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Long-term Investigations of Larch Forests in Cryolithic Zone of Siberia: Brief History, Recent Results and Possible Changes Under Global Warming

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Abstract

Brief history of forest cover investigations in Siberian cryolithic zone is outlined. Since 1950 the detailed studies in the system "permafrost-forest" have been developed by the scientists of V.N. Sukachev Institute of Forest under supervision of Prof. L.K. Pozdnyakov in Yakutiya. Vast research of hydrothermal regime of forest frozen soils, of spatial, age and size structure of larch stands as well as of primary productivity of larch forests has been carried out that period.
In the latest decades of the 20th century V.N. Sukachev Institute of Forest has faced the low studied northern forests of Central Siberia. New data on ecosystem diversity of forest vegetation and its post fire change, on the structure and variability of larch populations, on fire ecology and pyrological zonation as well as on permafrost table dynamics, cycling of mineral nutrition, the soil respiration rate and adaptation mechanisms of larch species to extreme northern environments has been obtained. Resulted from these investigations generalized scheme of the most typical post fire succession patterns in the cryolithic larch forests is described. Forest successions are considered in relation to possible vegetation changes under climate warming. These changes are discussed with respect to wet and dry warming scenarios.

Keywords: Central Siberia, climate changes, cryolithic zone, forest fires, forest successions, larch ecosystems, postfire transformation

Introduction

Total cryolithic area of our planet appears to be about 35 billion km^2, which makes up one fourth of the Earth. In the Northern Hemisphere the cryolithic area covers 21 billion km^2. The share of Russia is almost half as large, about 11 billion km^2 (Basic knowledge of geocryology 1959). Mountain tundra occupies 14% of the territory, both forest-tundra and plane tundra – 13%, forest vegetation – 66% and isolated mountain cryolithic plots outside the range – 7% (Pozdnyakov 1986). Thus, such coincident distribution of permafrost and forest vegetation is of the most interest and importance to be studied.

Forest fire is an important ecological factor controlling both environments for vegetation establishment and vegetation succession in the cryolithic area (Abaimov and Sofronov 1996). Fire frequency per one forest site here can vary from 40-100 up to 200 years predicting proper cycles in the forest association development (Abaimov *et al.* 2000). Depending upon site conditions, fire power, intensity and periodicity, fire regimes determine forest structure and succession patterns in their trends and rates (Abaimov 1999).

In this paper, we present a summary of long-term investigations of forests, particularly larch forests, in the cryolithic zone of Siberia. We focus on these sparse forests because of their great environmental, biosphere and social functions as well as of a number of peculiar features (Pozdnyakov 1986, Abaimov *et al.* 1997).

Brief history of larch forest investigations in Siberian cryolithic zone

The first scientific data on the forests of high latitudes of Siberia were obtained in the second part of the 19th century (Middendorf 1867). Systematic investigations of vast permafrost forests of Russian northern Eurasia have been begun since the first decades of the 20th century. Sukachev (1912), Drobov (1927), Nedrigailov (1932), Abolin (1929), Povarnitsin (1933) and Birkengof (1932) have made the pioneer descriptions of forest vegetation in various regions of Yakutiya while Avramchik (1937), Tjulina (1937) have described northern forests of Krasnoyarsk region. Sukachev (1912) has first mentioned larch ability to form adventitious roots with permafrost rise. Later on this larch ability was recognized as protective adaptation to extremely cold environments (Dylis 1981).

Papers of the other Russian scientists were devoted to the study of systematic and variability of Siberian species of *Larix* (Kolesnikov 1946, Dylis 1961), of the ecosystem's diversity and natural regeneration of Siberian larch forests (Tjulina 1937, 1957, Tchugunov 1961, Krylov 1962, Shcherbakov 1975,

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Panarin 1965, Utkin 1965, etc.) as well as of soil investigations in Yakutiya (Zol'nikov 1954, Konorowskii 1963, Elovskaya *et al.* 1965, etc).

Since 1950 the detailed route and field-station investigations in the system "permafrost-forest" have been carried out by Prof. L.K. Pozdnyakov. He studied the permafrost forests of Yakutiya for more than 40 years of his scientific activity, and supervised research on hydrothermal regime of frozen soils, tree stand composition and structure, primary productivity of larch forests, seed production and seed quality as well as on destructive insect composition. He also investigated root distribution in soil, its thermal regime as well as surface and subsurface runoff.

Detailed studies of hydrological regime made under supervision of Prof. L.K. Pozdnyakov tried to answer the following questions: 1) how does tree canopy effect on precipitation distribution on the ground floor?; 2) how does precipitation penetrate through tree canopy?; 3) how much is the stem runoff?; 4) does snow depth differ in various larch ecosystems?; 5) how does litter influence on the hydrological regime of forest soils? He has studied the permafrost depth dynamics for 7 years from 1955, and has established that under various environments the permafrost thawing had completed at end of September or beginning of October (Fig. 1). Maximal permafrost depth of 240 cm and more was found in pine forests on sandy soils while minimal depth (128 cm only) was observed in 50-year aged larch forests

