Unendliche Taiga? Gefährdung und Schutz der borealen Wälder
Internationale Konferenz, Berlin, 27.-28. März 1995
Klimaforum 1995

THE BOREAL FOREST AND THE GLOBAL CLIMATE

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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 contiguous forested area of the globe; the main share of 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 sub-zones, the maritime, the continental and the high-continental sub-zones (Kuusela 1992). 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 sub-zone 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 sub-zone 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.), fire (*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 with multi-year drought periods and extreme dry years (Fig.1), associated with lightning fires and insects outbreaks.

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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 large parts of the *taiga* are considered to be highly productive and economically valuable forests, their vulnerability has been disregarded largely in the past. Inappropriate forestry practices, e.g. large-scale clearcuts with subsequent degradation go along with extended industrial pollution, oil pipeline leakages, radioactive contamination and 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 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 intends to give some thoughts on 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*.

Figure 1 (next page)

Fig.1. Maximum density chronologies (indices) from living spruces and larches growing at the northern tree limit (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 man April to September temperatures and serve as long-term "meteorlogical" 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

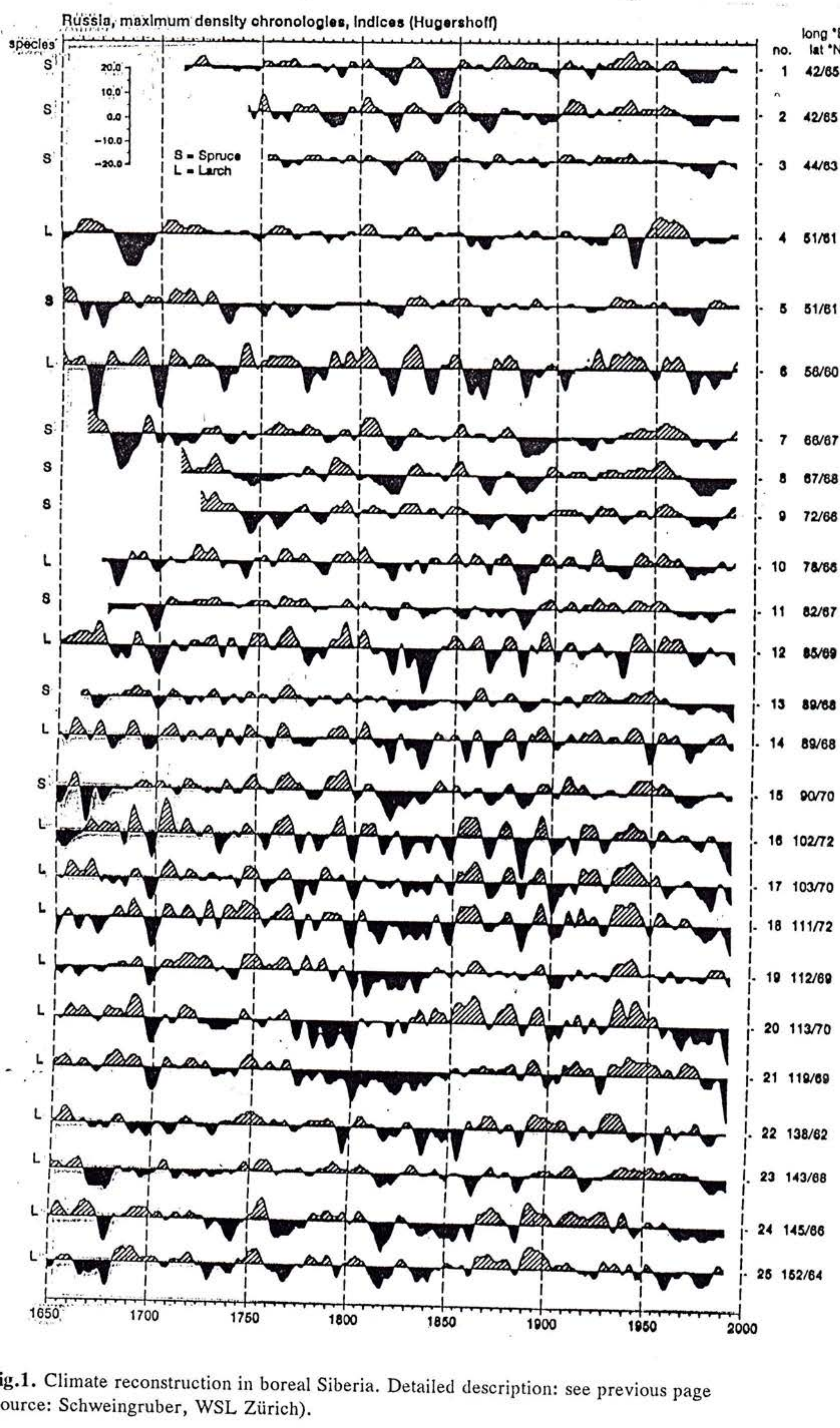

Fig.1. Climate reconstruction in boreal Siberia. Detailed description: see previous page (source: Schweingruber, WSL Zürich).

2. The boreal forest: Extent and economic importance

The world's total boreal forests and other wooded land within the boreal zone cover 1.2×10^9 ha of which 920×10^6 ha are closed forest.[2] 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% respectiveley of the world total). The export value of forest products from boreal forests is ca. 47% of the world total (Kuusela, 1990, 1992; summary numbers are compiled in Tab.1.).

The vast majority of the boreal forest lands (*taiga*) of Eurasia are included in the Russian Forest Fund, covering ca. 900×10^6 ha. Depending on the criteria used to define "boreal forest", the area of closed boreal forest in the Russian Federation varies from 400 to 600×10^6 ha (Pisarenko and Strakhov, 1993). These numbers correspond to a 43-65% share of the world's closed boreal forest.

