Wildfire-Related Changes of Forest Structure and Functions in Siberia

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Abstract

Changes of forest ecological functions and structure associated with wildfire were studied in the southern, central and northern taiga subzones of central Siberia. Our observations focused on the current decade burns and post-fire succession stages. We estimated levels of fire impact on forest stands in different subzones based on forestland structure analysis. A geographical comparison of the scales of post-fire stand replacement related to climatic differences between the subzones is a fundamental step towards extrapolating stand replacement trends under expected global warming.

Wildfire/climate interactions determine zonal trends of post-fire forest recovery, fire frequency, and fire return intervals. Fire regimes control age patterns of regenerating forest, as well as vegetation community structure and productivity at every forest succession stage. Comparative analysis of succession trajectories within the same ecosystem has revealed both qualitative and quantitative climate-caused differences in overstory age structure and regrowth and understory parameters at the same succession stages in different subzones.

Fire interval increases, while area burned and the scale of forest fire disturbance decrease from the west to the east in western Siberia, along the Yenisei Mountain Range, and on the Central Siberian Tableland. Secondary forest communities of fire origin account for 43%, 30%, and 35% of the total forest area in the southern, central and northern taiga subzones, respectively. Absolutely, these areas comprise millions of hectares. Along with wildfire extent itself, the post-fire stand replacement scale is determined by how resistant individuals and stands are to fire and by wood species fire resistance in general, the latter defined as a woody species capability to successfully recover after fire and to maintain its distribution area. Successful post-fire forest regeneration without stand replacement is possible under certain conditions in a given natural complex.

Ecological fire effects characterized by carbon emissions differ in scale among the subzones and are significant, however, in each of them. For example, annual biomass burning and atmospheric carbon emission range from 0.39 to 2.6 million tons and 0.20 to 1.32 million tons, respectively, across the subzones from the south to the north. The central and northern subzones are remarkable for the greatest biomass burning and, hence, the biggest carbon release to the atmosphere. Several factors account for this: forest covers vast areas in these subzones; fires are of a relatively big extent annually; and fires consume a lot of forest fuels. Interestingly, annual area burned (0.13%) in northern taiga under the current climatic conditions is twice less than that (0.25%) in southern taiga, whereas, due to a higher fuel accumulation, biomass burning and fire carbon emission is 7 times greater in the north. This estimate allows us to anticipate a multi-fold increase in carbon emission under expected

global warming and, hence, an increase in northern taiga annual fire coverage. Indirect influence of wildfire on carbon sequestration is in that the long-term fire impacts lead to changes of stand species and age structure and proportions of native and post-fire small-leaved communities.

Forests disturbed by fire account for 30-84% of the total forestland in western Siberia, 16-78% in the Yenisei Mountain Range landscapes, and 33-51% on the Central Siberian Tableland. These estimates suggest that repeated fires have resulted in replacement of conifers by secondary small-leaved stands and a change in age structure in many boreal landscapes along the Yenisei meridian. It is obvious that, apart from forest woody resource changes, the carbon pooling capability has also changed in every subzone. At the point, it is impossible, however, to get a reliable enough estimate of the capability and accurately predict its dynamics, since this would require integrated studies of spatial distribution of post-fire succession stages and modelling their trends in time and space.

Introduction

Boreal forest existence depends to a big extent on wild and human-caused fires. Their influence on ecosystem health and dynamics has noticeably increased over several past decades due to a sudden increase in the human-caused fire share (Vaganov and Arbatskaya 1996). At present, up to 30,000 human-caused fires can occur in an extreme fire year to cover up to ten million ha of boreal forests (Furyaev and Goldammer 1996, Goldammer and Furyaev 1996).

The situation is aggravated by that a significant proportion of boreal forests is outside fire protection areas. Unprotected forestlands account for 45% of both the Russia's total area burned and vegetation communities killed (Korovin et al. 1998). Fires themselves and their effects, such as large-scale replacement of forest generations and conifer replacement by deciduous softwood species, are responsible for drastic changes of ecological ecosystem functions. As a result, hydrological and ecological regimes become disturbed over vast areas, along with nutrient cycling, and the role of boreal forest as a natural stabilizer gets reduced. As annual forest fire, influence has increased in scale and, hence, the total area of ecosystems damaged by fire has grown for many years, changes of ecological functions that now occur in Eurasian and North American boreal forests are considered to have a global biospheric impact (Vaganov et al.1998).

Wildfire/climate interaction mechanisms govern vegetation zone-specific processes of post-fire forest regeneration (Furyaev et al. 1999). They determine fire frequency and, consequently, fire return intervals in different vegetation environments. Climate dependent fire regime of every vegetation zone determines, in turn, forest regeneration dynamics and community structure and productivity at all forest succession stages.

