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The Ecological Role of Moss-Lichen Cover and Thermal Amelioration of Larch Forest Ecosystems in the Northern Part of Siberia

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Abstract

Forest ecosystems in the northern part of Siberia are generally dominated by sparse larch (*Larix gmelinii*) forests consisting of individual trees with thin crowns. This sparse stand structure is considered to be linked primarily to the limited thawing depth of permafrost soils in summer. The depth of soil thawing is further affected by organic layers, which densely cover the ground surface, such as moss, lichen, litter and duffs. Particularly, the moss-lichen layer functions as a "thermal insulator", and predetermines the soil temperature and hydrological regimes. This paper deals with data regarding field observations, and analysis concerning such functions of the organic layer, and discusses how individual growth is linked to the unique environments that are under the influence of periodical fire disturbances in this forest ecosystem. The field data show that the depth of soil thawing increased with a reduction in the moss-lichen and duff layers thickness. Summer soil temperatures (at 35cm depth) were much lower at the sites with thicker organic layers than the sites with thinner ones. Growth pattern analysis showed that the diameter growth rates of younger larch trees (i.e., regenerated 80-90 years after the ground surface fire) were relatively high in the early stages, but decreased gradually for 30-40 years after the regeneration. This growth decline was likely to be caused by the reduction of the average soil thawing depth as a result of the recovery of the moss-lichen and duff layers. As for some older larch trees (i.e., 200-220 years-old) which had survived the fire damage, they also experienced the same depressed growth stage up to the fire event. After the fire disturbance, however, the growth rates recovered sharply, indicating that organic layers were destroyed by fire and soil-temperature conditions were improved or initialized. Based on these findings, it's recommended that prescribed burning of the moss-lichen layers (i.e., artificial surface fires) may be a useful technique for increasing the potential timber production of the larch trees in this region where forest productivity has shown a low potential.

Key Words: fire disturbance, larch forest ecosystems, moss-lichen cover, northern part of Siberia, organic layer, thermal amelioration.

Introduction

Trees are known to function as an edificator of physical environments in a given forest ecosystem. Namely, environments inside the forests with a closed canopy structure are modified to some extent when compared with the sparse forests or open woodlands. For example, they have lower solar irradiance input on the ground surface, smaller daily fluctuation of air temperatures, and lower wind speeds. In the northern part of Siberia, however, rather sparse larch (*Larix gmelinii*) forests dominate and individual trees have relatively thin crowns. This sparse forest zone expands from the Podkamennaya Tunguska River basin (63°N) to the northern part near the tundra region of Taimyr (71-72°N). Relative basal areas of these larch forests are only about 0.3 (Zakharov 1967), in other words the relative value of total basal areas when compared with the normal level (=1) of a typically closed forest in Russia. Under such open-growth conditions, the effects of trees' existence on environmental modification are considerably diminished. For example, in the northern larch stands, the solar irradiance input on the ground surface is 1.5-3 times larger than those of well-closed taiga forests (Sofronov and Volokitina 1998). The amounts of rainfall intercepted by canopy layers are only half of those of the typical closed forests (Volokitina *et al.* 1998). Also, winds blow freely inside the forest, which results in a high frequency of running fire events (or ground-fires) in this region (Sofronov and Volokitina 1996).

The formation of the sparse larch forests, as well as the thinner crown forms of individual trees, seems to be linked primarily with the limited depth of soil thawing in summer (in other words, the thickness of the active

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soil layer). Soil thawing depths are generally less than 1m, except for some particular sites, such as those near streams, on the edges of slopes, and on sandy soils. The soil thawing depth is further affected by organic layers, such as moss, lichen, litter and duffs, that densely cover the ground surface (Sofronov 1988). Although summer temperatures often exceed 40°C just above the surface of the moss-lichen layers (with a thickness of 15-30cm on the weakly drained terrace), frozen soils still remain under this coverage. This is primarily due to the low heat conductivity of the moss-lichen and duff layers, especially under dry conditions (Oechel and Van Cleve 1986). Therefore, such an organic layer is an important component, and could play a key role in the chain of many ecological processes in the larch forest ecosystem (Fig. 1).

