International Forest Fire News (IFFN) No. 32 (July – December 2004, 43-49)

Long-term Environmental Impact of Catastrophic Forest Fires in Russia's Far East and their Contribution to Global Processes

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When assessing the negative consequences of forest fires, researchers usually limit the consideration of the problem to the relatively short period of time that is presumably needed for restoration of the destroyed biotope. The impacts and consequences considered include direct fire-related loss of biological resources and commercial products, the rate and capacity of biological resources restoration, emissions of carbon and other pyrogenic products, specific features of the destruction of existing phytocenosis and formation of initial post fires, etc. It is commonly believed that post-fire rehabilitation leads to the formation of a new stand whose structure and composition would be very close to those of the pre-fire stand, and where the negative consequences of fire are extinguished and graded in a relatively short period of time. The philosophical background of this approach is recognizing the reversible nature of pyrogenic disturbances of forest ecosystems. However, recent studies have indicated that post-pyrogenic consequences of forest fires, in particular, of catastrophic forest fires, are cumulative in nature. Based on the fire's duration and severity, the level of the fire's concentration over territories, landscapes' and ecosystems' specifics, etc., the transformation of historically stabilized ecological processes is observed in all ramifications, including both biotic and abiotic spheres, in particular, synoptical processes.

In this respect, the major objectives of this paper are to:

- provide a brief characteristic of transformation and long-term environmental consequences of large forest fires and post-pyrogenic disturbances of forest;
- assess the global role of regional catastrophic forest fires;
- describe the trends and rates of "green desertification" (deforestation), as well as signs and criteria of pyrogenic impacts on forest ecosystems;
- consider specific features of fire emissions of greenhouse gases after catastrophic fires.

In this context, catastrophic forest fires mean fires covering an area of more than 10,000 ha, resulting in the total destruction of vegetation and organogenic horizons of soils, or the simultaneous occurrence of several fires of the same total area and intensity over a total area of 1,000 km^2 (Sheshukov, 1971). The term *catastrophic* is sometimes used in a different but close context. The classification of post fire catastrophic "traumatism" by Sapozhnikov (1984) includes the highest level of a fire's impacts following destruction of the soil cover, intensive soil erosion, and development of stone fields in mountains. The forests are destroyed completely, and are not restored before new soils are generated. For this class, the loss of potential productive forest land is estimated at more than 80% and lasts for a period of over 20 years (Sapozhnikov, 1984). Shvidenko and Nilsson (2003) used the term *catastrophic fire year* as a year for which the extent of fire is three-fold, more than the multi-year average and where the severity of fire is extremely high.

Long-term pyrogenic consequences are the irreversible transformation of the forest environment, which is obvious beyond the restoration period of an indigenous forest ecosystem, i.e. exceeds the length of the rotation period (i.e., ranging from 100-400 years for major forest forming species of the Russian Far East).

Russia's Far East has a clearly expressed geographical distribution of forests and specific nature of forest growing conditions that causes the high burning ability of forests. It makes this region an ideal model for studying the patterns and roles of forest fires in the evolution of forest vegetation and their input into global processes. This study is based on the long-term research of consequences caused by catastrophic forest fires in Khabarovsk Krai over a historically observable period of time.

In the context of the Far East, forest fires have always been the main factor determining forest-forming and forest-producing processes and specifics of succession regularities. To judge by the retrospective analysis of the vegetation cover structure and by the presence of charcoal in soil horizons and native bed rock depositions, catastrophic forest fires have occurred over the entire quaternary period. Peaks of the highest forest fire occurrence coincided with droughts and peaks of solar activity, as their frequency was between 40 to 80 years. In recent years, there has been a trend toward an increased magnitude and frequency of catastrophic fire occurrence. In particular, over the last 40 years, we observed peaks of catastrophic forest fire occurrence in 1976, 1988, and 1998, i.e. every 10 to 12 years (Fig. 1). There appears to be a clear link between the increased magnitude of catastrophic fires and enhanced anthropogenic impact on forests. The history of linear trends prior and after the 80s clearly shows an increased level of natural fire incidence, which might be viewed as an increase in the share of forest fire caused by anthropogenic factors. If we assume the indicators of burning given in Table 1 as the rate of natural forest fire regimes, we observe a dramatic prevalence in the rate of actual fire occurrence during recent decades over the rate of (mostly) natural fire occurrence of the previous periods, as well as an extensive destructive effect of forest fires regarding to the total forest fund area and, in particular, to local forest areas affected by repeated forest fires.

