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Effects of Fire and Climate on Successions and Structural Changes in The Siberian Boreal Forest

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Abstract

Climate-fire-forest relationships at different scales (tree, stand, subbiome), based on the results of studies carried out in central Siberia, are summarized. Fire and climate are shown to be powerful external factors transforming the Siberian boreal forest. They change ecological environments in the forest ecosystems, their biogeochemical and hydrologic cycles, stability and productivity. Various climates and forests within vegetation zones of Siberia and specific fire regimes over the vast area are characterized. Fire history and tree growth response to fire and climate fluctuations studied by dendrochronological methods are presented. The most typical post fire succession patterns in the dominant pine/green moss and larch/green moss forest types in the northern, middle, and southern taiga zones are described. Some forest formation patterns (tree species composition, structure and productivity) at different stages of post fire recovery are analyzed.

Fire occurrence and forest succession are considered in relation to possible vegetation shifts and phytomass change in Siberia under climate warming. Tree, ecosystem and subbiome levels are discussed with respect to modeling spatial and temporal states of Siberian vegetation cover under changing climate and fire impact.

Key words: boreal forest, central Siberia, climate change, dendrochronological methods, forest successions, forest fires

1. Introduction

Forest fires and climate are the main external factors affecting the Siberian boreal forest (Valendik 1992, Goldammer and Furyaev 1995, Goldammer and Furyaev 1996). Combined, they transform biogeochemical cycles in the forest ecosystems and change both ecological regimes and ecosystem stability and productivity (Van Cleve and Viereck 1981, Pastor and Post 1986, Clark and Robinson 1993, Mellilo *et al.*, 1993, Crutzen and Goldammer 1993). Depending on topography and soils, they influence plant community distribution and forest cover mosaics, tree species proportions in a stand, and spatial, age, and size structures of a stand (Sannikov 1992, Furyaev 1996).

Forest fire itself is an important ecological factor controlling both environments for vegetation establishment and vegetation succession (Chandler *et al.* 1992, Abaimov and Sofronov 1996). Depending on regional climates, ecotope (site) conditions, and fire intensity and periodicity, fire regimes determine forest structure and productivity, and succession patterns (Buzykin and Popova 1978, Sannikov 1981). The understanding of how long-term climate change, fire regimes, and forest vegetation interact provides a tool to predict forest succession trends under predicted climate change (Clark and Richard 1996).

In this paper, we present a summary of available data on climate-fire-forest relationships in the Siberian boreal forest at different levels of generalization, tree, stand, and biome/subbiome (vegetation zone) levels. We focus on central Siberia as a case study to define zonal patterns of forest fire dynamics, climate, and forest succession because this large area of the Siberian boreal forest is best studied by fire scientists (Goldammer and Furyaev 1996). Our goal is aimed to expose Russian literature on this problems to Western readers. While we focus mainly on results and do not provide a detailed methods section, the methods used are briefly outlined at the beginning of each section.

2. Results

The vast Siberian subcontinent stretches for 7000 km from the Ural mountains in the west to the Pacific Ocean and for 3500 km north to south from the Arctic Ocean to Kazakhstan and Mongolia. The climate in Siberia varies greatly. The average temperature in July ranges from 5 °C to 23°C, and annual precipitation ranges from 100-200 mm in the far north to 2000 mm on the windward macroslopes of the Altai-Sayan mountains in the south. The

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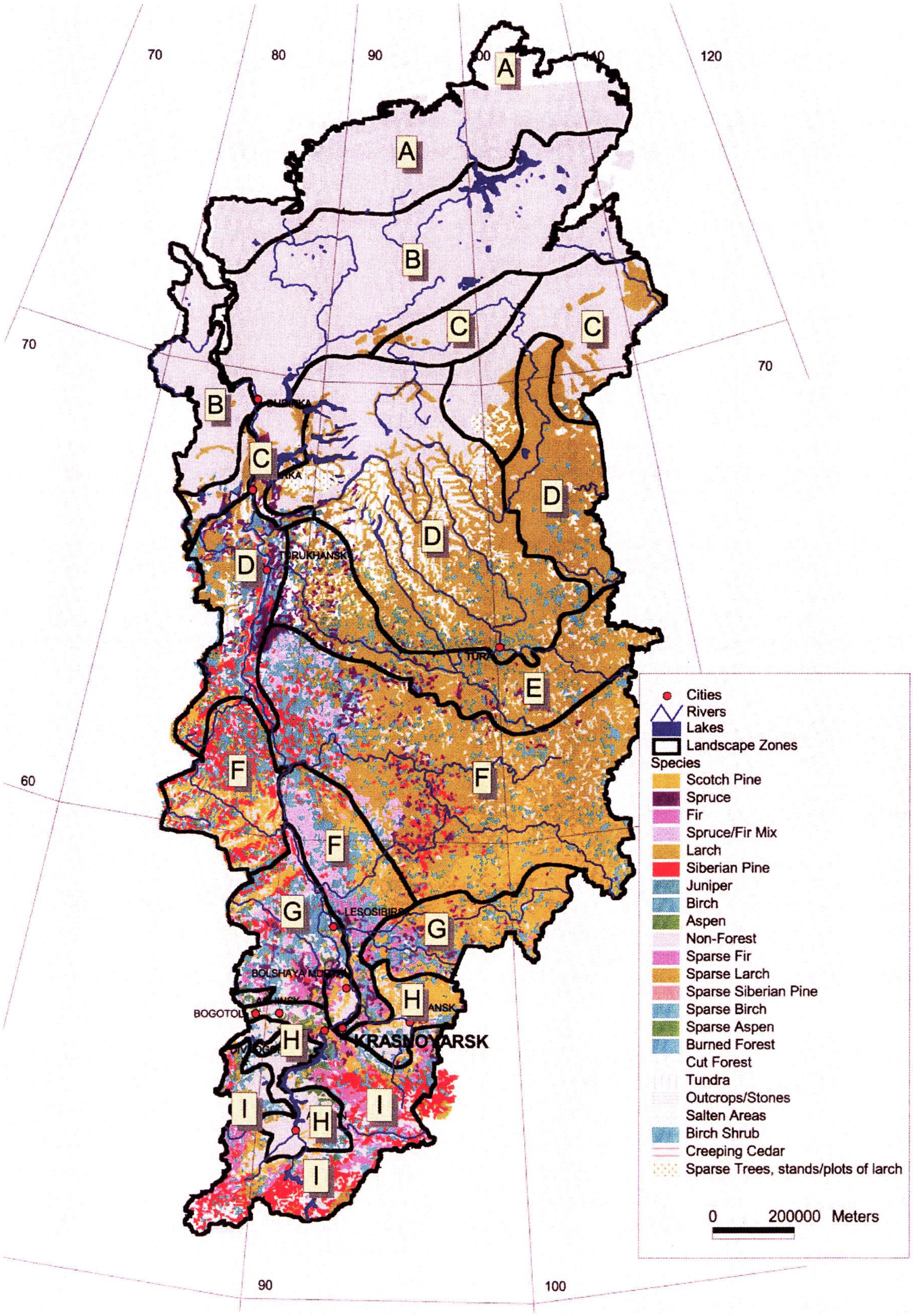

Fig. 1. Vegetation zones and forests of central Siberia.