As illustrated in Fig. 1, if we consider the moss-lichen layer to be an initial component in the chain of ecological processes, it could cause direct and/or indirect effects on soil temperature and hydrological regimes (Sofronov and Volokitina 1998). However, we do not yet understand the details of each and every process of the chain in which many factors interact in many ways. For example, the moss-lichen cover can be disturbed by periodical wildfires, and its function as a thermal insulator can change temporarily. For example, summer soil thawing depths change after fires in response to the recovery of organic layers (Pozdnyakov 1986). Following such recovery of the moss-lichen and duff layers, the average depth of the active soil layer will be reduced gradually, and growth rates of the individual larch trees will also decrease to a great extent (Sofronov 1991). Thus, in order to clarify the effects of the moss-lichen covers on both the physical environments and tree growth in the larch forest ecosystem, we need to pay attention to the effect of periodical fire disturbances on each process within the ecological chain shown in Fig. 1.

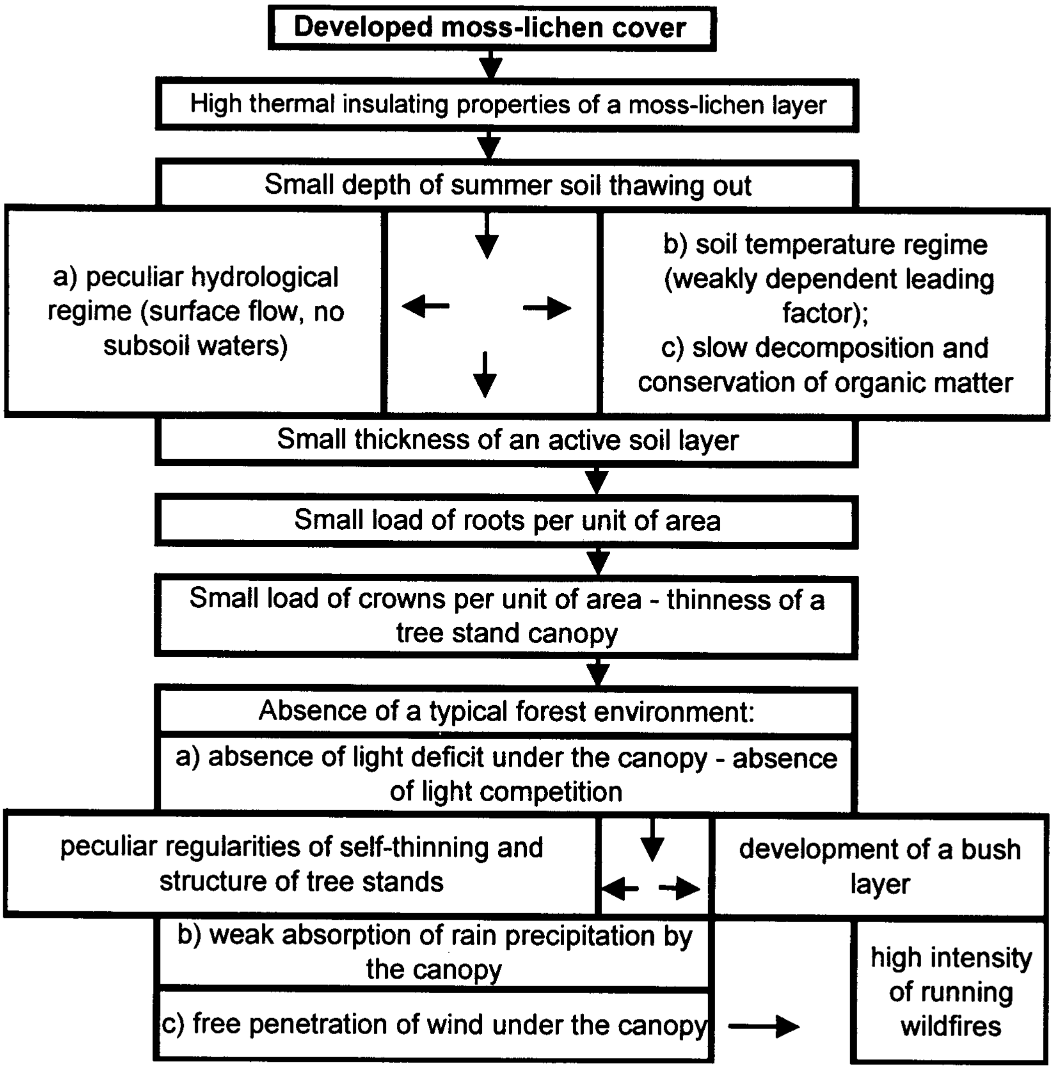

Fig. 1. Roles of moss-lichen cover on ecological chain of physical environments, tree growth and fire disturbance in the larch forest ecosystem of northern Siberia.

