Chapter 4
Wildfire Ecology in Continuous Permafrost Zone

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4.1 Introduction

Climatic conditions are ecologically the most important factors influencing the differentiation and character of the vegetation cover at a global scale (Archibold 1995). In particular, fluctuations in climate and weather during drought periods affect vegetation both directly and indirectly through factors such as those related to forest fires.

Characteristics of permafrost and vegetation vary considerably in Siberia, creating quite heterogeneous environments in this region. For instance, the depth of soil active layer often reaches 2 m or more in the summer in the southern part of the permafrost zone. Interactions among permafrost, vegetation, and wildfire are not so obvious. On the other hand, in the northern part of the permafrost zone, the soil usually thaws to 0.3–0.6 m in depth. The mutual influence among the permafrost, vegetation, and wildfires is strong due, for example, to dominance of fire-prone plant species over a permafrost soil, resulting in the development of unique forest ecosystems. Thickness of tree's root layer and the root volume per unit of ground are both small, leading to thin tree canopies. These characteristics suggest us to categorize the forests on permafrost soil differently from the taiga forests to the south of the region. Therefore, forests on the permafrost should be considered an independent biome (Kolesnikov 1969; Parmuzin 1979; Sofronov 1991a; Sofronov and Abaimov 1991).

Peculiarities of wildfire ecology in the northern part of the permafrost zone are presented in this chapter. Typical vegetation in the region of the permafrost is the 'northern open woodlands' biome where it is characterized by forests with thin canopy (Nazimova 1996; see also Chap. 1, this Vol.). This feature is easily visible in aerial photographs. In Central Siberia, the area of the northern open woodlands extends northward from the basin of the Podkamennaya Tunguska River (63°N). The forest vegetation spreads up to 72°N due to warm summer. In the northern part of Siberia, rather sparse larch (*Larix gmelinii*) forests dominate. Typical northern taiga forests with denser canopies are located in patches only in river valleys and sites with relatively warm soils.

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There have been few pyrological studies in the northern open woodlands zone of Siberia. Stepanov (1985) investigated reforestation through natural regeneration in burnt areas of northwestern Yakutia. Sofronov (1988, 1991b) investigated pyrological characteristics of vegetation in the Turukhan River basin and in the Taimyr Peninsula. Matveev (1992) studied the consequences of wildfires in the basins of the Kheta, Nizhnaya Tunguska, Lena, and Kolyma Rivers. Tsykalov (1987, 1991) collected data of fire experiments on fuel dry mass in the region of Tura, and estimated the damage to larch stands. Fire effects and tree regeneration in burnt-over areas of the same region were studied by Tsvetkov (1994, 1998) and the Laboratory of Permafrost Forest Science group at V.N. Sukachev Institute of Forest at Krasnoyarsk (Abaimov and Sofronov 1996; Sofronov and Volokitina 1996a, 1996b; Abaimov et al. 1997; Sofronov et al. 1998a, 1998b; 2000a, b, 2001, 2004Abaimov and Prokushkin 1999). In this chapter, we summarize studies on permafrost vegetation from the viewpoint of wildfire ecology mainly in the northern parts of Western Siberia (62°–86°E) and Central Siberia (86°–108°E). New data were collected and analyzed from a few sites in Central Siberia.

We will describe subjects regarding (1) vegetation fuel; (2) seasonal condition of fuel moistening, drying, and burning; (3) conditions of wildfire spread over the territory; (4) causes and affected area of wildfires; and (5) ecological consequences of wildfire.

4.2 Approaches to Study Wildfire Ecology

Field studies were carried out at three different sites along two tributaries of the Yenisey River in Central Siberia (central Evenkia). One site was in the Kureyka River basin (67°N, 88°E). Two other sites were located along the Nizhnyaya Tunguska River: one was within the vicinity (<10 km) of Tura settlement (64°N, 100°E) at Kochechum site (Fig. 1.2, this Vol.), and the other was farther from the settlement (about 80 km west) in the basin of the Degigli River (64°N, 98°E). Details of the field study are given in Sofronov et al. (2004).

On the Kureyka River basin site, four experimental plots (K1–K4) of *L. gmelinii* dominating and mixed forests of *Betula pendula*, *Pinus sibirica*, *Larix gmelinii*, *Picea obovata*, and *Abies sibirica* at various proportions were established (Table 4.1) to examine the function of organic layer as a "thermal insulator." Stands of various species' mixtures were included so that characteristics of the organic layer could be examined for a breadth of stand types. Soil temperature was measured in each plot at the depth of 35 cm (from the surface of moss or litter layer) during midsummer (from early to mid-August). The term "organic layer" is defined as the sum of layers of moss, lichen, litter, and duff: duff means a layer of decomposing fine vegetation remnants which are under the layer of live (growing) upper part of moss and lichen or under the layer of litter. However, not all parts are necessarily present. Soil temperature was recorded in the plot ($n=5$–8 for plots K1–K3; $n=1$ for plot K4). The thickness of the organic layer was also measured in a vertical

Table 4.1 Characteristics of four experimental plots in the Kureyka River basin site

Plot number	K1	K2	K3	K4
Species composition[a]				
Upper layer	9B1P	5L 5B	7B2LIS	9BIS+P
Lower layer	10S	6S4F	–	–
Tree age (yrs-old)	90–140	110–170	100–140	110–140
Sight index	V	IV	Va	V
Tree density (ha^{-1})				
Upper layer	700	600	1,300	1,100
Lower layer	600	300	–	–
Total basal areas (m^2 ha^{-1})				
Upper layer	16.6	21.3	14.0	17.7
Lower layer	8.5	2.8	–	–
Stemwood stock (m^3 ha^{-1})				
Upper layer	120	190	90	130
Lower layer	50	20	–	–
Mean tree height (m)				
Upper layer	17	20	12	14
Lower layer	12	1	–	–
Mean diameter by species (cm)	17 (B) 13 (S) 17 (B) –	30 L 18 (B) 12 (S) 12 (F)	11 (B) 17 (L) 12 (S) –	14 (B) 13 (F) 10 (S) –
Undergrowth tree composition[b]	10 S	6S 2F	9B 1S	5S 3F 2B
Undergrowth tree density (ha^{-1})	500	200	1400	400
Undergrowth biomass ($kg\ m^{-2}$)[c]	0.05	0.11	0.22	0.20
Organic layer biomass ($kg\ m^{-2}$)				
Moss	–	0.6	0.7	1.5
Litter	0.1	–	–	–
Duff	0.2	1.5	2.1	4.1
Organic layer thickness (cm)[d]	2–3	9–11	13–17	23–27

[a] Relative proportion of each tree species based on tree density; *L*, larch; *B*, birch; *S*, spruce; *F*, fir; *P*, Siberian pine. For example, plot with 5L 5B consists of larch (50%) and birch (50%). Layers refer to those of the canopy

[b] Tree species composition belonging to the undergrowth (i.e., height of 20–300 cm); this index is called "re-growth composition" in the Russian Forest Science)

[c] Including undergrowth trees, and other shrub species and grasses

[d] Sum of thickness of litter, moss, and duff

soil profile around each point of soil temperature measurement. When studying the organic layer it was cut with secateurs for the layer structure not to be disturbed.

