Conard[2] and Eduard P. Davidenko[3]

Abstract

Boreal forests and woodlands comprise about 29 percent of the world's forest cover. About 70 percent of this forest is in Eurasia, mostly in the Russian Federation. Boreal forests contain about 45 percent of the world's growing stock and are an increasingly important part of global timber production. Fire impacts large areas of boreal forest annually in Russia, and in excess of 60 percent of these fires are believed to be caused by human activity. Because of the large extent of boreal forest, the large amount of fire activity, and the expected sensitivity of carbon cycling in these systems to fire and climate patterns, there is justifiable concern about the potential effects of boreal fire regimes on atmospheric chemistry, global carbon cycling, and global climate, as well as potential feedback effects of global climate change on fire regimes and carbon cycles in these systems. Accurate estimates of these impacts are hampered by a lack of good data on the area burned and on fire severity. We estimate that the average area burned annually in Russian boreal forests is around 7.3 million ha, an order of magnitude greater than indicated by official fire statistics. This discrepancy has major implications for estimates of emissions of CO_2 and other greenhouse gases. In severe fire seasons, there are also frequent long-term episodes of air pollution caused by wildfire smoke. Because of the interactions between fire, landscape patterns, air quality, and climate in boreal forests, fire regimes and fire management in Siberia have potentially large impacts on regional air quality and on the global environment.

Introduction

Boreal forests and woodlands cover a large area of the earth's surface between 45 and 70° north latitude. Boreal forest and woodland cover an estimated 1.2 billion ha, about 900 million ha of this in closed boreal forest (FIRESCAN 1994). This represents about 30 percent of the world's forested area. More than 50 percent of the world's forests are in North America and Eurasia (Nyejlukto 1994). Russia alone contains about 620 million ha of boreal forest (Tchebakova and others 1994), about 520 million ha of which is in closed (stocked) boreal forest (Alexeyev and others 1995).

Because of their extent, and the large carbon reserves they contain, boreal forests have long been recognized as critical to the earth's carbon balance (e.g., Bonan 1991, Crutzen and others 1979, Levine 1991). Estimates vary, but suggest carbon storage in boreal forest worldwide in the range of 66-127 Pg C in plant material, and 135-247 Pg C in soils and downed woody material and litter (Apps and others 1993, Bolin 1986, Kauppi and others 1992, Olson and others 1993, Tans and others 1990.) This represents perhaps 10 to 17 percent of the total global terrestrial carbon reserves in soils and plant materials (2,100-2,200 Pg C; Bolin 1986). A recent comprehensive analysis of carbon in Russian ecosystems (Alexeyev and Birdsey 1994) estimates that the boreal forests in Russia contain 99.8 Pg C, with 25 percent of this in vegetation and the remainder in soils and forest floor material.

This paper discusses the potential effects on carbon cycling, global climate, and air quality of fires in the boreal forests of Russia, which comprise about two-thirds of the world's boreal forest.

Extent of Fire in Russia's Boreal Forests

Fire is one of nature's primary carbon-cycling mechanisms. It is a critical disturbance factor in Russia's boreal forests, where many fire scars are visible across the landscape and vegetation patterns are often dominated by evidence of past fire history. During the summer fire season, one can hardly fly across central Siberia without observing smoke plumes from the often numerous wildfires. Although data are somewhat

[1] An abbreviated version of this paper was presented at the International Symposium on Air Pollution and Climate Change Effects on Forest Ecosystems, February 5-9, 1996, Riverside, California.

[2] Formerly Project Leader, USDA Forest Service PSW Research Station, Forest Fire Laboratory, 4955 Canyon Crest Drive, Riverside, CA 92507, and now Program Leader, Forest Vegetation Management and Protection Research, USDA Forest Service, P.O. Box 96090, Washington, D.C. 20090-6090.

[3] Chair, Department of Science and Technology, Russian Aerial Forest Protection Service (Avialesookhrana), 20 Gorkova Street, Pushkino, Moscow District 141200, Russia.