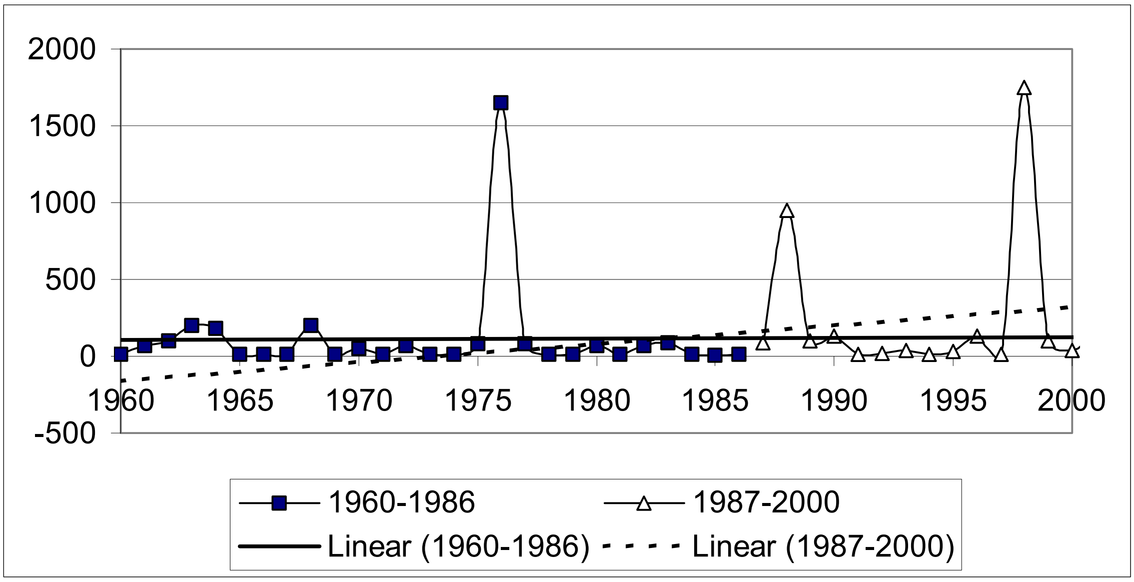

Figure 1. Area affected by fire in Khabarovsk Krai by periods (ha x 1000)

For example, in Khabarovsk Krai alone, 1,314 forest fires, which occurred there in 1998, affected 2.7 million ha or 3% of the total forest fund area. The fires were concentrated on an area of some 15 million ha. The severity of fire was extremely high and significant areas (estimated at 0.4 million ha) have lost organogenic horizons of soils almost completely (Kulikov, 1998). It is worth to mention that we use data of official forest fire statistics, which are very probably underestimated (Shvidenko and Goldammer, 2001). However, under any estimates, it is evident, that fires of that magnitude should be viewed as a pyrogenic disaster beyond a regional context, with century-long biotic, environmental, and socio-economic consequences.

Generally, the long-term environmental consequences of catastrophic forest fires became apparent in the following aspects:

1. A significant (up to several times) decrease of the biological productivity of forest lands due to the destruction of the indigenous ecotope and replacement of indigenous vegetation formations.

2. Irreversible changes in the cryogenic regime of soils and rocks.
3. Change of long-term amplitude of hydrothermal indicators beyond natural fluctuation.
4. Changes of multi-year average hydrothermal and bio-chemical indicators of aquatic and sediment runoff, as well as of hydrological regimes and channel processes of water streams.
5. Accumulative impacts on atmospheric processes resulting in global climate change.
6. Acceleration of large scale outbreaks of insects and disease.
7. Irreversible loss of biodiversity including rare and threatened flora and fauna species.
8. Transboundary water and air transfer of pyrogenic products.
9. Change of historical migration routes for migratory birds, ground and water animals.

Table 1. The ecologically permissible norm of fire occurrence rates for forest formations of Russia's Far East.

Indicators	Rate (percent of total area of forest fund)
Actual overall average annual fire occurrence rate	0.35
Maximum	4.0
Minimum	0.02
Hypothetically allowable rate for main forest formations	
Dwarf pine forest	0.01
Spruce - fir forest	0.1
Cedar - broadleaf forest	0.07
Hardwood deciduous forest	0.2
Larch forest	0.3
Forests of river valley	0.5
Softwood deciduous forest	0.3
Grass-meadow communities	0.6

Note: fire occurrence rate means a ratio (in %) of the total fire-affected forested area to total forest fund area or the area of individual forest formation.