Zones: A - Arctic desert; B - Tundra; C - Forest-Tundra; D - Northern open forest; E - Northern Taiga; F - Middle Taiga; G - Southern Taiga; H - Subtaiga, Forest-Steppe, and Steppe; I - Mountain Taiga; Species: 1 - pine; 2 - spruce, fir, cedar; 3 - larch; 4 - birch and aspen; 5 - others; 6 - non-forested.

continentality of climate, characterized by very low winter temperatures, short frost-free periods, and low humidity and moisture, increases towards the center of the continent. The greatest continentality value is in Verkhoyansk (northeastern Yakutia), the so-called "Pole of Frost".

The distribution of zonal vegetation follows general climatic patterns (Fig. 1). In more humid West Siberia, the relative proportion of dark-needled conifers (*Picea obovata, Pinus sibirica, Abies sibirica*) is much greater than that in east Siberia, with *Larix* spp. dominating the interior part of Siberia. *Pinus sibirica* and *Abies sibirica* still prevail on elevated tablelands and ridges. In permafrost regions, the well-adapted *Larix* spp. dominates other species. When moving from north to south, as permafrost and frozen soils decrease, the larch forest is replaced by pine (*Pinus sylvestris*) and mixed conifer/hardwood (*Betula pubescens*) forests.

2.1. Tree growth response to climate and fires in different climatic-geographic zones of central Siberia

Tree growth response to climatic fluctuations is one of the basic "elementary" processes to initiate succession mechanisms. Growth responses are then integrated by higher-level or longer duration processes such as competition, leading to stand composition and structure changes (Kuzmichev 1977, Schweingruber 1988).

Climatic influence on tree increment has been studied using dendrochronological methods (Cook and Kairiukstis 1990). A great number of local tree-ring chronologies of two major tree species, *Pinus sylvestris* and *Larix sibirica,* has been obtained for various climatic-geographic zones of central Siberia, including the northern tree line, northern, middle and southern taigas, and the forest-steppe zone (Fig. 1). Because these local chronologies were found to be highly correlated within a vast area, stretching 200 km from north to south, they were averaged to obtain regional chronologies showing tree growth response to climate fluctuations over fairly large areas. A routine procedure (Fritts 1976, Schweingruber 1988) for calculating climatic response functions from regional chronologies and climatic variables of corresponding weather stations was used. Fig. 2 summarizes the results of a number of dendrochronological studies in central Siberia (Vaganov 1989, Vaganov *et al.* 1996a, b, Panyushkina *et al.* 1996, 1997, Arbatskaya and Vaganov 1997).

When moving from north to south (from the polar tree line to the forest-steppe zone), both growth-limiting climatic factors themselves and signs of their influence change (Fig. 2). Near the polar timberline, July temperature seems to be a key factor limiting growth to a greater extent than does June temperature. In the northern taiga, the major is factor positively correlated with tree increment variability is the temperatures of June (with a greater correlation) and July (with a smaller correlation). In the middle taiga, tree increment variability is mostly controlled by temperatures in April and May (positive influence), while high temperatures in June suppress tree growth.

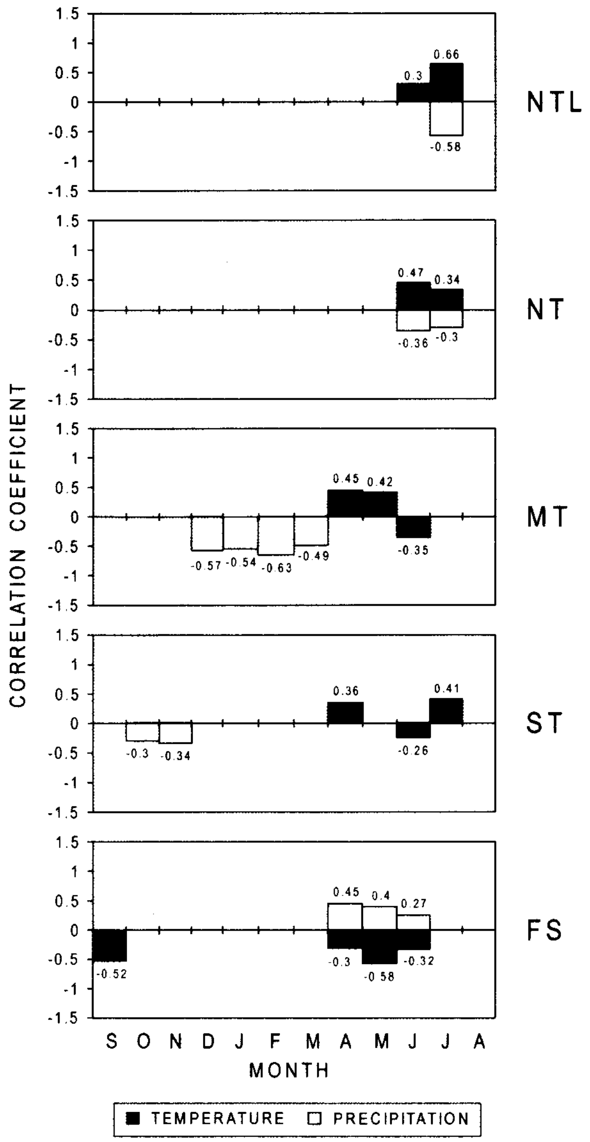

Fig. 2. Statistically significant correlations between tree-ring increments and climatic variables (typical climatic response functions) for different vegetation zones of central Siberia.

NTL - Northern timberline,
NT - Northern Taiga,
MT - Middle Taiga,
ST - Southern Taiga,
FS - Forest-Steppe.

Data are cited from earlier published papers (Vaganov 1989, Vaganov *et al.* 1985, 1996 a, b, Panyushkina *et al.* 1997).

High temperatures in April and June are positively correlated with growth in the southern taiga, whereas they are negatively correlated with tree growth in the forest-steppe zone (the Minusinsk hollow).

Tree increment correlation with precipitation ranges from negative during the summer months in the northern taiga to positive in the March-May period in the forest-steppe zone. These latitudinal patterns of climatic response functions determine growth response of major tree species to global climate change. If, for example, predicted warming is accompanied by elevated precipitation, tree growth may be expected to increase in the northern taiga with no or negative growth response in the middle and southern taigas depending on seasonal distribution of precipitation.

Climatic factors controlling tree-ring growth have a direct influence on fire situations in the forest. Dendrochronological methods can be used to reconstruct fire frequency using long-term tree-ring chronologies (Swetnam 1996, Vaganov and Arbatskaya 1996 a, Vaganov *et al.*, 1996 b). This, of course, concerns only surface fires of different intensities, which do not kill stands but significantly influence tree mortality and competition, and change ground cover structure (Furyaev 1996, Arbatskaya and Vaganov 1997). The influence of forest fires is clearly manifested in tree growth, and growth variability reflects both direct fire effects (e.g. degradation of competition) and indirect fire effects (destruction of ground layer and removal of organic matter). The method of "superimposed epochs" (Lough and Fritts 1987, Swetnam 1996) enables us to track pre- and post fire growth dynamics and to analyze its important characteristics. The pattern shown in Fig. 3 summarizes the curves of pre- and post fire (later more than 20 fires) growth dynamics of many larch trees in the northern taiga and pine trees in the middle taiga.

