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THE BOREAL FOREST, FIRE AND THE GLOBAL CLIMATE SYSTEM: ACHIEVEMENTS AND NEEDS IN JOINT EAST-WEST BOREAL FIRE RESEARCH AND POLICY DEVELOPMENT

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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, at the same time being highly vulnerable to disturbances. Because of its size and ecological functions the boreal forest and fire — its most dynamic disturbance factor — play an important role in ecosystem processes at a global scale. This paper provides an overview on the role of boreal forest fires on ecosystems, atmosphere and climate.

1. INTRODUCTION

The global circumpolar ecosystems include the boreal forest belt — the taiga — and the non-forested tundra ecosystems. The boreal forest biome occupies nearly one third of the total global forested area. More than seventy percent of the global boreal forest cover are 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 Scandinavia.

The boreal climate has been classified by three subzones [1], the maritime, continental and high-continental subzones. The maritime subzone has summer temperatures of 10–15 °C, winter temperatures of 2–3 °C, and annual precipitation of 400 to 800 mm. The continental subzone has long, cold winters with mean temperatures of −20 to −40 °C, and summer mean temperatures of 10 to 20 °C. The growing season is between 100 and 150 days, annual precipitation ranges between 400 and 600 mm. The high continental subzone covers the largest portion of the boreal zone and is characterized by more extreme winters and milder summers.

The distinct climatic seasonality with a short vegetation period and low average temperatures leads to the accumulation of organic layers and widespread permafrost soils. Both features critically determine species composition and dynamics of the forest landscapes in which bogs and grasslands are intermixed. The main coniferous tree species are pine (Pinus spp.), larch (Larix spp.), spruce (Picea spp.), and fir (Abies spp.); the main broadleaf trees are birch (Betula spp.), poplar (Populus spp.), and alder (Alnus spp.).

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 cover of icecaps. The boreal forest biome as developed in the present interglacial — starting ca. 10 000 years ago — has been subjected to inter- and intra-annual climate variability associated