Losing forest-producing lands is the most pronounced negative post-fire consequence of catastrophic forest fires. It leads to a dramatic degradation of the indigenous ecotope up to the irreversible and complete loss of forest-producing potential. There is a pronounced statistical link (Fig.2) between deforestation of lands and a forest fire occurrence rate. In particular, the correlation coefficient between the share of unforested areas and a forest fire occurrence rate is estimated to be 0.49 (0.05 level of statistical significance) (Sheingauz, 2001). At the level of a *Leskhoz*, a 1% increase in a forest fire occurrence rate will cause an 8.4% increase in the share of forested areas.

Over the last 50 years, forest fires increased the total area of deforested lands in the region by up to 8.0 million ha. Generally, single or repeated catastrophic forest fires transform about 30% of highly productive forest land (with a total stock of phytomass of up to 1000 Mg dry matter per ha) to barren land areas for which forest regeneration is postponed for an indefinitely long period of time. These lands include up to 70% of bogs, 15% of grass-small shrub and shrub lands, 10% of open woodlands, and up to 5% of stone fields and stone outcrops. Such lands can only be rehabilitated through targeted and labour-consuming meliorations. The natural restoration of forests requires hundreds of years in these areas.

The post-fire mechanism of indigenous ecotope transformation is closely linked to the changes of the multi-year average hydrothermal regime of soils. In particular, the average temperature of surface and near-surface subsoils of burned out forested areas is twice as high as the surface's temperature of soils under the forest canopy of areas that have not been affected by fire. Maximum soil temperatures could reach as high as 65°C resulting in a thawing of the near-surface layer of permafrost. The future succession trajectories depend on climatic peculiarities, properties of landscapes and severity of fire. As usual, given the lack of the forest stands' main drainage capability leads to changes in the water regime of habitats, irreversible swamping or meadow formation or, eventually, to the formation of post-fire stands with a lower productivity. On permafrost of continental territories with an insufficient amount of precipitation, it leads to the development process of northern steppization and replacement of forests by aridized steppe and shrub vegetation. Catastrophic fires eventually increase albedo and substantially impact all components of heat balance over large territories.

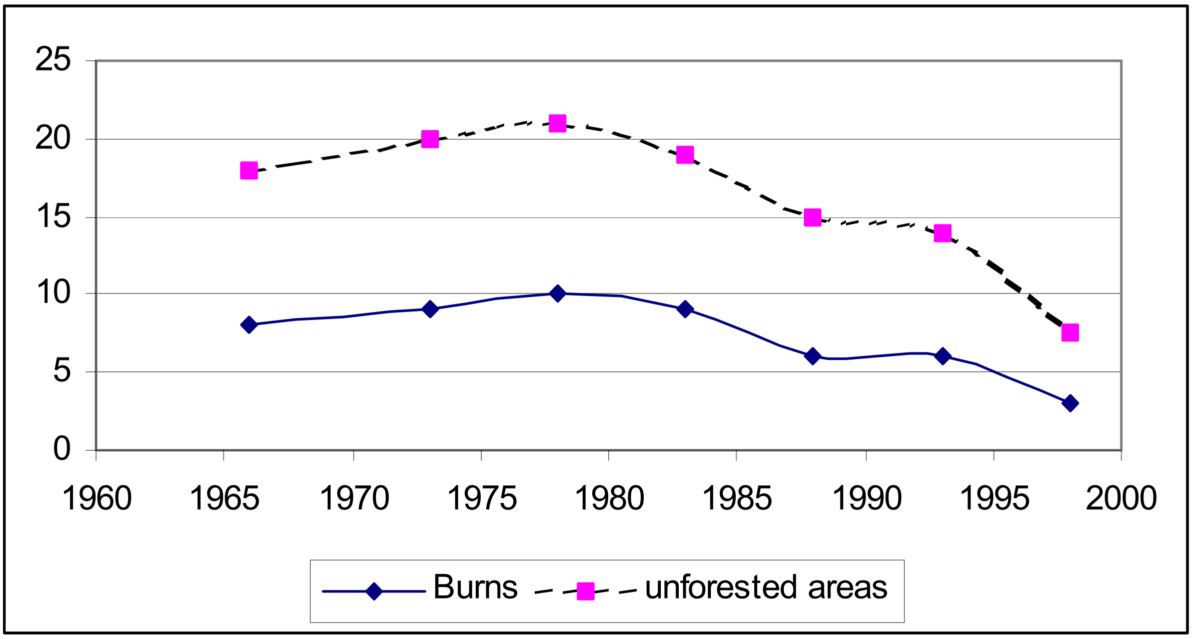

Figure 2. Percentage of burned out forest lands and unforested areas against forest fund areas