In this paper, we report some data from field observations and analysis obtained from the different larch forests in central Siberia (here, called "Central Evenkia"), and discuss the function of organic layers as the "thermal insulator" focusing on the following three topics:

1) The dependency of the soil temperature on the thickness of the upper organic layers,
2) The relationships between summer thawing soil depth, micro-relief and fire disturbance,

and

3) The effects of ground-fire (i.e., independent fire) on the growth patterns of the larch trees.

Materials and methods

Study site

Field studies were carried out at four different sites along the two branches of the Yenisey River in central Siberia. One site was in the Kureyka River basin (67°N, 88°E), and the other three sites were located along the Nizhnya Tunguska River; two were within the vicinity (<10km) of Tura settlement (64°N, 100°E), and another was farther from the settlement (about 90km west).

Field measurements and analysis

1. Soil temperature

In the Kureyka River basin site, four experimental plots (K1-K4) of *L. gmelinii* dominated and co-mixed forests were established (Table 1). To examine the function of the organic layer as the "thermal insulator," soil temperatures were measured in each plot at a depth of 35cm (T_{35}; from the surface of moss or litter layer) during mid-summer (from early to mid-August). In this paper, the term "organic layer" is defined as the sum of

Table 1. Characteristics of four experimental plots in the Kureyka River basin site.

	Plot			
	K1	K2	K3	K4
Species composition 1)				
Upper layer	9B1P	5L 5B	7B2L1S+P	9B1S+P, F
Lower layer	10S	6S4F	–	–
Tree age (yrs-old)	90–140	110–170	100–140	110 – 140
Sight index	V	IV	Va	V
Tree density ($\mathrm{ha^{-1}}$)				
Upper layer	700	600	1300	1100
Lower layer	600	300	–	–
Total basal areas ($\mathrm{m^2\,ha^{-1}}$)				
Upper layer	16.6	21.3	14.0	17.7
Lower layer	8.5	2.8	–	–
Stemwood stock ($\mathrm{m^3\,ha^{-1}}$)				
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)	30 (L)	11(B)	14 (B)
	13 (S)	18 (B)	17(L)	13 (F)
	17 (B)	12 (S)	12(S)	10 (S)
	–	12 (F)	–	–
Undergrowth tree composition 2)	10 S	6S 2F	9B 1S	5S 3F 2B
Undergrowth tree density ($\mathrm{ha^{-1}}$)	500	200	1400	400
Undergrowth biomass ($\mathrm{kg\ m^{-2}}$) 3)	0.05	0.11	0.22	0.20
Organic layer biomass ($\mathrm{kg\ m^{-2}}$)				
Moss	–	0.6	0.7	1.5
Litter	0.1	–	–	–
Duff	0.2	1.5	2.1	4.1
Organic layer thickness (cm) 4)	2 – 3	9 – 11	13 – 17	23 – 27

1) 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%).

2) Tree species composition belonging to the undergrowth (i.e., height of 20-300 cm; this index called "Regrowth composition" in Russian Scientists).

3) Including undergrowth trees, and other shrub species and grasses.

4) Sum of thickness of litter, moss and duff.

the moss, lichen, litter and duff layers, however, there are some exceptions but they are explained. Vertical holes were dug out in each plot using a thin wood bar (12 x 6mm) (n=5-8 for plots K1-K3; n=1 for plot K4). A thermometer was inserted into each hole, and the soil temperature was recorded after 10 minutes. The thickness of the organic layer was also measured on a vertical soil profile around each hole.

On one of the two sites within the vicinity of the Tura settlement, the vertical soil profile and temperatures were examined in the two experimental plots (II-4 and II-5) with different conditions of organic layers (Table 2). One plot (II-4) was located inside the burnt area of the *L. gmelinii* forest where a wildfire occurred in 1994 and partially destroyed the organic layer, and another plot (II-5) was established outside of the burnt area (about 20m apart from II-4). Tree density, mean tree height and stem diameter at breast height were 1030 ha^{-1}, 10.0m and 10.8cm for the plot II-4, and were 1600ha^{-1}, 9.0m and 9.0cm for the plot II-5, respectively (Table 2). In each plot, the organic layer thickness and soil temperature were measured along a line transect (17m in length) at 50cm intervals by making small soil profiles (total n=35 for the observation in each transect). These measurements were carried out in the summer following 1994's fire.