Tab.1. Base data on the global forest and Eurasia, with particular emphasis on boreal Eurasia.

Base Data on the Global and Eurasian Boreal Forest	
Total Global Boreal Forest Area:	1.2×10^9 ha
Thereof Closed Forest:	920×10^6 ha
Share of Total Global Forest:	29 %
Total Exploitable Area	800×10^6 ha (= 41% World Total)
Growing Stock (over bark)	95×10^9 m^3 (= 45% World Total)
Total Global Value of Exports of Forest Products	47% of World Total
Total Boreal Forest Area in Eurasia:	~ 900×10^6 ha (= 70% World Total)
Thereof Closed Forest in the Russian Federation:	$400\text{-}600 \times 10^6$ ha

[2] 1×10^9 ha = 1 billion ha; 1×10^6 ha = 1 million ha.

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 mosaic, and influencing energy flows and biogeochemical cycles, particularly the global carbon cycle since prehistoric times (cf. monographs and synopses e.g. by Sofronov, 1967; Slaughter et al., 1971; Zackrisson, 1977; Sherbakov, 1979; Viereck and Schandelmeier, 1980; Alexander and Euler, 1981; Heinselman, 1981; Wein and MacLean, 1983; Kurbatsky, 1985; Johnson, 1992; Sannikov, 1992; Furiaev, 1994; Shugart et al., 1992; Goldammer and Furiaev, 1995). 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 development. Low-intensity surface fires favour 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 damaging 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.

A couple of years later, in 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 ca. 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 ca. $14{,}2 \times 10^6$ 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 or humans were the prevaling 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, swidden agriculture, and pastoralism (Viro, 1969; Pyne, 1995). 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 the use of fire in the agricultural sector began to decrease because most of the deforestation had been accomplished, 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 (Korovin, 1994; Fig.2).

During the 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 Independant States (Tab.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 2-3x10^6 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. (1994) indicate that during the 1987 fire season approximately 14.5x10^6 ha were burned. In the same fire season ca. 1.3x10^6 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; Fig.4).

Tab.2. Selected basic data on global and Eurasian boreal forest fires.

Boreal Forest/Wildland Fires	
Boreal North America (Annual Average)	1-5 x 10^6 ha
Extreme Years, e.g. Canada 1989	7.4 x 10^6 ha
Boreal Western Europe (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?