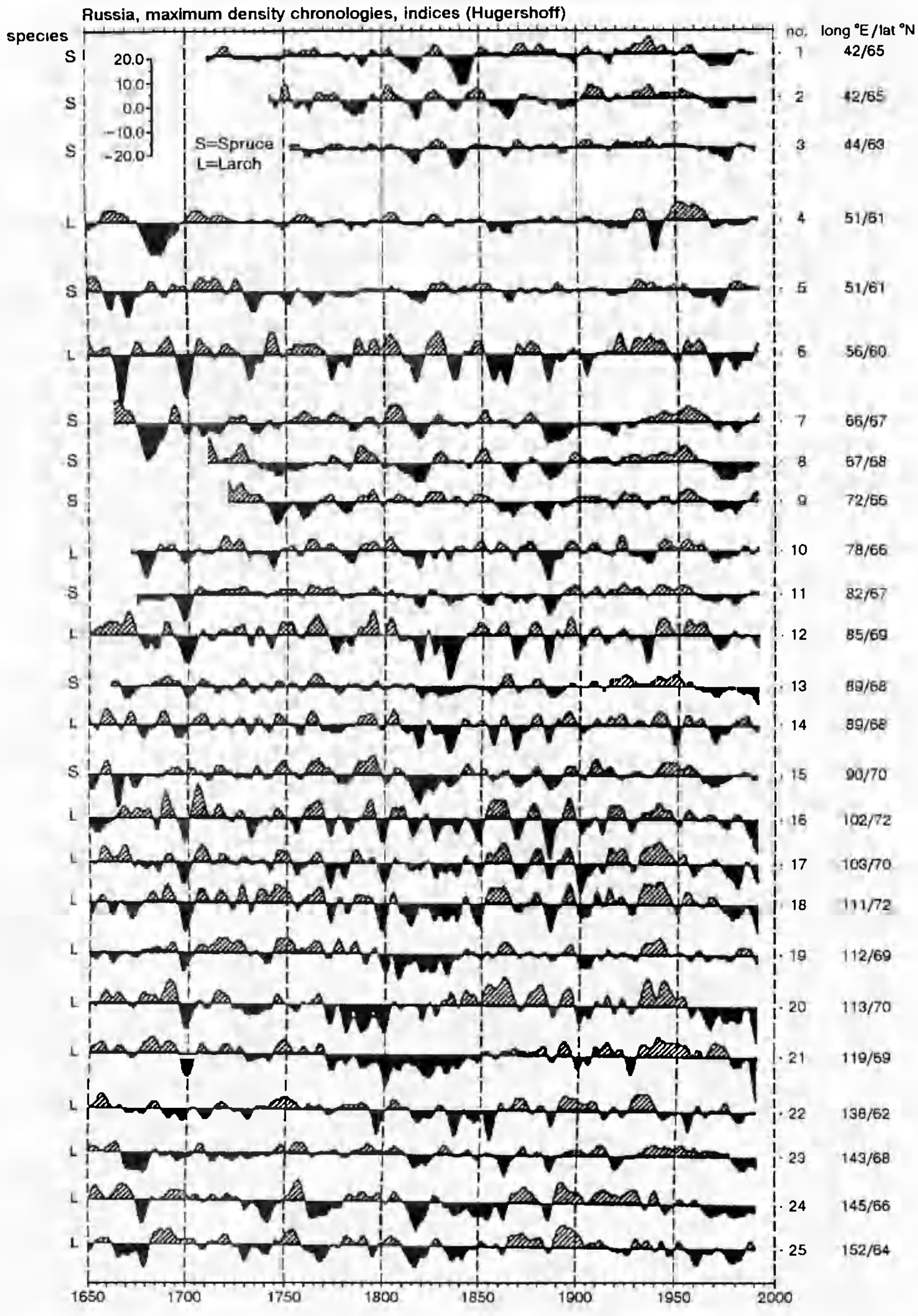

Fig.1. Climate reconstruction in boreal Siberia. Detailed description: see text

with multi-year drought periods and extreme dry years (Fig. 1), associated with lightning fires and insects outbreaks.

Figure 1 shows maximum density chronologies (indices) from living spruces and larches growing at the northern tree line (north of 60°) in the Russian Federation along a West-East transect from 42° E to 152° E (Schweingruber, in press). This transect is part of the Northern Hemispheric densitometric network. The latewood densities in conifers reflect mean April to September temperatures and serve as long-term "meteorological" records for remote regions in Russia. The chronologies show long-term climate fluctuations, e.g.:

1800–1850 cold period east of the Urals;
1900–1960 warm period, transcontinental;
1960–1990 cold period, transcontinental;

and decennial patterns, e.g.:

1700 cold from the Urals to the Lena;
1810–1820 cold from the Atlantic to the Yenissei;
1840 cold from the Urals to the Pacific;
1800 and 1805 cold, Yenissei to Lena.

The carbon stored in boreal ecosystems corresponds to ca. 37 % of the total terrestrial global carbon pool (plant biomass and soil carbon). Thus, the magnitude of the boreal forest area suggests that it may play a critical role in the global climate system, e.g. as potential sink or source of atmopsheric carbon.

While parts of the taiga are considered to be highly productive and economically valuable forests, their vulnerability has been largely disregarded in the past. Occasionally, inappropriate forestry practices, e.g. large-scale clearcuts with subsequent degradation, go along with extended industrial pollution, oil pipeline leakages, radioactive contamination and ecosystem modification by dam and water reservoir construction.

The impacts of anthropogenic climate change on the boreal zone and its ecosystems as currently predicted by global circulation models (GCM's) are severe. Increase of average annual temperatures may lead to longer and warmer vegetation periods, typically characterized by increased occurrence and length of droughts and lightning activities. With increasing human interferences the danger of extreme and extended wildfires may also increase. Fires, droughts and melting of permafrost may release high amounts of carbon to the atmosphere, thus accelerating processes of current atmospheric changes critical for global climate change.

This contribution will give some thoughts to interrelationships between natural and anthropogenic disturbances of the boreal forest and the atmosphere-climate system. The focus is on fire because it is the most important causative and reactive factor between boreal ecosystems and the atmosphere. The paper gives primary attention to the boreal forest of Eurasia, mainly the Siberian taiga.