Comparing forest succession trajectories within the same ecosystem reveals qualitative and quantitative differences in forest composition, stand age structure, and regrowth and understory vegetation parameters that occur within the same succession stage due to different climates. These differences are especially pronounced between ecosystems of southern, central, and northern taiga.

Forest inventory and composition characteristics of succession stages in different vegetation subzones are not the only indicators of long-term fire effects. Big differences can also be observed in terms of ecological fire impacts. For example, dead vegetation residues are decomposed and turn into humus quite rapidly in moderately humid and cool climate of the southern taiga subzone. Fires have only negative influence on these site conditions to result in that newly developed forests become much less productive.

The central taiga subzone, where permafrost patches are common and soils freeze seasonally, is influenced by fires, relatively infrequent, in many ways. On the one hand, fires most often eventually destroy a given forest stand, since slow organic matter decomposition enables development of a deep moss layer and forest floor rich in peat and, thus, fires, although rare, are highly intensive. From the evolutionary viewpoint, on the other hand, fire seems very likely to play a positive role in forest cover development in the central taiga subzone with discontinuous permafrost (Utkin 1965, Sheshukov 1979). In these conditions, fires are the only external factor that can drastically change the ecological environment in the shortest possible time, as well as soil biological process direction and intensity, and vegetation community structure and trends of development. Fire prevents peatland spread, makes nutrients more available and redistributes them, and generally improves hydrothermal regime of soils. All these effects contribute to forest development.

In the northern taiga subzone, fire influence on forest development is complex and very much like in central taiga ecosystems. This is true, however, only for sites with discontinuous and shallow permafrost layers. Further investigation is required for accurate estimating full-scale long-term fire impacts on forest development in northern and central taiga.

The level of fire influence on forest structure in the northern, central and southern taiga subzones for the past 300 years is clear from Figure 1.

The available data indicate that post-fire replacement of native conifers by deciduous softwood species accounts for 20%, 12%, 13%, and 5% of the total forested land in southern, central and northern taiga and near-tundra open woodlands, respectively (Table 1). In absolute terms, these percentages are tens of millions hectares. Apart from forest inflammability itself, post-fire stand replacement scale is determined by individual tree fire resistance, stand fires resistance (Furyaev 1978), and population fire resistance. The latter refers to the capability of a given woody species to regenerate on burned sites and maintain its area of distribution (Sannikov 1973). Post-fire forest regeneration without stand replacement depends, in turn, on a variety of ecological regime parameters characteristic of natural complexes making up a given landscape.

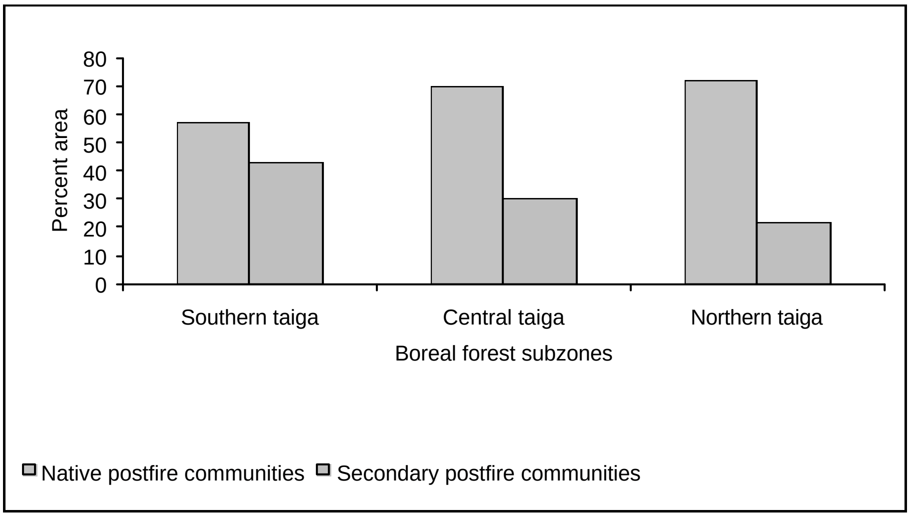

Figure 1. Percent areas of native (i.e. major conifer) and secondary post-fire communities in boreal forest subzones of central Siberia

Regarding prediction of annual area burned (this is annually burned pre cent area per one million ha forest area) and post-fire stand replacement scale in relation with expected global warming, it is interesting to compare today's climatic conditions in southern taiga and near-tundra open woodlands. Table 1 shows that, proceeding from southern taiga to near-tundra open woodlands, average June-August air temperature decreases by 3.3°C, its absolute maximum by 4.7°C, and mean daily >10°C temperature sum by 937°C, whereas frost-free period decreases by 56 days on average and mean annual precipitation increases by 220 mm.