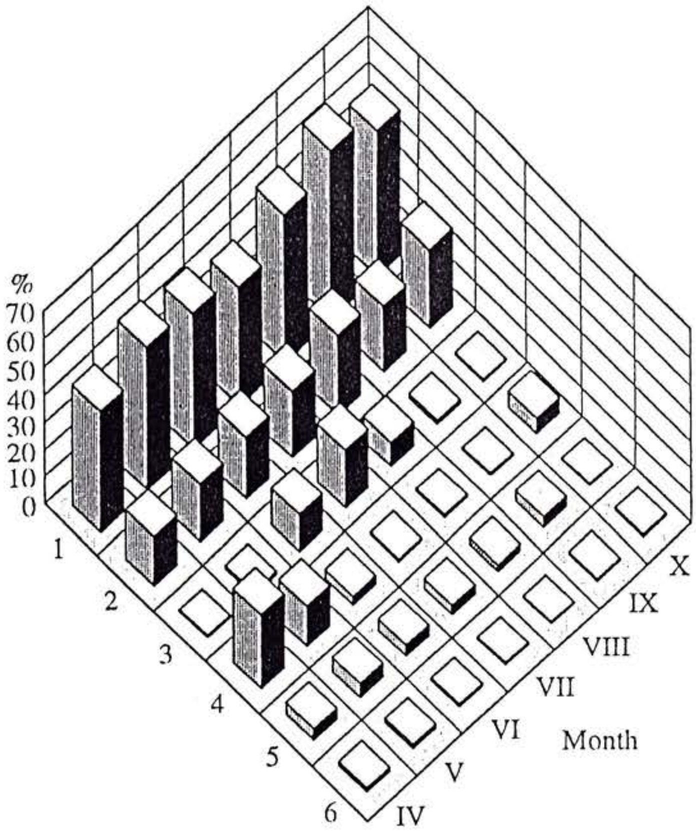

Fig.2. Monthly distribution of causes of wildfires on protected lands in the USSR and the Russian Federation between 1947 and 1992. Source: Avialesookhrana (Korovin, 1994).

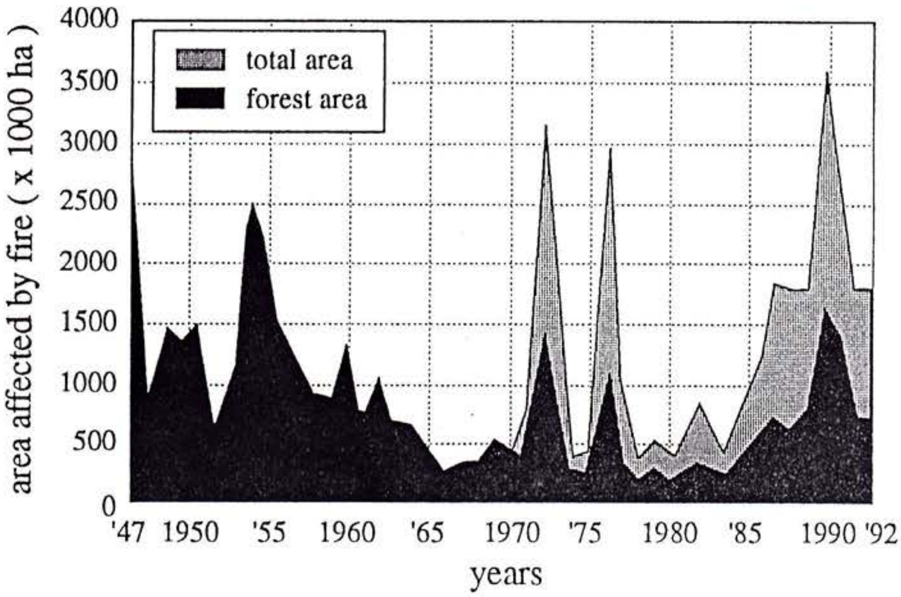

Fig.3. Area of protected lands affected by wildfires in the USSR and the Russian Federation between 1947 and 1992. Source: Avialesookhrana (Korovin, 1994).