At the site within the vicinity of the Tura settlement, vertical soil profiles and soil temperature were examined in two experimental plots II-4 (burned plot) and II-5 (unburned plot) in Site 2 (see Fig. 1.3). These plots had different conditions of organic layers (Table 4.2. Notes: description of tiered canopy unburned plot TB-1 is used in Sect. 4.8.3). The burned plot II-4 was located inside the burnt area created by a wildfire of 1994, and its organic layer was partially destroyed; the unburned

Table 4.2 Characteristics of three experimental plots of *L. gmelinii* forests established within the >220-year-old stand at Kochechum site near Tura

	Burned plot	Unburned plot[a]	Tiered canopy
Plot number	II-4	II-5[a]	unburned plot TB-1
Slope aspect	North–East	North–East	East
Slope gradient	12°	13°	5°
Stand parameters			
Tree age (years)			
Upper layer	170–180	170–180	180–220
Lower layer			80–90
Tree density (ha^{-1})			
Upper layer	1,030	1,000	700
Lower layer			4,900
Mean tree height (m)			
Upper layer	10.0	9.0	10.5
Lower layer			4.5
Mean stem diameter (cm)			
Upper layer	11.3	9.0	11.0
Lower layer			4.5

[a] The unburnt plot II-5 was about 20 m away from the burnt plot II-4 where fire occurred in 1994

plot II-5 was set outside of the burnt area (about 20 m away from the burned plot). Tree density, mean tree height, and stem diameter at breast height were 1,030 ha^{-1}, 10.0 m, and 10.8 cm for the burned plot, and were 1,600 ha^{-1}, 9.0 m, and 9.0 cm for the intact plot, respectively (Table 4.2). In each plot, the organic layer thickness and soil temperature were measured along a line transect at 50 cm intervals by making small soil profiles (total $n=35$ for each transect). These measurements were carried out in the summer following the 1994 fire.

In order to examine the interactions between thawing soil depth, organic layer thickness, and micro-topography in detail, we established three plots in a mature larch forest (250–320 years-old) along the Nizhnyaya Tunguska River (80 km west of Tura). Large variation of micro-topography in this stand allowed us to examine its effect on soil and organic layer characteristics. One plot (P1) was on the river terrace close to a lake where micro-relief (shallow depressions and mounds in the area with elevation fluctuation usually not more than 1 m) was well-developed. The second plot (P2) was on the lower end of south-facing slope covered with dense shrubs (mostly *Duschekia fruticosa*), and the third plot (P3) was on the convex part of the slope (Table 4.3). In each plot, soil thawing depth and thickness of organic layer were measured along a line transect at 20 cm intervals (total $n=200$ for each transect). Thawing depth was measured under two different soil moisture conditions (normal year and dry year) in summer. Significance of the dependence of soil thawing depth on the thickness of total organic layers (hereafter also referred to as 'organic layer thickness') was tested by simple correlation coefficient using all data of each transect.

Table 4.3 Characteristics of three experimental plots of *L. gmelinii* forests on the site 80 km west of Tura settlement

Plot number	P1	P2	P3
Slope aspect	North	South	East
Slope gradient	2°	15°	6°
Stand parameters			
Tree density (ha^{-1})	495	665	1,191
Tree age (years)	320	300	250
Mean tree height (m)	10.5	15.0	8.5
Mean stem diameter (cm)	14.0	16.6	9.5

4.3 Vegetation Fuel

Green mosses (e.g., *Hylocomium splendense*, *Pluerozium schreberi*) commonly dominate the surface cover of northern open woodlands, and are known to be a fire-hazard. Lichens can increase the fire danger by settling on the green moss cover. Simultaneously, accumulation of litter takes place. As the organic layer thickness increases, the soil becomes progressively colder. This further slows organic matter decomposition and contributes to more litter accumulation. For example, in the Turukhan basin in Western Siberia (66–67°N, 83–86°E), dry mass of the organic layer is as large as 4 kg m^{-2} in 100–120 year-old larch stands, and can amount to 6.7–7.5 kg m^{-2} in forest stands over 200 years old (Sofronov 1988). In the northern part of Northeastern Siberia, the dry mass of organic layer (green moss, lichen, and litter) varies from 2.5 to 8 kg m^{-2} (Sofronov and Volokitina 1998). Usually an average load of green moss-lichen cover, litter, fallen branches, and combined *Vaccinium uliginosum-Ledum palustre* equals 1 kg m^{-2}, 2–3 kg m^{-2}, 0.5 kg m^{-2}, and 0.1–0.3 kg m^{-2}, respectively.

Depth of soil active layer increases in the burnt-over areas where the organic layer has been removed by fire. However, this increase in the thickness of active layer is a temporary phenomenon. It provides a suitable environment for growth of tree seedlings and understory shrubs. In the basin of the Nidym River (30 km west of Tura settlement), the height of shrubs in a 12–13 year-old larch stand was 2–2.5 m, whereas the canopy height of trees reached 4–5 m. After recovery of the moss and litter layer, about 30–50 years later, the thickness of the active layer starts to decrease again.

Northern part of Western Siberia is affected strongly by widespread wetlands called “flat frost mound bogs.” This feature is defined as hillocks consisting of ice and peat, and is alternating with thermokarst lakes and depressions. About 80% of the area is occupied by well-drained flat mounds. The mounds are composed of a core of ice mixed with peat, and are often found to be covered with both lichens (1.5 kg m^{-2}) and *Ledum palustre* (1 kg m^{-2}). This indicates that fire danger of the mounds is very high. The mounds are typical for tundra, but they are not typical swamp elements (they are dry). It is more correct to call such landscape as a complex of swamp and forest tundra, and not merely swamps or bogs (Shumilova 1962).

4.4 Seasonal Conditions of Fuel Moistening, Drying, and Burning

A characteristic trait of the permafrost is high content of ice. This is the main difference of permafrost from the seasonally frozen soils, i.e., the soil that covers the permafrost is frozen in winter and melts in summer. It is due to the ice content of the permafrost that such characteristic features as thermokarst and heaving arise and develop.

Seasonally, frozen soils can actively absorb the melting water in spring. But permafrost with its high ice content does not absorb water and acts as a waterproof layer. In spring, melted water runs off to rivers. Therefore, fires do not practically occur in the northern open woodlands zone for about six weeks after snow melt, except for the limited areas of inflammable sites covered with dry herbs and sedges on the riversides and frost mound bogs in the northern part of Western Siberia.

The thin canopy of northern open woodlands creates favorable conditions for drying of the vegetation fuel. The quantity of radiation energy and illumination under the canopy of the northern larch stands is 1.5–3 times higher than those in typical taiga stands (Table 4.4) (Sofronov and Volokitina 1998).

In the beginning of summer, only lichens and mosses become dry while the litter remains wet. Therefore, this period is characterized by running surface wildfires. Wind, the main factor of spreading fires, freely penetrates the thin canopy of northern open woodlands. Surface fires may be exceedingly intense with a flame height of more than two meters. They are harmful to the forests. Wildfires are usually surface fires since the thin canopy prevents their development into crown fires.

In summer, rain water rapidly flows into rivers and lakes. Water is nearly absent in the subsoil. Therefore, precipitation and surface water run-off provide major source of water to moisten the forest floor. Location on a micro-elevation influences water regimes of the soil, duff, and moss (Table 4.5) (Sofronov et al. 2000).

During hot and dry periods of summer, the permafrost does not thaw out actively since it is protected from the sun by the layers of moss and duff. At the same time, the duff dries out and surface fire can acquire a steady form, if there is a zone of smoldering behind the flaming front. Higher above this zone, a vertical flow of hot air keeps the wind off the frontal edge of the flame. As a result, creeping surface fire spreads slowly, lowering the fire intensity.