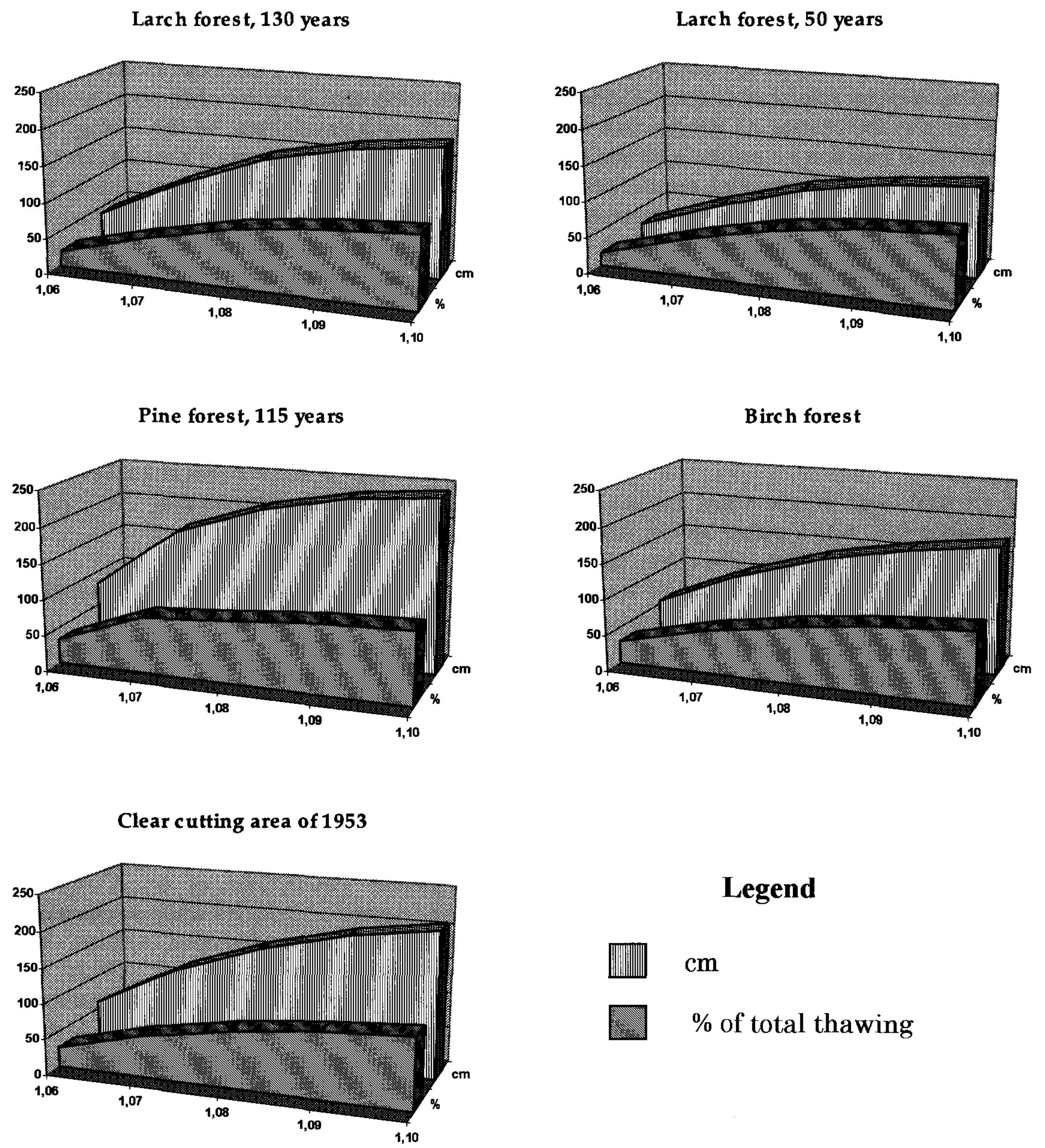


Fig. 1. The depth of soil thawing in tree stands and on clear cutting areas of central Yakutiya (Pozdnyakov 1963)

