Fire in Ecosystems of Boreal Eurasia

Edited by
Johann Georg Goldammer
and Valentin V. Furyaev

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Preface

One of the first priority areas among joint East/West research programs is the rational use of natural resources and sustainable development of regions. In the boreal zone of North America and Eurasia forests are economically very important and, at the same time highly vulnerable to disturbances. Because of its size and ecological functions the boreal forest zone and its most dynamic disturbance factor – fire – play an important role in ecosystem processes on global scale.

Interest within the global change research community in Northern Eurasia (Fennoscandia, European Russia, Siberia, and the Far East of Russia) has grown dramatically in the last few years. It is a vast area about which very little is known. It is a region where temperature rise due to anthropogenic climate forcing is predicted to be the greatest, and where the consequent feedbacks to the atmosphere are potentially large. In addition, it is poised to undergo rapid economic development, which may lead to large and significant changes to its land cover. Much of this interest in Northern Eurasia, as in the high latitude regions in general, is centerd on its role in the global carbon cycle, which is likely to be significantly affected under global change.

New research initiatives between Western and Eastern countries have been designed to address a series of phenomena, problems and management solutions. Cooperative research agreements under the International Geosphere-Biosphere Programme (IGBP) and the International Global Atmospheric Chemistry (IGAC) project, in conjunction with the International Boreal Forest Research Association (IBFRA), provide instruments to initiate joint research.

In June/July 1993 two scientific events established a new platform of joint East-West fire research, the international scientific conference "Fire in Ecosystems of Boreal Eurasia" and the start of the Fire Research Campaign Asia-North (FIRESCAN).

This volume presents the results of the conference, which aimed to compile, interpret, and discuss the state of knowledge of the role and impacts of fire in boreal ecosystems, with special emphasis on Eurasia. For the first time this publication makes available the in-depth knowledge in fire science achieved in the former Soviet Union and in the Russian Federation. Together with the contributions from Fennoscandia and boreal North America, this volume aims to stimulate a new era of pan-boreal fire research, especially considering the need to put basic and specific local aspects of fire ecology into the broader context of the newly emerging global fire science.

The book is particularly aimed at supporting the upcoming IGBP Northern Eurasia Study, a joint effort of several IGBP Core Projects, the Biospheric Aspects of the Hydrological Cycle (BAHC), International Global Atmospheric Chemistry (IGAC) and Global Change and Terrestrial Ecosystems (GCTE) Projects.

The conveners of the conference and editors of this volume are indebted to the sponsors and organizers of the meeting as well as to the inputs by the fire science community. Particular acknowledgements are given to the VOLKSWAGEN Foundation (Germany) which supported the Max Planck Institute for Chemistry, Biogeochemistry Department, and the V.N. Sukachev Institute for Forest, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, Forest Fire Laboratory, for hosting the conference. Dimitri Odintsov, Deputy Chief of the Federal Forest Service of Russia, and Nikolay A. Andreev, Eduard P. Davidenko, and Nikolay A. Kovalev, all from the Aerial Forest Fire Protection Service *Avialesookhrana*, actively supported the organization and logistics of the conference and the international Bor Forest Island Fire Experiment in the frame of the Fire Research Campaign Asia--North (FIRESCAN) which took place immediately after the conference (cf. Annex III).

The International Boreal Forest Research Association (IBFRA) provided the frame for countries and scientists cooperating in the Stand Replacement Fire Working Group to actively participate in the conference (cf. Annex II). The opening remarks by Eldon W. Ross, former president of IBFRA, underscored the importance of this very first active program of IBFRA (cf. Annex I).

The conveners gratefully acknowledge the tremendous efforts by colleagues who helped to translate and interpret the Russian manuscripts into English. While Ms. Irina Savkina, interpreter at the V.N. Sukachev Institute for Forest, provided the base translations, much work had to be done to identify appropriate English terminology without violating the Russian style of scientific writing.

First, the editors are indebted to Susan Conard (Riverside Fire Laboratory, USDA Forest Service) for helping edit many more manuscripts than previously envisioned. A tremendous amount of work was done by Frank Albini (University of Montana) in reviewing all manuscripts dealing with the mathematical modeling of forests, insects and fire. Anders Granström (University of Umeå), Günter Helas (Max Planck Institute for Chemistry), Eino Mälkönen (The Finnish Forest Research Institute), Brian J. Stocks and Bruce Lawson (both Canadian Forest Service), and Ross W. Wein (Canadian Circumpolar Institute) also devoted considerable time to help review and edit Russian manuscripts.

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Johann Georg Goldammer
Valentin V. Furyaev

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Fire in Ecosystems of Boreal Eurasia: Ecological Impacts and Links to the Global System

J.G. Goldammer[1] and V.V. Furyaev[2]

1. Introduction

The circumpolar belt of the boreal zone stretches in two broad trans-continental bands across North America and Eurasia. The northern boundary of the zone corresponds to the July 13°C isotherm, while the southern boundary is limited by the July 18°C isotherm (Kuusela 1990). The boreal zone has been classified into three sub-zones, the maritime, continental and high-continental sub-zones. The maritime sub-zone has mean summer temperatures of 10-15°C, winter temperatures of 2-3°C, and annual precipitation of 400 to 800 mm. The continental sub-zone has long, cold winters with mean temperatures from -20 to -40°C, and summer mean temperatures from 10 to 20°C. The growing season is between 100 and 150 days, and annual precipitation ranges between 400 and 600 mm. The high continental sub-zone covers the largest portion of the boreal zone and is characterized by more extreme winters and milder summers. In Europe, the influence of maritime air masses decreases from west to east, reaching West Siberia as far as the Yenisei river. East Siberia and the Far East are characterized by high-continental climate.

The definition of the boundaries of the boreal zone is often considered synonymous with the occurrence of northern coniferous forests. However, the northern forest limit which exceeds 70°N latitude only in Eurasia, in fact, is a broad forest-tundra ecotone characterized by the transition between tundra associations and discontinuous forest cover (Treter 1993). The southern limit of the boreal forest zone is at ca. 45°N. As a consequence of geography (size of the continent, orography, oceanic and atmospheric circulation) ca. 40% of the North American boreal forest is between 45 and 55°N, much further south than in Eurasia's boreal forests which are mainly north of 55°N latitude (cf. map on p. 496).