Table 4.4 Relative illumination under forest canopy (%, compared to open)

Zonal type	Relative basal area							
	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
(I)	70	60	50	40	30	24	22	22
(II)	(95)	90	84	76	67	59	58	(58)

(I) – in typical taiga forests of Scots pine, spruce, Siberian pine, and larch
(II) – in larch forests (parentheses indicate calculated illumination values)
Relative basal areas are characteristic of forest density used in Russia (Zakharov 1967)

Table 4.5 Classification of relief elements according to their impact on run-off distribution and soil moistening

Relief elements	Major features	Impact on run-off and soil water regime
Convex forms	Radius of curvature	Run-off dispersal, soil drainage, and dryness
Smooth upper surfaces (plateaus)	Surface gradient	Weak run-off and moderate soil moistening
Slopes	Steepness, slope aspect, slope height; upper, middle, or lower parts of a slope	Soil moistening varies from insufficient to excessive depending upon location
Concave forms (depressions, stream valleys, etc.)	Radius of curvature and bottom gradient (for unclosed depressions)	Run-off concentration and increased or excessive (including stagnant) soil moistening
Smooth lower surfaces (terraces, flood-lands)	Surface gradient and height in relation to the maximum water level in the river	Weak run-off, moderate soil moistening, sometimes flooding

4.5 Wildfire Spread over the Territory

Wildfire spread over the territory is determined by characteristics of the landscape. In the zone of northern open woodlands, three categories of pyrological landscape can be distinguished: (1) flat lowlands; (2) mountain localities (with watersheds above the altitudinal tree line); and (3) plateaus and hilly plains (with watersheds below the altitudinal tree line).

Flat lowlands are located in the northern part of Western Siberia. The number of fire breaks in this territory is large due to thermokarst lakes and humid hollows occupied by sedge-*Sphagnum* swamps. For example, the area of thermokarst lakes and humid hollows amounts to 15–20% in the region of “flat frost-mound bogs,” which is the typical landscape in Western Siberia. The average distance between fire breaks is about 1 km. Although the mounds covered with lichens and *Ledum palustre* are extremely fire-prone, lakes and humid hollows hamper the wildfire spread over the territory. However, the humid hollows and lakes are not perfect fire breaks, since wildfires can jump over them under strong winds (Sofronov 1988).

In Central and Northeastern Siberia, the territory of northern open woodlands zone includes areas of mountainous relief (Putorana Mountains, the Anabar Ridge, and mountains in the northern part of Yakutia) where vertical zonality of vegetation is common. The altitudinal tree line is at about 400 m above the sea level, and even 200 m in the Anabar Ridge. The mountain tundra followed by polar deserts is situated at even higher altitudes.

A noncontinuous vegetation floor is characteristic to the mountain tundra. Thereupon watersheds covered with noninflammable mountain tundra or mountain tundra in combination with polar deserts can be considered absolute fire breaks in the areas of open forests in the mountainous regions. A system of such noninflammable watersheds is supplemented by other fire breaks (e.g., mountain rivers and streams that remain wet in summer, and stony screes). Altogether they create considerable pyrological barriers of the territory. Therefore, wildfires cannot spread over a vast territory (maximum 0.8–1.5 thousand ha).

Plateaus and hilly plains occupy almost the whole territory of northern open forests in Central and Northeastern Siberia (with the exception of mountain localities in the northern regions). A characteristic feature of these landscapes is that watersheds, which are situated below the mountain tundra, are the most typical routes for the spread of large wildfires since there are no elevated *Sphagnum* bogs. The *Sphagnum* bogs serve as the main fire breaks in the taiga zone.

Absence of upper *Sphagnum* bogs on watersheds is explained by permafrost heaving under the patches of *Sphagnum*. This phenomenon makes the *Sphagnum* cease its growth, and it gradually dies out. Without the subsoil waters, favorable conditions for *Sphagnum* development are created only by the active moisture supply from surface water, which flows to the lower parts of north-facing slopes. Such *Sphagnum* patches of 5–10 m^2 usually do not die during fires, and begin to grow out actively after them. We often find *Sphagnum* patches of about 1 ha on north-facing slopes. These are not bogs since a core of ice is always formed under the *Sphagnum*, though small *Sphagnum* bogs sometimes develop in the upper part of hollows, foot slopes, and slope terraces (Sofronov and Volokitina 1996a). The general extent of wetland is only about 10% of the total area of the northern open woodlands zone in Central and Northeastern Siberia (the area of peat bogs is about 4–6%).

Absence of upper *Sphagnum* bogs in watersheds is also related to drying-out of streams and shallow rivers in summer because of the absence of subsoil water. This decreases the number of fire breaks on the territory to a greater extent; therefore, wildfires freely spread along watersheds and slopes, and can burn over vast areas amounting to tens of thousands of hectares.

4.6 Causes of Wildfire and Areas of Wildfire Occurrence

The northern part of Siberia is characterized by low population density. Therefore, the main cause of forest fire is not people but lightning; however, also see Mollicone et al. (2006) and Achard et al. (2008) for indirect evidence of many human-caused fires at perimeter of intact boreal forests in Russia. Lightning activity in the Taimyr region is weak: only two days with thunderstorm during a fire season is observed (Agroclimatic reference book 1961). The size of burnt area in this region is not large. To the south, in the Putorana mountains, fire breaks are numerous because unburnable mountain tundras occupy the watersheds. Therefore, burnt area is restricted here as well. On the other hand, there are favorable conditions for high fire occurrence in the forests of central Evenkia: thunderstorms in summer occur rather often, e.g., 10 days with thunderstorms at Tura, and fifteen days at Vanavara and Baikit. The watershed area has no mountain tundras and unburnable *Sphagnum* bogs. Fire can spread freely in the watershed area and cover large areas.

In the northern part of Siberia, the continental climate is characterized by warm summers with long days and short nights. Duration of the fire season is three months from the second half of June to the first half of September. The percentage distribution of wildfire occurrences for June, July, August, and September are 25, 40, 25, and 10%, respectively. But favorable weather conditions for fire (long hot dry periods) do not happen every year. Dry seasons seem to migrate on the Siberian territory. For example, in 1989, catastrophic fires occurred in Western Siberia to the south of 64°N parallel; and in 1990, to the north of it. In 1992, the forests of central Evenkia burnt extremely heavily (Sofronov et al. 1998a).

About 36% of the Russian forests are too remote to provide any fire protection. Unprotected areas are basically located in the northern open woodlands zone: in Western Siberia – 43 million hectares, in Central Siberia – 119 million hectares, and in Northeastern Siberia and the Far East – 249 million ha (Goskomstat of the Russian Federation 1993). Therefore, there is no official information on the size of burnt area in the zone of northern open woodlands.

Analysis of 1979–1984 space images for parts of the Taimura, Chuna, and Ilimpeya River basins in central Evenkia (9 million ha) gives relative evaluation of the burnt area amounting to about 1.5%, i.e., extremely high. It was found that burnt areas are seen during a six-year period after fire in the "Kosmos" space images for the Evenkia territory. Burnt areas are seen on the TIROS/NOAA thermal space images also during these six years after fire (Fig. 4.1).

Analysis of the TIROS/NOAA and SPOT-3 space images for the area near Tura settlement (10 million ha) showed that 51 large fires occurred from 1990 to 1995 (burnt areas over 1,000 ha for each fire). These fires covered 675,000 ha: 1.1% of the territory per year. According to "Soyuz" space images, 20 large fires occurred between 1978 and 1989 on the same territory; burnt area being about 300,000 ha: 0.3% of the territory per year. They characterize that the area surrounding Tura is highly burnable (the average fire recurrence time is 60–90 years) (Sofronov and Volokitina 1996b; Sofronov et al. 1998a).