These changes have been the focus of many studies and are well quantified. Mechanisms and levels of the impacts of forest fire on the hydrological regime and water flow of rivers and, consequently, on spawning conditions for salmon and other valuable fish are less understood. The latter is of major importance for the Russian Far East, e.g., for the Amur River basin. A number of studies identified a linkage between the forest cover percentage in a watershed and annual runoff. Thus, a 10% change in the forest cover percentage in a watershed results in a 1.5-2% change in annual runoff. More importantly, deforestation of watersheds results in a dramatic fluctuation of water levels and flood performance. In addition, large fires impact temperature and contaminate water with ash and products of soil erosion that can lead to the mass mortality of fish.

There are specific features of the impacts of catastrophic fires on major biogeochemical cycles. The ratio between ground, peat (sod) and crown fires shifts to increasing crown and peat fires. The consumption of fuel is about 1.5 times higher compared to multi-year averages. The total amount of consumed carbon reaches 5 to 10-fold during catastrophic years. In 1998 the area of fire for entire Russia was estimated to be about 10 million hectares and consumed carbon – about 165 TgC (Kaji et al., 2002). The increase of peat and sod fires changed the gas composition of emissions increasing the share of methane (up to 2-3%) and carbon monoxide (up to 10-12%). It substantially increased the global warming potential of emissions. The post-fire mortality on areas affected by non-stand replacing fires is on average twice as big as under “normal” fire conditions. Eventually, large previously forested areas can be completely destroyed due to the post fire die-back accelerated by following windfalls. Taking into account the increasing probability of recurrent fires, this situation usually initiates degressive succession developments, which lead to the impoverishment and degradation of forest landscapes.

Much less attention was given to the study of forest fire impacts on large-scale atmospheric processes, because such impacts appear to be obvious if significant areas are enveloped by hot spots of high concentration. For example, the 1998 summer and autumn fires generated smoke that affected an area of over 500,000 km^2. In the southern part of Khabarovsk Krai, the smoke generated by the 1976 autumn forest fires spread over an area that was five to seven times larger than the burning area. The NOAA-5 weather satellite infrared images showed that the haze covered the north-east of China, the southern part of Khabarovsk Krai, the northern Japanese Sea including the Tatar Strait and Sakhalin. This is quite comparable with the scale of impacts of baric systems.

For nearly four months during the 1998 summer and autumn catastrophic forest fires, the solar-flux levels at a height of 2 m in the smoke affected area was between 10 to 20 percent under completely fair weather due to light-scattering effects. This reduced the maximum air temperature by 10 to 15°C and produced a pronounced "nuclear winter" phenomenon.

Observations of atmosphere patterns over the burning and smoking forests in Eastern Siberia and the Far East recognized (Sokolova and Teteryatnikova, 2002) the presence of anticyclones above huge chunks of Asian territory, from the Yenisei River to the Okhotsk Sea. These territories where enormous amounts of forest fuels is accumulated and which are characterized by a special atmospheric state, had a large-scale smoke blanket, the size of which is comparable to the extent of baric systems (i.e. over an area of 350-400,000 km^2) and which have a long period of high atmospheric pressure. It forces the cyclones to take a southern bypass (Fig. 3). The latter is the cause of intensified drought episodes over the fire-affected areas that extenuate the forest fire situation. The presence of anticyclones in temperate latitudes of Eastern Asia both in winter (this is common) and summer time (which is unusual) is due to the increased air density (through the cooling down of near-surface layers caused by the smoke aerosol), and summer anticyclones are duplicating the mechanism of winter ones. Alternatively, such a meteorological situation can generate long periods of rainfall and catastrophic floods like the basin of Yangtze River in summer of 1998.