2. THE BOREAL BIOME: EXTENT AND ECONOMIC IMPORTANCE

The world's total boreal forests and other wooded land within the boreal zone cover $1.2 \cdot 10^9$ ha of which $920 \cdot 10^6$ 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 [2]. About $800 \cdot 10^6$ 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

TABLE 1

Base Data on the Global Forest and Eurasia, with Particular Emphasis on Boreal Eurasia

Total Global Boreal Forest Area	$1.2 \cdot 10^9$ ha
Closed Boreal Forest	$920 \cdot 10^6$ ha
Share of Total Global Forest	29 %
Total Exploitable Area	$800 \cdot 10^6$ ha (= 41 % World Total)
Growing Stock (over bark)	$95 \cdot 10^9$ m^3 (= 45 % World Total)
Total Global Value of Exports of Forest Products	47 % of World Total
Total Boreal Forest Area in Eurasia	$\sim 900 \cdot 10^6$ ha (= 70 % World Total)
Closed Boreal Forest in the Russian Federation	$400\text{–}600 \cdot 10^6$ ha

is ca. 47 % of the world total ([1, 3]; summary numbers are compiled in Table 1).

The vast majority of the boreal forest lands (taiga) of Eurasia are included in the Russian Forest Fund, covering ca. $900 \cdot 10^6$ ha. Depending on the criteria used to define "boreal forest", the area of closed boreal forest in the Russian Federation varies from 400 to $600 \cdot 10^6$ ha [4]. These numbers correspond to a 43–65 % share of the world's closed boreal forest.

3. DISTURBANCES IN TRANSITION: FROM NATURAL TO ANTHROPOGENIC

Among natural disturbances fire (lightning fire) is the most important factor controlling forest age structure, species composition and physiognomy, shaping landscape diversity, and influencing energy flows and biogeochemical cycles, particularly the global carbon cycle since prehistoric times (cf. monographs and synopses e.g. [5–18]).

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. 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 without eliminating it.

Large-scale forest disturbances connected with drought and fires are known from the recent history. The Tunguska Meteorite Fall near Yenisseisk (ca. 60° 54′ N–101° 57′ E) on 30 June 1908, a 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 (see [19]).

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 fires was between Angara River and Nijnya Tunguska, and the total area burned was estimated at $14.2 \cdot 10^6$ ha. However, the smoke of these fires covered the region between 64–72° N and 61–133° E, corresponding to ca. $680 \cdot 10^6$ ha. Shostakovich estimated continuous smoke (visibility ca. 100 m) on $284 \cdot 10^6$ ha, heavy smoke (visibility 25–100 m) on $215 \cdot 10^6$ ha and thick smoke (visibility 5–20 m) on ca. $181 \cdot 10^6$ 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 Eurasia fire has been for long time an important tool for land clearing (conversion of boreal forest), silviculture (site preparation and improvement, species selection) and in maintaining agricultural systems, e.g. hunting societies,