sparse, dendrochronological studies have estimated typical fire return intervals of 25 to 50 years for *Pinus sylvestris* forest types in central Siberia (Furyaev 1996, Swetnam 1996). Longer fire return intervals (90-130 years) appear more typical for forests dominated by *Larix* species (Furyaev 1996, Valendik [In press]) and by *Abies siberica* and *Picea obovata*. Fire return intervals also decrease from north to south (they may be as short as 10 years on some sites), and are longer on the most well-watered sites along rivers or in areas where forest stands are isolated by wet bogs (FIRESCAN 1997). As a reflection of the difference in dominance and in fire return intervals of the various forest types, about 70 percent of the fires in Russia occur in light coniferous pine and larch-dominated stands (*Pinus sylvestris* or *Larix*), and only about 15 percent in dark coniferous boreal forest (primarily *Abies*, *Picea;* based on Korovin 1996), although the latter cover about 31 percent of the boreal forest area (Tchebakova and others 1994). About 80 percent of the area typically burns in surface fires (Furyaev 1996, Korovin 1996), but patchy crown fires are common, and in severe fire seasons, crown fires may dominate. The Russian Forest Service (Nyejluktov 1994) reports a range of 12,000 to 34,000 wildfires a year in Russia during the period from 1974-1993, with a long-term average of about 17,000 fires per year. Most of these fires occur in a 4-month fire season that extends from May through August (*fig.1*).

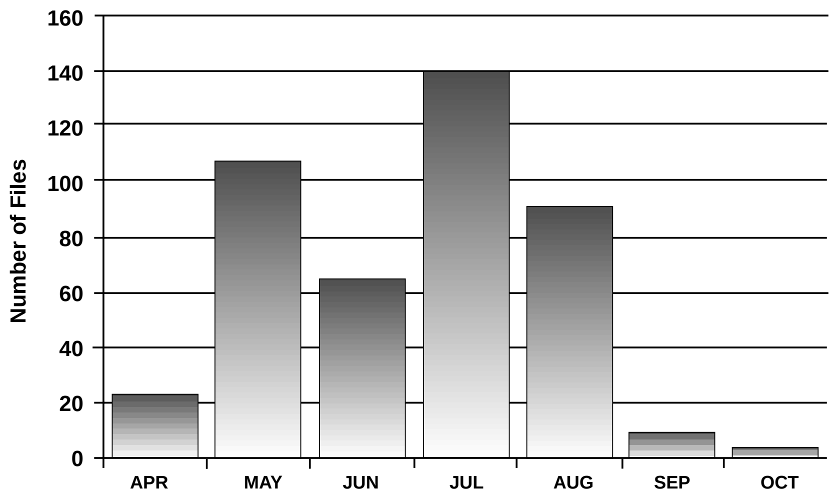

Figure 1 — Monthly distribution of fire frequency during the fire season in Russia. Source: Unpublished fire statistics on file at Russian Aerial Forest Protection Service, 20 Gorkova Street, Pushkino, Moscow Region 141200, Russia.

Estimates of the extent of fires in Russia's boreal forest vary over an order of magnitude (*table 1*); those made by Russian government agencies are among of the smallest. Some of the variation in these estimates undoubtedly results from differences in areas covered. The official Russian fire statistics cover only areas that receive fire protection. The fire protection area includes most of European Russia, but is more limited in Siberia and the Far East. Overall, about 66 percent of the forested area of Russia was monitored for fires in the early 1990's (Dixon and Krankina 1993), most of this by airborne pilot-observers. With recent budget decreases, this area is now considerably less. While the monitored area in the past included most of the closed boreal forest, some boreal forest fires, especially in the more northern regions, were not reported. Other estimates have been based on extrapolations from North American fire regimes (Kasischke and others 1993, Stocks 1991). On the basis of satellite data for three areas of Siberia in 1992, Stocks and others (1996a) estimated close to 1 million acres had burned in the study areas, and suggested this might represent 30 to 40 percent of the area burned in Siberia that year. This would lead to an estimate of 2.5 to 3.3 million acres of burned area for all of Siberia in 1992. On the other hand, analysis of satellite data at the time of the 1987 China fires led to an estimate of about 14 million ha burned in southern Siberia and China (mostly in Siberia) during May and June of 1987 (Cahoon and others 1994). Emissions from this amount of burned area were estimated to represent about 4 percent of the annual global emissions from biomass burning. Although progress is being made in analysis of current satellite data, it is likely to be a number of years before adequate information will be available from satellite data to allow better long-term estimates. At this point the uncertainty in the area burned seems one of the greatest barriers to accurate estimates of the effects of boreal forest fires in Russia on global biogeochemistry.