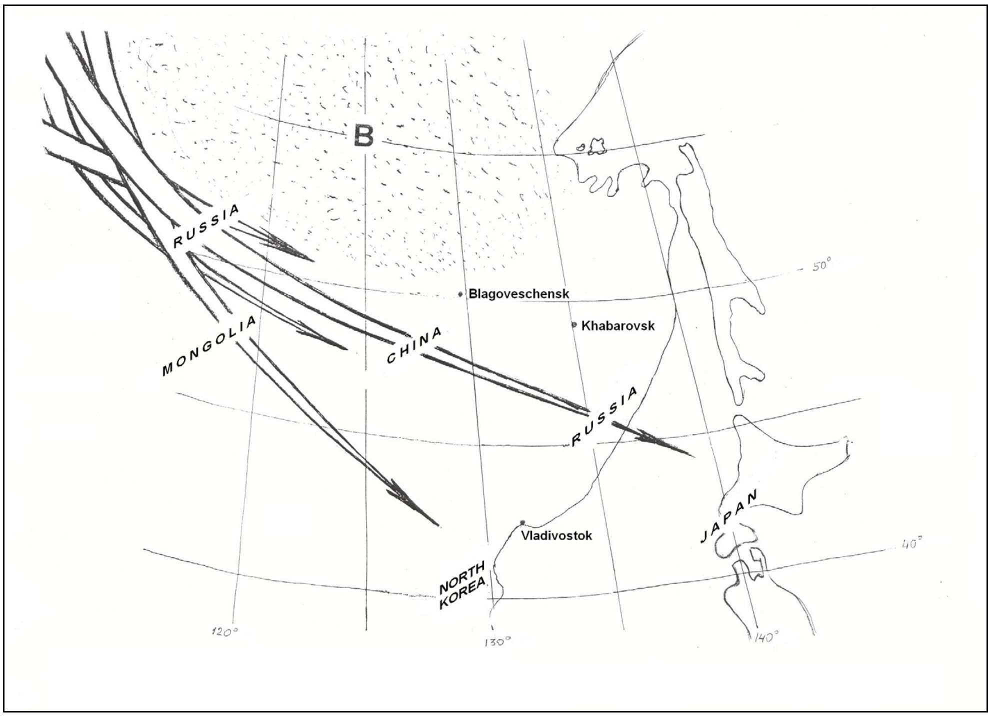

Figure 3. Trajectories of cyclones bypassing the anticyclones over burning and smoking forests of the Far East in the summer of 1998

Analysis of the meteorological processes based on pressure charts identified one specific feature. In all the years, when in early summer the usual tropospheric ridges at a baric height of AT-500 came into being in the smoke affected atmosphere, rather than in a clear one, the anticyclones (associated with a drought) persisted in this area over the entire summer (Fig. 4). This smoke-affected anticyclone is not destroyed over the entire warm period. Similar spatio-temporal sustainability for the continental ridges that are not affected by smoke aerosol does not exist in contrast to the smoke affected ones. During the summer, the continental tropospheric ridge is being supported by powerful heat fluxes from fire and hot smoke. Only the decreased solar radiation in late summer eliminates the influence of smoke atmospheric aerosol that leads to the gradual destruction of the continental tropospheric ridge.