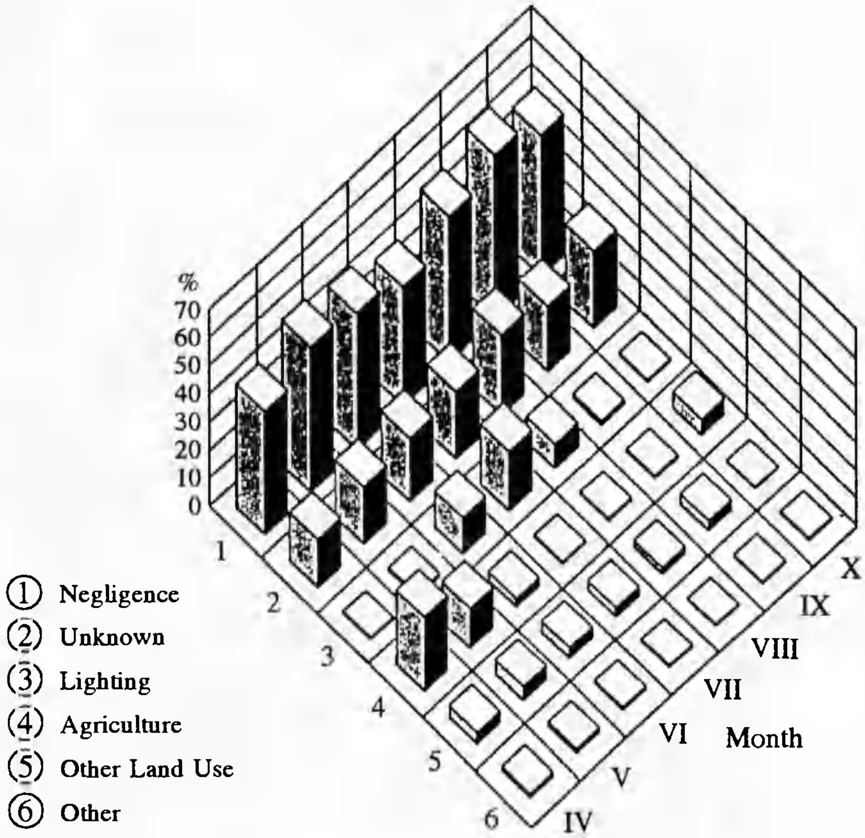

Fig. 2. Monthly distribution of causes of wildfires on protected lands in the USSR and the Russian Federation between 1947 and 1992 (Source: Avialesookhrana [22])

swidden agriculture, and pastoralism [20, 21]. In addition to the 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 because most of the deforestation had 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 ([22]; Fig. 2).

In recent years wildfires were more or less eliminated in Western Eurasia (Norway, Sweden, Finland). Thus, the major occurrence of Eurasian fires is on the territory of the Russian Federation and other countries of the Commonwealth of Independent States (Table 2). 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 $2\text{–}3 \cdot 10^6$ ha of forest and other land (Fig. 3). 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 is much higher. For instance, satellite-derived observations by Cahoon et al. [23] indicate that during the 1987 fire season approximately $14.5 \cdot 10^6$ ha were burned. In the same fire season ca. $1.3 \cdot 10^6$ ha of forests were affected by fire in the mountain-boreal forests of Northeast China, south of the Amur (Heilongjiang) River [24, 25].

TABLE 2

Selected Data on Global Boreal Forest Fires

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

4. BOREAL FOREST FIRES AS CYCLIC SOURCE AND PERMANENT SINK OF CARBON

Several investigators (e.g. [26, 27]) have been calculating the carbon released by boreal forest fires in the form of the radiatively active trace gases, e.g. carbon dioxide (CO_2), carbon monoxide (CO), or methane (CH_4). Such data are meaningful only if temporal patterns and the fate of the carbon released into the biosphere is distinguished or put into the context of ecosystem history.

Boreal Fire: a Natural Source of Trace Gases. As indicated above, forest fires play an important role in the sustainability of the taiga forest — as long as other disturbances such as human activities are not interfering with natural fire regimes and fire-maintained equilibria, e.g. by changing the forest fuel complex, preventing natural regeneration, or introducing additional fires.

Natural boreal forest fire-return intervals range between several years, decades, and cen-

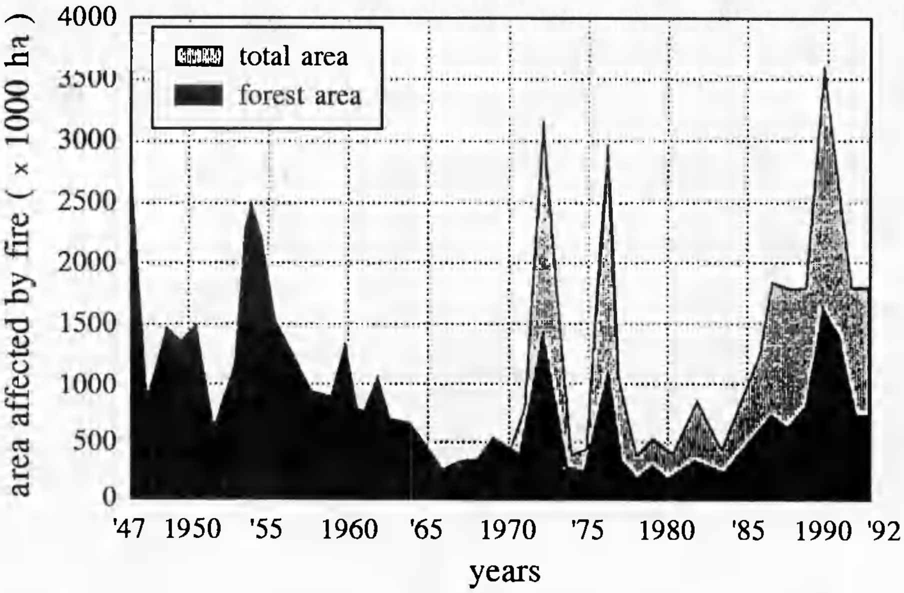

Fig. 3. Area of protected lands affected by wildfires in the USSR and the Russian Federation between 1947 and 1992 (Source: Avialesookhrana [22])