Table 2. Outlines of three experimental plots of *L. gmelinii* forests within the vicinity of Tura settlement.

		Plots	
	Ⅱ-4	Ⅱ-5	TB-1
Slope aspect	North-East	North-East	East
Slope inclination	12°	13°	5°
Year of the last fire	1994	not burnt*	1910
Soil thawing depth (cm)	60	25	30
Thickness of organic layer (cm)	5.0	17.3	15 - 20
Biomass of organic layer (kg m^{-2})	2.5	8.2	8.5
Stand parameters			
Tree age (yrs-old)			
Upper layer	170 - 180	170 – 180	180 - 220
Lower layer	—	—	80 - 90
Tree density (ha^{-1})			
Upper layer	1030	1600	700
Lower layer	—	—	4900
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

*Not-burnt plot (Ⅱ-5) was located about 20m apart from burnt plot (Ⅱ-4) where fire occurred in 1994.

Table 3. Outlines of three experimental plots of *L. gmelinii* forests on the distant site (90km west) of Tura.

		Plots	
	P1	P2	P3
Slope aspect	North	South	East
Slope inclination	2°	15°	6°
Stand parameters			
Tree density (ha^{-1})	495	665	1191
Tree age (yrs-old)	320	300	250
Mean tree height (m)	10.5	15.0	8.5
Mean stem diameter (cm)	14.0	16.6	9.5

2. Summer soil thawing depth

Our preliminary survey around the Tura settlement (including the site at 90km west) indicated that the summer soil thawing depths on fire slashes and inside larch forests were negatively related to the average thickness of the moss and the duff layers, but also varied largely depending on some other factors, such as the slope aspect and earth hummock micro-topography (i.e., nano-relief)(Sofronov *et al.* 2000a, 2000b). In order to examine in more detail the interactions between thawing soil depth, organic layer thickness and micro-topography, we established the following three plots of mature larch forest (250-320 years-old) in one site along the Nizhnya Tunguska River (90km far from Tura). One site on the river terrace close to the lake where nano-relief was well-developed (P1). A second site, on the lower end of the south-facing slope covered with dense shrubs (mostly alder species)(P2), and a third site on the convex part of the slope (P3)(Table 3). In each plot, soil thawing depth and thickness of the organic layer were measured along a line transect (40m in length) at 20cm intervals (total n=200 for the observation in each transect). The thawing depth was measured in the summer under two different soil moisture conditions (normal and dry). The significance of the dependency of the soil thawing depth (STD) on the thickness of the total organic layer (TOL) was tested by simple correlation coefficient (r) including all of the data of each transect.

3. Influence of fires on growth of larch trees

In Central Evenkia, fire is a major disturbance agency (Abaimov and Sofronov 1996), and the average interval of fire events is about 80 years (Sofronov *et al.* 1998). According to our pre-reconnaissance along the Nizhnya Tunguska and Kochechum rivers near the Tura settlement, this territory suffered from wildfires intensively during the early 20th century (Sofronov *et al.* 1998). To examine how such fire disturbances influenced the growth of the larch trees, we analyzed the tree-ring data obtained for some *L. gmelinii* trees growing on the old burnt site within the vicinity of Tura settlement (plot TB-1; Table 2). This larch stand experienced fire disturbance about 90 years ago (in 1910), and contains two age groups of trees (or two different layers) at present: older trees (180-220 yrs-old), which escaped the damage of the 1910 fire, form or dominate the upper layer and younger trees (80-90 years-old) of the lower layer were mostly regenerated after the fire. Tree density, mean tree height and stem diameter were 700ha^{-1}, 10.5m and 11cm for the older age group (i.e., upper layer trees), and were 4900ha^{-1}, 4.5m and 4.5cm for the younger age group (i.e., lower layer trees), respectively (Table 2). 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 1.3m for the younger trees, while the disk samples were taken at a height of 0.5 - 1m in order to include the parts with fire scars. On this plot (TB1), the thickness of the organic layer was 15-20cm (only moss and duff layers as lichens did not occur at this location) and summer soil thawing soil depth was about 30cm (Table 2).