Fig.4. Total forested area affected by the large-scale wildfires in the montane-boreal coniferous forest, Daxinganling mountains, Heilongjiang Province, NE China. The area burned in May 1987 totalled ca. $1.3x10^6$ ha (for details: see Ende and Di, 1990; Goldammer and Di, 1990).

4. Boreal forest fires as cyclic source and permanent sink of carbon

Numerous investigations 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). In general these emissions were used in *Greenhouse Gas* emission scenarios in a rather simplifying way, e.g. by estimating that they would constitute no more than 1-3% of the average annual global biomass burning emissions, without distinguishing temporal patterns and the fate of the carbon released into the biosphere or putting them into the context of environmental 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 centuries, 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, in 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 in periodical scales (Fig.1).

Particularities 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.5) 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 (FIRESCAN Science Team, 1994; Cofer et al. 1995; Tab.3).

Some boreal fires are characterized by sepcific behaviour, 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.5). 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. Manö and Andreae, 1994, WMO, 1992).

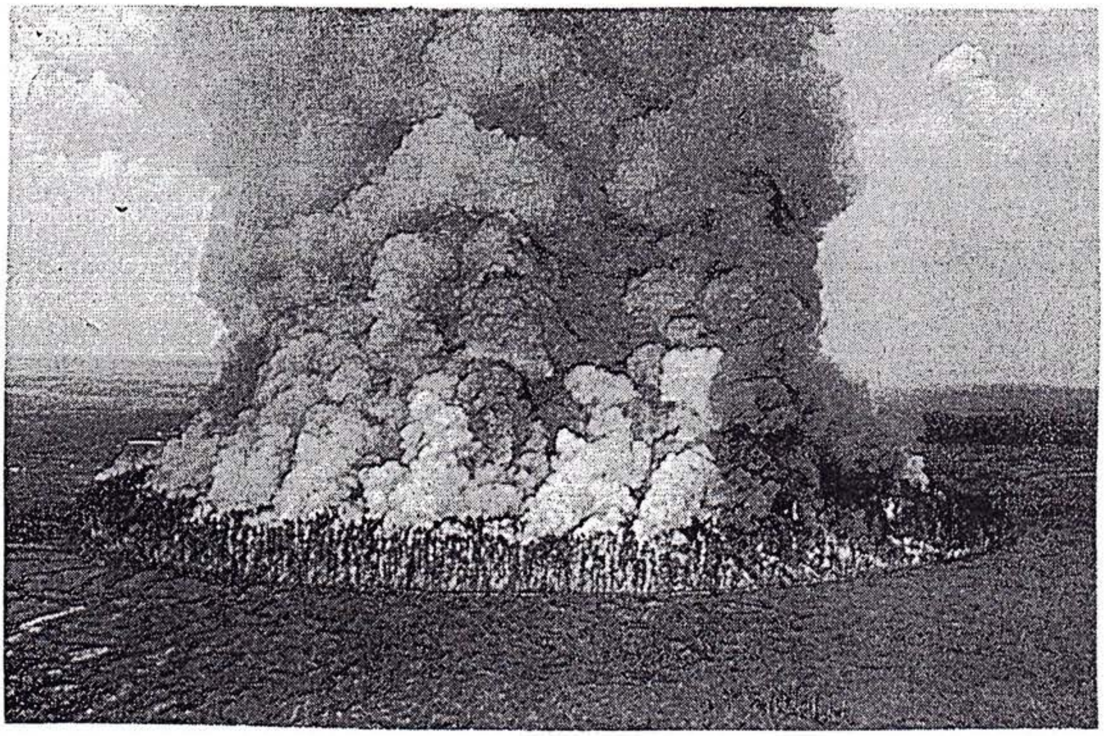

Fig.5. Aerial view of the Bor Forest Island Fire Experiment of July 1993. The results of this first East-West fire experiment have given important insights into the ecology and atmospheric chemical impacts of boreal forest fires (Source: FIRESCAN Science Team, 1994).