TABLE 3

CO_2-*Normalized Emission Ratios (in %) for Fires in Different Vegetation Types* (Source: [28, 29])

Ecosystem Type and Combustion Phase* (Number of Samples)		$\Delta CO/\Delta CO_2$	$\Delta CH_4/\Delta CO_2$
Wetlands	F (13)	4.7 ± 1.1	0.3 ± 0.1
	S (19)	5.3 ± 1.2	0.4 ± 0.1
Savanna	F (21)	4.8 ± 0.8	0.3 ± 0.1
	S (11)	4.6 ± 1.0	0.5 ± 0.2
Boreal Slash Fires	F (28)	6.7 ± 1.2	0.6 ± 0.2
	S (22)	12.3 ± 1.9	1.3 ± 0.3
Bor Forest Island	F1 (4)	8.8 ± 2.7	0.5 ± 0.1
Fire Experiment	F2 (5)	11.3 ± 2.7	0.4 ± 0.1
	S (4)	33.5 ± 4.5	1.3 ± 0.2

* F — Flaming Phase (F1: Surface Fire — F2: High-Intensity Crown Fire)
S — Smoldering Phase

turies, maintaining a dynamic equilibrium between site potential and climate. Theoretically there are no fire-induced net fluxes of carbon 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 densitometric 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 (Fig. 1).

Characteristics of Gaseous Emissions. Certain radiatively active trace gases, e.g. incompletely oxidized reactive combustion products such as CO an CH_4 are emitted from boreal fires in a larger proportion (emission ratio as compared to other ecosystems, e.g. the tropical and subtropical savannas, the most extended fire landscapes of the globe. A large fire experiment conducted in Krasnoyarsk Region in 1993 (Fig. 4) revealed that CO and CH_4, the quantities of chemically/photochemically active combustion products produced per unit of fuel burned in boreal fires are consistently higher than those resulting from fires in other major global ecosystems ([28, 29]; Table 3).

Some boreal fires are characterized by specific behavior, e.g. high-intensity stand replacement fires producing strong convective activity and injecting smoke emissions into higher altitudes of the troposphere from where they even might be transported into the stratosphere (Fig. 4). One of the major outcomes of the large Siberian fire experiment in 1993 was the sampling of emissions for specific analyses 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. [30, 31]).

The emission ratios of CH_3Br and CH_3Cl measured in the Bor Forest Island Fire were in the range of $1.1\text{–}31 \cdot 10^{-7}$ and $0.2\text{–}12 \cdot 10^{-5}$ respectively. This was considerably higher than those found in savanna and chaparral fires or in laboratory experiments (cf. [30]). Highest values were found over smouldering surface fuels. This can be explained by the lower combustion efficiency of the smoldering process 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 $Gg \cdot yr^{-1}$, or 10–50 % of the total source strength