***Table 1** — Average area (ha) of boreal forest burned annually in Russia and worldwide.*

Russia	Worldwide	Period	Source
——	1.3×10^6	——	Crutzen and others 1979
3.0×10^6	5.6×10^6	1980-1989	Stocks 1991
4.5×10^6	8.5×10^6	1940-1991	Kasischke and others 1993
1.9×10^6	——	1971-1986	Dixon and Krankina 1993
7.4×10^6	——	1987-1991	Dixon and Krankina 1993
2.9×10^6	——	1971-1991	Dixon and Krankina 1993
0.3×10^6	——	1979-1988	Nyejlukto 1994
0.8×10^6	——	1989-1994	Nyejlukto 1994

In the light of this wide range in estimates of fire area, we decided to take another approach to obtaining a reasonable independent estimate of area burned in Russian boreal forests based on the relationship between fire-return interval and area burned per year. By using a relatively conservative estimate of 500 million ha of closed boreal forest in Russia, we can predict (*fig. 2*) the average burned area per year for different fire return intervals. For a fire return interval of 60-80 years, which seems reasonable based on the literature, we would estimate between 6.25 and 8.3 million ha of burned area per year. This is similar to a recent estimate of 7.4 million ha/yr for the 1988-1991 period by Dixon and Krankina (1993), but considerably higher than their longer-term estimate of 2.9 million ha/yr (*table 1*), which would imply a fire return interval of 172 years (267 years if you use their estimate of 774 million ha of total forest area). Some of the lower estimates of burned areas (*table 1*) would yield fire return intervals in excess of 1000 years. This has clearly not been the pattern over the last several hundred years, or in the 1900's, as revealed by landscape patterns and dendrochronology data (FIRESCAN 1994, 1997).

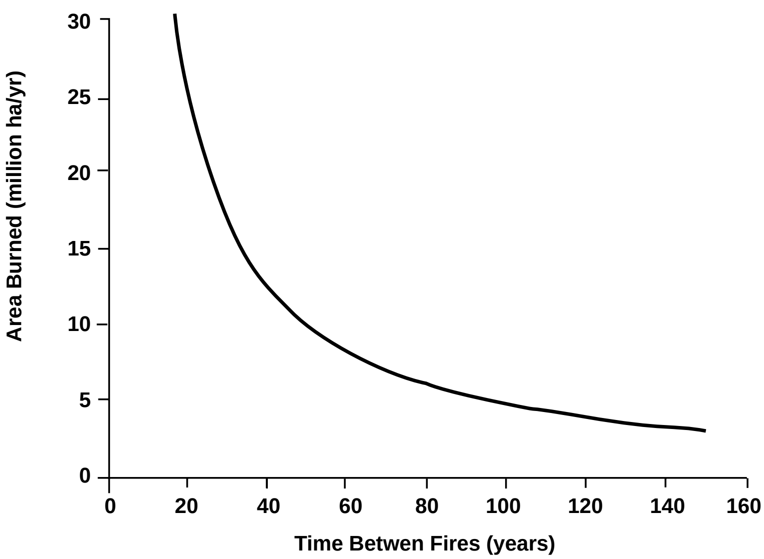

Figure 2 — Relationship between annual area burned in forest fires and the average fire return interval. This graph uses a conservative estimate of 500 ha of closed boreal forest in Russia and assumes no variability in fire return intervals.

We recognize the possibility of some error in this approach, as it does not consider possible recent impacts on fire regime of fire suppression activities and changes in ignition patterns because of human activities. Although evidence from Ontario, Canada, suggests an 89 percent decrease in area burned annually (increase in fire return interval from 65 to 580 years) in areas under fire suppression (Ward and Tithecott 1993), we find no compelling evidence for a similar trend in Russia

(Antonovski and others 1992, Korovin 1996, FIRESCAN 1997). Many fires in Russia, especially large fires and those in remote areas, are little affected by fire suppression. In fact, Russian Forest Service statistics suggest a possible trend toward increasing areas burned over the past 10-15 years (Nyejlukto 1994), which may be associated with increased human ignitions. Despite the great interannual variability of area burned and the unreliability of fire size data for Siberia, it would certainly be possible to detect a major trend of decreased burned areas or increased fire return intervals. In the absence of such evidence, we believe that our estimate is a reasonable one until more accurate ones are available.