The distinct climatic seasonality with a short vegetation period and low average temperatures facilitates the accumulation of organic layers and widespread permafrost soils in the boreal zone. Together with topography both features critically determine species composition and dynamics of the forest landscapes in which bogs and grasslands are intermixed (Shugart et al. 1992; Treter 1993).

[1] Max Planck Institute for Chemistry, Biogeochemistry Department, Fire Ecology Research Group, c/o Freiburg University, D-79110 Freiburg, Germany
[2] V.N. Sukachev Institute of Forest, Siberian Branch, Russian Academy of Sciences, 660036 Krasnoyarsk, Russian Federation

The ecologically and economically most important coniferous tree species are pine (*Pinus* spp.), larch (*Larix* spp.), spruce (*Picea* spp.), and fir (*Abies* spp.); the main broadleaf tree species are birch (*Betula* spp.), poplar (*Populus* spp.), and alder (*Alnus* spp.) (Nikolov and Helmisaari 1992).

Boreal forests cover ca. 1.2×10^9 ha, of which 920×10^6 ha are closed forest. The latter number corresponds to ca. 29% of the world's total forest area and to 73% of its coniferous forest area (ECE/FAO 1985). About 800×10^6 ha of boreal forests with a total growing stock (over bark) of ca. 95 billion m^3 are exploitable (41% and 45% respectively of the world total). The export value of forest products from boreal forests is ca. 47% of the world total (Kuusela 1990).

The carbon stored in boreal ecosystems corresponds to ca. 37% of the total terrestrial global carbon pool (plant biomass and soil carbon) (Apps et al. 1993). Thus, the magnitude of the boreal forest area suggests that it may play a critical role in the global carbon budget and its influence on the climate system of the earth (potential sink or source of atmospheric carbon).

More than seventy percent of the global boreal forest cover is in Eurasia, mainly in the Russian Federation, and represent the largest unbroken forested area of the globe; the remainder is in Canada and Alaska, and relatively small areas of boreal forests are found in the North East of China and in the Nordic countries (Fennoscandia).

The total area of the Russian Forest Fund comprises ca. $1{,}181 \times 10^6$ ha, of which 886×10^6 ha (= 75,0%) are forested and 763×10^6 ha (= 64%) are stocked (Federal Forest Service of Russia 1994). The Federal Forest Service of Russia exercises control over 94% of the total Forest Fund area and 91% of the total growing stock of Russia. Depending on the criteria used to define "boreal forest", the area of closed boreal forest in the Russian Federation varies from 400 to 600×10^6 ha (Pisarenko and Strakhov 1993). These numbers correspond to a 43-65% share of the world's closed boreal forest.

2. Disturbances in Boreal Ecosystems

Over evolutionary time periods boreal ecosystems have been subjected to climate changes, and species were forced to migrate in accordance with advancing and retreating glacial land ice cover. At the end of the last glacial (Weichselian) major parts of Eurasia's present forests and wetlands were still covered by inland freshwater lakes (Grosswald 1980). During the present interglacial - starting ca. 10,000 years ago - the boreal forest biome has been subjected to inter- and intra-annual climate variability associated with multi-year drought periods and extreme dry years (cf. Schweingruber, this volume), which in turn are associated with insect outbreaks (cf. Holling 1992) and lightning fires (FIRESCAN Science Team 1996; Clark and Richard, this volume).

Among these natural disturbances, lightning-ignited fire is the most important factor controlling forest age structure, species composition and physiognomy, shaping landscape diversity, and influencing energy flows and biogeochemical cycles.

Small and large fires of varying intensity have different effects on the ecosystem. High-intensity fires lead to the replacement of forest stands by new successional sequences, offering a rich variety of floristic and faunistic habitats. Low-intensity surface fires favor the selection of fire-tolerant trees such as pines (*Pinus* spp.) and larches (*Larix* spp.) and may repeatedly occur within the lifespan of a forest stand.

In Eurasia fire has for a long time been an important tool for land clearing (conversion of boreal forest), silviculture (site preparation and improvement, species selection) and in maintaining agricultural systems, e.g. swidden agriculture, pastoralism, and hunting societies (Viro 1969; Pyne 1995 and this volume). In addition to natural fires, these old cultural practices brought a tremendous amount of fire into the boreal landscapes of Eurasia. In the early 20th century, the intensity of fire use in the agricultural sector began to decrease since most of the deforestation had already been accomplished for agriculture, and traditional small-sized fire systems (treatment of vegetation by free burning) became replaced by mechanized systems (use of fossil-fuel driven mechanic equipment). Despite the loss of traditional burning practices, however, humans are still the major source of wildland fires; only 15% of the recorded fires in the Russian Federation are caused by lightning (cf. Korovin, this volume).

Large natural and human-caused fires have been reported in this century, e.g. as a consequence of the Tunguska meteorite impact (ca. 60°54' N-101°57' E) on 30 June 1908. This cometary nucleus explosion at ca. 5 km altitude was one of the more exceptional events which caused large-scale forest fires in the region of impact (cf. Grishin, this volume). Several years later, from June to August 1915, the largest fires ever recorded, occurred as a consequence of an extended drought in Central and East Siberia (Tobolsk, Tomsk, Yeniseisk, NE Irkutsk, S Yakutsk regions). Shostakovich (1925) estimated that the fires were burning ca. 50 days in the region between 52-70°N and 69-112°E. The main center of the fires was between the Angara River and Nijnya Tunguska, and the total area burned was estimated at 14.2×10^6 ha. However, the smoke of these fires covered the region between 64-72°N and 61-133°E, corresponding to ca. 680×10^6 ha. Shostakovich estimated continuous smoke (visibility ca. 100 m) on 284×10^6 ha, heavy smoke (visibility 25-100 m) on 215×10^6 ha and thick smoke (visibility 5-20 m) on ca. 181×10^6 ha. It is not clear, however, whether lightning, humans or a combination of the two were the primary cause of the extended fires of 1915.

In recent years wildfires have been more or less eliminated in the Nordic countries (Norway, Sweden, Finland; cf. Parviainen, this volume). The major occurrence of contemporary Eurasian fires is on the territory of the Russian Federation. Statistics compiled by the Russian Aerial Fire Protection Service *Avialesookhrana* show that between 10,000 and more than 30,000 forest fires occur each year, affecting up to $2\text{-}3 \times 10^6$ ha of forest and other land. Since fires are monitored (and controlled) only on protected forest and pasture lands, it is estimated that the real figures on areas affected by fire in Eurasia's boreal vegetation are much higher. For instance, satellite-derived observations by Cahoon et al. (1994) indicate that during the 1987 fire season approximately 14.5×10^6 ha were burned (cf. also Stocks et al., this volume). In the same fire season ca. 1.3×10^6 ha of forests were affected by fire in the montane-boreal forests of Northeast China, south of the Amur (Heilongjiang) River (Goldammer and Di 1990; Ende and Di 1990; Cahoon et al. 1994).