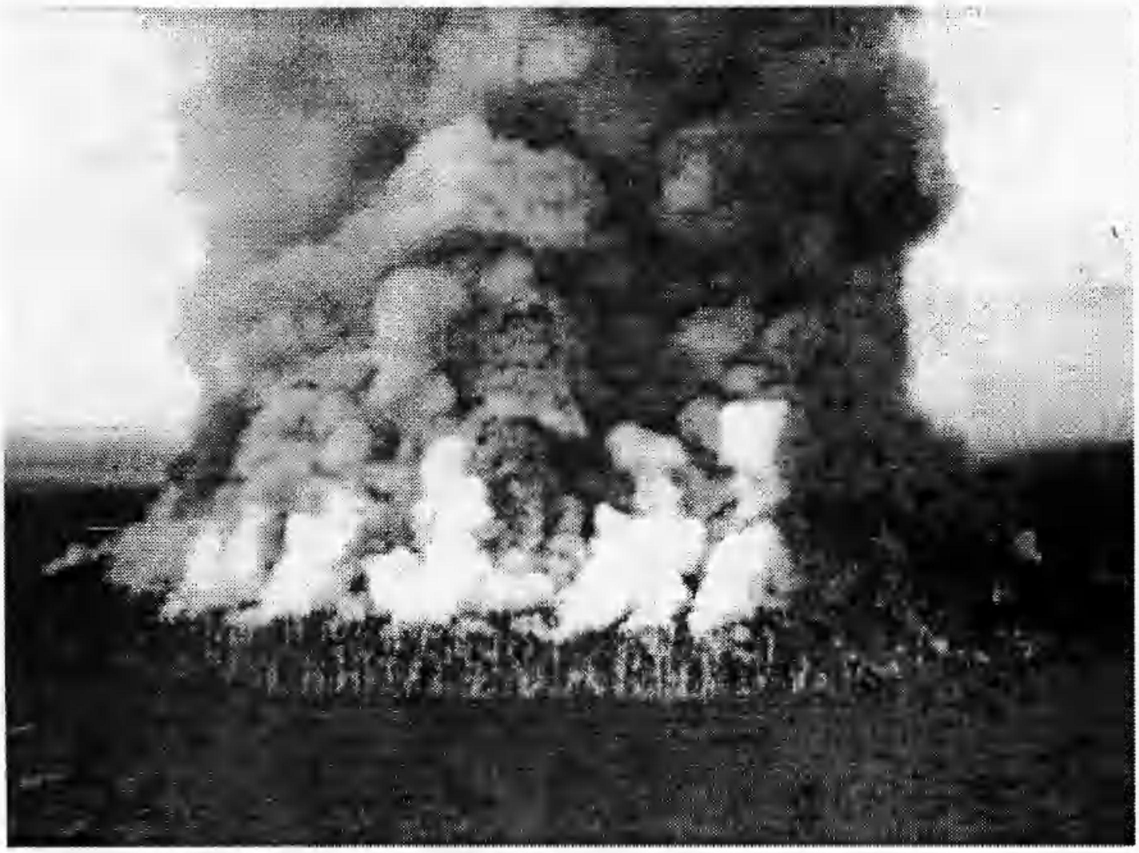

Fig. 4. Aerial view of the Bor Forest Island Fire Experiment of July 1993. The results of this first East-West fire experiment have given important insights into the ecology and atmospheric chemical impacts of boreal forest fires (Source: [28])

[30]. The share of boreal fires still needs to be defined to improve 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 is basically consisting 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 (Table 4).[1] 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.

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

[1]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" [32].

TABLE 4

Black Carbon in the Boreal Forest System

Black Carbon (BC): A Biospheric C-Sink			
Formation	Pyrolysis		
Characteristics	Biologically non-degradable, non-available for uptake by plants, chemically inert		
	Resistant to 339 °C in pure O_2		
Occurrence	Smoke (short residence time), Sediments (oceanic [near-coast]), Lakes, Soils		
Determination of emitted BC	Derived from Burning Efficiency		
	Emission Ratio BC/CO_2–C		
	Forest Fires, Forest Conversion Burning:		7–15 %
	Savanna/Gras Fires:		1.2–2.6 %
Boreal Forest Fires	Average Area Burned	$10 \cdot 10^6$ ha·yr^{-1}	
	Plant Biomass Combusted	$250 \cdot 10^6$ t (ca. 25 t·ha^{-1})	
	CO_2–C emitted	$125 \cdot 10^6$ t	
	BC emitted	$8–20 \cdot 10^6$ t	

sites distant from the fire are not available for plant life and are not subjected to degradation.

We are still in the beginning of quantifying this global carbon sink through BC formation and deposition [33], and much work needs to be done to collect pan-boreal charcoal storage data. However, the present state of knowledge allows to conclude that fires in sustainable fire ecosystems in general, and boreal fires in particular, may help to explain at least a part of the "missing sink" for carbon.

5. GLOBAL CLIMATE CHANGE: BOREAL FOREST IN POSSIBLE TRANSITION FROM CARBON SINK TO CARBON SOURCE

Present global boreal carbon storage. Estimates of carbon stored at present in living and dead plant biomass (without soil organic matter) above- and belowground in the global boreal forest area range between 66 and 98 Gt ($66–98 \cdot 10^{15}$ g) [34, 35]. Additional large amounts of carbon are stored in the boreal forest soils (ca. $200 \cdot 10^{15}$ g) and in the boreal peatlands (ca. $420 \cdot 10^{15}$ g) ([35]; Table 5).