The emission ration of CH_3Br and CH_3Cl measured in the Bor Forest Island Fire were in the range of $1.1\text{-}31 \times 10^{-7}$ and $0.2\text{-}12 \times 10^{-5}$ 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 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, 1993). The share of boreal fires still needs to be defined on the base of improving estimates of boreal vegetation area and biomass affected by fire. Special attention must be given to the specific behaviour of boreal fires, inlcuding the injection of ozone-destroying gases into the high troposphere and the further transport into the stratosphere.

Tab.3. CO_2-normalized emission ratios (in %) for fires in different vegetation types (Source: Cofer et al. [1995], FIRESCAN Science Team [1994]).

CO_2-normalized Emission Ratios (%) for Fires in Different Vegetation Types			
Ecosystem Type & Combustion Phase* (Number of Samples)		$\Delta CO/\Delta CO_2$	$\Delta CH_4/\Delta CO_2$
Wetlands	F (13) S (19)	4.7 ± 1.1 $5.3. \pm 1.2$	0.3 ± 0.1 0.4 ± 0.1
Savanna	F (21) S (11)	4.8 ± 0.8 4.6 ± 1.0	0.3 ± 0.1 0.5 ± 0.2
Boreal Slash Fires	F (28) S (22)	6.7 ± 1.2 12.3 ± 1.9	0.6 ± 0.2 1.3 ± 0.3
Bor Forest Island Fire Experiment	F1 (4) F2 (5) S (4)	8.8 ± 2.7 11.3 ± 2.7 33.5 ± 4.5	$0.5. \pm 0.1$ 0.4 ± 0.1 1.3 ± 0.2
* F = Flaming Phase (F1: Surface Fire - F2: High-Intensity Crown Fire) S = Smoldering Phase			

Fire effects: a carbon sink ?

A close look to 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 (Tab.4).[3] 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.

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[3] 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 in the long term do not destabilize the ecosystem (e.g. towards a lower phytomass productivity or lower biomass carrying capacity), 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.

We are still in the beginning of quantifying this global carbon sink through BC formation and deposition (Kuhlbusch et al., 1995), and tremendous 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" of carbon.

Tab.4. Black carbon in the boreal forest system

Black Carbon (BC): A Biospheric C-Sink	
Formation	Pyrolysis
Characteristics	Biologically non-degradable, non-available for uptke by plants, chemically inert Resistant to 339°C in pure O_2
Occurrence	Smoke (short residence time); Sediments (ozeanic [near-coast]); Lakes, Soils
Determination of emitted BC	Burning Efficiency, thereof derived: Emission Ration BC/CO_2-C: Forest Fires, Forest Conversion Burning: 7-15% Savanna/Gras Fires: 1,2-2,6 %
Boreal Forest Fires	Average Area Burned: 10×10^6 ha yr^{-1} Plant Biomass Combusted: 250×10^6 t (ca. 25 t ha^{-1}) CO_2-C emitted: 125×10^6 t BC emitted: $8\text{-}20 \times 10^6$ t

	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.

Tab.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 Apps et al. (1993).

5. Global climate change: Boreal forest in 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 ($66\text{-}98 \times 10^{15}$ g) (US Department of Energy, 1983; Apps et al., 1993). Additional large amounts of carbon are stored in the boreal forest soils (ca. 200×10^{15} g) and in the boreal peatlands (ca. 420×10^{15} g) (Apps et al., 1993; Tab.4).

Greenhouse climate, global warming, and vegetational changes

Expected global warming over the next 30-50 years, as projected by Global Circulation Models (GCM's) 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, 1992; Shugart et al., 1992). Zonal warming will lead to the shift of vegetation belts, e.g. causing the boreal forest to shift north ca. 500-1000 km (Kauppi and Posch, 1988). The shift of ecosystems will 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., 1994).