The pre-fire growth dynamics is considerably suppressed in the northern taiga owing to a very deep moss layer which perturbs a thermal soil regime. Tree growth starts to gradually increase after a fire, reaches maximum in 19-21 years, and then slows down. In the middle taiga, pre-fire growth is much less suppressed. After a fire, tree growth is suppressed for 1-2 years and gradually increases and reaches the maximum 8-10 years following the fire. Direct measurements give similar estimates of ground layer regeneration following fires of different intensities (Furyaev 1996). Thus, there are reasons to believe that post fire growth dynamics is closely related to recovery of a disturbed ecosystem rather than to response to decreased competition for light, for this response seems to be more immediate (Schweingruber 1996).

2.2. Post fire stand successions in the taiga zone of central Siberia.

In this section, post fire succession data from long-term studies (Furyaev and Kireev 1979, Abaimov and Sofronov 1996, Furyaev 1996) in larch forests in the northern taiga and pine forests in the middle taiga are

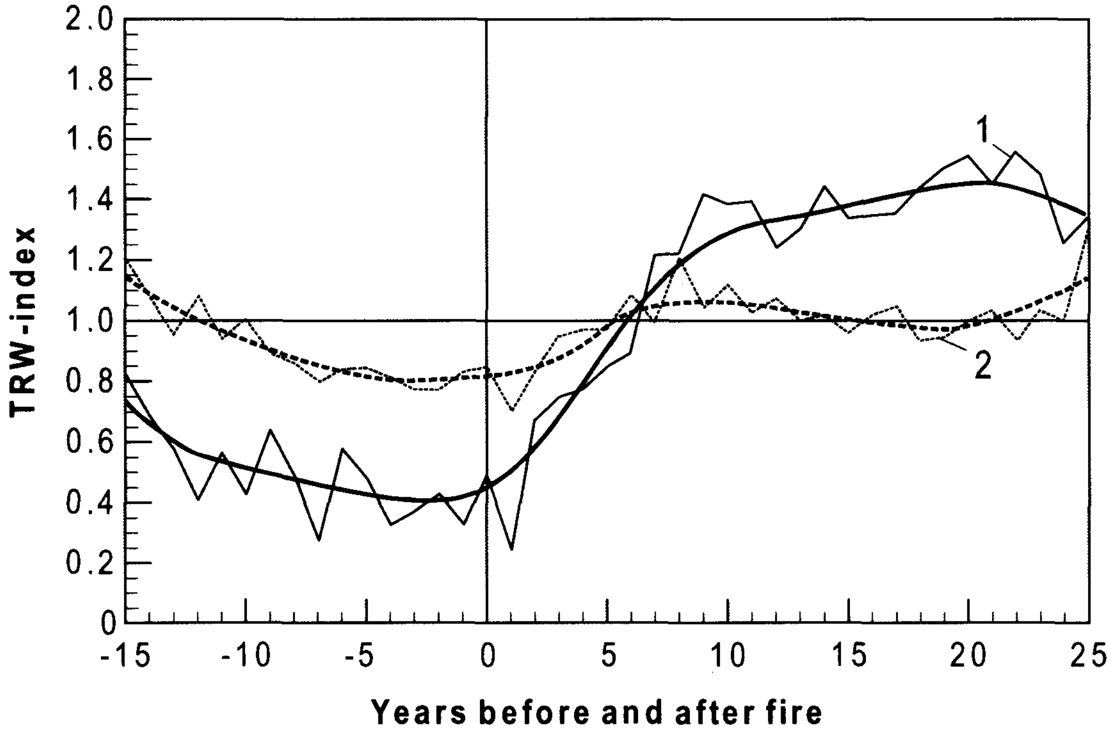

Fig. 3. Pre- and post fire growth (TRW, tree-ring width) responses of larch forests in northern taiga (1) and the pine forests in middle taiga (2).

presented. Fire frequency in forest ecosystems has been studied by analysis of tree fire scars from the past 2-3 hundred years according to the methodology of Melekhov (1948). Forest regeneration on burned ground and types of post-fire succession have been studied on the base of Kolesnikov's (1956) concept of the forest formation process using Pobedinsky's (1962) methods.

Fig. 4 shows the principal post fire succession types in larch stands of the northern taiga (Abaimov and Sofronov 1996). Five major dynamics types can be combined into three classes: 1. succession with no tree species replacement, 2. succession with a tree species replacement, and 3. succession with open larch stands replaced by shrubby tundra. Each of the five post fire succession types is characterized by a specific tree growth rate, a moss layer accumulation rate, and a stand self-thinning rate. Post fire dynamics of type 2 (succession with no tree species replacement, a normal initial seedling density, and 200-600 trees per ha under the age of 100-140 years) is most common. It accounts for some 75% of the total area of the larch forest in the northern taiga. Relatively small sites mostly found on hills of about 400 m in height fall within post-fire dynamics of type 4 (a succession with a tree species replacement). The type of post-fire succession with open larch stands replaced by shrubby tundra accounts for an area of the same size as that of type 4. This type is found mostly at the upper tree line.

Pinus sylvestris is distributed from 68°N latitude in the north to 50°N latitude in the south of central Siberia. Fire interval duration and, correspondingly, fire frequency vary considerably with the geographical zone. Fire regimes in combination with different climates in a given zone and forest succession rates determine the characteristics of forest regeneration dynamics and community structure and productivity at all stages of forest formation.

Data on post fire dynamics of pine stands on elevated sandy erosion-cryogenic plains (Furyaev 1996) are schematically generalized in Fig. 5. Three classes of progressive succession depending on fire intervals are identified: a) with no tree species replacement and a fire interval of 20-30 years, b) with no tree species replacement and a fire interval of 45-50 years, and c) with pine replaced by birch and a fire interval of less than 20 years. The figures shows succession stages of pine/green moss stands in the case of fire intervals of 20-30 years. Such successions are characteristic on burned ground after high-intensity fires that consume all of the forest floor and exposed mineral soil.