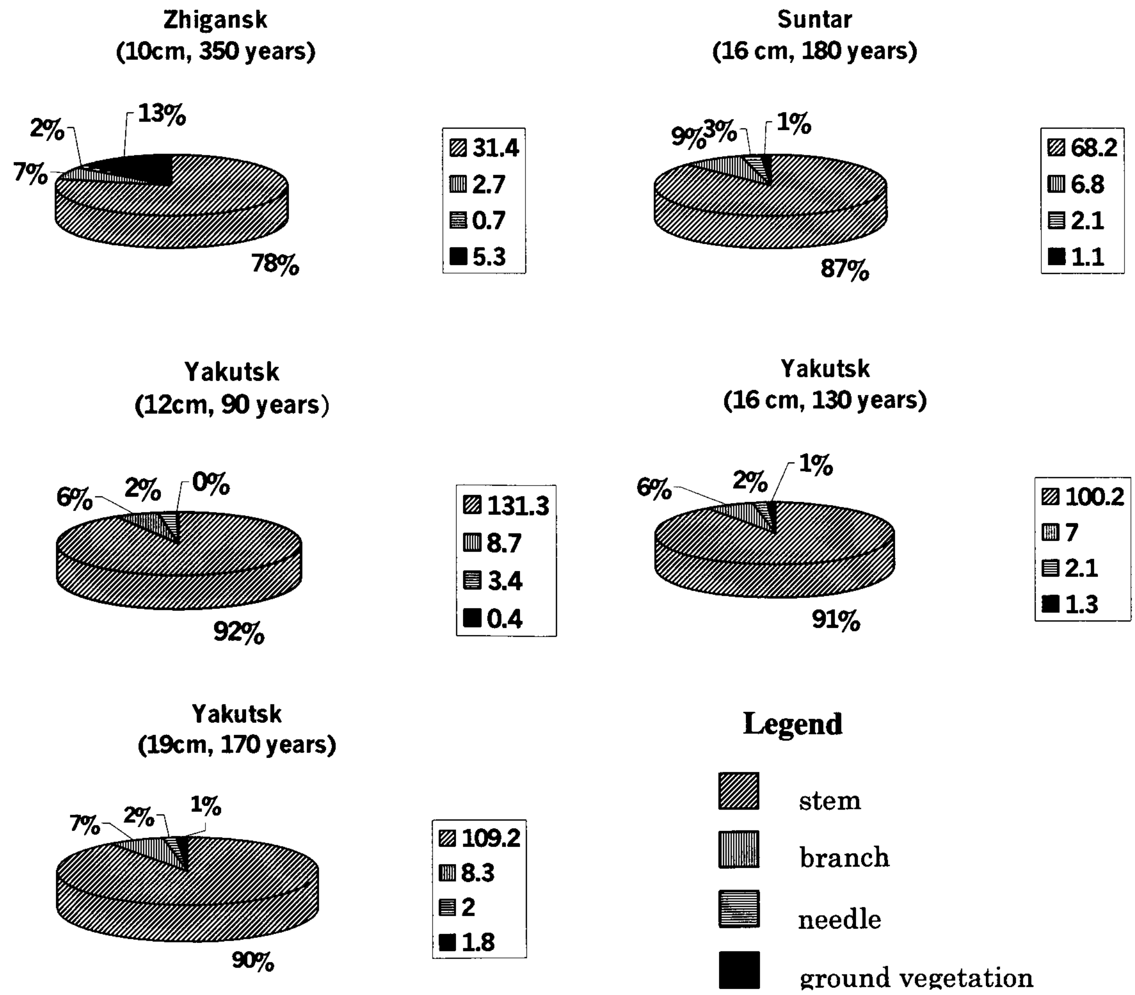


Fig. 2. Above ground biomass of larch forests in Yakutiya (Pozdnyakov 1967). DBH and age are in the parenthesis

with *Duschekia fruticosa* in the understory (Pozdnyakov 1963). The permafrost depth in Yakutiya was established to depend on the tree and shrub density as well as on moss-lichen and litter thickness.

Prof. Pozdnyakov has firstly estimated above ground biomass of the most widespread larch forests of Yakutiyan permafrost area (Fig. 2). According to his data stem biomass makes up 85-91 percent of the total ones, while the share of the needle does not exceed 1,5-3,0 percents (Pozdnyakov 1967, 1975). Nevertheless, under overmoisten soil conditions the biomass of ground vegetation in the forest site can increase up to 13 percents or more.

Larix cajanderi is high reproductive ability and can produce about 12 thousand cones (Pozdnyakov 1975). At successful seed crops the weight of larch seeds produced per 1 ha ranges from 20- up to 65 kg. The seeds are of high quality (Table 1). Just such important biological feature of the species is responsible for the conservation of its ecological niche under severe environmental conditions of Yakutiya. Based on the long-term investigations of Siberian permafrost forests Prof. L.K. Pozdnyakov has outlined the basic knowledge of the Permafrost Forest Science, a new branch of traditional forestry (Pozdnykov, 1986). He also proved that the alternative likelihood options should be identified and developed for the cryolithic zone of Siberia to avoid inappropriate exploitation of natural resources of this territory.

Recent results of cryolithic larch forests research

The latest decades of the 20th century V.N. Sukachev Institute of Forest has faced the low studied northern forests of Central Siberia. The investigations have been mainly continued in the next directions: study of ecosystems diversity of forest vegetation (Zyryanova and Shitova 1995, Abaimov *et al.* 1997), evaluation of fire influence on forest ecosystem dynamics and species diversity changes (Abaimov *et al.* 1996, 1999, Zyryanova *et al.* 1998, 1999, 2000a, 2000b), the investigation of the structure and variability of larch populations (Abaimov *et al.* 1998); study of fire ecology and pyrological zonation (Sofronov, Volokitina, 1990, 1996, 1998) as well as

Table 1. Seed quality (mean and SD) of Cayander larch in central Yakutiya (Pozdnyakov 1968)

Year	Weight of 1000 filled seeds (g)	Germinating ability (%)	Seed germination energy (%)
1952	2,69 ± 0,06	46,5 ± 3,0	44,9 ± 3,5
1955	2,86 ± 0,08	52,9 ± 2,5	36,4 ± 2,2
1957	3,43 ± 0,11	60,0 ± 2,7	39,8 ± 4,2
1960	3,84 ± 0,16	47,9 ± 2,9	38,0 ± 3,1
1963	3,15 ± 0,11	50,2 ± 3,0	41,6 ± 2,9
1965	3,26 ± 0,07	61,4 ± 1,9	41,1 ± 2,3
Average	3,24 ± 0,05	55,0 ± 1,3	39,8 ± 1,3