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., 1994). 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 Flanningan and van Wagner (1991), Stocks (1993), Wein and de Groot (1995), and Stocks et al. (1995) underscore, fire may be a driving force in changing the taiga under zonally warming conditions. The prediction of 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 will lead to a higher occurrence of large, high-intensity wildfires. Wotton and Flannigan (1993) predicted an increase of 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. (1995) used the Canadian Climate Center atmospheric general circulation model (McFarlane et al., 1992) 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 ("2xCO_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 Fosberg et al. (1995) 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). Among other, they used the 90th percentile level of the indices at each of 224 climate stations in Russia and 191 stations in Canada.[4] The results show that the current worst 10 percent which are currently classed as moderate or high, in future are classed as extreme fire ignition and severity potential. Extreme monthly severity will be close to doubling of area in boreal North America, and extreme ignition index virtually saturating Eurasia in future.

Combined effects of zonal warming and fire

Kasischke et al. (1995) 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. Over shorter 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 down 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 carbon levels were established ([1] all ground layer carbon is stored in 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 shorter term (the next 50-100 yr) would range between 2.8 and 3.9 kg m^{-2}, or 33.0 to 46.0×10^{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 m^{-2}, or 36.6 to 55.5×10^{15} g on a global basis; an

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[4] This corresponds to the worst 10 percent of the weather-related fires which will result in 90% of environmental and social impact. 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., 1995).

increase of annually area burned by 50% would result in the global decrease in ground layer carbon between 41 and 66×10^{15} g.

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

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 accumulative to the indirect effects induced by climate change, and both will certainly contribute to an unprecedented era of fire.

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 (1993) reported that in the Russian Federation ca. 9×10^6 ha of forest lands are severely damaged by industrial pollution (cf. also Kharuk, 1993). While it is known in general that dying and dead forest stands are 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. 7×10^6 ha 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 (Dusha-Gudym, 1992, 1994; Fig.3). 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 (Dusha-Gudym, 1992).