In the first succession stage, pine regenerates successfully and its proportion becomes equal to that of birch 5 years after a fire. The second succession stage lasts up to 20 years after a fire. The canopy becomes closed at around 10 years after a fire, and the proportion of hardwoods varies considerably. The grasses are thinned and rapidly replaced by green mosses under a closed canopy. Repeat fires bring the stand back to the first succession stage. The third succession stage is characterized by pine-dominated pole stands. The ground cover is dominated by herbs (70-80% of the total area), with a small proportion (10%) of mosses. Intense surface or crown fires can also return a stand back to the initial succession stage. The fourth succession stage is represented by middle-aged stands with a grass/low shrub ground layer. Moderate-intensity surface fires control the development of several pine generations. The fifth succession stage is characterized by mature (100-180 years old) pine stands with solitary hardwoods and green moss in the ground layer. At this stage, surface fires occur frequently and promote stand unevenness. The sixth succession stage is represented by old (more than 180 years old) pine stands that experience

	SUCCESSION CLASS	SPECIFIC FEATURE	TYPE	RELATIVE FOREST AREA,%	
a)	RESTORATION WITH NO TREE SPECIES REPLACEMENT	LARGE DENSITY	1	5	LOW GROWTH, HIGH RATE OF MOSS ACCUMULATION, LOW SELF-THINNING
		NORMAL DENSITY	2	75	MODERATE GROWTH, MODERATE RATE OF MOSS ACCUMULATION MODERATE SELF-THINNING
		LOW DENSITY	3	10	FAST GROWTH. LOW RATE OF MOSS ACCUMULATION, LOW SELF-THINNING
b)	RESTORATION WITH TREE SPECIES REPLACEMENT	HILLS UP TO 400 M	4	5	FAST GROWTH OF DECIDUOUS SPECIES(BIRCH). LOW RATE OF MOSS ACCUMULATION. MODERATE SELF-THINNING
c)	RESTORATION TOWARDS SHRUBBY TUNDRA	UPPER TREELINE	5	5	SEVERE SOIL LAYER DESTRUCTION, FAST GROWTH OF TYPICAL TUNDRA SHRUBS

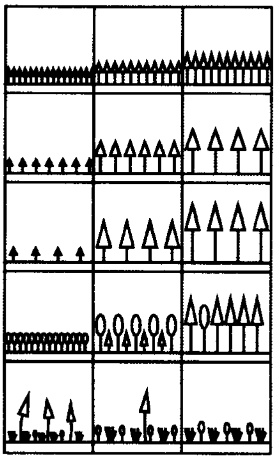

Fig. 4. Successional stages of the northern taiga larch forests (see 2.2).

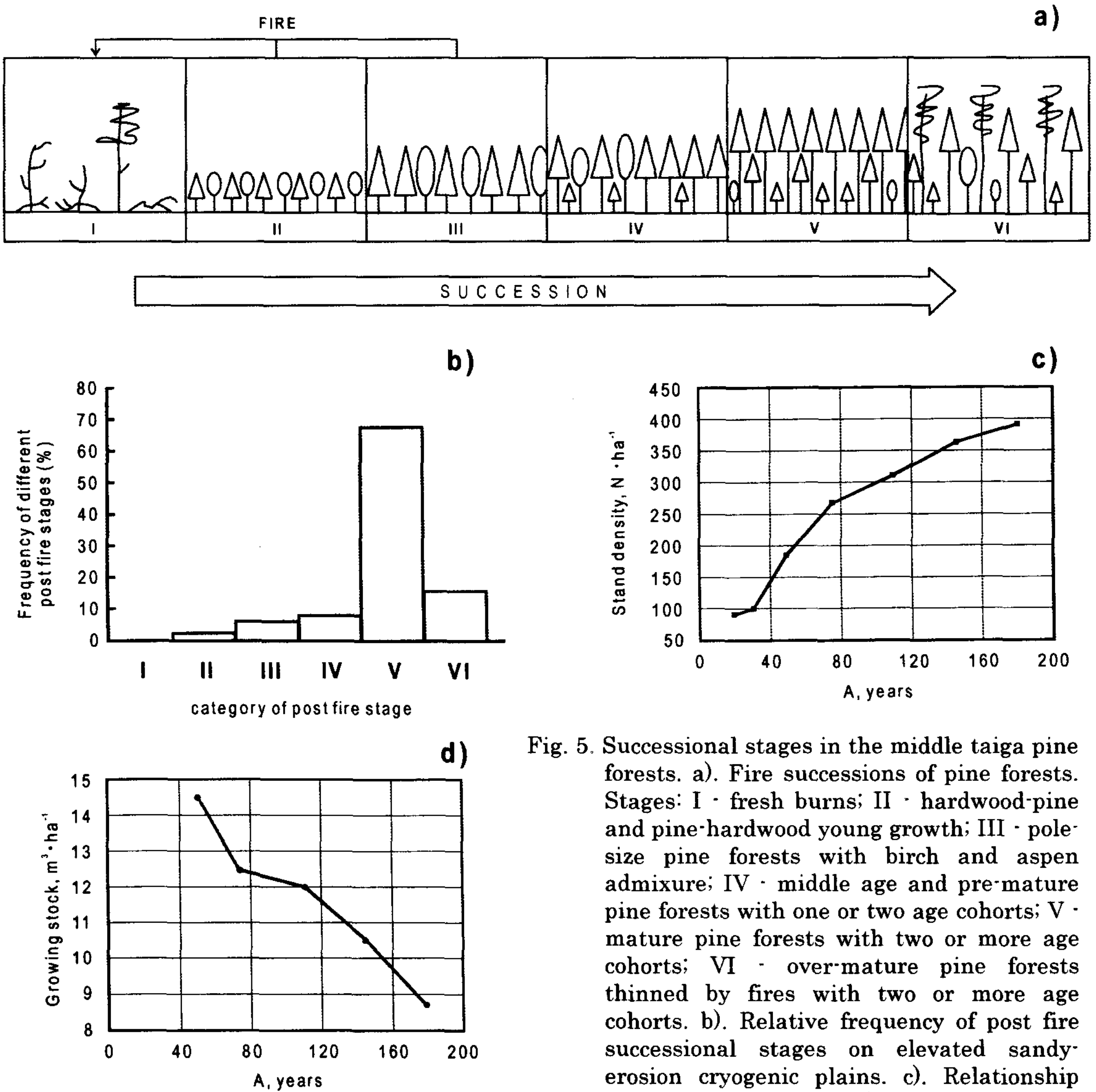

Fig. 5. Successional stages in the middle taiga pine forests. a). Fire successions of pine forests. Stages: I - fresh burns; II - hardwood-pine and pine-hardwood young growth; III - pole-size pine forests with birch and aspen admixure; IV - middle age and pre-mature pine forests with one or two age cohorts; V - mature pine forests with two or more age cohorts; VI - over-mature pine forests thinned by fires with two or more age cohorts. b). Relative frequency of post fire successional stages on elevated sandy-erosion cryogenic plains. c). Relationship between Stand age (years) and stand density (N·ha^{-1}). d). Relationship between stand age (years) and growing stock (m^3·ha^{-1}).

repeated surface fires of varying intensities.

2.3. Variability of average fire return intervals in stands along the Yenisei meridian

Dendrochronological methods have been used to accurately date fire scars and reconstruct the fire history over the past 300-400 years for the regions of typical northern, middle, and southern taigas in central Siberia (Vaganov *et al.* 1996 a, Arbatskaya and Vaganov 1997, Panyushkina and Arbatskaya 1999). Statistical fire data for the given sites (e.g., 13-14 fires over a period of 450 years for a site in the middle taiga region) and a sufficient sample size of sites (e.g., 19 sites for the middle taiga) allowed us to both obtain reliable fire return intervals for a long period and analyze long-term changes of fire occurrence over the past several centuries (Vaganov and Arbatskaya 1997). Results summarized in Fig. 6 show a) that the average fire return interval varies with latitude; b) that the average fire return interval correlates positively with the recovery period of growth rate determined from pre- and post fire growth dynamics ; and c) that the average fire return interval correlates negatively with the above-ground phytomass.