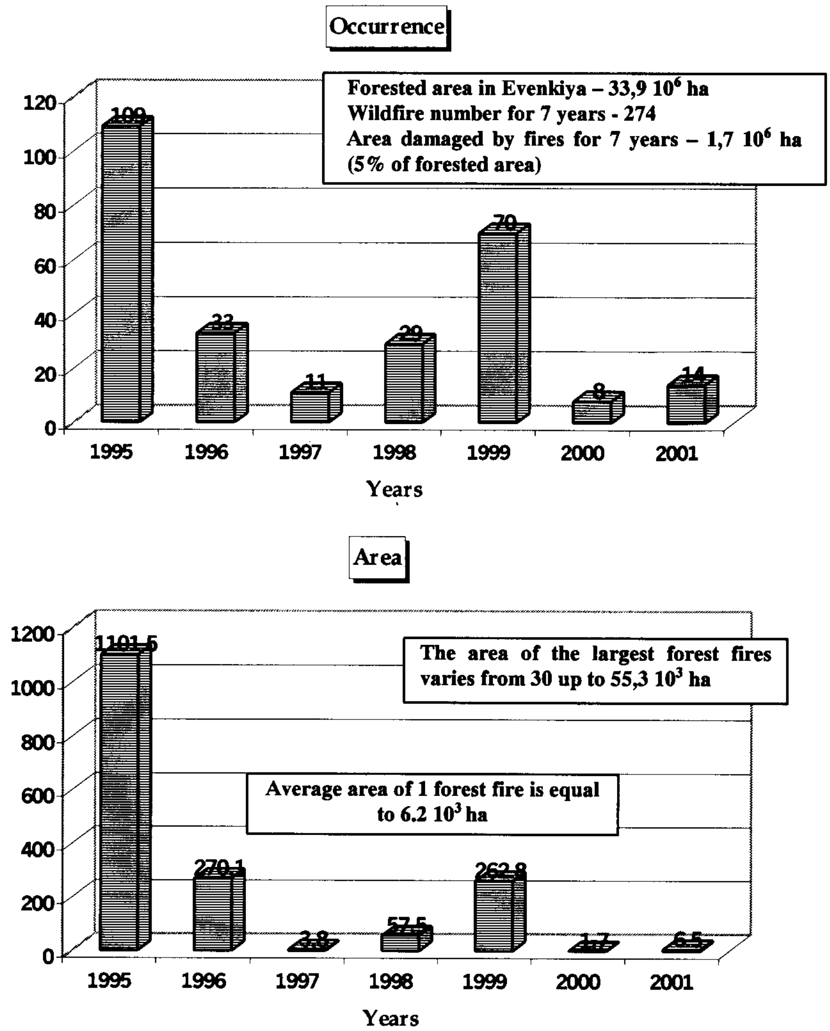


Fig. 3. Occurrence and area of wildfires in Evenkiya (resulted from NOAA-14 satellite data)

the research of permafrost table dynamics, cycling of mineral nutrition, the soil respiration rate and adaptation mechanisms of larch species to extreme northern environments (Abaimov *et al.* 2001, Prokushkin *et al.* 1998, 2000, 2002).

It is well known that wildfires are the major disturbing factors of boreal forest ecosystem's stability (Utkin 1965, Shcherbakov *et al.* 1979, Sofronov and Volokitina 1990, Goldammer and Furyaev 1996, Furyaev *et al.* 2001). In the cryolithic zone of Siberia the fires provide the harshest influence on the forests and their environments. Here they change the thermal regime of active soil layer, accelerate the organic matter transformation and CO_2

emission. Wildfires are often followed by tree stand dieing and forest dynamics changes (Abaimov 1997, Abaimov *et al.* 1997, 1998, 1999, 2000, Sofronov and Volokitina 1996, 1998, Abaimov and Sofronov 1996, Sofronov *et al.* 2000, 2001, Zyryanova *et al.* 1998, 1999, 2000).

According to dendrochronological data various forest sites can be subjected to wildfire in average each 80-90 years. It means that one forest generation is affected by fire 3-5 times. The NOAA satellite data demonstrate strong effect of wildfires on forest cover on Evenkiya, central Siberia, e.g. for 7 years (1995-2001) there were registered 274 fires in this region (Fig. 3), whose area makes up 1,7 million ha. In which the area of larger forest fires varied from 30 up 55 thousand ha while average area of one fire was equal to 6,2 thousand ha.

Considering forested area of Evenkiya makes up 33,9 million ha, about 5 % of this territory, was damaged by fires for the 7 years. Besides, weak wildfires could not been registered by the satellite yet. That is why, the data mentioned above are slightly less than actual burned area. However, they well illustrate the modern scale of wildfires distribution.

Wildfires considerably influence floristic diversity of larch associations in Siberian cryolithic zone. Species richness of secondary post-fire associations is 1,4–1,6 times higher than in the primary larch ones. The most important families in primary larch forest are *Cyperaceae*, *Ericaceae* and *Salicaceae*, while *Asteraceae*, *Rosaceae* and also above-mentioned families are of the most significance in the secondary associations. *Larix gmelinii*, *Duschekia fruticosa*, *Ledum palustre*, *Vaccinium uliginosum*, *V. vitis-idaea*, *Empetrum nigrum*, *Aulacomnium turgidum*, *Cladonia sylvatica*, *Cl. rangiferina*, *C. amaurocraea*, *C. alpestris*, *Cetraria cucullata* and *Cetraria islandica* are the most important species in the primary forest, while *Corydalis sibirica*, *Chamaerion angustifoum*, *Calamagrostis lapponica*, *Carex media*, *Marchantia polymorpha* and *Ceratodon purpureus* are the most important species in the secondary plant associations. Similarity indices at species level of primary and secondary associations ranges between 0,28 and 0,55 at various regeneration stages. Species richness and floristic composition is still significantly different even by 50 years after the ground fire, but the spatial structure (vertical and horizontal) is similar. This demonstrates that duration of 50 years is sufficient time for the secondary forest to recover the original structure of primary larch forest, but is not for the original species richness and floristic composition. The low species similarity between primary and disturbed associations indicates that the floristic composition is quite distinct and that the mixture of these associations has led to an increase in total species diversity.