4.7 Wildfire Impact on Larch Regeneration

There is always much light under the canopy of northern open forests; however, regrowth is not abundant. Even in old stands (> 200 years), sapling density does not customarily exceed one thousand per ha. Root competition with old larch trees may not be the cause. For example, in the Degigli River basin (the tributary of the Nizhnyaya Tunguska River), there were no larch seedlings in a stand where the larger larch trees had died of natural causes other than fire ten years earlier.

Considerable thickness of the moss and duff layers is likely to influence the larch regeneration negatively. In other words, thin organic layer on the forest floor is likely to promote establishment of larch seedlings. For example, the number of tree seedlings was 3–10 thousand per ha in larch stands after weak intensity fires, which generally reduce the moss layer thickness (Matveev and Usoltsev 1991). A comparison of a fire-disturbed site and unburned control near Tura settlement suggests a similar pattern (Sofronov and Volokitina 1996b). The control plot had

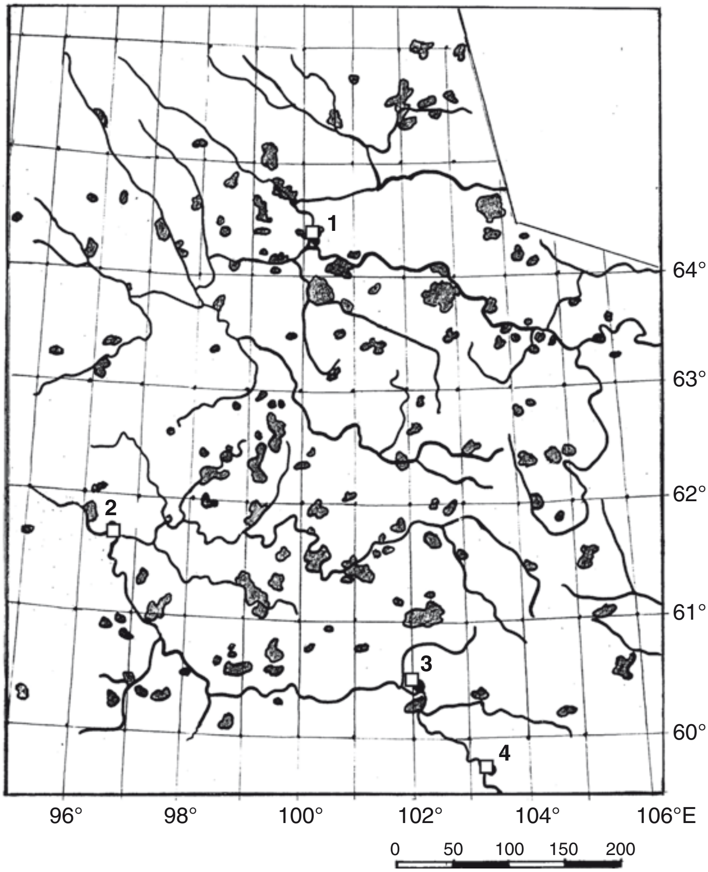

Fig. 4.1 Large burnt areas (> 1,000 ha) in Evenkia, the northern part of Central Siberia, from 1990 to 1995 (from TIROS/NOAA satellite images). Numerals 1–4 represent the towns of Tura, Baikit, Vanavara, and Chemdalsk, respectively

170 year-old larch trees, 10 m high. There were almost no regrowth (12 seedlings per ha). The mean thickness of the organic layer (moss, lichen, and duff) was 17.3 cm. The burnt plot had 37% of old trees that had died in a fire one year earlier. The number of larch seedlings was 165 thousand per ha there. We noted that the seedlings have become established successfully where thickness of the organic layer was 4.2 cm. On the other hand, seedlings were absent where the mean thickness of organic layer was 6.3 cm.

Similar impact of the organic layer thickness on forest regeneration was also observed in a nearby larch stand disturbed by a creeping ground fire 8 years ago. There was abundant larch regeneration (about 60,000 seedlings per ha) in 3.5 cm of moss and duff layer; but the regeneration was absent in 6.6 cm of moss and duff layer.

In the vicinity of the Tura settlement, there is an old 7-ha clear-cut of 1970. This clear-cut had only 180 small larch trees and saplings of various sizes (0.8–2.5 m high) per ha. The thickness of the moss and duff layer was 15–24 cm. It is probable that the large thickness was the cause of seedlings' absence. A fire occurred in this clear-cut in August 1994. In the following summer, larch saplings were counted with a linear method. The transect to forest edges did not exceed 100 m. The transect was 236 m in total length, and sample plots (0.5 m^2 each area) were set at 4 m intervals. Seedling density was 135 thousand per ha. Analysis of the obtained data showed that larch seedlings become established only in small depressions and on flat places. The thickness of the organic layer was 2 cm when the seedlings were the densest. The thicker the organic layer, the lesser the number of seedlings. Regrowth was almost absent when the organic layer was 8–10 cm thick.

Examination of 1–5 year-old burnt areas suggests that optimal conditions for larch seedling establishment are created under partial burning of the forest floor, since the partly burnt duff plays the role of mulch, and prevents the soil from drying.

It is concluded that the main barrier to larch regeneration in the northern open woodlands is the moss and duff layer that is typically 10–25 cm thick. Satisfactory larch regeneration can take place where the organic layer thickness has decreased to 2–5 cm as a result of wildfires.

4.8 Ecological Effects of Wildfires

In the forest ecosystems of northern Eurasia, pyrogenic succession occurring after fires is predominant. Fire impact leads to dynamic biodiversity (for details, see Chap. 5, this Vol.). Fire with a certain periodicity can stabilize biodiversity within a large territory, though fire impact on each ecosystem may be destructive (Furyayev 1996).

The effects of fire on forest ecosystems depend on their periodicity and intensity. The absence of fires during a very long period not only promotes predominance of climax stages in plant communities, but also can lead to a gradual degradation of the forest vegetation and to its replacement by different nonforest vegetation types. In the forest ecosystems of northern Siberia, absence of fire promotes the increase in moss and duff layer and decrease in soil temperature. This leads to active permafrost development and exacerbates the poor soil conditions (Sofronov and Volokitina 1996a, 1996b, 1998). As a result, forest ecosystems may be replaced by a forest tundra or tundra ecosystem.

Frequency of forest fires may be categorized into three types: rare, frequent, and very frequent fires. The first type is likely to affect a given forest approximately once in a century; the second type occurs once every 20–30 years; and the third type may be as frequent as every 3–5 years. Rare fires provide "natural rotation" of boreal forests. Fires with such a periodicity act as the periodic natural factor that allows existence of stable forest vegetation and relatively high biodiversity of plants in the forest ecosystems of northern Eurasia.

Frequent fires are likely to act as a destructive factor in forest ecosystems. When young stands are destroyed by fire, regeneration is difficult for the absence of seeds.

This may lead to replacement of the forest vegetation by nonarboreal vegetation such as meadow, shrub, or tundra.

Very frequent fires will be less intense, but may function as a factor that favors stability. Very frequent fires do not allow vegetation fuel to accumulate, and therefore, exclude possibility of intense fires.

In the zone of northern open woodlands, forest vegetations are likely to be affected by three major factors: (1) soil temperature regime, (2) soil water regime, and (3) soil fertility (nutrient status). These factors are interdependent and depend also on other factors (Sukachev 1931). There is a complex relationship between the regimes of water and temperature in the soil. A schematic diagram of the complex relationships among the different factors within the permafrost of northern Siberia is shown in Fig. 4.2.