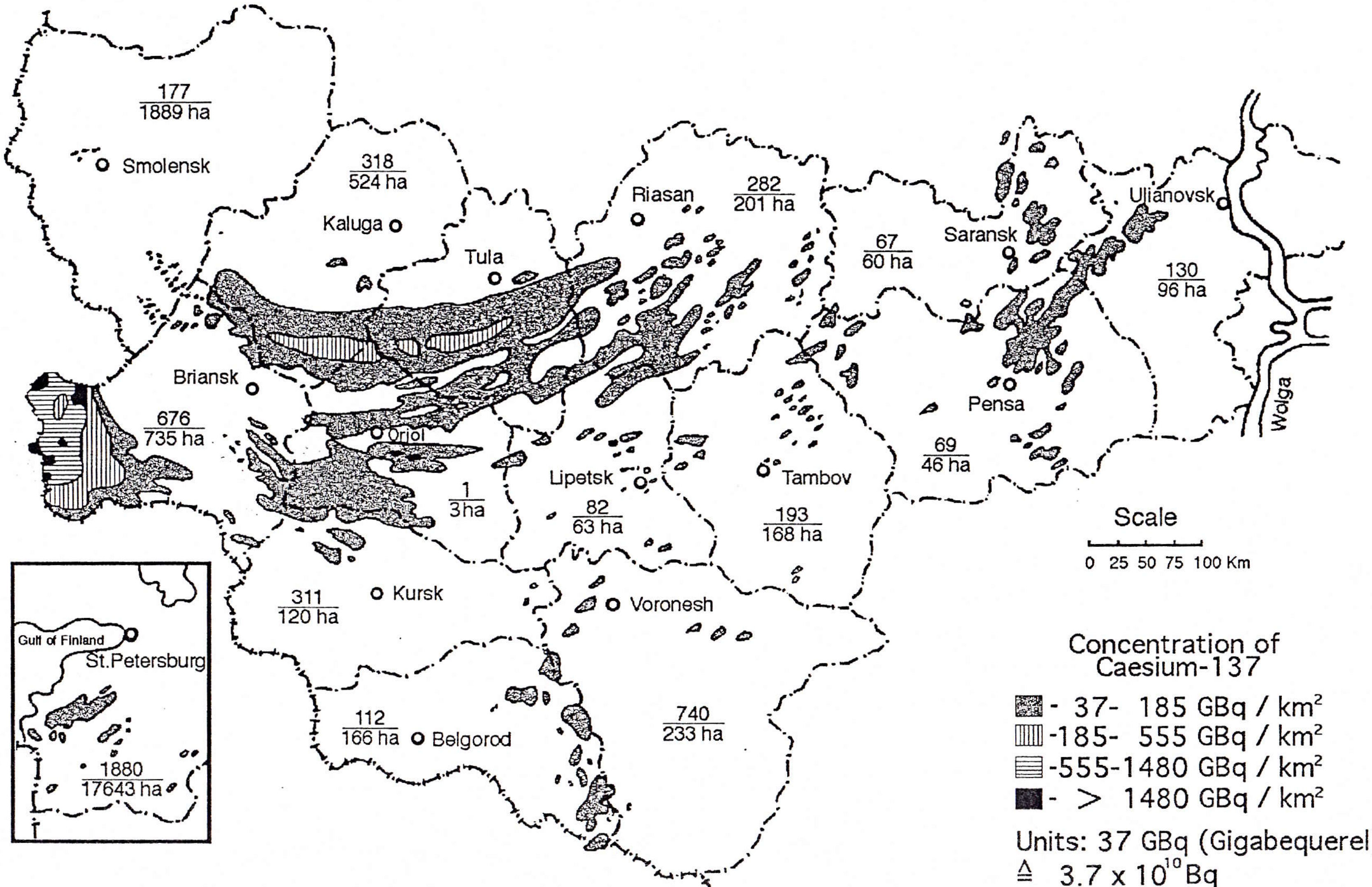

Fig.6. Land area in the Russian Federation contaminated by Caesium-137 (main map shows territory East of Chernobyl nuclear power plant). The numbers within the districts (Oblasts) give the number of forest fires and the total area affected by fire in 1992 (from Dusha-Gudym, 1995). The well investigated problem in the Chernobyl region may reflect the dangerous and largely unknown potential in other forest regions of Eurasia, including the boreal zone.

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 million hectares of forest land is considered as 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 1986 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 to the atmosphere and caused nuclear fallout in distant places. 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.

Impacts of artificial reservoir construction

Among other disturbances the construction of hydroelectric dams with subsequent large-scale flooding of forests by water reservoirs has not been brought to the world's attention. The ongoing construction of the Angara reservoir is one of the most critical exmples. This hydroelectric reservoir will flood and submerge the Angara Pine forests, one of the ecologically and economically most valuable forest regions of the world.

The consequences of this, e.g. the alteration of hydrological regimes, the creation of large water surfaces, and the release of trace gases like methane as a consequence of flooded forests, are not well understood by most likely will cause considerable environmental problems.

7. Conclusions: Consequences for policies, politics and research

The present development of the global boreal forest, particularly in Eurasia, is influenced by a multitude of direct and indirect anthropogenic factors which threaten the sustainable function of this forest zone in the local and global environment and economies as well as ahabitat for humans.

The global boreal forest crisis reminds us to the very similar development in the tropics many years ago - the crisis is just lagging behind. The depletion of tropical forest resources, in terms of biodiversity, ecological stability and human carrying capacity through inappropriate management practices has resulted in a global outcry.

Global humanity has not yet overcome the wasteful use of forest resources. Therefore a new, cheap resource for forest products is needed: The boreal forest.

Inappropriate use of fossil energy leads to a global crisis, global climate change, which in the transition period becomes less evident if there is a large buffer. The boreal forest is a buffer acting as carbon sink - until it strikes back. Zonal warming will affect the balance of the boreal carbon pool and lead to the additional release of carbon into the atmosphere, thus acting as temporary feedback loop to global warming.

Urgent action is required on all levels of politics, policy and strategy development, management - and research.

I am proposing an Action Plan:

A Global Boreal Forest Convention

It is necessary and timely to agree upon a global convention which considers the need to take all steps which reduce or mitigate the direct and indirect impacts on the boreal forest which may reduce the sustainability of the system.