3. Forest Fires in Boreal Eurasia as a Cyclic Source and Permanent Sink of Carbon

The contributions in this volume reveal that natural fire-return intervals in boreal forests range between several years, decades, and centuries, maintaining a dynamic equilibrium between site potential, climate and vegetation. Theoretically there are no fire-induced net C fluxes to the atmosphere in the present interglacial because carbon released by fire will be sequestered by new growth at varying time scales. However, past climate fluctuations, as established by dendrochronological and densitrometric analyses in the boreal zone, show that decadal and centennial periods warmer or cooler than the long-term average must have changed carbon fluxes periodically.

Modern carbon emissions from forest fires have been estimated on the basis of official fire statistics and average fuel consumption data. These estimates indicate a broad range of numbers due to uncertainties in the reliability of base data (averages of area burned and fuel consumed). Shvidenko et al. (1995a) estimated a net release of C by forest fires in the Russian Federation in 1990 at 58.1 Tg. Taking into account the post-fire C emissions, the authors conclude that a total of 150 Tg C yr was released by forest fires in 1990. Kolchugina and Vinson (1995) estimated the total C emissions associated with forest fires at 137 Tg yr^{-1} (all figures include surface and crown fires in forests, fires in non-forested land and fires in organic layers, e.g. peatland fires). Higher estimates were given by Dixon and Krankina (1993) who estimated an average fire-related C emissions of 199 Tg yr^{-1} for the period 1971-1991. Our own estimates, based on experimental data (e.g. FIRESCAN Science Team 1996), reveal the annual area burned in Eurasia (mainly on the Russian territory) in protected and non-protected lands may well reach $10x10^6$ ha yr^{-1} and consume between 20 and 40 t of ground, surface and aerial fuels per hectare. This would be equivalent to 200-400 Tg plant biomass combusted, equaling ca. 100-200 Tg C released as direct effect of fire.

Tab.1. Selected data on global boreal forest fires

Boreal North America (Annual Average)	1-5 x 10^6 ha
Extreme Years, e.g. Canada 1989/1995	7.4/7.1 x 10^6 ha
Boreal Fennoscandia (Annual Average)	< 4,000 ha
Extreme Years, e.g. Sweden 1933	30,000 ha
Boreal China (Annual Average)	< 55,000 ha
Extreme years, e.g. NE China 1987	1.3 x 10^6 ha
Boreal Eurasia, Recorded Fires (Annual Average)	2-3 x 10^6 ha
Extreme Years, e.g. 1987	16 x 10^6 ha
Boreal Eurasia, Unrecorded Fires (on Non-Protected Lands)	10 x 10^6 ha ?

Specific characteristics of boreal fire emissions

Certain radiatively active trace gases, e.g. incompletely oxidized reactive combustion products such as CO and CH_4, are emitted from boreal fires in a larger proportion (CO_2-normalized emission ratio [ER]) compared to other ecosystems, e.g. the tropical and subtropical savannas. This was confirmed by the Bor Forest Island Fire Experiment, conducted in a boreal coniferous forest in the Krasnoyarsk Region in 1993. This large fire experiment revealed that the ERs of CO and CH_4 are consistently higher than those resulting from fires in other major global ecosystems (FIRESCAN Science Team 1996; Cofer et al. 1996 and this volume).

Some boreal fires are characterized by specific behaviour, e.g. high-intensity stand replacement fires producing strong convective activity and injecting smoke emissions into the high altitudes of the free troposphere. One of the major objectives of the Bor Forest Island Fire Experiment in 1993 was the analysis of methyl bromide (CH_3Br) and methyl chloride (CH_3Cl). Decay products of these compounds are, like the longer-lived chloro-fluorocarbons (CFC), known to induce depletion of stratospheric ozone. (It should be noted here that bromine is much more efficient on a per atom basis than chlorine in breaking down ozone by a factor of about 40; cf. Manö and Andreae [1994]; WMO [1992].) The emission ratios of CH_3Br and CH_3Cl measured in the Bor Forest Island Fire were in the range of $0.11\text{-}3.1 \times 10^{-6}$ and $8\text{-}140 \times 10^{-6}$ respectively. This was considerably higher than those found in savanna and chaparral fires or in laboratory experiments (cf. Manö and Andreae 1994). Highest values were found over smouldering surface fuels. This can be explained by the lower combustion efficiency of the smoldering process associated with boreal fires as compared to the prevailing flaming combustion of grass-type fuels.

Estimates of global pyrogenic emissions of CH_3Br from all vegetation fires and other plant biomass burning falls in the range of 10-50 Gg yr^{-1}, or 10-50% of the total source strength (Manö and Andreae 1994). The share of boreal fires still needs to be defined through improved estimates of boreal vegetation area and biomass affected by fire. Special attention must be given to the specific behavior of boreal fires, including the injection of ozone-destroying gases into the high troposphere and possible further transport into the stratosphere.

Fire effects: a carbon sink ?

A close look at soils and organic layers in boreal forests and other organic terrain (raw humus, peat) reveal the abundance of charcoal. Most of the charcoal basically consists of black carbon (BC, also called elemental carbon), which is formed during pyrolysis. Basically BC is biologically non-degradable, chemically inert and not available for uptake by plants.[2] In addition to the deposition of larger BC-containing charcoal particles, BC is also emitted in small fractions and transported as aerosol; quantitative data are not yet available on this feature.

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[2] The state of international discussion on a standard definition of black carbon and charcoal will be published in the pages of the proceedings of the NATO Advanced Research Workshop "Global Biomass Burning and Climate Change" (Clark et al., 1996).

In general, most boreal forest fires do not destabilize the ecosystem (e.g. towards a lower phytomass productivity or lower biomass carrying capacity) in the long term, regardless of the sustainable fire return interval. Thus, the formation of BC represents a net atmospheric carbon sink because the cycling uptake of atmospheric carbon (through photosynthesis) remains constant, and the deposition of ground and soil charcoal as well as the aerosol BC deposited in sites distant from the fire are not available for plant life and are not subjected to degradation.