Soil thawing depths are generally less than one meter in the larch forests, except for some peculiar sites, such as stands near streams, near edges of slopes, and on sandy soils. The soil thawing depth is further affected by the thickness of the organic layer covering the ground surface.

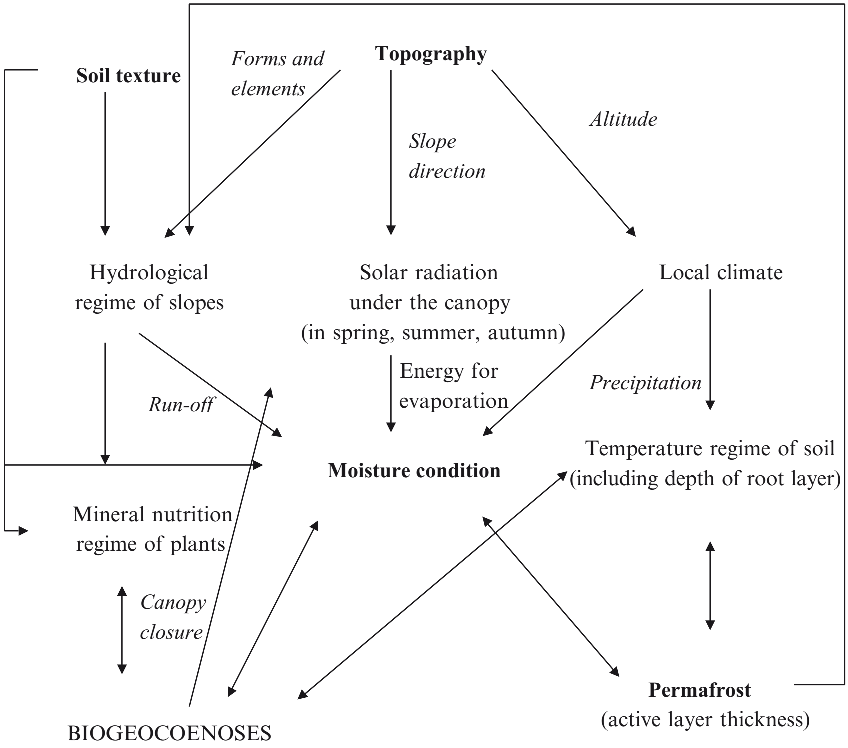

Fig. 4.2 Schematic diagram of the relationship between ecological factors and their influence on the ecosystems in the northern open woodlands of Siberia

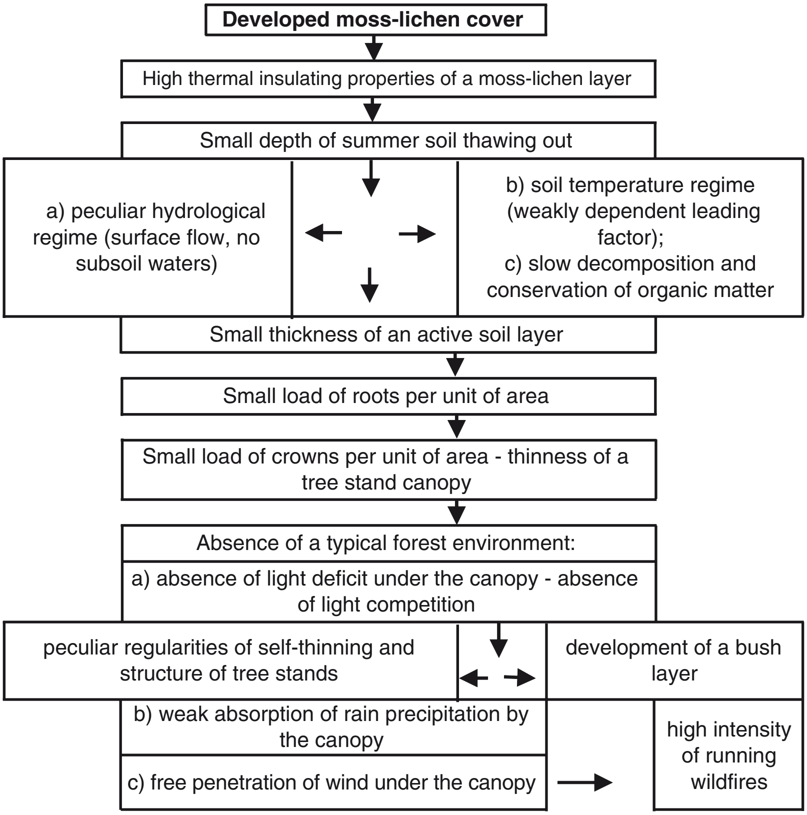

Fig. 4.3 Role of moss-lichen cover in the ecological chain of physical environments, tree growth, and fire disturbance in the larch forest ecosystem of northern Siberia

Temperature regime of the soil is more or less independent of air temperature, since the organic layer functions as a considerable thermal insulator. The organic layer weakens the influence of air temperature on soil temperature: the difference between surface air temperature and soil temperature is large in the summer (Pozdniakov 1986). The summer surface temperature often exceeds 40°C just above the moss-lichen layer with thickness of 15–30 cm on the weakly drained terrace. However, the soils can still be frozen under this cover (Sofronov 1988). This is primarily due to the low heat conductivity of moss-lichen and duff layers, especially under dry condition (Oechel and Van Cleve 1986). Therefore, such organic layer is an important component, affecting many ecological processes in the larch forest ecosystem.

If we consider the moss-lichen layer as the initial component throughout the chain of ecological processes (Fig. 4.3), it will cause both direct and indirect effects on the soil temperature and hydrological regimes (Sofronov and Volokitina 1998). However, details of each process are to be further studied, since many factors are involved interactively. The moss-lichen cover is disturbed by periodical wildfires, and its function as the thermal insulator varies temporally: the summer soil thawing depths change after fire in response to recovery of the organic layers (Pozdnyakov 1986). If wildfires are absent for a long time, the thickness of the organic layer increases. Then, the soil becomes progressively colder, further slowing organic matter decomposition and contributing to further accumulation of duff. For example, the 100–120 year-old pyrogenic larch stands in the Turukhan basin have an organic layer thickness of 8–10 cm, whereas the stands over 200 years have a layer thickness of 22–27 cm (Sofronov 1988).

According to such recovery of moss-lichen and duff layers, the average depth of soil active layer will be reduced gradually, and growth rate of larch individuals will also decrease greatly (Sofronov 1991a). Thus, to clarify the effects of moss-lichen cover on both the physical environment and tree growth in this forest ecosystem, we need to pay attention to the influence of periodic fire disturbance on every process of the ecological chain shown in Fig. 4.3.

4.8.1 Soil Temperature

Soil temperatures at the depth of 35 cm (T35) varied within each plot, as well as among the four plots on the Kureyka River site (Fig. 4.4). If all data are compared, T35 decreased from 8 to 0°C with the increase of organic layer thickness (OL; being the sum of litter, moss, and duff; lichen was absent here) from 2 to 30 cm. This negative relationship indicates that the moss and duff organic layers play a major role as a thermal insulator, since the amount of litter accumulation in each plot (<0.1 kg m^{-2} in biomass) is much smaller than that of the moss (0.6–1.5 kg m^{-2}; except K1) or duff (0.2–4.1 kg m^{-2}) layers (Table 4.1).