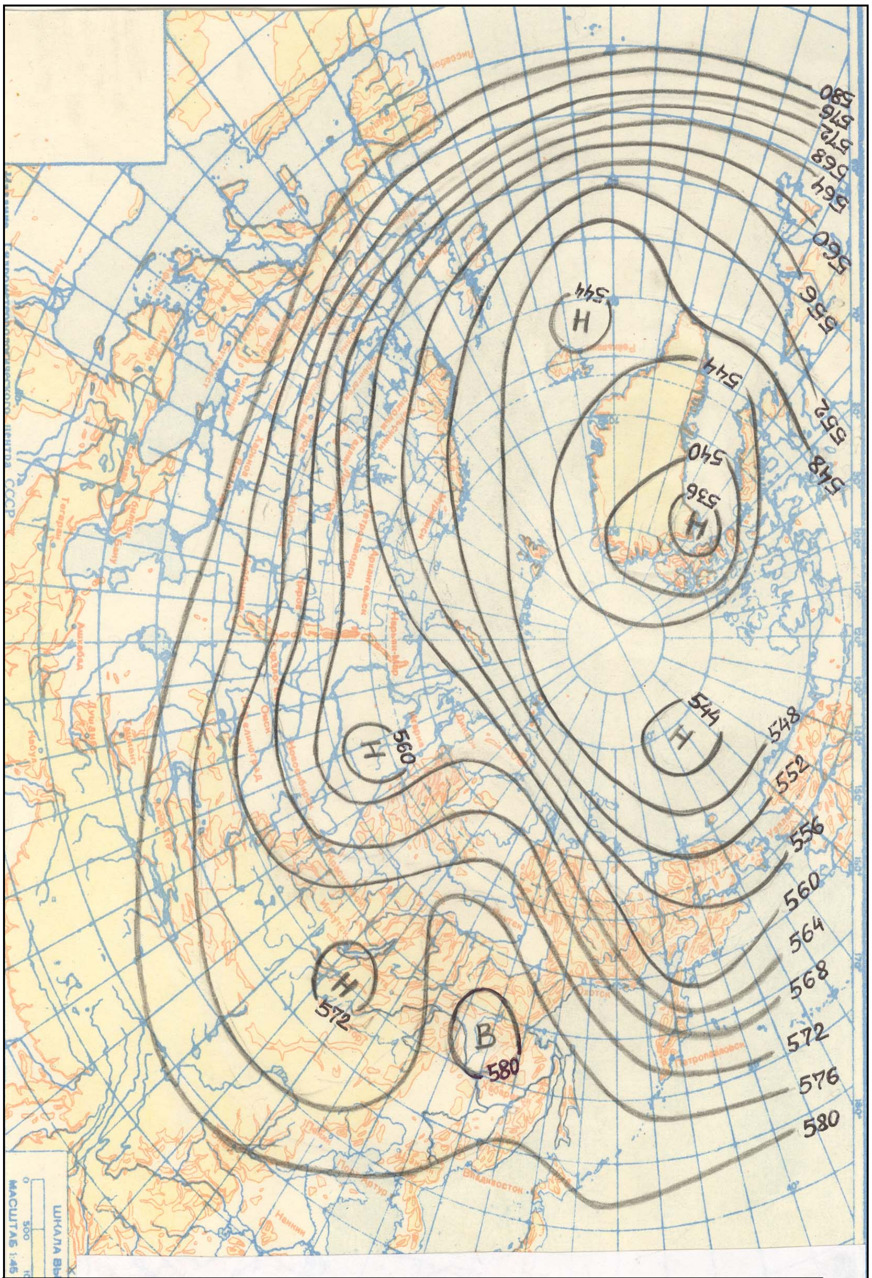

Figure 4. Constant Pressure Chart the Northern Hemisphere at a height of 5,000 m (surface 500 hPa) between 2 to 6 August 1998

During catastrophic forest fires, such meteorological conditions occurred in 1954, 1968, 1976, 1988, and 1998 in the Amur River Region, in 1979 and 1985 – in the Eastern Siberia (Krasnoyarsk Krai), in 1996 – in Amur Oblast and in the Republic of Sakha-Yakut, and in 2002 – in the Republic of Sakha-Yakut (Sokolova and Teteryatnikova, 2002). Despite an incomplete understanding of the mechanism of the above-mentioned regularities, we may safely assume that catastrophic forest fires have a substantial influence on the formation and alteration of surrounding parameters of the regional climate, with an apparent effect on global climate through a hierarchy of linkages.

Climate change is linked to the profound transformations of biotic processes. In particular, in recent years, for the first time in its history, Khabarovsk Krai faced an intensive outbreak of gypsy moss

(*Limantria dispar*) on an area of some 8 million ha. There is evidence that this phenomenon is an aftereffect of the pyrogenic disaster of 1998. It is worth to note that the synergism of fire and biotic disturbances is typical for whole Northern Eurasia. Hence, the outbreak of Siberian eggar (*Dendrolimus superans sibiricus*) impacted from 8 to 10 million hectares in Yakutia in 2001-2002 under similar conditions.

Negative impacts of catastrophic fires on biodiversity is evident (Kulikov, 1998), in particular, at ecotones' boundaries and boundaries of natural habitats of animal and plants. They decrease the amount of fodder, lead to fragmentation of habitats and eventually substantially decrease populations of animals, reptiles and birds. Also migrating birds and ungulates now use routes that differ from their traditional ones.

In this work we are not in the position to quantitatively illustrate the effects of catastrophic forest fires on erosion processes and increased solid runoff, whose redistribution will change both the productivity of soils and aqueous runoff quality, transform river flows and bring about the irreversible loss of spawning sites. There could be other dramatic consequences as well. It is necessary to note, that all these are of a transboundary nature and their significance is beyond the regional context.

It is readily apparent that the international community should recognize the importance of catastrophic forest fires in the context of global climate change. It should identify criteria for the assessment of global threshold indicators regarding regional-level pyrogenic disasters and international responses for the management of catastrophic forest fires around the world.

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