Fire frequently plays a major role in determining vegetation structure. However, the vegetation structure largely determines fire intensity (Chandler *et al.* 1992). The main point is that fire frequency has shaped the evolution of vegetation, and any change in the fire cycle of a community will automatically entail a change in its floristic composition and structure (Chandler *et al.* 1992). These two statements outline the importance of the fire cycle (fire return interval) for the dynamics and succession of a stand. Sannikov and Goldammer (1996) showed that a naturally

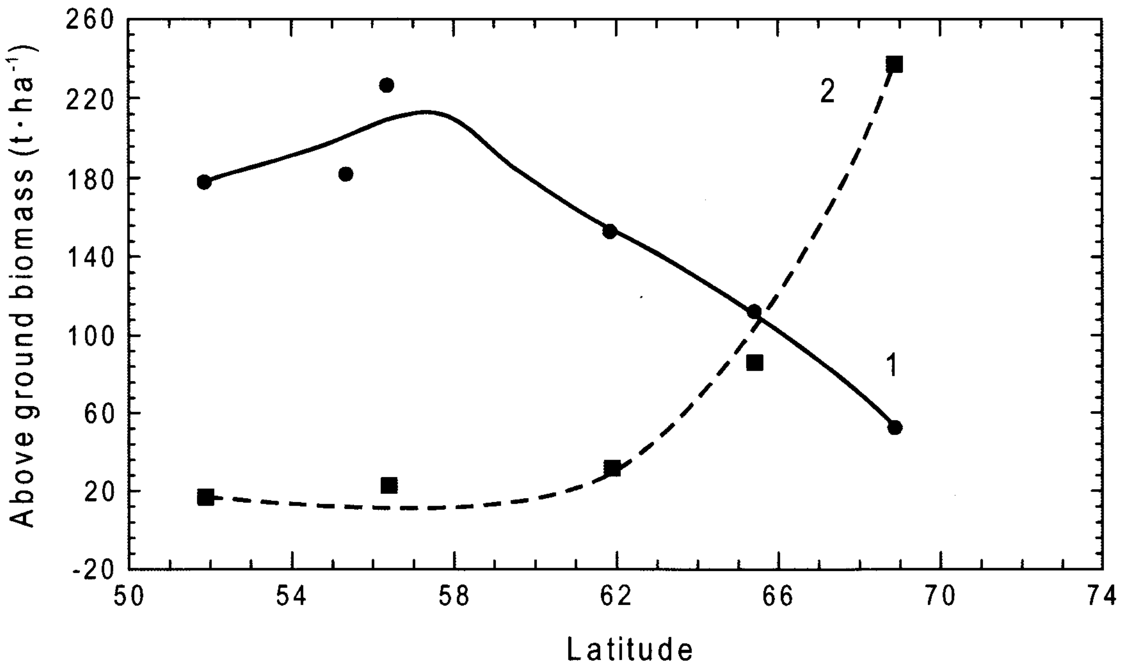

Fig. 6. Meridional change in annual productivity (1) adopted from Monserud *et al.*(1996), relative number of years with Nesterov's Index above a critical level (2), along the central Siberian Transect.

induced fire index (the number of lightning fires per 100,000 ha) changes across the meridional profile of the Trans-Urals - Northern Kazakhstan from 0.3 in forest-tundra to 2.1 in the middle taiga and to 7.3-15.8 in the steppe zone. The main reason for this is changes in the continentality of climate and rainfall in a site.

There are three major factors that determine fire occurrence (Kurbatsky 1964, Sofronov and Volokitina 1990): 1) fuel availability (P_{fuel}), 2) the weather (meteorological) situation (P_{met}), and 3), availability of an ignition source (P_{source}). Then, in the case of non-human-induced fires, the fire probability (P_f) can be estimated by the following simple equation:

$$P_f = P_{fuel} * P_{met} * P_{source},$$

where P_{fuel}, P_{met}, and P_{source} are the partial probabilities of each factors.

Undoubtedly, P_{fuel} is closely related to NPP (net primary productivity) of the forest (Shugart *et al.* 1992, Kasischke *et al.* 1995, Goldammer and Furyaev 1996). P_{met} depends on aridity of the climate and dryness of the fuel. P_{met} can be evaluated by Nesterov's index (NI) used in Russia and the Fire Weather Index (FWI) used in Canada and USA. Both indices are based on daily meteorological data and calibrated to measure a fire ignition potential (Stocks and Lynham 1996). P_{source} is the probability of a natural ignition (mainly lightning) occurrence. The two first partial probabilities depend on the stand composition and its characteristics (Fosberg *et al.* 1996). Above-ground fuel material is related to annual stand productivity and rate of decomposition of organic matter (Kasischke *et al.* 1995). Dryness of organic matter greatly differs in light-needled (e.g., pine and larch) forests compared to dark-needled (spruce, fir, cedar) forests with mainly moist forest floor. For instance, Stocks and Lynham (1996) reported that NI values below 300 indicate a low probability, values between 300 and 1000 indicate a medium probability, and the values greater than 4000 indicate an extremely high probability. Note that the partial probability P_{met} is smaller in a dark-needled forest than in a light-needled forest under the condition of the same NI value.

We tested this probabilistic model in a pine forest of the middle taiga on dry and moderately dry soils. We calculated the partial probabilities (P_{fuel}, P_{met}, and P_{source}) from data of Furyaev (1996) and Ivanov (1996) and the final fire probability. The average fire return interval (FRI) was calculated from the fire probability to be FRI = $1/P_f$ = 30.8 years, which is close to the FRI measured by fires scars (29.5) for 19 sites of this area (Arbatskaya 1998).

2.4. Fire history in northern and middle taiga stands related to summer temperature fluctuations

There has been much speculations on increase in flammability in a boreal forest due to global warming (Fosberg *et al.* 1993, Goldammer and Furyaev 1996, Stocks and Lynham 1996). However, there is little data to supporting such speculations. Analyses of fire frequency related to climate change along decadal and centennial time scales have been made in a few regions of the globe. The only clear historical relationships obtained were for the semi-arid west of the USA and the southern edge of the North America boreal forest (Clark 1988, Swetnam 1993). In some other regions of the boreal forest, current temperature increase is not correlated with increase in the number of fires (Bergeron and Archambault 1993, Bergeron and Flannigan 1995). Thus, analysis of the regional history of fire frequency over the past several centuries is needed.

Here, we present some results of analysis of long-term fir history data in two northern and middle taiga regions of central Siberia. In the northern taiga, summer (June and July) temperatures correlate with long-term variations in tree-ring width with high significance ($R = 0.75$-0.81, $p<0.001$) on the one hand and with the number of fires ($R = 0.65$, $p=0.001$) on the other hand (Vaganov *et al.* 1996 a, Panyushkina and Arbatskaya 1999). Thus, in northern taiga larch forests, there is a quite good correlation between regional tree-ring chronology and fire frequency ($R = 0.62$ for annual variations and $R = 0.8$ for smoothed data). These results allow to use the regional tree-ring chronology as an indicator of past fire frequency.