Figure 4.5 compares vertical soil profile and change of soil temperature between the two larch stands in Site 2: II-5 shows the unburned site and II-4 shows the burned site. In both plots, soil temperature decreased sharply within the upper organic layers. However, the thickness of the organic layer was much thinner in burned plot II-4 (only duff, about 5 cm) than in unburned plot II-5 (moss and duff, about 18 cm), and soil temperature just below the organic layer was much higher in II-4 (about 12°C) than in II-5 (about 5°C). Consequently, the soil thawing depth in late summer differed considerably between the two plots, and the potential rooting layer (Rt) above the frozen soil (Pf) was much deeper in the burned plot than in the unburned one (Fig. 4.5). This indicates that ground-fire disturbance improves the thermal condition of the soil for plant growth by eliminating moss and duff covers.

4.8.2 Summer Soil Thawing Depth

A preliminary survey around the Tura settlement (including a site 90 km west) indicated that summer soil thawing depth on a site that burned recently and inside a larch

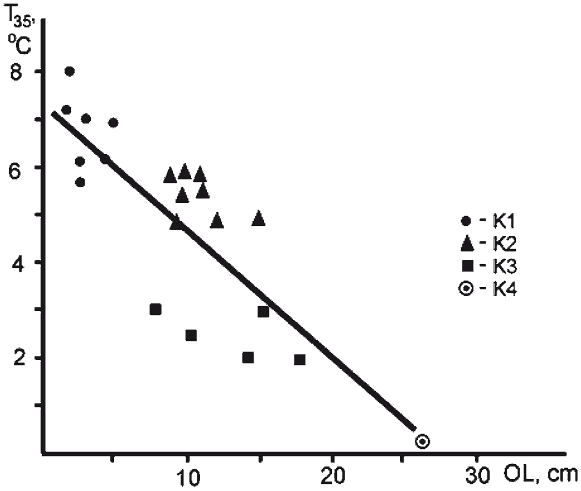

Fig. 4.4 Relationship between depth of organic layer (OL: moss, litter and duff) and soil temperatures (T_{35}: at 35 cm from the surface of moss or litter) in four experimental plots (K1-K4) of the Kureyka River basin site (See Table 4.1). Measurements were made from early to mid-August

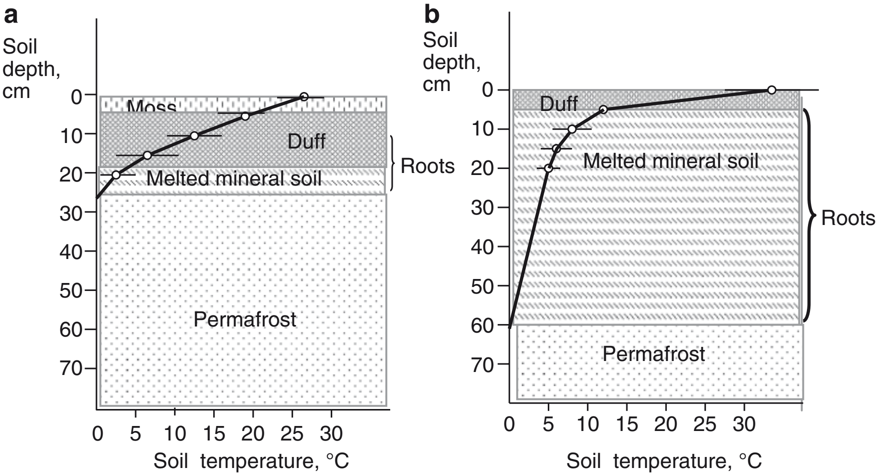

Fig. 4.5 Vertical soil profiles and soil temperatures in the two experimental plots of *L. gmelinii* forests at Site 2 near Tura, (**a**) unburned plot II-5 and (**b**) burned plot II-4 by 1994 surface fire. T: Mean soil temperature with standard deviation (*bars*)

forest was negatively related to the average thickness of the moss and duff layers. However, the thawing depth is also dependent on other factors, such as the slope aspect and earth hummock micro-topography (Sofronov et al. 2000a, 2000b).

Table 4.6 summarizes thickness of each component of the organic layers (here called “prime conductors of burning”, PCB) in three larch stands near Tura (P1–P3).

Table 4.6 Coverage area and average thickness of prime fire carriers, total organic layer thickness (TOL), and summer soil thawing depth (STD) in three experimental plots on the site 80 km west of Tura settlement. (after Sofronov et al. 200b)

Plot number	P1	P2	P3
Coverage area (%)			
Lichen[a]	–	–	23
Green mosses[b]	68	74	44
Mixture of mosses and lichen	26	4	30
Litter (α-layer)	2	8	–
Duff[c]			
F-layer	94	–	95
H-layer	86	83	92
Bare ground	4	14	3
Thickness (cm)[d]			
Lichen	–	–	5.3 ± 1.6
Green mosses	5.6 ± 1.4	4.2 ± 1.3	3.5 ± 1.2
Mixture of mosses and lichen	6.6 ± 1.4	3.4±1.6	2.5±1.4
Litter (α-layer)	2.0 ± 0.5	2.0 ± 0.5	–
Duff			
F-layer	7.6 ± 3.1	–	4.6 ± 1.3
H-layer	8.0 ± 4.0	11.3 ± 3.8	10.7 ± 2.4
Average TOL (cm)[e]	21.2 ± 3.8	17.7 ± 3.6	18.8 ± 2.0
Soil thawing depth (STD) (cm)[f]			
In late July (normal condition)	46	39	44
In late July (drought condition)	44	44	50
Correlation of STD with TOL[g]			
Soil thawing depth (normal condition)	−0.22	−0.18	−0.07
Soil thawing depth (drought condition)	−0.19	−0.04	0.44*

[a] *Cladina* species

[b] *Pleurozium schreberi* prevails

[c] Duff was separated into two components: dead moss (F-layer) and decomposed moss (H-layer)

[d] Average and standard deviation for each component of organic layers

[e] Sum of the thickness of each component estimated by multiplying the average thickness by average coverage area (%) within each plot: this is not equal to the sum of absolute values of the average thickness determined separately for each component of organic layers

[f] Soil thawing depth measured under two moisture conditions (normal and dry) in late July; each value shows average of all measurement points along the transect of 40 m long

[g] Simple correlation coefficient of the relationship between TOL (absolute value) and STD using all data at each measurement point; correlation was significant at $p = 0.05$ (*)

Additionally, the results of the correlation analysis between total organic layer thickness (TOL) and soil thawing depth (STD) are shown. In each plot, duff (F- and H-layers) covered the ground surface densely (11–16 cm thick) among the components of organic layers, and TOL reached 20–30 cm. There were no significant relationships between TOL and STD, except for one case in P3 where the STD measured under dry soil condition was positively correlated with TOL ($r = 0.44$, $p < 0.05$).

No clear dependence of STD upon TOL (Table 4.6) may contradict the pattern that soil temperature (T35) generally decreased with increase in organic layer thickness (Fig. 4.4). However, the present data (P1–P3) were obtained from multipoint measurements along line transects across the earth hummock micro-topography. Namely, the transect included both convex (elevated mounds) and concave (depressed hollows) parts, and the TOL–STD relationship differed largely between these two contrasting micro-topography. Soils on the concave parts were generally colder, and thawed more slowly during the early summer, resulting in much shallower soil thawing depths than that observed in the soils on the convex parts. Thickness of the organic layer may not be of major importance under this situation (e.g., Sofronov et al. 2000a, 2001; Kajimoto et al. 2003). As seen in Fig. 4.6, spatial variation of the thawing depth is considerable. Therefore, multiple measurements are required to determine the average thawing depth. Weak correlation between TOL and STD in each larch stand is likely to reflect the large variation in soil thermal regime due to micro-topography. Further discussion of the interaction between thickness of organic layer and summer thawing depth in relation to micro-topography requires additional data and analysis.