Table 1. Climate and post-fire stand replacement in landscapes of southern, central and northern taiga and near-tundra open woodlands

Taiga forest subzone	**Air temperature (°C)**				**Mean frost-free period (days)**	**Mean annual precipitation (mm)**	**Average post-fire stand replacement scale (% area)**
	Mean June-August temperature	Average maximum	Absolute summer air temperature maximum	Mean daily >10°C sum			
Southern taiga	14.8	25.2	37.2	1600	100	370	20
Central taiga	14.4	24.0	36.5	1278	81	450	12
Northern taiga	13.3	22.4	35.5	1023	74	600	13
Near-tundra open woodlands	11.0	19.4	32.5	663	44	600	5
Difference between southern taiga and near-tundra open woodlands	-3.8	-5.8	-4.7	-937	-56	+220	4 times

Fire frequency is most strongly correlated with summer air temperatures (Vaganov and Arbatskaya 1996) and fire season duration (Furyaev and Kireyev 1979) at high latitude. Analysis of many-year annual forest area burned in central Siberia shows that, among all climatic factors, mean June-August air temperature has the biggest impact on the area, given other conditions are equal. Annual area burned and post-fire stand replacement, no doubt, depend on a combination of factors, and to accurately separate the contribution of summer air temperature is a difficult task. Anyway, this factor does have influence and the data obtained allow to estimate its relative share.

The scale of post-fire stand replacement, thus, varies widely along the meridian. There exist no direct relationship between annual forest area burned and post-fire stand replacement, since the area of the latter is determined, along with climatic parameters, by the ratio between the major (i.e., forest-forming) woody species and ecological regimes of their environments.

Preliminary data are now available on forest fire contribution, including CO_2 release, to atmospheric pollution (Isaev and Korovin 1997, Vaganov et al. 1999, Sofronov et al. 2000). While the contribution of forest fires to the total atmospheric pollution has not been yet fully estimated, it is evident that the contribution is significant enough to be considered when predicting global and local ecological processes.

Besides atmospheric pollution, periodical production of smoke cover over vast boreal and forest-steppe areas results in reducing insolation, which, in turn, affects dynamics of phenological plant parameters, enhances air and soil drying processes, disturbs ground water level and has a general negative impact on ecological regimes of natural complexes and on forest productivity (Furyaev and Kireyev 1979).

Among ecological fire effects, the most important, however, is the influence of forest fire on carbon balance of the atmosphere and forest ecosystems. Direct influence occurs through carbon emissions resulting from the process of combustion in organic matter of ground cover and other forest community components. In order to estimate carbon emission from fires for different taiga subzones, we multiplied the area annually burned in a given subzone by average load of ground fuels consumed by fires.

As is clear from estimated data, carbon emission-related ecological fire effects vary in scale among the subzones, but they are generally fairly strong in every subzone. For example, annually burned biomass and atmospheric carbon emissions range, south to north, 0.39-2.6 million tons and 0.20-1.32 million tons, respectively (Table 2).

Table 2. Annual biomass burned and carbon emissions from fires in central Siberian taiga forest subzones

Taiga subzone	**Subzone area (million ha)**	**Annual area burned (%)**	**Total annual fire coverage (x 1000 ha)**	**Mean ground fuel loading (t/ha)**	**Biomass burned (million tons)**	**Fire carbon emissions (million tons)**
Southern taiga	14.0	0.25	35.2	11.2	0.39	0.20
Central taiga	58.5	0.16	93.6	25.0	2.34	1.17
Northern taiga	60.8	0.13	79.0	33.6	2.65	1.32

The highest biomass burning and, hence, carbon losses are observed in the central and northern taiga subzones. This can be attributed to vast forest lands, relatively big annual area burned, and great accumulation of available ground fuels. Importantly, relative annual area burned in northern taiga (0.13%) in today's climate is almost twice less than that in southern taiga (0.25%). In northern taiga, however, due to high ground fuel loading, biomass consumed and carbon emissions from fires are about seven times those in southern taiga forest. Based on this estimate, we can expect fire-caused carbon emission and, hence, annual area burned to increase many times in the northern subzone under global warming.

Also, forest fires have indirect influence on carbon sequestration, since repeated fires result in changing woody species proportions, ratios between the major conifer and secondary post-fire deciduous softwood species, as well as stand species composition and age structure. Ecological forest functions, particularly that of carbon accumulation, are known to vary with forest stand composition, age structure, and other inventory parameters. It is a common viewpoint, for example, that conifer stands have a considerably bigger ecological effect than deciduous communities, and conifer needles play the most important role in both stabilizing ecological processes and accumulating carbon.