Root competition for the nutrients and moisture

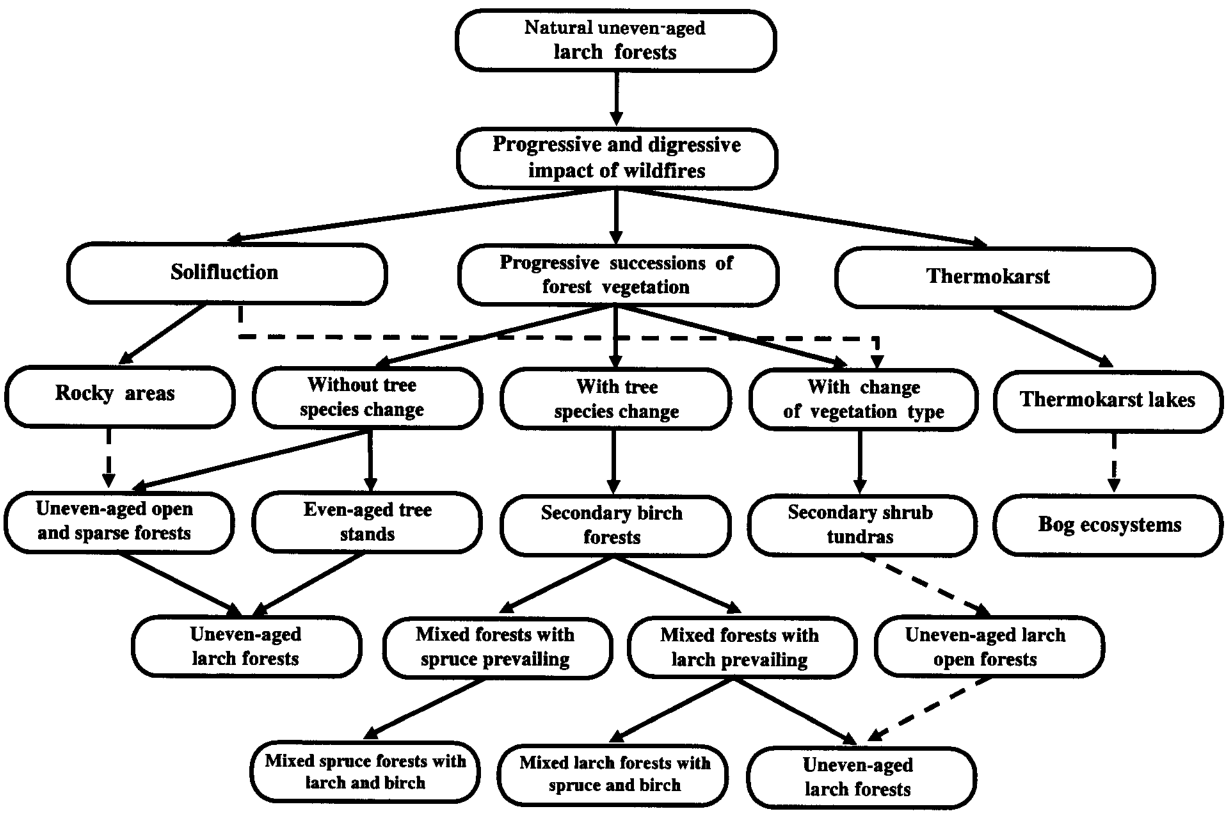


Fig. 4. The main trends of postfire successions in larch forests of Siberian cryolithic zone

provides peculiar features of forest successions in Siberian cryolithic zone. Intra- and interspecific root competition takes place mainly due to small depth of active soil layer and its low temperature. Based on the long-term observation and stocktaking and assessment of all existing literature, we have developed general scheme of postfire forest dynamics in the cryolithic zone of Siberia (Fig. 4). It reflects the leading trends of modern successions. Uneven-aged sparse and closed larch forests are considered to be the primary unburned communities.

Depending on the kind and power wildfires differ in their influence on thermal exchange between atmosphere, soil and permafrost. Both progressive and regressive trends of postfire successions resulted from these relationships (Fig. 4). After weak and middle fires progressive successions can develop either without larch forest change or by birch and even by vegetation type replacement. In the last case larch forests are followed by secondary shrub tundras (Fig. 4). Weak and middle ground fires provide positive thermal change in rhyzosphere.

Heterogeneity in the depth of the permafrost table has been studied in different larch stands and postfire ecosystems. In primary stands thawing depth is driven by numerous factors such as stand age, thickness of litter horizon, heat flux and precipitation (Abaimov *et al.* 2000, Pozdnyakov 1963). Three categories of larch stands distinguished by litter thickness showed differences in permafrost table. Figure 5A indicates that thawing depth on earth hummocks in late July averages 0.86 m ± SD 0.09 and 1.1 ± 0.08, respectively under thinner forest floor (<5 cm, 5-10 cm) and reaches 0.50 m ± 0.11 in *Sphagnum* dominated larch stands (>10 cm). This fact is readily mentioned in literature of boreal forest ecology (Barnes *et al.* 1997; Aber and Mellilo 1991). Our data also show deepening of thawed layer in all communities, perhaps due to the observed increase of liquid precipitation: summer precipitation in 1994 observed only 10 mm, in 1995-1998 ranged between 30-40 mm, in 1999 reached 73 mm and in 2000 it was 124 mm.