In middle taiga pine stands, Arbatskaya and Vaganov (1997) reconstructed the fire frequency since 1600 using fire scars on old and dead trees in 19 dry and moderately dry sites. These forest types cover 25 % of the middle taiga territory. Long-term fire frequency dynamics in these forest types is affected by two main factors: summer temperature and water table fluctuations.

We compared long-term annual temperature fluctuations in the northern hemisphere (Bradly and Jones 1993) with long-term fire frequency dynamics reconstructed from fire scar in these northern taiga larch forests and middle taiga pine forests (Fig. 7).

In larch stands of the northern taiga, long-term fire frequency fairly well follows the summer hemisphere temperature. In contrast, long-term variations of fire frequency in the pine forests of the middle taiga are negatively correlated with the northern hemisphere temperature ($R = -0.52$, $p = 0.01$). The warming in the late 18th century and in the middle of the 20th century are related to a decrease in fire frequency. Therefore, the data presented here show that "fire" response to global warming is of a regional scale rather than a global scale. Bergeron and Flannigan (1995) and Arbatskaya (1998) indicate that the fire response is determined by both regional summer temperature and precipitation dynamics in some regions of a boreal forest. Annual precipitation and its intra-seasonal distribution are of special importance for evaluating fire regimes in the regions with a short summer.

2.5. Large-scale fire regimes in the Siberian boreal forest

Based on latitudinal and longitudinal climatic differences, topography, and a stand tree-species composition, two types of forest fire regimes in Siberia can be identified (Valendik 1996). The largest number of fires (up to 83%) occurs in central and east Siberia and the Far East, while only 17% of fires occur in the west Siberian Lowland. Large fires (more than 200 ha in area) occur in west Siberia for 2-3 consecutive years. These fires occur once or twice

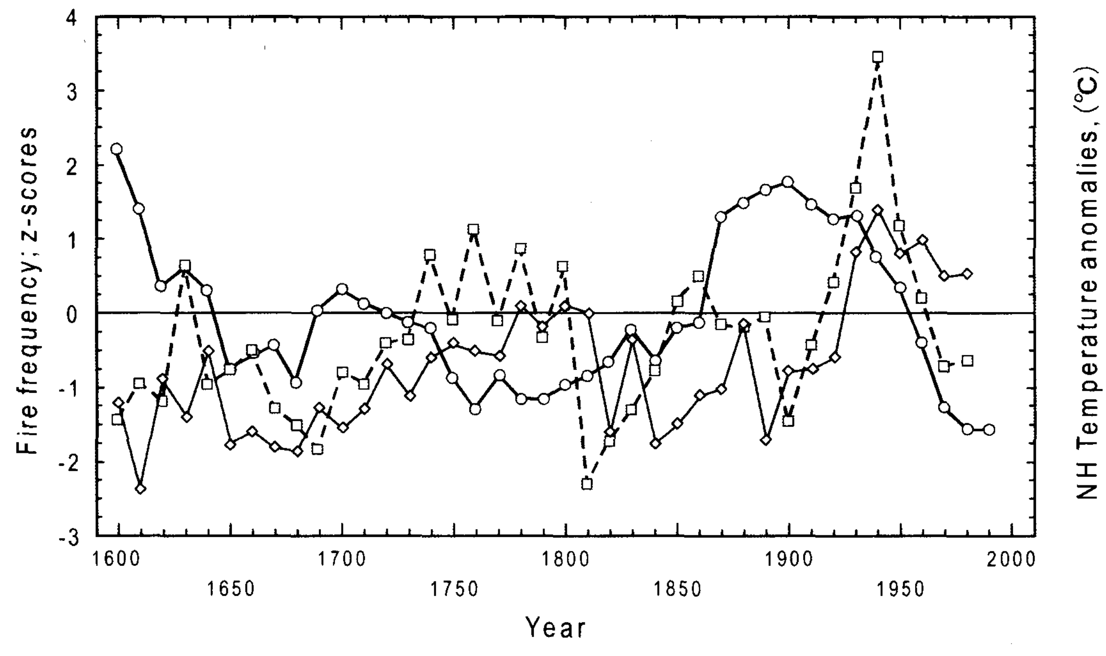

Fig. 7. Variation of summer temperature in Northern Hemisphere (NH) from Bradly and Jones (1993, Bold line) compared to fire frequency (in z-scores) variation in the northern taiga larch forests (solid line) and in the middle taiga pine forests (dashed line) derived from data of Panyushkina and Arbatskaya (1999).

times a decade. In other regions of Siberia, large fires typically occur every year, and outbreaks are observed once every three or four years (Valendik 1990).

The results of analysis of seasonal fire distribution data over zonal Siberian landscapes show that there are three major fire season types (Valendik *et al.* 1993, Korovin 1996):

1. Short discontinuous fire season is found in northern and middle taigas when forest fire occurrence is very high during the months of June, July and August.
2. Long fire season is typical in southern taigas when forest fires occur periodically over a period of 4-6 months, from April to September.
3. Double-peak fire season, when fire occurrence is foremost in short periods of spring and autumn months.

In the larch-pine forests of central Siberia, fire frequency increases mainly from the north to the south, although abnormal regions with increased flammability are also found. Fire frequency is related to duration of the fire danger period and availability of natural and anthropogenic fire-starting agents. Under impact of these factors, fire frequency in the northern taiga forests of central Siberia varies between once every 27 years to once every 200 years (with a mean frequency of about once every 80 years) in the near-Yenisei region, once every 20 to 60 years in the eastern part, and once every 7 to 40 years in other regions (Sofronov and Volokitina 1996). In the middle taiga forests, fire frequency varies from once every 17 to 77 years (with a mean frequency of about once every 30 to 35 years). In the southern and subtaiga forests (the near-Angara region), reported fire frequency varies from once every 26 to 59 years (with a mean frequency of about once every 35 years) in the northern part and from once every 2 to 34 years (with a mean frequency of about once every 16 years) in the southern part (Valendik and Ivanova 1996, Vaganov *et al.* 1996 a). Fire frequency in the southern montane pine forests varies from once every 6 to 11 years (Valendik *et al.* 1993, see also Fig. 6).

A landscape-based analysis of long-term statistical data on large forest fires in the boreal zone of Siberia allowed us to roughly differentiate Siberia by "fire regime" and determine prevailing vegetation complexes for each unit (Table 1, Valendik 1996). In Table 1, the fire occurrence is given as the number of fires per one million ha of the forested area per year.

Forests of central Siberia manifest combined fire regime features characteristic of west Siberia, the more continental eastern regions, and the steppe zone as well. Ecosystem response to forest fire impacts manifest differently and depend on fire type and intensity, regional climate, and forest and ground layer structures. The most successful forest regeneration by climax tree species occurs in northern and middle taigas. In the southern taiga, the forest regeneration process is more complex in dark-needled forests, which can be replaced primarily by pine and hardwood forests with climax tree species following.