Forest area disturbed by fire was found to make up 30-84% of the total forest land in west Siberia, 16-78% in Yenisei Mountain Range, and 33-51% in Central Siberian Tableland (Furyaev and Kireyev 1981, Furyaev et al. 1983). The estimates suggest that repeated fires have resulted in conifer replacement by deciduous softwood species and a change of forest generations in many boreal landscapes along the Yenisei meridian (Furyaev 1996, 2002; Furyaev et al. 2001). Also, carbon potential of vast areas has obviously changed, along with resource diversity, in every taiga subzone (Figure 2).

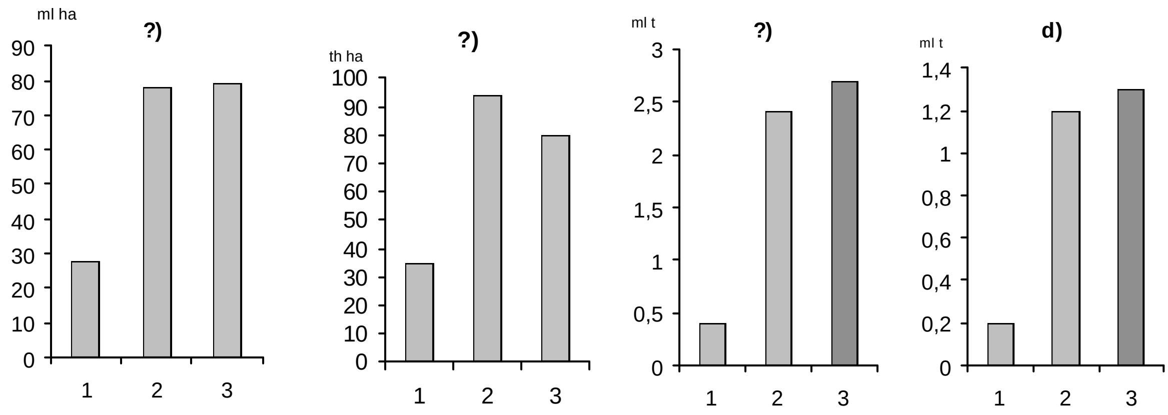

Figure 2. Regional-scale fire influence on the atmosphere and ecosystems of the boreal forest zone in central Siberia.

a) areas of stand replacement due to past fires
b) areas subjected to fires
c) amount of ground fuel burned
d) carbon losses in the southern (1), central (2), and northern (3) taiga subzones

Fire effects are extremely diverse in boreal forests of Siberia. One of the problems the diversity presents is to classify post-fire forest structure changes in terms of either reducing or increasing forest fire danger rate. Such a classification would be especially important for wildland/population unit interface areas. Research studies have revealed that, historically, Siberian forest fires periodically burned across mature Scots pine and larch stands only consuming excessive ground fuels and partially conifer regrowth and understory vegetation. The canopy was usually left intact.

With the start of intensive forest harvesting and establishment of a forest fire protection system, the situation has changed greatly. Extremely big logging sites with very high slash loading occurred in wildland/population unit interface areas. Dense conifer regrowth has developed and ground fuels have increased under the parts of the overstory that remained after harvesting and was intensively protected from fire. In time, severe surface and crown fires began to kill these forests and replace them by extremely inflammable young coniferous stands. As a result of forest age structure changes and occurrence of big young conifer stands in wildland/population unit interface areas, fire danger has increased here drastically, and so has the fire risk to population units situated in the forest. The twentieth century is crammed with examples of how fires can burn up big population units in Eurasia and North America. Changing structure of wildland/population unit interface forests and fighting fires in them has become an urgent and very difficult task.

In attempt to solve this problem, methodologies were proposed of increasing forest fire resistance, particularly of forests adjacent to population units (Furyaev 1978, Furyaev et al. 2001).

The most effective approach to increasing forest fire resistance is to control factors that govern post-fire tree mortality. Methods for increasing forest fire resistance constitute a system of silvicultural treatments and fire prevention measures properly designed in time and space.

A considerable experience has been gained in implementing the system of measures aimed at increasing wildland/population unit interface forest fire resistance in some regions of Siberia, Altai Mountains, and the European Russia. The system has proved to be ecologically, socially and economically effective. The system is believed to be especially useful in the Earth's regions with arid, fire-risky climates, where forests prevail whose composition and age structure were changed by past fires and human activities.

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