The fire science community is just beginning to quantify the potential role of BC formation and deposition as a global atmospheric carbon sink (Kuhlbusch and Crutzen 1995; Kuhlbusch et al. 1996). This will require data collection on charcoal storage in soils, peatlands, and sediments at pan-boreal scale. The present state of knowledge allows the conclusion, however, that fires in sustainable fire ecosystems, particularly in the boreal zone, may help to explain at least a part of the global "missing sink" of carbon.

4. Global Climate Change: Boreal Forest in Possible Transition from Carbon Sink to Carbon Source

Estimates of carbon stored at present in living and dead plant biomass (without soil organic matter) above- and below-ground in the global boreal forest area range between 66 and 98 Pg (e.g., Apps et al. 1993). Additional large amounts of carbon are stored in boreal forest soils (ca. 200 Pg) and in boreal peatlands (ca. 420 Pg) (Apps et al. 1993).

Expected global warming over the next 30-50 years, as projected by GCMs for a doubled carbon dioxide equivalent greenhouse gas forcing scenario ("2xCO_2 climate") will be most evident in the northern circumpolar regions (Bolin et al. 1986; Maxwell 1992; Shugart and Smith et al. 1992; Shugart et al. 1992). According to these models, zonal warming may lead to the shift of vegetation belts, e.g. causing the boreal forest to shift north (e.g. Kauppi and Posch 1988). The shift of ecosystems is projected to have a considerable impact on the distribution of phytomass. Zonal warming will also affect the balance of the pan-boreal carbon pool. The processes involved, however, are rather complex and should not be generalized.

A model developed by Smith et al. (1992) shows that in a 2xCO_2 climate 72% of today's boreal forest area would be covered by temperate mixed-deciduous forests. Based on the assessment that mixed-deciduous forests in the region will have ca. 43% more carbon in living biomass than do *taiga* forests (Kolchugina and Vinson 1993), the total carbon in living biomass in the region occupied by today's boreal forests would increase by approximately one-third over the long term (Kasischke et al. 1995).

Climate-induced changes in carbon stored in the ground layer, however, are different. The predicted increase of average temperatures in the boreal zone will increase the decomposition rate of dead and dissolved organic matter in the ground and mineral soil layers, thus reducing the amounts of carbon stored (Bonan et al. 1990; Kasischke et al. 1995). A model developed by Bonan and Van Cleve (1992) predicts a net 6-20% decrease in total ground layer carbon in response to a 5°C increase over a 25-yr period.

Climate change and fire regimes

As Flannigan and van Wagner (1991), Stocks (1993), Wein and de Groot (this volume), and Stocks et al. (this volume) underscore, fire may be a driving force in changing the taiga under zonally warming conditions. The prediction of an increasing occurrence of extreme droughts in a 2xCO_2 climate indicates that fire regimes will undergo considerable changes. An increase in the length of the fire season would lead to a higher occurrence of large, high-intensity wildfires. Wotton and Flannigan (1993) predicted an increase in the length of the fire season in Canada by an average of ca. 30 days in a 2xCO_2 climate, resulting in an additional 20% increase in the annual area burned in Canadian boreal forests.

Fosberg et al. (this volume) used the Canadian Climate Center GCM (McFarlane et al. 1992) to predict forest fire danger and severity in Canada and Siberia. The climate model projects a global mean temperature increase of 3.5°C for a doubled carbon dioxide equivalent greenhouse gas forcing scenario ("2xCO_2 climate"). Regional warming during winter would be as follows: continental regions of Siberia and Canada: + 6-8°C, Alaska + 2-4°C, and Scandinavia with little change. Spring temperatures are projected to be uniformly 2-6°C warmer and spring precipitation 8-30% greater than at present. Early fire season temperature changes show up to + 6°C in western Siberia, with precipitation greater than at present. While mid and late fire season temperatures will be nearly the same as present, the precipitation is projected to decrease.

In their analysis Fosberg et al. (this volume) used two measures of fire danger and severity (the Russian *Nesterov* Index of ignition [Nesterov 1949] for calculating the ignition potential, and the Canadian Fire Weather Index System [Van Wagner 1987] for assessing fire severity). They used the 90th percentile level of the indices at each of the 224 climate stations in Russia and 191 stations in Canada.[3] The results show that the present worst 10 percent which are currently classed as moderate or high, in future are classed as having extreme fire ignition and severity potential. Extreme monthly severity will be close to double the area for boreal North America, with an extreme ignition index virtually blanketing Eurasia in future.

Combined effects of zonal warming and fire

Kasischke et al. (1995) concluded that changes of above- and below-ground biomass characteristics due to zonal warming would also affect the flammability of vegetation. Over the longer term they expect flammability to decrease for the above-ground biomass because of the long-term shift towards less flammable deciduous trees. In the near term the surface fuels (ground layer) would become drier and more flammable, thus increasing the overall fire risk of forests in transition to the new equilibrium. Consequently, over the shorter term (the next 50-100 yr) there would be an overall increase between 20 and 50% in the annual area burned, resulting in a decrease in the fire return interval from the present average of 150 yr to 125-100 yr.

Considering the fact that it is still largely unknown where exactly the ground layer carbon is stored, Kasischke et al. (1995) developed a carbon flux model in which two baseline

[3] This corresponds to the worst 10 percent of the weather-related fires which will result in 90% of environmental and social impacts. The evaluation of the change in the highest 10 percent of the indices give a more accurate depiction of the change in risk, since this is the range in which fire control becomes extremely difficult (Fosberg et al., this volume).

carbon levels were established ([1] all ground layer carbon is stored in litter, humus and peat; [2] half of the ground layer carbon is stored in the mineral soil). The model predicts that the net loss of carbon in the ground layer due to zonal warming only (no change of annual area burned) in the short term (the next 50-100 yr) would range between 2.8 and 3.9 kg m^{-2}, or 33.0 to 46.0 Pg on a global basis.

An increase in the annual area burned of 20% would lead to a net loss of ground layer carbon ranging between 3.1 and 4.7 kg m^{-2}, or 36.6 to 55.5 Pg on a global basis; an increase of annually burned area by 50% would result in the global decrease in ground layer carbon between 41 and 66 Pg. Considering the net gain of carbon by increasing aboveground biomass, there would still be a net carbon loss between 46.0 and 53.7 Pg from the global boreal forest to the atmosphere.