Table 1. Fire regimes of Siberian vegetation complexes

Vegetation complex	Major reasons for droughts	Yearly fire occurence, number per million ha	Severe fire periods	Fire season duration, months	Number of years with large fires per decade
Mountain-tundra open forests	Central Siberian and Yakutian anticyclones	2.0	late June and July	1.5	2
Larch and spruce-larch forests with dwarf birch and mosses or small shrubs and mosses	Anticyclones from Central Siberia and Yakutia, plus local air mass transformations	2.1	June	2.0	3
Larch forests with spruce admixture and pine-larch forests with small shrubs and mosses	Anticyclones from the Trans-Baikal region, Mongolia, China, and Central Yakutia	3.8	June and July	4.0	10
Middle and high mountain mixed *P.sibirica*/fir/larch forests and subtaiga-forest-steppe pine/larch forests	Anticyclones from Central Asia, Mongolia, and China	2.4	May and July	4.0	4

Mountain larch forests usually regenerate after fire with no tree species replacement.

According to Flannigan and Van Wagner (1991) and Stocks (1993), fire may be considered as "a driving force" to promote vegetation shifts and change of the forest physiognomy under warming. The data shown in Table 1 together with observations on succession stages (Abaimov *et al.* 1996, Furyaev 1996, Sofronov and Volokitina 1996) can be interpreted as fire forcing of vegetation change.

In the southern vegetation zones, for instance, frequent occurrence of large fires per unit area and frequent fire recurrence favor steppe vegetation to invade deep into forest vegetation. The higher frequency of occurrence of the fires (which is predicted under global warming), the longer are the distances that steppe species may invade into the adjacent zones. In contrast, in the northern vegetation zones with low frequency of large fires, recruitment of new species from adjacent zones would slow down. Therefore, a vegetation mosaic would evolve as the frequency of occurrence of large fires increases. This view helps us to picture the mechanism by which vegetation shifts occur due to warming.

2.6. Possible Siberian vegetation response to climate change

Studies in the last decade on possible impacts of climate change on terrestrial ecosystems suggest that perturbations will be most pronounced in the northern circumpolar ecosystems (Emanuel *et al.* 1985, Smith *et al.* 1992, Monserud *et al.* 1993). In Siberia, vegetation shifts (Tchebakova *et al.* 1995) and phytomass changes (Monserud *et al.* 1996) under global warming predicted from general circulation models of the atmosphere were evaluated using a regional Siberian vegetation model based on climatic parameters (Tchebakova *et al.* 1994). A comparison of modern zonal vegetation (Isachenko *et al.* 1988) and vegetation distributions predicted from four climate change scenarios (GFDL, UKMO, GISS, and OSU) demonstrated significant vegetation shifts. The most dramatic shifts are predicted in the case of GFDL and UKMO scenarios with global temperature changes of 4.0°C and 5.2°C, respectively. In the case of OSU and GISS climate change scenarios with global temperature changes of 2.8°C and 4.2°C, respectively, vegetation shifts are predicted to be moderate.

According to the GFDL and UKMO scenarios, large changes associated with greater warming are predicted to occur in the boreal zone. The northern taiga will shift northwards, and the middle and southern taigas will continue to occupy their current positions. In west Siberia, the northern boundary of the subtaiga zone will shift from about 57°N to 70 °N latitude, and the forest-steppe zone will extend to the Polar Circle, where the boundary between the northern taiga and forest-tundra is currently observed. A temperate forest-steppe zone, currently not found in Siberia, will penetrate far northwards up to the 65 °N parallel.

Under extreme warming, a 70-75% phytomass decrease is predicted for all northern vegetation classes (forest-tundra, northern and middle taiga), with a small (15%) decrease predicted in the southern taiga. Although the subtaiga phytomass will double under these two scenarios, the total taiga vegetation phytomass will decrease by one third. The forest-steppe phytomass will double on average (Monserud *et al.* 1996).

According to the OSU and GISS scenarios, which predict moderate warming, the northern and middle taigas will survive in 65-70% of the current area and shift northwards: their southern border in west Siberia will shift from the 60 °N to the 65°N latitude, and in east Siberia, it will move from the 50°N to the 62°N latitude. Cold regions of taiga will be replaced by warm regions such as southern taiga and subtaiga. The area of southern taiga will remain about the same, but the area of subtaiga will increase 3 to 4 times. The temperate forest-steppe area will increase considerably in all four scenarios. Distances of zonal vegetation shifts predicted from the moderate scenarios are 1.5-times less than those predicted from the extreme scenarios, although directions of change will remain about the same.

Under moderate warming, total phytomass in forest-tundra, northern taiga, and middle taiga will increase by 40%. Phytomass will increase by 30-50% in southern taiga and will quadruple in subtaiga. Forest-steppe phytomass will double under these scenarios (Monserud *et al.* 1996).

3. Discussion

A variety of landscapes with specific climates and climax forest vegetation controlled by these climates is found in subzones of the boreal forest in central Siberia. Climate transforms ecological regimes of forest ecosystems through permanent natural and man-caused forest fires and determines the direction and rate of post-fire succession.

Forests of central Siberia have fire regimes characteristic for those in both west and east Siberia. In this respect, central Siberia is a unique model territory in which effects of climate change and forest fire on forest formation can be systematically studied and regularities found can be reliably extrapolated to the vast area of Siberia.

Specific features of tree species response to climate change and fire impacts in different subzones of the boreal forest are the basis of the elementary succession mechanism. A typical sequence of post-fire succession associations found for larch forests of northern taiga and pine forests of middle taiga can be applied to modeling forest-forming processes under environmental changes.

Climate change would undoubtedly cause forest ecosystem response at individual tree, stand, and landscape/subbiome levels. Because each of these levels has its specific characteristic response time, it would be a logical step to develop a three-level model with three corresponding compartments in order to quantify these responses. In the first compartment, individual tree response to climate change is modeled; in the second compartment, stand response to climate change is modeled; and, finally, in the third compartment, the response of a larger regional ecosystem like a landscape or a subbiome is modeled. In doing so, integrated output characteristics of a lower hierarchic compartment are input characteristics of the upper hierarchic level compartment. Such an approach is justified by the fact that an individual tree response can be most precisely modeled as an element of the forest. To the best of our knowledge, such hierarchic models have not yet been developed.

The most feasible approach to analyze forest response to climate change is to use models describing processes of the same or close characteristic times: e.g., a tree model, an ecosystem model, and a landscape model (Shugart *et al.* 1992). With this approach, a concordance of results (even qualitative) obtained with the use of the hierarchic models is very important. For example, if in a two-species ecosystem, the growth of one species increases and that of the other species decreases under warming, then, in a stand model based on competition, the first species has to have a greater temperature multiplier than the second species.

This qualitative analysis can be demonstrated as follows: if a higher temperature (especially in summer) accelerates tree growth in the northern taiga, this will increase the frequency of forest fires due to both fuel accumulation and direct impacts of temperature on flammability. Finally, if both forest flammability and total fire frequency increase and the fire return interval decreases, the area of larch forests in early succession stages increases. Young growth is known to accumulate carbon from the atmosphere more rapidly than does old growth. Thus, the prevalence of early stages of forest succession can be considered as a biosphere feedback to global warming to compensate a CO_2 increase in the atmosphere.