Greenhouse Climate, Global Warming, and Vegetational Changes. Expected global warming over the next 30–50 years, as projected by GCM's for a doubled carbon dioxide equivalent greenhouse gas forcing scenario ("$2 \cdot CO_2$ climate"), will be most evident in the northern circumpolar regions [17, 36–38]. According to these models zonal warming will lead to the shift of vegetation belts, e.g. causing the boreal forest to shift north (e.g. [39]). 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. [40] shows that in a $2 \cdot CO_2$ 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 [41], 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 [42].

TABLE 5

Contemporary Boreal Forest Biome Areas and C *Pools. Totals May Not Agree Due to Rounding Errors*

(for more details on sources of investigations: see [35])

	Area, 10^6 ha		Carbon Pools, Pg C					
	Area	Peat Land	Plant Biomass	Plant Detritus	Forest Soil	Peat	Forest Products	Total
Alaska	52	11	2	1	10	17	< 0.1	30
Canada (Boreal Forest Biome)	304	89	8	*	65	113	0,2	186
Canada (Cordilleran)	72	3	6	*	16	4	0.3	27
Russian Federation	760	136	46	31	100	272	2.9	451
Scandinavia	61	20	2			13		15
Total	1249	260	64	32	199	419	3.4	709

* Plant detritus estimates are included in soil C pool.

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 [42, 43]. A model developed by Bonan and Van Cleve [43] 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 underscore in Ref. [44–47], fire may be a driving force in changing the taiga under zonally warming conditions. The prediction of increasing occurrence of extreme droughts in a $2 \cdot CO_2$ climate indicates that fire regimes will undergo considerable changes. An increase in the length of the fire season will lead to a higher occurrence of large, high-intensity wildfires. Wotton and Flannigan [48] predicted an increase of the length of the fire season in Canada by an average of ca. 30 days in a $2 \cdot CO_2$ climate, resulting in an additional 20 % increase in the annual area burned in Canadian boreal forests.

Fosberg et al. [49] used the Canadian Climate Center GCM [50] for predicting forest fire severity and frequency. The climate model projects a global mean temperature increase of 3.5 °C for a doubled carbon dioxide equivalent greenhouse gas forcing scenario ("$2 \cdot CO_2$ climate"). Regional warming during winter will be as follows: Continental regions of Siberia and Canada: +6–8 °C, Alaska +2–4 °C, and Scandinavia 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 [49] used two measures of fire danger and severity (the Russian Nesterov Index of ignition [51] for calculating the ignition potential, and the Canadian fire weather index system [52] for assessing fire severity). They used the 90th percentile level of the indices at each of 224 climate stations in Russia and 191 stations in Canada.[2] 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, and extreme ignition index virtually blanketing

[2]This corresponds to the worst 10 % of the weather-related fires which will result in 90 % of environmental and social impact. The evaluation of the change in the highest 10 % the indices give a more accurate depiction of the change in risk, since this is the range in which fire control becomes extremely difficult [49].

Eurasia in future.

Combined Effects of Zonal Warming and Fire. Kasischke et al. [42] concluded that changes of above- and belowground biomass characteristics due to zonal warming would also affect the flammability of vegetation. Over the longer term they expect the flammability to decrease for the aboveground 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 will be an overall increase of 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. [42] developed a carbon flux model in which two baseline 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 $kg \cdot m^{-2}$, or 33.0 to $46.0 \cdot 10^{15}$ g 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 $kg \cdot m^{-2}$, or 36.6 to $55.5 \cdot 10^{15}$ g on a global basis; an increase of annually area burned by 50 % would result in the global decrease in ground layer carbon between 41 and $66 \cdot 10^{15}$ g.

Considering the net gain of carbon by increasing aboveground biomass, there will still be a net carbon loss between 46.0 and $53.7 \cdot 10^{15}$ g from the global boreal forest to the atmosphere.

6. OTHER DISTURBANCES: NON-SUSTAINABLE FORESTRY, INDUSTRIAL EMISSIONS AND RADIONUCLEAR CONTAMINATION

Forestry. Traditional forestry practices and low-impact and sustainable use of non-wood forest products in boreal Eurasia are 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 reportedly are 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 the 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 regime.

Industrial Emissions. Additional fire hazards and environmental consequences which are still mainly unpredictable are created on forest lands affected by industrial emissions. Pisarenko and Strakhov [4] reported that in the Russian Federation ca. $9 \cdot 10^6$ ha of forest lands are severely damaged by industrial pollution (cf. also [53]). While it is known in general that availability of inflammable fuels makes dying and dead forest stands more susceptible to fire than living stands, 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? Many open questions remain to be answered.