5. Interactions Between Modern Anthropogenic Disturbances and Wildland Fire

Traditional forestry practices and low-impact and sustainable use of non-wood forest products in boreal Eurasia are being subjected to dramatic changes which are stimulated by increasing national and international demands for boreal forest products. This has resulted in the widespread use of heavy machinery, large-scale clearcuts, and thereby in the alteration of the fuel complexes. Many clearcut areas are reportedly not regenerating into forest but are rather degrading into grass steppes which may become subjected to short-return interval fires. The opening of formerly closed remote forests by roads and subsequent human interferences bring new ignition risks. These direct effects on the ecosystem are, in addition to the indirect effects, induced by climate change, and both together will certainly contribute to an unprecedented change in fire regimes.

Additional fire hazards and environmental consequences, which are still mainly unpredictable, are created on forest lands affected by industrial emissions. Krankina et al. (1994) report that in the Russian Federation ca. 26.5×10^6 ha of forest lands are severely damaged by industrial pollution (cf. also Kharuk, 1993; Shvidenko et al. 1995b). While it is known in general that the availability of inflammable fuels makes dying and dead forest stands more susceptible to fire than living stands (Alexeyev 1995), other mechanisms are still unknown. For instance, what will be the effects of combusting those chemical depositions which have caused the die-back of forests? How will these agents be converted and re-distributed? Research on fire effects in vegetation polluted by industrial nitrogen deposition in the U.S.A. revealed that post-fire wathershed NO_3 yield contributes to regional groundwater pollution (Riggan et al. 1985).

Radionuclear contamination on ca. 7×10^6 ha land on the territory of the Russian Federation may create considerable problems in the redistribution of radionuclides through forest fires. The mechanisms have been investigated by research on the contaminated Savanna River Site in the U.S.A. (Murphy 1991) and in forests in the impact region of the 1986 Chernobyl nuclear power plant accident (Dusha-Gudym 1992 and this volume). The latter accident caused massive deposition of radionuclides on the surrounding land, e.g. plutonium (^{239}Pu) within the 30 km zone around the plant. Cesium (^{137}Cs) and strontium (^{90}Sr) radionuclides contaminated a number of districts in more distant sites. These contaminated sites were abandoned by humans up to a distance of 100-120 km from the accident site. In the Russian Federation a total of ca 4.5×10^6 ha of forest land is considered contaminated from nuclear fallout. Contamination is also observed in the successional vegetation which developed on large areas of abandoned agricultural lands.

In the years after the 1986 accident wildfires occurred repeatedly in the Chernobyl region, predominantly in successional vegetation and forests. In May 1992 a 500 ha wildfire occurred within the 30-km zone around the power plant. With the smoke plumes of the wildfires, radionuclides were lifted from the contaminated litter layers. Within the 30-km zone, the level of radioactive cesium in the aerosols increased about ten times. The contaminated aerosols were injected into the atmosphere and caused nuclear fallout in distant places (Dusha-Gudym, this volume); the most recent fire event in contaminated terrain was in April 1996.

This unprecedented example of interaction between anthropogenic environmental pollution and wildland fire shows a new dimension of fire problems that may become of increasing importance in the technologically altered global environment - a challenge to modern fire research and environmental management.

6. Fire Research in Eurasia in Transition: Linking with the Global System

With the increasing awareness of the multi-functional values of forests, the need for fire protection became a major focus in Russia's forestry literature of the last century (e.g., Semyonov 1845; Shafranov 1872; Baranetsky 1880). It was soon followed by the exploration of basic fire-vegetation relationships, e.g. the description of fire adaptations by Tkachenko (1911). It was also Tkachenko who introduced the term "forest pyrology" (Tkachenko 1931). In the same year fundamental work on the impact of fire on the biogeocenosis was published, e.g. by Gulisashvili (1931), Kazanski (1931) and Sushkina (1931). In his fundamental work on "Forest Pyrology" Melekhov (1944) based applied fire protection concepts on the study of the "nature of fire". In 1949 N.P.Kurbatski established a Forest Fire Protection Department affiliated with the St.Petersburg Institute of Forestry, and ten years later he founded the Forest Fire Research Laboratory in the V.N.Sukachev Institute of Forest, Siberian Branch, Russian Academy of Sciences. His fundamental work on "Fires in the Taiga Forests. Patterns of Their Occurrence and Growth" (Kurbatski 1964) and numerous other publications on fire basics and management technologies made him widely recognized as the leading fire scientist in Russia (cf. Pyne, this volume).

Early concepts for forest fire prevention as an integral part of the forestry system were suggested by Nat (1902) and Yatsenko (1917), but implemented only several decades later. Development efforts during the post-revolutionary decade (1918-27) concentrated on organizational and methodological questions of fire protection. In the 1930s fire suppresssion technology development dominated the field of fire, especially in aerial fire fighting and advanced fire suppression technologies, e.g the use of chemicals and explosives (for more details on Russia's history in fire science and development cf Kurbatski [1967] and Pyne [this volume]). The use of prescribed fire was first applied in West Siberian forests which had been infested and destroyed by the Siberian silkworm (*Dendrolimus sibiricus*) on a total area of 3×10^6 ha between 1952 and 1957. The large-scale broadcast burning program was planned on the scientific base of fire behavior and fire effects. It proved to be successful for inducing the regeneration of a new forest (Furyaev 1966).

In Fennoscandia the use of fire for improving grazing in forests, for slash and burn agriculture, and for forest regeneration was discussed throughout the 18th and 19th century, but hardly anything was done in terms of research.[4] When modern science developed in this

[4] The short outline on Fennoscandia's fire research history is based on Granström (1995)

field towards the end of the 19th century, wildfires were really not a major threat anymore and the research relating to fire was driven by forest regeneration problems. Soil nutrient dynamics (Hesselman 1917) and plant colonization (Kujala 1926; Sarvas 1937) was analysed in burnt forests with the aim of understanding natural processes. Researchers were aware that the forests had developed earlier under the repeated influence of fire, and the underlying idea was that practical forestry would benefit from a better understanding of the role of fire. Extensive documentation of the influence of wildfire and fire practices were published by Heikinheimo (1915), Wretlind (1934) and Tirén (1937). Prescribed burning had been used locally for a long time, but was fine-tuned by Wretlind in the 1920s and 1930s. After the first three decades of this century, there seems to have been a slack in the interest of fire research. Nevertheless, prescribed fire was used extensively and in the 1950s and 1960s some research was done around the effects of prescribed fire on e.g. vegetation and soil (Uggla 1957), seedling establishment (Yli-Vakkuri 1961) and nutrient dynamics (Viro 1970). From 1965-70 prescribed fire was no longer applied, and virtually no research was done on fire. In the 1970s, Zackrisson (1977) made the first quantitative study of fire history. In recent years there has been a renewed interest in the role of fire in natural forest ecosystems and the use of prescribed fire to maintain biodiversity in the managed boreal forests of the future.