Fires enhance permafrost thawing directly and through removal of the forest floor, which acts as a heat insulator. Our study of fire effects was conducted in two burnt larch feathermoss communities (fires in 1978 and 1994) with highest thickness of litter. In the first year after the fire occurred in 1994 we found increasing depth of thawing permafrost (Fig. 5B). Increases in permafrost table depth have persisted for four years after this fire (Fig. 5B) at a constant rate of about 10% annually. In 1998 it deepened at an accelerated rate (about 20%), reached a depth of 1.1 m and then remained constant. Behaviour of the permafrost table in 1998-2000 is in part explained by higher precipitation, which interferes recovery to its former state. In total, the soil depth to permafrost table almost doubled from 1994 to 2000 from 0.65 to 1.17 m. The old fire plot (fire in 1978) has already reached a depth of permafrost comparable to undamaged larch stands of second group, due to the recovery of ground vegetation and an associated decrease of soil temperature (Abaimov *et al.* 1996). Hydrological regime and mineral nutrition improve compared to primary community. Microbiological activity also rises. Such conditions, as a whole, are favorable to successful regeneration of larch and other species (Fig. 6).

The scheme shows that progressive succession with or without the change of dominant tree is diverse in their trends. The latter is usually characteristic of different dynamic patterns of the forest cover. As it was mentioned above, these trends resulted from wildfires and interspecific competition of the trees (Fig. 4). Secondary shrub tundras begin to develop after catastrophic running ground fires (Fig. 7). The litter usually remains after fire and prevents

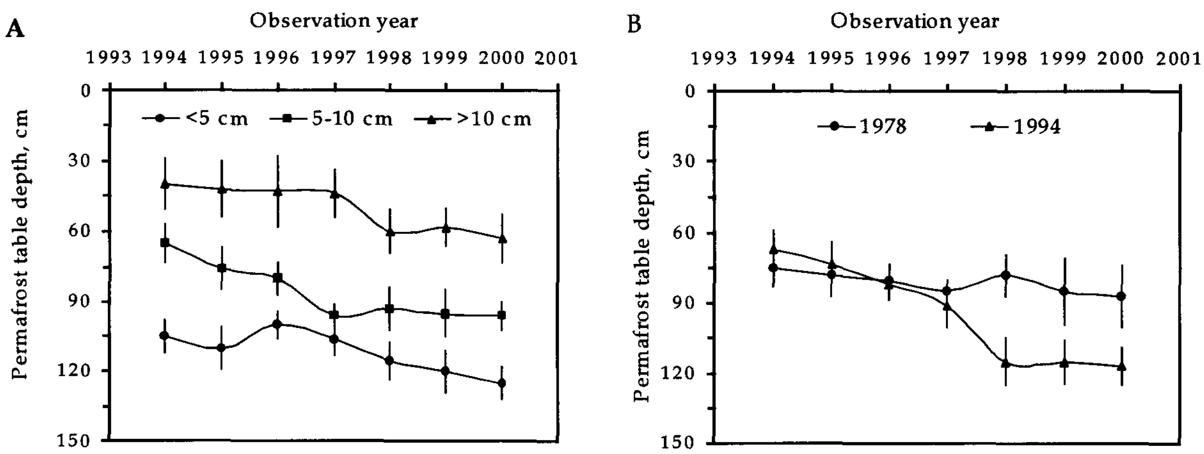


Fig. 5. Permafrost depth dynamics in (A) primary larch stands with different thickness of moss+muck layer: < 5 cm, 5-10 cm and > 10 cm; and (B) on post fire plots of different age: 1978 – fire in 1978 and 1994 – fire in 1994, correspondingly. Depth of permafrost presented in cm from surface, not mineral soil

germination of larch seeds and rootage of young seedlings. On the contrary, different shrub species are successful in vegetative reproduction. For 5 -10 years after the fire such shrubs as *Duschekia fruticosa* and *Betula nana* develop stable communities for the decades. High density of these shrubs also prevents larch seed invasion.

Catastrophic ground fires in the cryolithic zone of Siberia usually take place at dry seasons. They completely destroy moss-lichen cover and litter in the forests. Such wildfires change thermal exchange in forest ecosystems and cause slope solifluction and thermokarst. For the first 2-3 years after fire the rocks develop on the upper steep slopes (Fig. 8). Lower gentle slopes can be covered by secondary shrub tundras. On flat watersheds and river valleys the thawing of fossil ice lenses leads to the thermokarst lakes. This process takes about 30 -40 years (Fig. 9). The thermokarst lakes gradually transform into bog ecosystems. Then the tundras replace the latters. Later, in 200-300 years, open and sparse larch forests will replace tundra communities.