An ***International Boreal Forest Convention (IBFC)*** is proposed. This convention shall reflect the progress we have made in understanding the processes which threaten the boreal forest, and what the impacts of indiscriminate use of boreal forest resources have on the global environment.

The IBFC shall also reflect the progress to be initiated in the spririt of the United Nations Conference on Environment and Development (UNCED), the United Nations Framework Convention on Climate Change, the Convention on Biological Diversity, the Helsinki Ministerial Conference on Protection of Forests in Europe, and the objectives of the work of the UN International Decade for Natural Disaster Reduction (IDNDR) and the UN Commission for Sustainable Development (CSD). And finally we should do better than what the revised International Tropical Timber Agreement (ITTA) has in mind.

A relevant International Boreal Forest Organization (IBFO) must be founded and made responsible for the devlopment of adequate policies, strategies and management concepts that would serve the objectives of the IBFC.

The role of research

The research community, both in East and West, have significantly contributed to clarify the role of boreal forests in the global system.

At the same time this conference "***Unendliche Taiga? Gefährdung und Schutz der borealen Wälder***" is being held, major cutbacks of forest and climate research funding in Canada, the USA and in the Russian Federation have most detrimental effect on our capability to assess what and how we should overcome the causes of the boreal forest crisis.

We need to re-evaluate and to restructure the sectors of society in which we are investing energy, brain, and money. One of the sectors to be restructured is the military. For instance, the North Atlantic Treaty Organization (NATO), well known in its political and military dimensions, offers a "Third Dimension" which seeks to encourage interaction between people, to consider some of the challenges facing our modern society, and to foster development of Science and Technology. The NATO Science Programme is a major component of this Third Dimension.

Those of us who are living in a member country of NATO are responsible to restructure priorities within our treaty organization, especially considering the new links with the Commonwealth of Independent States (CIS) and Central and Eastern Europe, NATO's new Cooperation Partners (see also Goldammer and Furiaev, 1995).

The ***International Boreal Forest Research Association (IBFRA)*** plays an important pioneer role pan-boreal research.[5] IBFRA is not adequately funded to deliver products. Global ecosystem research cannot be financed by enthusiasm of scientists only. High priority must be given to support the work of IBFRA.

The scope of work of the Center for International Forestry Research (CIFOR) must also be re-oriented. Although the founder and member states of CIFOR did not have in mind to restrict CIFOR's activities on the tropical forest, the reality is different: CIFOR has so far completely neglected its global mandate. The member and sponsor countries are urged to change this policy.

The need to urgently pull emergency brakes

While it is not possible to immediately reduce the emissions from fossil fuel burning - this is a rather lengthy way to go - there are some negative developments that may effectively be reconsidered through negotiations and moratoria.

One of the examples is the construction of the Tunguska River Dam in Siberia, a hydroelectric power dam which has no use in that region because there is no adequate electricity consumer there at all. The dam is a fossil dating back to the Soviet era misconception of exploring and exploiting the Siberian *taiga*.

This dam is not only causing the submerging of villages and towns along the river, e.g. the town of Khezma. The water reservoir will also destroy vast tracts of forest stocked with Angara Pine, one of the most valuable forest region all over the global forest belt. As mentioned before, the consequences of the dam construction may be the additional release

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[5] The International Boreal Forest Research Association was first proposed at a meeting of the International Panel on Boreal Forests in Arkhangelsk, Russia. In June 1991. Subsequently an organizational meeting was held in the Ukraine between the United States, Canada, and Russia. Norway, Sweden and Finland have joined IBFRA. Member countries are represented by coordinators for priority research areas. Two priority areas were identified at this organizational meeting: Inventory and Monitoring, including classification; and Global Climate Change and Ecosystem Function.

of trace gases like methane as a consequence of flooded forests. Other consequences are not yet understood - and this is why we need a moratorium.

Final Remark

This paper intends to highlight some selected aspects on boreal forests and climate. Flames and smoke were described a little more in detail, last not least because they are a symbolic link connecting the boreal forest with the global climate system.

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