As in many other disciplines of science, the historical development of boreal forest fire research clearly suffered from being separated by political boundaries between East and West for a critical phase of at least four to five decades. Except for some courtesy contacts between government institutions during the Cold War and some occasional joint participation at international meetings (e.g., Wein and MacLean 1983), no exchange or cooperation in fire science took place until very recently. Under the given and predicted developments of the global boreal forest, it is evident that new initiatives in cooperative fire research are needed. The differences in research structures and economic situations in the East and the West, however, will require specific approaches to perform joint research.

The research facilities of the former USSR, capable of supporting regional fire research programs, are now mainly part of the Russian Academy of Sciences. These rather large research complexes are suffering heavy financial problems due to Russia's current economic transition. At present, the total funding made available to the Academy of Sciences is so insufficient that adequate salaries cannot be paid. "Brain drain" and the release of personnel has weakened the scientific potential dramatically.

In western countries, the present economic depression coupled with high unemployment rates has also had severe repercussions on research. Increasing costs for advanced research hardware coincide with decreasing research budgets. Fire research in Canada and the U.S.A. has been affected dramatically. While the US Forest Service reduced funding and personnel for fire research successively during the past years, the reduction in Canada was sudden and occured mainly in 1995. The shrinking research resources in the East and in the West unfortunately take place in a period in which interdisciplinary research programs are becoming mandatory and require increasing research investments (cf Weber 1995).

However, the first phase of East-West cooperation in forest fire research is now underway. Its outline, objectives and implications for further activities are described in the following pages. First steps towards cooperative fire research were initiated in 1990-91. At the invitation of the Aerial Forest Fire Protection Service (*Avialesookhrana*) and the Academy of Sciences of the USSR, two fire scientists from the U.S.A. and Germany explored the most important fire research and management facilities and programs of the Soviet Union in 1991 (Pyne 1991, 1992). In 1992, a meeting of the **International Boreal Forest Research Association (IBFRA)** took place in Krasnoyarsk and resulted in signing a formal agreement for cooperation in fire research (Fosberg 1992). In the same year an exchange program between U.S. and Russian fire scientists and managers was established (Davidenko and Goldammer 1994). One of the outcomes of the 1991-92 activities was the decision to jointly prepare and conduct a conference and a field campaign in the summer of 1993, both devoted to the exploration of fire in ecosystems of boreal Eurasia. The objective of the conference, which was held in Krasnoyarsk, 29 June to 3 July 1993, was to compile, interpret, and discuss the current state of knowledge on the role and impacts of fire in ecosystems of boreal Eurasia.

The volume presented here is the result of this first major East-West encounter in fire science with the participation of prominent fire scientists of all boreal countries. The publication of the re-examined knowledge aims to stimulate a new era of pan-boreal fire research, especially considering the need to put basic and specific local aspects of fire ecology into the broader context of the newly emerging global fire science (Crutzen and Goldammer 1993).

The re-examination of the state of knowledge in boreal fire science was followed by the first joint fire experiment. The **Fire Research Campaign Asia-North (FIRESCAN)** was prepared and implemented in its first phase under the co-sponsorship of the **International Geosphere-Biosphere Programme (IGBP)** and IBFRA. The research campaign was supported by the **Volkswagen Foundation** and various national sources of IBFRA member countries.

The IGBP provides a platform for international and interdisciplinary research programs. One of the operational IGBP core projects is the **International Global Atmospheric Chemistry Project (IGAC)**. One of the activities of its foci (Focus 2: Natural Variability and Anthropogenic Perturbations of the Tropical Atmospheric Chemistry) is oriented towards investigating the impact of biomass burning on the atmosphere and biosphere ("Biomass Burning Experiment" [BIBEX]) (IGAC 1992; Annex II).

The boreal fire research program is a joint activity with the IBFRA. Following the recommendations of the **White Sea Declaration** of 1990, IBFRA was founded in 1991 in Mezhgorje, Ukraine (Fosberg 1992). The two priority research areas are (1) Inventory, Monitoring, and Classification of Boreal Forests and (2) Global Climate Change and Ecosystem Function of Boreal Forests. Under the second area the first IBFRA Working Group established was on **Stand Replacement Fire** (Annex III).

Several international meetings of fire scientists, managers and policy makers provided a platform to develop new visions and concepts in research and policies. The international conference "Fire in Ecosystems of Boreal Eurasia" (Krasnoyarsk, 1993) was the starting point, accompanied by the first phase of the **Fire Research Campaign Asia-North (FIRESCAN)**. Additional joint activities are manifested in three conferences, the NATO ASI "New Mechanisms for Scientific Collaboration Between East and West" in Novosibirsk (1993) (Goldammer and Furyaev 1995); the International Conference on Mathematical and Physical Modelling Forest Fire and Ecology Problems at the University of Tomsk (1995); and the World Congress of the International Union of Forestry Organizations (IUFRO), in Tampere, Finland (1995), during which the Forest Fire Research Group (S.1-09) presented the results of FIRESCAN phase 1993-95 (IUFRO 1995).