Fig. 6. Even-aged larch forests, recovering after forest fires

Fig. 7. Secondary postfire shrub tundra

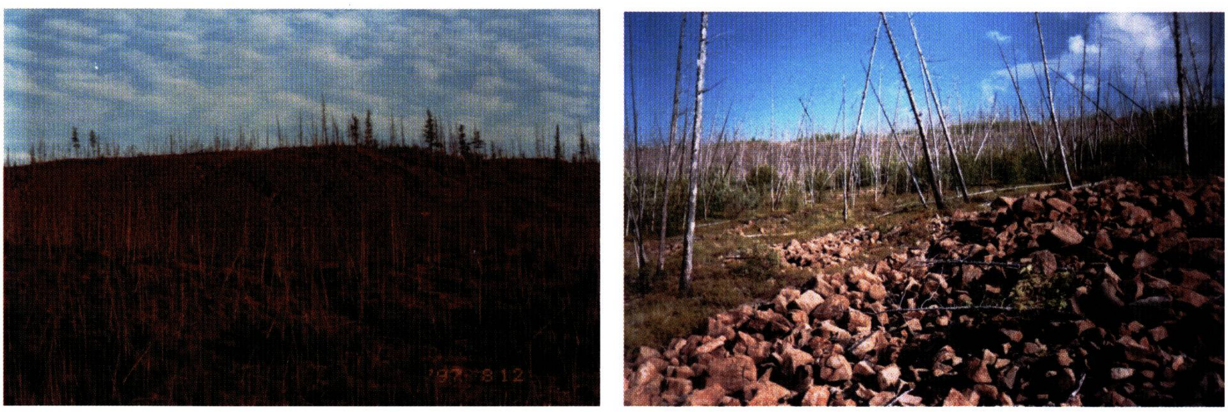
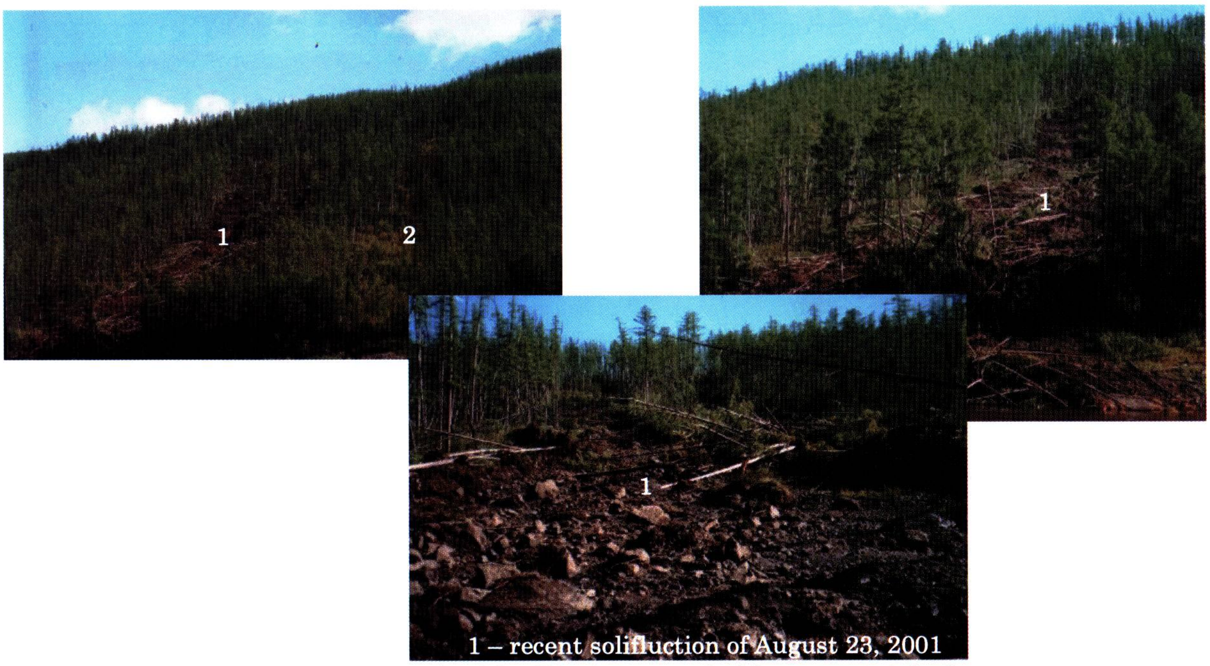


Fig. 8. Rocky slopes as resulted from catastrophic forest fires and subsequent solifluction

Fig. 9. Thermokarst lakes as resulted from forest fires and subsequent melting of fossil ice lenses



2 – old solifluction covered with regenerated shrubs

Fig. 11. Recent and old solifluction areas on the south-western slope in Central Evenkiya

1 – fossil ice lens of 70-80 cm thickness

2 – temporary flow resulted from fast melting of this lens

Fig. 12. Fossil ice lenses thawing and larch forest destroy

Discussion: possible changes of larch forests under Global Warming

The knowledge of the modern trends of forest cover development in the cryolithic zone of Siberia is needed to forecast its possible changes under Global Warming. We would like to discuss possible changes in environments and vegetation of the northern taiga at moderate OSU and GISS climate change scenarios with global rise in air temperature of 2.8°C and 4.2°C (Furyaev *et al.* 2001). We follow the opinion that two scenarios would be possible: dry and wet warming (Utkin 2001).

Dry warming would take place without increase in summer precipitation while wet one would be with it. Both scenarios might lead to 1) the increase of active soil layer and permafrost table depth decrease as well as to 2) the rise in soil temperature and its humidity (Fig. 10).

The main consequences of such environmental changes in forest vegetation are expected to be: 1) productivity increase of northern forests (Furyaev *et al.* 2001; Mellilo *et al.* 1993); 2) rise up of the share of spruce (*Picea obovata*) and birch (*Betula pendula*) forests in forested area. Birch species is assumed to keep its ecological niche even post catastrophic wildfires in well-heated watershed sites at 400-600 m a.s.l. Sprouting regeneration of birch tree may confer an advantage in competition with the other species. Dark-needled pine (*Pinus sibirica*) and spruce regeneration under a shelterwood of primary larch forests in Central Evenkiya may make an assumption that these species might expand their ranges northwards at moderate climate change scenarios; 3) shift of timberline into plane and mountain tundras. As we observed in the Putorana Mountains (the northwestern part of Central Siberia) the permanent invasion of forest vegetation into mountain tundra has taken place for the last five decades. The age of larch trees studied near the upper timberline is about 40-50 years old. Due to natural seeding abundant young larch trees provide fast natural afforestation of transitional larch forest-mountain tundra area; 4) remove of Scots pine (*Pinus sylvestris*) forests northwards (Furyaev *et al.* 2001).