It should be noted that summer soil thawing depth in the permafrost zone depends not only on organic layer thickness, but also on relief (convex or concave relief, slope steepness, and aspect) of the plot. It is known that southern slopes are warmer and northern slopes are colder than horizontal plots. Upper part of slopes and convex elements are better drained. This tends to increase the soil thawing depth. Lower part of slopes and concave elements are likely to be wet. This tends to decrease the soil thawing depth. Tables 4.6 and 4.7 show the impact of a complex of factors on soil thawing depth (Sofronov and Volokitina 1998). It is deep at locations with well-developed hummocky micro-topography (Fig. 4.6c).

It is a well-known fact that the depth of summer thawing of permafrost soils increases in burnt-over areas where the organic layer was partly destroyed by fire

Table 4.7 Mean values of depth of soil thawing and thickness of soil organic layer examined in the study site at the basin of the Degigli River

Plot number[a]	1	2	3	4	5	6	6c	7
Organic layer thickness (cm)	15	16	23	19	7	7	19	12
Soil thawing depth (cm)	49	9	44	50	47	59	30	47
Length of transect (m)	30	30	30	30	300	40	40	40

[a] Notes on plots examined: Plot 1 is *Ledum*-green moss larch stand on the flat eminence; Plot 2 is *Duschekia*-green moss larch stand on the lower part of the southern slope (8°); Plot 3 is shrubmoss larch stand on the river terrace; Plot 4 is-*Ledum*-lichen-green moss larch stand on the convex slope; Plot 5 is 1990 burnt area, the lower position of the northern slope (10–20°); Plot 6 is 1990 burnt area, river terrace; Plot 6c is dwarf shrub-green moss larch forest (control for. 6); and Plot 7 is 1975 burnt area on the river terrace. All plots were located in the basin of the Degigli River (64°N, 98°E). Observation period is July 1991 for plots 1–4, and July 1992 for plots 5, 6, 6c, 7 (after Sofronov and Volokitina 1998; Sofronov et al. 2004)

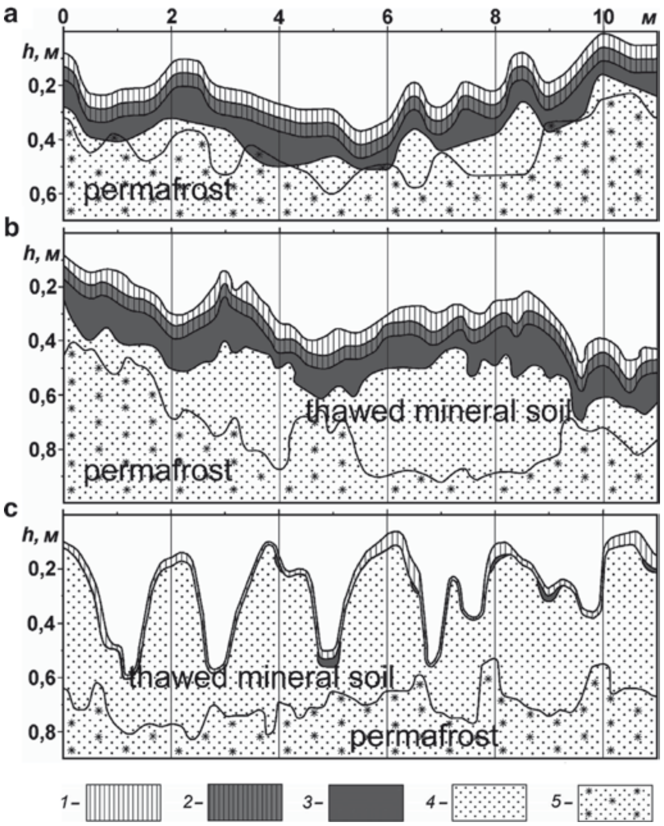

Fig. 4.6 Cross-section of transects with measured thawing depths and thickness of the moss and duff layers. Transects: (**a**) *Ledum*-moss larch forest (unburned plot II-5, Table 4), date of measurements August 3, 1995, (**b**) *Ledum*-lichen-moss larch forest (plot P3, Table 5), date of measurements August 10, 1991, and (**c**) lichen-moss larch forest with hummocky topography on river terrace gently sloping (3°) to the south (about 300 m west of the unburned plot II-5), tree stand: 175-year-old trees with an average height of 8.9 m, 1,120 trees ha^{-1}, date of measurements August 3, 1995 (location see Fig. 1.3, this Vol.). 1 – live part of moss and lichen; 2 – dead part of moss and lichen; 3 – duff; 4 – melted mineral soil; and 5 – permafrost

(Pozdnyakov 1986). For example, according to our field research in a green moss-*Ledum*-larch stand (plot II-5, Table 4.2), the mean thawing depth in early August 1995, measured from the moss surface on a transect of 20 m long, was 25 cm, and the mean thickness of the moss and litter layer was 17 cm. Nearby, in a similar larch stand affected by a creeping surface fire in August 1994 (plot II-4, Table 4.2), the organic layer decreased to 5 cm (i.e., 3.5 times). Due to this, thawing depth increased up to 72 cm (i.e., 3 times) (Sofronov et al. 2000b).

No connection was found between wildfire and "classical" forms of thermokarst (i.e., depressions, lakes). On steep slopes, wildfire often causes the development of a peculiar form of thermokarst – solifluction. When moss and litter are destroyed by fire, the soil on the slopes is washed off by spring water and/or heavy rain. As a result, permafrost begins to thaw out actively, further intensifies the wash-out, and prevents forest floor and litter layers from developing. In places of active thawing out of large ice lenses, mud streams may develop. Sometimes they are active periodically, throwing out a large mass of material that rushes down as mud flow (Sofronov and Volokitina 1998).

4.8.3 Influence of Fires on Growth of Larch Trees

Larch trees in northern open forests in Siberia are 5–15 m high and have a shallow root system. The running surface fire that usually occurs in early summer can damage or destroy forest stands by crown heating. Therefore, creeping ground fire (with active smouldering of duff) that damages tree roots and causes tree mortality are common during the period of summer drought in July and August. Trees may tip over in case of complete burning of the roots.

In central Evenkia, fire is a major disturbing factor (Abaimov and Sofronov 1996). The average interval of fire events is about 80 years (Sofronov et al. 1998a). According to our reconnaissance along the Nizhnyaya Tunguska and Kochechum Rivers near the Tura settlement, this territory suffered from wildfire intensively early in the twentieth century (Sofronov et al. 1998b). To examine how such fire disturbance influenced the growth of larch trees, we analyzed tree-ring data obtained for some *L. gmelinii* trees growing on an old burnt site near Tura (a tiered canopy unburned plot TB-1; Table 4.2). This larch stand experienced a fire about 90 years ago (in 1910) and contains two age groups of trees (or two different layers) at present. The older trees (180–220 years old) form the upper canopy layer. They escaped the damage of the 1910 fire. The younger trees (80–90 years old) of the lower canopy layer were regenerated mostly after the fire. Tree density, mean tree height, and stem diameter were 700 ha^{-1}, 10.5 m, and 11 cm for the older age group; the values were 4,900 ha^{-1}, 4.5 m, and 4.5 cm for the younger age group, respectively (Table 4.5). For the analysis of individual growth patterns, three larch trees were selected from the older age group, and five trees were chosen from the younger age group. The diameter growth curve of each tree was reconstructed by reading the annual ring-widths on each stem disk sample. Stem disk samples were taken at a height of 1.3 m for the younger trees, while the disk samples were taken at a height of 0.5–1 m for the older trees in order to include the parts with fire scars. On this plot (TB1), the thickness of the organic layer was 15–20 cm (with only moss and duff layers as lichens did not occur at this location) and summer soil thawing soil depth was about 30 cm (Table 4.2). Figure 4.7 shows that growth rates of younger trees (No. 4 and 5) were relatively high during the early growth stage, but decreased gradually in 30–40 years after regeneration. As for two older trees (Nos. 2 and 3; ca. 200 years old), which regenerated before the fire of 1910, their growth rates were also reduced for several decades after the regeneration of each tree. However, growth rates recovered after the depressed stage (i.e., 110–150 years