Emissions from Boreal Forest Fires

Obviously, wide variations in estimates of area burned will lead to similar variations in estimates of the contribution of emissions from boreal forest fires to the global carbon balance, and this is reflected in the literature. We can assume, for example, that the estimates by Crutzen and others (1979) of 40 to 60 Tg dry matter (18-27 Tg C) consumed per year are probably about an order of magnitude too low, as they are based on an estimate of 1.3 million ha burned annually worldwide (including North America and Eurasia). A better combined global estimate might be about 10 million ha per year (0.2 million ha per year for Alaska and Scandinavia, and 2.4 million ha per year for Canada [Stocks 1991]; 7.3 million ha per year for Russia (our estimate)). On the basis of various sources of Russian fire statistics for the period 1971 to 1991 (see *table 1*), Dixon and Krankina (1993) estimated an average of about 47 Tg C emissions per year after fires. If we adjust this upward based on our estimate of an average burned area of 7.3 million ha per year, we can project annual average C emissions from fire in Russia of about 118 Tg C per year, and 292 to 702 Tg C/yr from biogenic sources. Adding in a rough estimate for North American forests would increase these values by about 30 percent (to about 153 Tg carbon/yr from fire emissions, and about 380 to 913 Tg C/yr from postfire biogenic emissions). This direct amount from fire emissions represents about 4 percent of the estimated 3,900 Tg C/yr released globally from biomass burning (Andreae 1991). If our estimates are reasonable (and there is every reason to believe they are conservative), then annual contributions of boreal fire to global carbon release may have been vastly underestimated by many authors.

Even if we have a good estimate of the annual extent of boreal forest fires in Russia, extrapolation to impacts on emissions or on carbon cycling is complicated by the wide variability in fire intensity across the landscape. Perhaps only 20 percent of the burned area in Russia burns in crown fires (Furyaev 1996, Korovin 1996). In the other 80 percent of the area, low levels of combustion of needles and other fine aerial fuels will result in lower emissions of carbon compounds in smoke per unit area. On the basis of data on a *Pinus sylvestris*/lichen forest in central Siberia (FIRESCAN 1997) we can estimate that fuel consumption in a surface fire in this vegetation would be about 80 percent of that in a crown fire (assuming 4.059 kg/m^2 consumed in crown fire; 3.252 kg/m^2 consumed in a surface fire). So estimates of emissions based on assumption of crown fires will be about 20 percent too high. Dixon and Krankina (1993) recognized this concern and assumed that an average of 10 percent of the biomass was consumed in boreal forest fires in Russia. In other studies it is not always clear how this issue was dealt with.

An even greater potential source of error is the amount of combustion of the litter/forest floor and soil layers, which contain about 75 percent of the carbon stored in Russia's boreal forests (Alexeyev and Birdsey 1994). Depending on the seasonality and intensity of fire and on the vegetation type, combustion of these layers in North American boreal forests can range from about 16 to 90 percent, with an average of perhaps 40 to 60 percent (Kasischke and others 1995). Furthermore, fire characteristics also have generally poorly understood, but substantial, effects on the magnitude of postfire increases in biogenic emissions, which have been estimated to be 70 to 85 percent of the total fire-related emissions (Dixon and Krankina 1993). Still another source of error is that tree mortality in areas of surface fire can vary widely, and may occur over several years, affecting photosynthesis and respiration, as well as temporal and spatial patterns of postfire decomposition and biogenic emissions. Accurate estimates of the extent and severity of fire in boreal Russia and their effects on combustion patterns and biogenic emissions are desperately needed.

Fire and Global Climate Change

Several authors suggest that, for boreal forest areas in North America, there will be increased fire weather severity (Flanigan and Van Wagner 1991, Stocks 1993), increased length of fire season (Street 1989, Wotton and Flannigan 1993), and increased lightning (Fosberg and others 1990) with CO_2-induced global climate change. Changes in temperature are expected to be considerably higher in boreal regions than the global averages. Stocks (1993) discussed the possible impacts of a doubled CO_2 scenario on fire danger for Canada, based on predictions of the Canadian Climate Center global climate model and the Canadian fire danger rating system. This model predicts a 4-5 °C increase in summer temperatures and a 8-10 °C increase in winter temperatures, along with decreased soil moisture availability throughout central Canada. Wotton and Flannigan (1993) have predicted an increase in the length of the fire season by 30 days, and Flannigan and Van Wagner (1991) predicted a 46 percent increase in seasonal fire severity across Canada under a double CO_2 scenario. Stocks and Lynham (1996) used the Monthly Severity Rating from the Canadian Forest Fire Danger Rating System and the Russian Nesterov Index to compare fire weather severity between Canada and Russia. Both of these indices represent the fire danger if an ignition occurs, based on weather patterns and fuel moisture conditions. Their results suggest that Russia may be even more at risk of increased fire activity in response to climate change than Canada, as Siberia currently has about three times as much area in extreme fire danger categories as Canada (based on Monthly Severity Rating for July). Increases in fire occurrence can also be expected to cause positive feedbacks with atmospheric CO_2, thereby exacerbating effects of global warming (Kurz and others 1994).