Radionuclear contamination. Radionuclear contamination on an area of ca. $7 \cdot 10^6$ ha

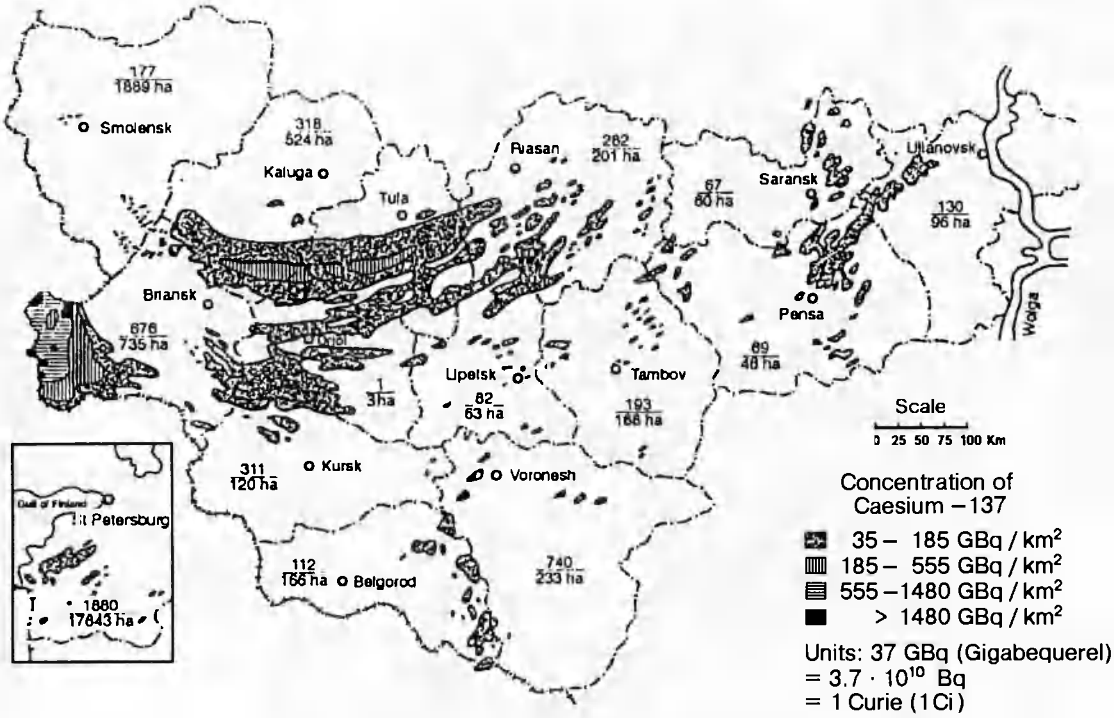

Fig. 5. Land area in the Russian Federation contaminated by Caesium-137 (main map shows territory East of Chernobyl nuclear power plant). The numbers within the districts (Oblasts) give the number of forest fires and the total area affected by fire in 1992 (from [55]). The problem in the Chernobyl region may reflect the dangerous and largely unknown potential in other forest regions of Eurasia, including the boreal zone

may create considerable problems in redistribution of radionuclides through forest fires. This has been demonstrated by the research in forests in the impact region of the 1996 Chernobyl nuclear power plant accident ([54, 55]; Fig. 5). This 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 [54].

These contaminated sites were abandoned by human land use up to a distance of 100–120 km from the accident site. A total of ca $4.5 \cdot 10^6$ ha of forest land is considered contaminated by 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 the 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 [55]. This example of an 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. It also shows a new dimension in modern fire ecology.

7. CONCLUSIONS

At the time the Tomsk Conference on Mathematical and Physical Modeling Forest Fire and Ecology Problems is being held, first cooperative projects in East-West fire research have been operational and scientific results achieved.

It is now the time to expand international cooperation by building up more specialized as well as interdisciplinary fire research activities, consisting of long-living groups or short-living projects.

The overall aim of the research must be that through better understanding of the ecology, behavior and impacts of fire in boreal forests the fire management policy and management principles must be adapted accordingly. The reform of the Russian fire control system into a fire management system must receive absolute priority.

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