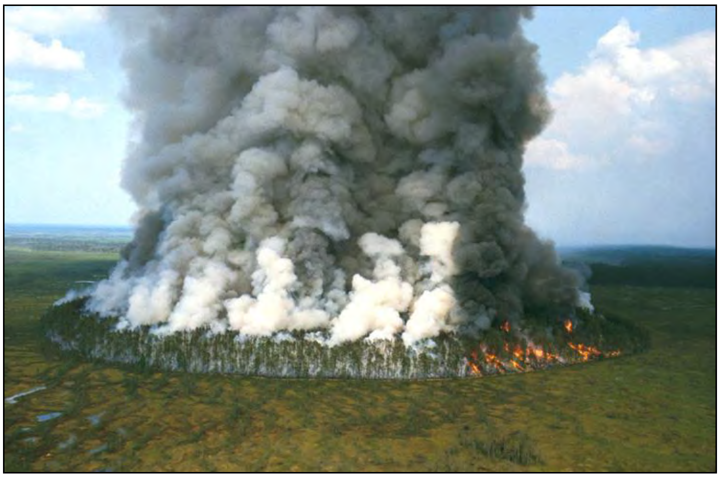
In November 1993, the "Taiga Aerospace Investigations using GIS Applications (TAIGA) Workshop" was held in Moscow (Stocks 1994). The workshop, sponsored by NASA's Office of Mission to Planet Earth and the International Forestry Institute (IFI) of the Russian Academy of Sciences, was aimed at developing a multi-national science plan for studying the boreal forests of Russia. The impetus for this workshop was the decision to place new satellite receiving stations in Siberia, a region of the world where previous satellite coverage was less than adequate, and to use this increased capability to intensively study the vast boreal forests of Russia to determine their role in global biogeochemical cycles. The first NASA HRPT (High Resolution Picture Transmission) station was installed in Krasnoyarsk in 1994. Cooperative projects developed at the workshop will make use of both AVHRR (Advanced Very High Resolution Radiometer) data from NOAA polar-orbiting satellites and existing ground and aircraft based datasets.

The United Nations FAO/ECE/ILO Seminar "Forest, Fire and Global Change", which will be held shortly after the publication of this volume in Shushenskoye, Krasnoyarsk Region (August 1996), will be based on the achievements of the joint research and exchange programs between 1993 and 1995. The UN activity, under the auspices of the FAO/ECE Team of Specialists on Forest Fire, aims to communicate with policy makers in order to build a bridge linking fire science with applied systems and international agreements for regional and global fire management.

6.1 IBFRA/FIRESCAN: The First Operational Fire Research Campaigns

The various regional fire research campaigns organized under the umbrella of IGBP/IGAC/BIBEX, IBFRA and other research agreements are operational or in the planning stage (Goldammer 1994; Annex II). These campaigns are designed to establish a comprehensive analysis of environmental impacts of fire at a global scale. The East European/North Asian part of this global research approach, as represented by the regional FIRESCAN program, is a contribution in which East-West collaboration is mandatory.

The first FIRESCAN activity mentioned above was a large experimental forest fire in Central Siberia, the **Bor Forest Island Fire Experiment**. In this fire experiment the ecological and atmospheric chemical impacts of a high-intensity fire were investigated by a mixed group of scientists from all boreal countries, representing a broad range of research disciplines (FIRESCAN Science Team 1994, 1996). A long-term follow-up research area has now been established, the first one in Eurasia's taiga forests. This site will serve as a research focus for future decades and hopefully for the next two centuries.



Aerial view of the Bor Forest Island Fire Experiment of July 1993. The results of this first East-West fire experiment have given important insights into the ecology and atmospheric chemical impacts of boreal forest fires (Source: FIRESCAN Science Team 1994).

The research will be complemented by various experiments, either directly linked to FIRESCAN or independent. In the late 1990s two major experiments are planned in Canada and the U.S.A.. The International Crown Fire Modelling Experiment will take place in the Northwest Territories, Canada (ca. June 1997). This is a cooperative international experiment, bringing together fire modelling experts from Canada, the U.S., and Russia, to address the prediction of high-intensity fire behavior. The NWT Fire Experiment will serve this purpose, with the goal of conducting a replicated series of highly-instrumented crown fires in order to quantify parameters essential to modelling the initiation and spread of crowning fires.

FROSTFIRE is a fire research program being proposed for the Caribou-Poker Creeks Research Watershed, near Fairbanks, Alaska. Under this proposal, a prescribed fire would be conducted over a 550 ha second-order basin within the watershed, permitting a variety of research activities, including catchment hydrologic response, permafrost thermal regimes, landscape stability, water quality, stream biota, regeneration and succession of terrestrial and riparian vegetation, and fire dynamics, emissions, and effects. FROSTFIRE is proposed for 1998 or 1999.

6.2 The IGBP Northern Eurasia Study: Integrated Global Change Research and its Fire Component

Interest within the global change research community in Northern Eurasia has grown dramatically in the last few years. Much of this interest in Northern Eurasia, as in the high latitude regions in general, is centred on its role in the global carbon cycle, which is likely to change significantly under global change.

During two planning meetings in Sweden (Stockholm, 1994) and Japan (Tsukuba, 1995) a prospectus was developed for an integrated hydrological, atmospheric chemical, biogeochemical, and ecological global change study in the tundra/boreal region of Northern Eurasia, the **IGBP Northern Eurasia Study**. The preparation of the research outline and justification of the study is a joint effort of scientists representing several IGBP Core Projects, the Biospheric Aspects of the Hydrological Cycle (BAHC), International Global Atmospheric Chemistry (IGAC) and Global Change and Terrestrial Ecosystems (GCTE) projects.[5] The unifying theme of the IGBP Northern Eurasia Study is the terrestrial carbon cycle and its controlling factors, and the most important overall objective of the study is to determine how these will change under the rapidly changing environmental conditions projected under global change. Two aspects are particularly important. First, understanding the interaction between ecosystem composition and ecosystem process is critical. Second, the overall objective demands a projection not just of net primary productivity or net ecosystem productivity but of "biome productivity", that is, net ecosystem productivity integrated over large spatial and temporal scales to account for such processes as successional dynamics and major disturbances such as fire, timber harvesting and insect outbreaks.

The IGBP Northern Eurasia Study will consist of an integrated set of experimental and observational studies at a number of scales, modelling and aggregation activities, and supporting databases and GIS systems. The major elements are:

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[5] The materials presented here are taken from the prospectus of the study and will be available soon as a IGBP publication (Steffen and Shvidenko 1996).

- North-south transect(s) in eastern Siberia (East Siberia/Far East) including sites in tundra, tundra-forest transition and in larch forest. This is a critical region for study; it has a high degree of continentality, it contains a vast expanse of larch forest, about which more needs to be known, and the potential for land-use change over the coming decades is high. The transect(s) will join others in Alaska, Canada and Scandinavia/northern Europe as part of the high latitude set of IGBP terrestrial transects.