Pollution

Direct impacts of fire on air pollution are also cause for concern. It is not uncommon in severe fire seasons for multiple fires to burn over long periods, casting a pall of smoke over large areas. This is by no means a recent problem. Shostakovich (1925) reported on extensive fires in Siberia in 1915. These fires burned for 50 days, and burned about 14 million ha, but the smoke pall from the fires covered 680 million ha, and severely reduced visibility at ground level over a large percent of the area. Extensive smoke plumes were visible on Advanced Very High Resolution Radiometer (AVHRR) imagery in 1987, during the period of the great China fires (Cahoon and others 1994). Given the large number of fires that burn in Russia every summer (an average of perhaps 140 starts per day over the 4-month fire season, and many more at the peak of the season), and the large areas burned, it is not surprising that smoke intrusion over extensive areas occurs.

In addition to the obvious effects of such extensive smoke on visibility and other aesthetic values, prolonged wildfire smoke episodes in western North America in recent years (particularly northern California in 1987, Yellowstone in 1988) have raised concerns over potential negative impacts of wildfire smoke exposure on human health, as well as short-term toxicity from elevated carbon monoxide levels (Reinhardt and others 1995). The main components of concern for human health in wildfire smoke include carbon monoxide, aldehydes, benzene, and particulate matter (Reinhardt and others 1994). Carbon monoxide has been recognized as a potential hazard to wildland firefighters for a number of years (Jackson and Tietz 1979), but specific information is scant. Studies on prescribed fires in the Pacific Northwest have observed smoke levels exceeding established exposure limits (Reinhardt and others 1994). In a recent study on levels of smoke exposure for firefighters on wildfires in northern California grass and light brush fuels (Reinhardt and others 1995), however, peak exposures never reached recommended ceiling limits of CO of 200 ppm, and only 2 of 23 peak exposures to respiratory irritants exceeded exposure limits. Reinhardt and others (1995) point out that these fires were all in relatively light fuels, and experienced firefighters involved in the incidents rated the smoke levels as low to average. Furthermore, exposures in these fires were typically of short duration. Other research (Materna and others 1992) has found high CO exposure among engine crews on wildland fires in California. Reinhardt and others (1995) concluded that extended exposure to forest fire smoke could exceed exposure guidelines for both CO and respiratory irritants, and recommended that more extensive studies be conducted under a wide range of fuel and burning conditions. A recent review (Reinhardt and Ottmar 1997) of published and unpublished research on exposure of wildland firefighters to smoke and potential health hazards reported mostly on studies conducted in the western U.S. The authors stated that few data on smoke exposure of wildland firefighters are available from other parts of the world. Considering the periodic exposure of rural and urban populations in Siberia to wildfire smoke over prolonged periods, further research on firefighter smoke exposure and on the effects of long-duration smoke exposure from wildfires on human health is vitally needed.

Human Influences on Fire Regimes

Statistics over a recent 3-year period for Russia show that more than 65 percent of wildfires are human-caused, and about 17 percent are confirmed to be caused by lightning (*fig. 3*). Newer information, however, suggests that the importance of lightning ignitions may have been underestimated. Of the 17 percent of fires where cause is unknown, evidence from recently-installed lightning detection systems suggests that many of these may be lightning fires. And the importance of lightning as an ignition source varies greatly geographically (*table 2*), with the highest percent of lightning ignitions in relatively unpopulated areas such as the Krasnoyarsk and Yakutia regions.

Nonetheless, even in these regions, a large percentage of fires is human-caused. Furthermore, it appears possible, based on tendencies visible in the fire statistics of the Russian Forest Service (Nyejlukto 1994) and those reported by Korovin (1996) that there has been an increase in fire numbers and area burned in the past 10 years. After some decrease in the number of fires and areas burned between the early 1970's and about 1983, the trend shows a gradual increase through 1992-93. Average burned area for 5-year periods reported by the Russian Forest Service (Nyejlukto 1994) increased from 0.23 million ha in the 1979-1983 period to 1.03 million ha in 1989-1993, although levels still are not as high as they were in the early 1950's (as high as 2.5 million ha in 1953 [Korovin 1996]). The large influence of human populations on fire occurrence is well-illustrated by Korovin (1996), who shows that about 68 percent of fires occur within 5 km of a road, and 60 percent of fires occur within 10 km of a populated area. Human-caused ignitions may be having a short-term net effect of increased fire in many parts of Russia, despite a strong fire suppression program. Changes in area burned, whether resulting from ignition patterns, weather cycles, or fire management strategies, have particularly important implications for global climate change, as alterations in fire return interval can have significant impacts on carbon storage (which increases with stand age). Model estimates for stored carbon in boreal forest (Kasischke and others 1995) show strong sensitivity to fire return interval in the range of 50 to 150 years, with projected increases in carbon storage of about 10 to 17 percent as fire return interval increases from 50 to 100 years, and increases of about 25 to 40 percent as fire return interval increases from 50 to 150 years. This