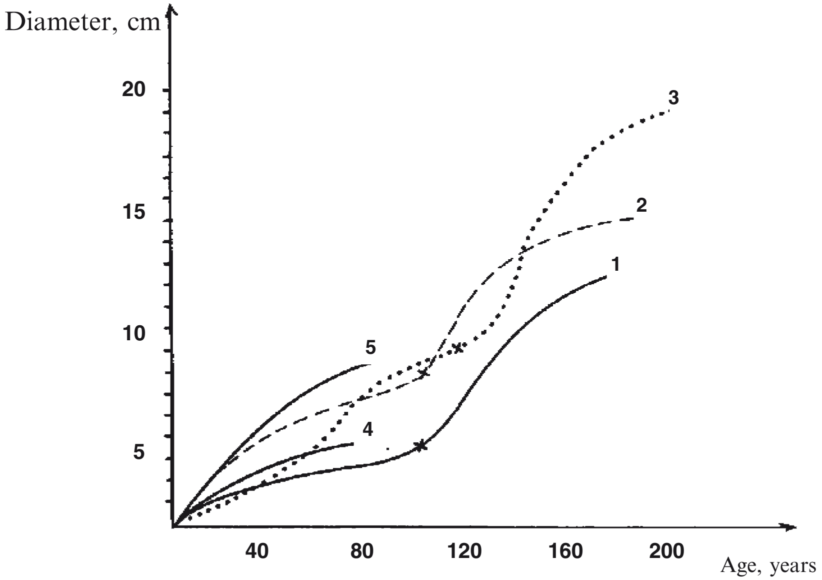

Fig. 4.7 Examples of stem diameter (D) growth curves for the *L. gmelinii* trees of the old burnt plot (TB-1) at Kochechum site near Tura. Three trees (No.1–3) of older age-group regenerated before the surface fire of 1910. Two trees (No.4–5) of younger age-group regenerated after the fire. *Cross mark* (x) in each growth curve of the three older trees (No.1–3) shows the year of 1910 surface fire

after regeneration). This growth recovery ("rejuvenation phenomena") occurred just after the 1910 fire. Likewise, the other older tree (No.1, ca. 220 years old) also showed a growth recovery after the 1910 fire (Fig. 4.7). These patterns suggest that growth activities of the larch trees, if they can escape heavy damage, are often enhanced by ground fire. The postfire growth recovery might be primarily a result of the amelioration of soil-temperature due to burning of the organic layers that act as thermal insulation (Table 4.2). In addition, other effects of fire disturbance, such as nutrient release from the organic layers (Oechel and Van Cleve 1986) and elimination of competitors for the uptake of soil nutrients, may also contribute to the rejuvenation phenomena of the surviving larch trees.

Figure 4.7 also indicates that the older trees can double in size (10–20 cm in diameter) after fire impact compared to the size before the fire (less than 7–8 cm). This supports the results of a previous study (Matveev and Abaimov 1979). They examined growth patterns of seven larch trees (up to 160 years-old) growing on four different sites within the continuous permafrost zone of Siberia, and showed that diameter growth rates after fire were 1.25–1.52 times higher than those before the fire disturbance. Likewise, such a positive effect of fire on individual tree growth was observed among old larch trees (150, 170, and 250 years-old) in central Evenkia (Abaimov et al. 1997; original data from M. Arbatskaya).

According to our data and previous findings, the growth pattern of *L. gmelinii* in central Evenkia (area directly north of Krasnoyarsk region) might be characterized by two distinct growth stages. The early stage just after fire regeneration has relatively high growth rates (both in diameter and height) and the subsequent stage shows several decades of conspicuous growth reduction (see also Fig.6.5, this Vol.). The beginning of the second growth stage, which depends on the speed of recovery of the moss-lichen and duff layers, could differ somewhat depending on the sites (Sofronov 1988). As for the evergreen taiga in Alaska, it is also known that postfire recovery of moss and lichen layers takes place 25–50 years following fire disturbance, during which time the active layer depth returns to its original level (Viereck 1982; Dyrness et al. 1986).

Our study showed that moss-lichen layers functioned as an important "thermal insulator," and regulates conditions of the summer soil temperature in the larch forest ecosystem of central Evenkia. It also suggested that the insulative function of the moss-lichen cover was eliminated by periodic fire disturbances, which results in enhanced growth rates of the survived larch trees. In terms of forest management in this region, we conclude that prescribed fires may be a way of increasing timber production of individual trees by eliminating the thermal insulator and ameliorating the soil environment, i.e., increasing soil temperature and available soil nutrients. There are, however, some problems that should be taken into consideration before applying the prescribed fire. For example, it is necessary to calculate and/or select optimal conditions for prescribed fire carefully by noting the fact that *L. gmelinii* is a fire-resistant species and extent of fire damage is largely dependent on tree size (Sofronov and Volokitina 1990). Nevertheless, on cold permafrost soils, prescribed burning may achieve effective "thermal amelioration" of the stands with low productivity (Sofronov et al. 2001). The 50–160 year-old larch trees growing on permafrost soils are under growth depression for a long time. They might enter a typical stage of growth rejuvenation by the fire impact, leading to considerable increases in tree size.

4.9 Conclusions

In the northern part of Siberia, larch (*L. gmelinii*) forests develop on permafrost soils with shallow depth of soil thawing in summer. The forests are characterized by thin canopy regardless of tree density. Therefore, light competition that is typical for the other forest biomes is less important and replaced by root competition. Such an ecosystem seems common in the northern open woodlands, with wildfire being an important ecological factor.

The zone of northern open woodlands has the following pyrological features in the Northeasten, Central, and Western Siberia:

- Predominance of fire-susceptible green mosses and lichens on the forest floor.
- Absence of upper sphagnum bogs and limited extent of swamps in the whole territory due to the lack of water in the subsoil in the permafrost.
- Long-term moistening of the moss and duff layers in spring and their subsequent drying during summer droughts.

- Free penetration of the main factors of fire intensity and speed – solar radiation and wind – through thin canopy of tree stands.
- Lightning as the main ignition source due to low population density.
- Low frequency of fire breaks in the territory with moderate relief of mountain and hills, and high frequency of fire breaks in the mountains and in the Western Siberian Plain.
- Many large and intense wildfires occur in some years.
- Wildfire causes tree mortality, but creates favorable conditions for forest regeneration by reducing the thickness of moss and duff layers.
- Reduction in the thickness of moss and duff layers increases the depth of summer soil thawing and temporal effect of "thermal melioration".

In the zone of northern open forests, wildfire creates a traditional ecological function as well: it causes postfire succession and maintains biological biodiversity. It is likely that without fire there would be a progressive cooling of the soil in this region as a result of constant increase of the organic layer. The cooled soil then feeds back to further increase in the organic layer thickness. This process could eventually lead to the development of a treeless tundra biome.

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