But dry warming might expand catastrophic wildfires and CO_2 emission into atmosphere. Rise in CO_2 emission, estimated by Siberian scientists, in the northern taiga of Central Siberia would be about 1,32 million ton per year while about 2,6 million ton of organic matter is burnt (Furyaev *et al.* in press). At the same time the calculations have been made for officially registered large forest fires only. In fact actual burned area is much more as was mentioned above. Dry warming can be followed by solifluction and thermokarst.

On the contrary, wet warming might decrease the number of wildfires in the cryolithic zone of Siberia. But increase in summer precipitation might expand solifluction of primary larch forests. This is the flow of wet clay soils along the slope under gravitation resulted from overmoistening. At present solifluction is distributed on well-heated south- and west-faced slopes. In 2001 such processes were observed in Central Evenkiya at the end of August. Both tree stand and active soil layer have been completely destroyed by solifluction (Fig. 11). Abundant

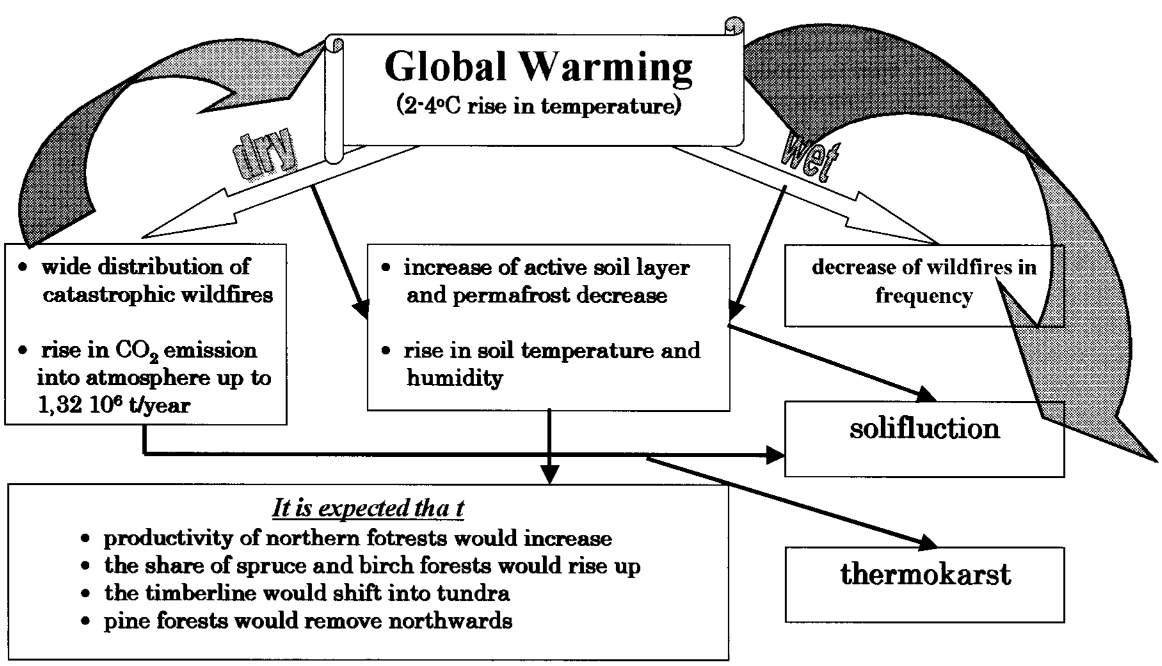


Fig. 10. The scheme of possible changes in northern taiga under moderate scenario of Global Warming

precipitation in August has caused such catastrophic event. Monthly precipitation made up 97,6 mm, which is as large as 20% more than that of average long-term data. Ice fossil lenses thawing also provided larch forest destroy (Fig. 12). That year we observed 72 solifluction areas within 100 kilometers distance in the middle stream of Nizhnyaya Tunguska River (Central Evenkiya). The area of each solifluction ranged from a few up to some thousands square meters.

Thus, we can suppose, that rise in summer precipitation in high latitudes coincident with Global Warming might expand slope solifluction and destroy forest ecosystems in vast territories. These processes as well as frequency of occurrence of large fires (Furyaev *et al.* 2001) can increase a vegetation mosaic in permafrost area. On the one hand, rocky areas might develop on the steep slopes resulted from larch forests destruction, while vegetation recover on the solifluctive areas might lead to the secondary shrub tundras as was mentioned above. Primary larch forests may regenerate without species replacement on the west and south gentle slopes. The area of larch forests in early succession stages may increase if fire frequency increase under dry warming (Furyaev *et al.* 2001). Since young larch forests accumulate increasing resulted from wildfires carbon from atmosphere more rapidly than does old tree stands the biosphere functions of cryolithic larch forests will be kept under moderate climate change scenarios.

Conclusion

Despite 50-years history of the investigations in Siberian cryolithic zone its forest cover still remain poor studied. It happened due to vast territory of Siberia. Forest fires are the major driving force changing environments and biodiversity of the northern larch forests as well as modern trends of cryolithic vegetation. The biosphere functions of forest cover in high latitudes of the Northern Eurasia will be kept under Global Warming.

Acknowledgments

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