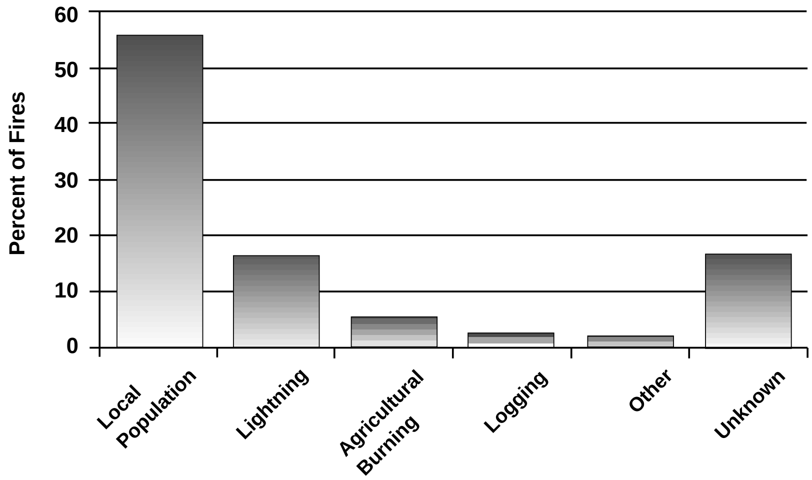

Figure 3 — Frequency of wildfire causes in Russia for the period 1985 through 1994. Source: Unpublished fire statistics on file at Russian Aerial Forest Protection Service, 20 Gorkova Street, Pushkino, Moscow Region 141200, Russia.

Table 2 — *Percent of fires caused by lightning in Russia's major aerial forest protection regions over the 3-year period 1993-1995.*[1]

Protection Region	1993	1994	1995	Average
		Percent of total fires		
Krasnoyarsk	42	35	43	40
Irkutsk	16	12	23	17
Far East	27	20	27	25
Yakutia	53	42	69	55
Arkhangelsk	47	2	17	22
Perm (Europe)	3	0.7	6	3

[1] Source: Unpublished fire statistics on file at Russian Aerial Forest Protection Service, 20 Gorkova Street, Pushkino, Moscow Region 141200, Russia.

sensitivity in the range of current fire return intervals suggests the great potential for human impacts on the fire regime to significantly affect carbon storage, as well as the importance of fire management in managing fire regimes and carbon cycling. An active fire suppression program will be a key element in maintaining desirable fire return intervals in the face of increased human ignitions.

Conclusions

Fire is an important factor in boreal forests of Russia. Despite the paucity of accurate data, it is clear that boreal forest fires in Russia contribute significantly to global CO_2 emissions. Increased CO_2 is likely to substantially increase fire danger and occurrence in boreal forests, leading to possibilities of positive feedbacks to global CO_2 and temperatures (Kurz and others 1994) and significant ecosystem impacts if fire suppression and other fire protection and prevention approaches are not able to compensate. Extensive fires can cause smoke pollution over large areas, which may result in hazards to human health and other negative impacts. The large percent of human-caused fires in Russia's boreal ecosystems suggests the critical importance of fire management and fire suppression for maintaining desirable fire regimes and preventing decreases in fire return interval and loss of carbon storage in these ecosystems.

References

Alexeyev, Vladislav A.; Birdsey, Richard A., eds. 1994. **Carbon in ecosystems of forests and peatlands of Russia.** Krasnoyarsk, Russia: Sukachev Institute of Forest Research; 170 p. [in Russian]

Alexeyev, V.; Birdsey, R.; Stakanov, V.; Korotkov, I. 1995. **Carbon in vegetation of Russian forests: methods to estimate storage and geographical distribution.** Water, Air, and Soil Pollution 82: 271-282.

Andreae, M.O. 1991. **Biomass burning: its history, use, and distribution, and its impacts on environmental quality and global climate.** In: Levine, J.L., ed. Global biomass burning: atmospheric, climatic, and biospheric implications. Cambridge, MA, USA: MIT Press; 3-21.