In the middle taiga, the growth response of a single pine tree to climate change will largely depend on a combination of temperature and precipitation and can be negative under warming. Warming without additional precipitation might increase fire probability related to weather (a meteorological probability) on the one hand and might decrease fire probability related to fuel load on the other hand. Thus, fire frequency, forest flammability, and fire return interval might remain about the same. However, responses of dark-needled cedar (*Pinus sibirica*) and spruce (*Picea obovata*) trees found in moist habitats may be different. Under more warming climate, their growth and productivity may increase and regeneration may improve, both of which might confer an advantage in competition with other conifer and hardwood species.

About 1% of the forested area annually been registered as have been subjected to fire for the past one hundred years in most landscapes of west and central Siberia (Furyaev 1996). Only in southern taiga and subtaiga, forest fires have annually occurred in an area of 1.5 million ha, resulting in tree species and age cohort replacement. Areas of boreal forests in Eurasia subjected to fire have greatly increased during the past two decades to an estimated 10 million ha annually (Furyaev Goldammer 1996).

Vegetation shifts predicted by GCMs will prolong the forest fire season. Owing to severe forest fire regimes and occurrence of large fires, actual fire spread in boreal forests in Eurasia will increase considerably. It is estimated that the fire extent will increase 3 fold, and the total area destroyed by fires may reach 30 million ha. Fires will be of higher intensity and become more frequent in all ecosystems, including bogged forests and bogs with a vast peat stock and ground litter. The bulk of organic matter annually burnt in uplands and former hydromorphic (bogged) ecosystems may account for 1 billion tons. This amount is comparable to that of annually utilized solid and liquid carbon-containing fuel. Hence, it is possible that CO_2 and solid aerosols in the atmosphere may double due to smoke of forest fire emissions. This increase the CO_2 content in the atmosphere will lead to additional global warming through feed-back mechanisms. Dynamic instability of the boreal ecosystems in Eurasia will remain during an transition period until a necessary equilibrium between climate, vegetation, and its resistance to forest fires is established.

Thus, direct impacts of human activities combined with expected climate change could induce an unprecedented epoch of fires in boreal forest in the future followed by global ecological after-effects. However, a possible response of the forest formation process to climate change and fire regimes in central Siberia would bear a regional character.

For instance, currently, uneven-aged stands dominate in the southern taiga zone under an optimal ratio of heat and moisture. With a changing heat/moisture ratio, these stands would experience stress because environments would shift beyond their optimum conditions. In these uneven-aged stands, new environments with better nutrient and light regimes for young growth would be created in gaps of fallen old trees. The course of the forest formation process viewed this way would promote forest survival in currently forested areas (Komin 1982). However, one may consider on such a forest formation process in southern taiga only with great revisions related to a significant increase of fire occurrence and changes in fire regimes. Because the current territory of southern taiga is predicted to be replaced by forest-steppe (Tchebakova *et al.* 1995) with a 15% phytomass decrease (Monserud *et al.* 1996) under a warmer climate, forest degradation and decline during the transition period would result in a dramatic increase in forest debris and forest flammability, respectively. Forest fires would control the even-aged young growth formation in the large area of currently existing uneven-aged stands. The young growth would be even less-resistant to climate change and fires than the old growth. Thus, in the southern taiga zone, vulnerable young growth would develop into open forest-steppe stands most fitted to a new climate. Trees would respond by growth rate decrease and reproduction reduction, resulting in poor natural regeneration.

In the current middle taiga zone, good climatic conditions for developing communities of southern taiga and forest-steppe would be found (Tchebakova *et al.* 1995). During the transition period, young growth of the southern taiga physiognomy at different succession stages of the forest formation process is expected in large areas of the current middle taiga. However, successions caused by an increased probability of forest fires would be prolonged. Initial succession stages of the forest formation process would be more common. The entire or nearly entire absence of climax conifer stands of the southern taiga physiognomy would be observed for a long time. Open poplar-birch stands of the forest-steppe physiognomy may become widespread.

Model predictions of the spatial-temporal dynamics of a boreal forest under climate change and fire impact are of significant interest. An attempt at such a prediction has been made for the landscape of the Kas-Yenisei erosion plain in the southern taiga of west Siberia (Ter-Mikaelian *et al.* 1991). It is predicted that the number of years in which there are severe fires will more than double under a summer temperature jump from 9.8°C to 15.3°C, the area of forests burned annually will increase by 146%, and average wood stock will decrease by 10%.

The questions addressed in this paper cannot be fully answered because of our limited knowledge. We have attempted to present some generalized data and results on how fires and climate influence forest vegetation at different hierarchic levels. However, the results of our analysis have enabled us to answer several important questions. Is our knowledge sufficient to predict what will happen to the Siberian boreal forest under global climatic and environmental change? The most probable answer is "No". Do climatic and fire successions in different forest zones of Siberia have specific features? Yes, they do. Can the findings on boreal forest transformations under fire and climate impacts obtained for other boreal regions (e.g., North America) be applied to the Siberian boreal forest? Yes, they can, but to a limited extent.

What are the issues to consider next in the context of effects of climate and fire on the Siberian boreal forest? Firstly, it would be of use to relate the results of studies on vegetation history should be related to climate history data during Holocene to identify past analogs of current climate and fire patterns. Secondly, data in Russian literature on biogeochemical and hydrological cycles in forest ecosystems along the temperature gradient (north-south transects) should be analyzed in order to relate these cycles to fire regimes and climates. Thirdly, existing forest succession simulation models should be validated, and they should be applied to the Siberian boreal forest.

Conclusions

1. In central Siberia, distinct differences in tree growth responses to main climatic factors along the meridian temperature gradient can be found; limiting influence of summer temperature on growth in the northern taiga, limiting influence of temperature in the first half of summer and precipitation in the second half of summer in middle and southern taigas, and limiting influence of precipitation and temperature in spring and early summer in the forest-steppe zone.
2. The mean fire interval decreases from the northern to southern vegetation zones and correlates well with temperature gradient and stand phytomass, both of which increase fire probability.
3. Mean fire interval variation is significant within a vegetation zone and is caused by both forest structure and landscape-specific features. The mean fire interval is greater in dark-leaf taiga and shorter in light-leaf taiga
4. Modern age, structure and succession of larch and pine forests in central Siberia are determined by fire regimes. Under the current climate, five main types of post-fire forest dynamics characterized by different rates of tree species and moss growth and stand self-thinning are specified in larch forests of the northern taiga. Three types of post-fire succession with different mean fire intervals are specified in pine /green moss forest types of the middle and southern taigas.
5. Under predicted summer temperature elevation and vegetation shift, fire-danger seasons are expected to increase in the middle and northern taigas and northern open woodland. Because of severe fire regimes, the forest area subject to fire in central Siberia and Eurasia as a whole will significantly increase. Forest fires will be of high intensity and more frequent in most ecosystems, although landscape and zonal features will be preserved.

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