- A network of sites throughout Northern Eurasia focussing on trace gas emissions and their controlling factors. The network will be concentrated on the extensive wetlands in western Siberia but should include at least two or three other sites in wetlands in the northern areas of European Russia and in eastern Siberia (including the area of continuous permafrost), one site in the coniferous evergreen forests, and one site in the tundra. Of particular importance is an apparent significant zone for gas emissions in the wetlands at the southern edge of western Siberia.

- A water, energy and carbon flux study, integrated with the transect and network components. The design of this component requires further background research and modelling sensitivity studies before it is finalized, but its linkage to the trace gas and ecological components as much as possible will provide a powerful mechanism for integrating much of the work in the IGBP Northern Eurasia Study.

- Studies of disturbance regimes. The studies should include work on all major disturbances of Northern Eurasian ecosystems, such as timber harvesting and insect infestations, but particular emphasis will be placed on fire. They should include work on both gas emissions from fires, and on the ecological role of fire in influencing the successional dynamics of boreal forests. An essential component is the development of a fire database, which includes extent, frequency and controlling factors so that fire regimes under a changing environment can be predicted.

- Scaling up, modelling, integration. A wide variety of models will be used to help design the experimental and observational studies, interpret the data, and project the impacts of global change on high latitude systems into the future. These include ecosystem physiology and dynamics models at various scales, trace gas flux models, models on soil-vegetation-atmosphere transfer, landscape hydrological models, atmospheric transport models, biome-scale simulations of the carbon and hydrological cycles, and comparisons to paleo-climate and paleo-vegetation studies. Scaling methodologies such as nested watershed studies and the boundary-layer averaging technique will be used, as appropriate, to scale up results of the process studies carried out at individual sites. Remote sensing, data assimilation and management, and GIS technology are important methods that will be used in the study.

- Associated studies. The IGBP Northern Eurasia Study provides a framework for related global change research. Examples include global change impacts on managed forests, observational and modelling studies of land-use/cover change in the region, and research on global change and ecological complexity (biodiversity). The land-use cover change study, in particular, is crucial to long-term projections of change in the carbon cycle in the Northern Eurasian region. Taken together, the IGBP Northern Eurasia Study and associated studies will provide valuable information to assist the development of sustainable management strategies for Northern Eurasia, in addition to elucidating its role in the global system.

The IGBP Northern Eurasia Study will be implemented in a phased approach. Where there is already general agreement that research is required in a particular area, such as a north-south transect(s) in eastern Siberia, appropriate sites can be selected and long-term observational studies can be initiated as soon as practicable. Care should be taken, however, that sites selected are compatible with the requirements of more intensive studies that will be phased in later. This is a critical consideration, as the "whole system" approach recommended for this study requires that the various individual studies be carried out at the same sites, if at all possible.

Other components of the study, such as the intensive measurements of water, energy, carbon and trace gas fluxes by eddy correlation or similar techniques, require preparatory (sensitivity) analyses before an experimental design can be finalized and work begun. Given the overall requirement for a general understanding of the composition/structure and physiology/productivity of Northern Eurasian ecosystems at a large scale, an early task is to survey the existing research that is being carried out in the region, analyse past work, and, where appropriate, retrieve and standardize data from existing and past work.

Design of the fire component

Fire-induced successional dynamics are a critical element in determining the productivity and carrying capacity of phytomass. Succession studies and measurements of plant biomass, carbon storage and fluxes made at point locations during relatively short time steps, must be scaled up over decades and over large regions containing ecosystems in various stages of succession. It is essential that the extent and frequency of fires under changing environmental conditions and management scenarios be predicted, based on data of present-day fire regimes and their relationship to climate and biomass.

The fire component of the IGBP Northern Eurasia Study will have four parts: (i) fire manipulations at individual forest sites; (ii) a series of campaigns based on air- and spaceborne research platforms; (iii) the construction of a fire database, relating the extent, frequency and intensity of fires to vegetation and climatic conditions for present-day and historic conditions; and (iv) development of aggregated models of forest fire frequency and extent, responsive to global change variables.

First, fire will be used as a treatment in the manipulative experiments at some of the intensive study sites in the transect and in the network. The experiments will measure the effects of fire on the successional dynamics of the vegetation, particularly on the composition of the regrowth forest, and will determine the effects on the nutrient dynamics of the soil and the vegetation. Special attention will be given to the consequences of fire on permafrost sites and to emission characteristics and black carbon formation of peat fires and other less explored fuel types.

Second, more research campaigns similar to FIRESCAN (or a continuation of FIRESCAN) are required to couple air- and spaceborne measurements of biogenic trace gas and aerosol emissions with pyrogenic sources. The newly established NOAA AVHRR receiving stations in Krasnoyarsk, Yakutsk and Khabarovsk will play an important role in identifying fires in real-time or in post-campaign reconstruction.

Third, given the importance of fire in terms of long-term and large scale ecosystem dynamics, a comprehensive ecologically-oriented fire database for Northern Eurasia is essential. The database will build on the National Resources Geographic Information System developed by the Russian International Forestry Institute and should include, in a geographically explicit format, the timing, areal extent, frequency, and intensity (in terms of effects on vegetation as well as gas emissions) of fires as well as the state of the vegetation and the climatic conditions at the place and time of the fires. A strong component of paleo-fire and historic fire research will link information from tree ring fire chronologies and densitrometric analyses with palynological and charcoal data in peat layers and lake sediment cores. This component will be a major inter-core project link and provide the base for the reconstruction of past fire regimes.

Fourth, the ultimate aim is to develop a model of change in fire frequencies and patterns under global change, based on an environmental response surface for fire. Such a model must also be responsive to natural disturbances such as lightning and to fire patterns caused by socio-economically driven land-use changes.

7. Conclusions and Outlook

In the second half of the 1990s the international fire research community has recognized the importance of a cross-disciplinary global fire science. The boreal zone of Eurasia is a vast, heterogeneous set of fire ecosystems which may become dramatically altered by anthropogenic climate forcing and the overall impacts of global change. The consequent feedbacks to the atmosphere are potentially large.

The conveners of the conference **Fire in Ecosystems of Boreal Eurasia** and editors of this volume are indebted to all of those scientists who contributed in preparing this comprehensive analysis of the role of fire on biosphere, atmosphere and climate. It is possible now for the first time to integrate the accumulated fundamental knowledge in fire science accomplished in the former USSR and in the Russian Federation into the context of global change research. At the same time it is hoped that the beginning scientific cooperation between fire scientists in the East and West will be deepened and new initiatives stimulated.

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