Antonovski, M. Ya.; Ter-Mikaelin, M.T.; Furyaev, V.V. 1992. **A spatial model of long-term forest fire dynamics and its applications to forests in western Siberia.** In: Shugart, H.M.; Leemans, R.; Bonan, G.B., eds. A systems analysis of the global boreal forest. Cambridge, UK: Cambridge University Press; 373-403.

Apps, M.J.; Kurz, W.A.; Luxmore, R.L.; Nilssohn, L.O.; Sedjo, R.A.; Schmidt, R.; Simpson, L.G.; Vinson, T.S. 1993. **The changing role of circumpolar boreal forests and tundra in the global carbon cycle.** Water, Air, and Soil Pollution 70: 39-53.

Bolin, B. 1986. **How much CO_2 will remain in the atmosphere?** In: Bolin, B.; Doos, B.; Jager, J.; Warnick, R., eds. The greenhouse effect, climate change, and ecosystems, SCOPE 29. London: John Wiley and Sons; 93-155.

Bonan, Gordon B. 1991. **Atmosphere-biosphere exchange of carbon dioxide in boreal forests.** Journal of Geophysical Research 96(D4): 7301-7312.

Cahoon, D.R.; Stocks, B.J.; Levine, J.S.; Cofer, W.R.; Pierson, J.M. 1994. **Satellite analysis of the severe 1987 fires in northern China and southeastern Siberia.** Journal of Geophysical Research. 99(D9): 18627-18638.

Crutzen, Paul J.; Heidt, Leroy E.; Krasnec, Joseph P.; Pollock, Walter H.; Seiler, Wolfgang. 1979. **Biomass burning as a source of atmospheric gases CO, H_2, N_2O, NO, CH_3Cl and COS.** Nature 282: 253-256.

Dixon, Robert K.; Krankina, Olga N. 1993. **Forest fires in Russia; carbon dioxide emissions to the atmosphere.** Canadian Journal of Forest Research 23: 700-705.

FIRESCAN Science Team. 1994. **Fire in boreal ecosystems of Eurasia: first results of the Bor Forest Island fire experiment, Fire Research Campaign Asia-North (FIRESCAN).** World Resources Review 6(4): 499-523.

FIRESCAN Science Team. 1997. **Fire in ecosystems of boreal Eurasia: the Bor Forest Island fire experiment, Fire Research Campaign Asia-North (FIRESCAN).** In: Levine, Joel S., ed. Biomass burning and global change. Cambridge, MA: MIT Press; 848-873.

Flannigan, M.D.; Van Wagner, C.E. 1991. **Climate change and wildfire in Canada**. Canadian Journal of Forest Research 21: 66-72.

Fosberg, M.A.; Goldammer, J.G.; Rind, D.; Price, C. 1990. **Global change: effects on forest ecosystems and wildfire severity.** In: Goldammer, J.G., ed. Fire in the tropical biota: ecosystem processes and global challenges; Berlin: Springer-Verlag; 466-486.

Furyaev, V.V. 1996. **Pyrological regimes and dynamics of the southern taiga forests in Siberia.** In: Goldammer, J.G.; Furyaev, V.V., eds. Fire in ecosystems of boreal Eurasia; Netherlands: Kluwer Academic Publishers; 168-185.

Jackson, G.; Tietz, J.G. 1979. **Preliminary anlysis: firefighters' exposure to carbon monoxide on wildfires and prescribed burns.** Missoula, MT: U.S. Department of Agriculture Forest Service, Equipment Development Center, project record.

Kasischke, Eric S.; Christensen, N.L.; Stocks, Brian J. 1995. **Fire, global warming, and the carbon balance of boreal forests.** Ecological Applications 5(2): 437-451.

Kasischke, Eric S.; French, Nancy H.F.; Harrell, Peter; Christensen, Norman L., Jr.; Ustin, Susan L.; Barry, Donald. 1993. **Monitoring of wildfires in boreal forests using large area AVHRR NDVI composite image data.** Remote Sensing and Environment 45: 61-71.

Kauppi, P.; Mielikainen, K.; Kuusela, K. 1992. **Biomass and carbon budget of European forests, 1971-1990.** Science 256: 70-74.

Korovin, G. N. 1996. **Analysis of the distribution of forest fires in Russia.** In: Goldammer, J.G.; Furyaev, V.V., eds. Fire in ecosystems of boreal Eurasia; Netherlands: Kluwer Academic Publishers; 112-128.

Kurz, W.A.; Apps, M.J.; Stocks, B.J.; Volney, W.J.A. 1994. **Global climate change: disturbance regimes and biospheric feedbacks of temperate and boreal forests.** In: Woodwell, G.M.; F. Maackenzie, eds. Biotic feedbacks in the global climate system: will the warming speed the warming? Oxford, UK: Oxford University Press; 119-133.

Levine, J.L., ed. 1991. **Global biomass burning: atmospheric, climatic, and biospheric implications.** Cambridge, MA, USA: MIT Press; 569 p.

Materna, B.L.; Jones, J.R. ; Sutton, P.M.; Rothman, N.; Harrison, R.J. 1992. **Occupational exposures in California wildland firefighting.** American Industrial Hygeine Association Journal 53(1): 69-76.

Nyejlukto, M.F., ed. 1994. **Russian forests.** Federal Forest Service of Russia, All-Russian Research and Information Centre for Forest Resources. Moscow: Company "Kolyev"; 15 p.

Olson, J.S.; Watts, J.A.; Allison, L.J. 1983. **Carbon in vegetation of major world ecosystems.** Report ORNL-5682. Oak Ridge, Tennessee: Oak Ridge National Laboratory; 180 p.

Reinhardt, Timothy.E.; Black, Janelle; Ottmar, Roger D. 1995. **Smoke exposure at northern California vegetation fires.** Unpublished report on file with: Pacific Northwest Research Station, USDA Forest Service, 4043 Roosevelt Way, NW, Seattle, WA 98105.

Reinhardt, T.E.; Hanneman, A.; Ottmar, R. 1994. **Smoke exposure at prescribed burns—final report.** Unpublished report on file with: Pacific Northwest Research Station, USDA Forest Service, 4043 Roosevelt Way, NW, Seattle, WA 98105.

Reinhardt, T.E.; Ottmar, R. 1997. **Smoke exposure among wildland firefighters: a review and discusion of current literature.** Gen. Tech. Rep. PNW-GTR-373; Seattle, WA: Pacific Northwest Research Station, USDA Forest Service; 61 p.

Shostakovitch, V.B. 1925. **Forest conflagrations in Siberia.** Journal of Forestry 23(4): 365-371.

Stocks, B.J. 1991. **The extent and impact of forest fires in northern circumpolar countries.** In: Levine, J.S., ed. Chapman conference on global biomass burning: atmospheric, climatic, and biospheric implications. Cambridge, MA: MIT Press; 197-202.

Stocks, B.J. 1993. **Global warming and forest fires in Canada.** Forestry Chronicle 69: 290- 293.

Stocks, B.J.; Cahoon, D.R.; Levine, J.S.; Cofer, W.R., III; Lynham, T.J. 1996. **Major 1992 forest fires in central and eastern Siberia: satellite and fire danger measurements.** In: Goldammer, J.G.; Furyaev, V.V., eds. Fire in ecosystems of boreal Eurasia; Netherlands: Kluwer Academic Publishers; 139-150.

Stocks, B.J.; Lynham, T.J. 1996. **Fire weather climatology in Canada and Russia.** In: Goldammer, J.G.; Furyaev, V.V., eds. Fire in ecosystems of boreal Eurasia; Netherlands: Kluwer Academic Publishers; 481-487.

Street. R.B. 1989. **Climate change and forest fires in Ontario.** In: Proceedings tenth conference on fire and forest meteorology; Ottowa, Ontario, CANADA; 177-182.

Swetnam, Thomas W. 1996. **Fire and climate history in the central Yenisey region, Siberia.** In: Goldammer, J.G.; Furyaev, V.V., eds. Fire in ecosystems of boreal Eurasia; Netherlands: Kluwer Academic Publishers; 112-128.

Tans, P.P.; Fung, I.Y.; Takchashi, T. 1990. **Observational constraints on the global atmospheric CO_2 budget.** Science 247: 1431-1438.

Tchebakova, Nadja M.; Monserud, Robert, A.; Nazimova, Dina I. 1994. **A Siberian vegetation model based on climate parameters.** Canadian Journal of Forest Research 24: 1597-1607.

Valendik, E.N. [In press]. **Basic principles of boreal forest fire protection strategy in Eurasia.** In: Proceedings, 20th annual tall timbers fire ecology conference. Boise, ID; 7-10 May 1996.

Ward, P.C.; Tithecott, A.G. 1993. **The impact of fire management on the boreal landscape of Ontario.** Ontario Ministry of Natural Resources AFFMB Pub. 305.

Wotton, B.M.; Flannigan, M.D. 1993. **Length of the fire season in a changing climate.** Forestry Chronicle 69: 187-192.