Results and Discussion

1. Soil temperature

Soil temperatures at the depth of 35cm (T_{35}) differed within each plot, as well as among the four plots on the Kureyka River site (Fig. 2). If comparing all data, T_{35} decreased from 8° to 0°C with the increase of organic layer thickness (OL being the sum of the litter, moss,

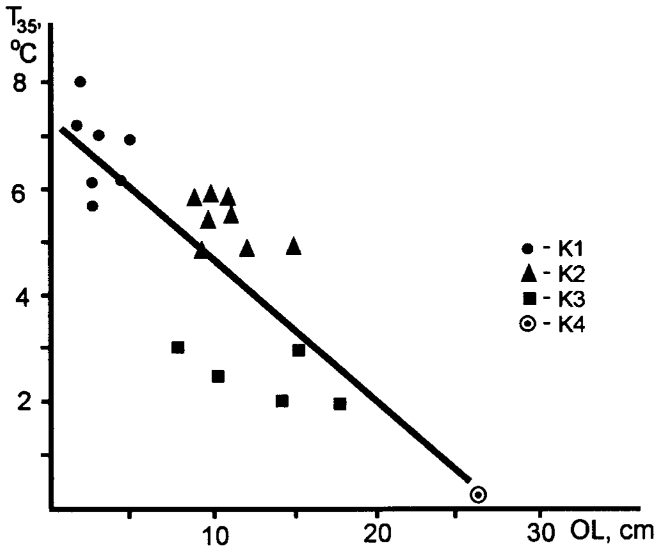

Fig. 2. Relationships between organic layer thickness (OL; moss, litter and duff) and soil temperatures (T_{35}; at 35cm depth from the surface of moss or litter) in the four experimental plots (K1-K4) of Kureyka River basin site. Measurements were conducted from early to mid-August.

and duff; here, lichens did not occur) from 2 to 30cm. This negative relationship indicates that the moss and duff organic layers play a major role as the thermal insulator, since the amounts of litter accumulation in each plot (<0.1 kg m^{-2} in biomass) are much smaller than those of the moss (0.6 - 1.5kg m^{-2}; except K1) and duff (0.2 - 4.1kg m^{-2}) layers (Table 1).

Fig. 3 compares the vertical soil profile and the change of soil temperature between the two contrasting sites of larch forest near the Tura settlement; II-5 shows the non-burnt site and II-4 shows the burnt site. In both plots, soil temperatures decreased sharply within the upper organic layers. However, the thickness of the organic layer was much thinner in II-4 (only duff, about 5cm) than in II-5 (moss and duff, about 18cm), 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 (R) above the frozen soil (Pf) was much deeper on II-4 than on II-5 (Fig. 3). This indicates that ground-fire disturbances improve the thermal condition of the soil by eliminating the moss and duff covers.

2. Summer soil thawing depth

Table 4 summarizes the coverage area and thickness of each component of the organic layers (here called "prime conductors of burning", PCB) in the three larch stands near Tura (P1-P3). Also, the results of the correlation analysis between the total organic layer thickness (TOL) and the soil thawing depth (STD) are shown. In each plot, duffs (F- and H-layers) covered the ground surface densely (11-16cm in thickness) among the components of organic layers, and TOL reached 20 - 30cm. There were no significant relationships between TOL and STD, except for one case in P3 where the STD measured under a drought soil condition was positively correlated with TOL ($r = 0.44$, $p<0.05$).

No clear dependency of STD with TOL (Table 4) may conflict with the fact that the soil temperature (T_{35}) generally decreased with the increase of organic layer thickness (Fig. 2). However, the present data (P1-P3) were obtained from the multi-point measurements along the line transect across the earth hammock 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 parts (Sofronov, unpublished data). Soils on the concave parts are generally colder, and melt slowly during the early summer, resulting in much shallower soil thawing depths than soils on the convex parts regardless of the thickness of the organic layer (e.g., Sofronov *et al.* 1999, Kajimoto *et al.* 2003). Thus, the weak correlation between TOL and STD in each larch stand might reflect the large variation of soil thermal regime due to micro-topography. To discuss the interaction between TOL and STD in relation to micro-topography in more detail, further field data and analysis are required.

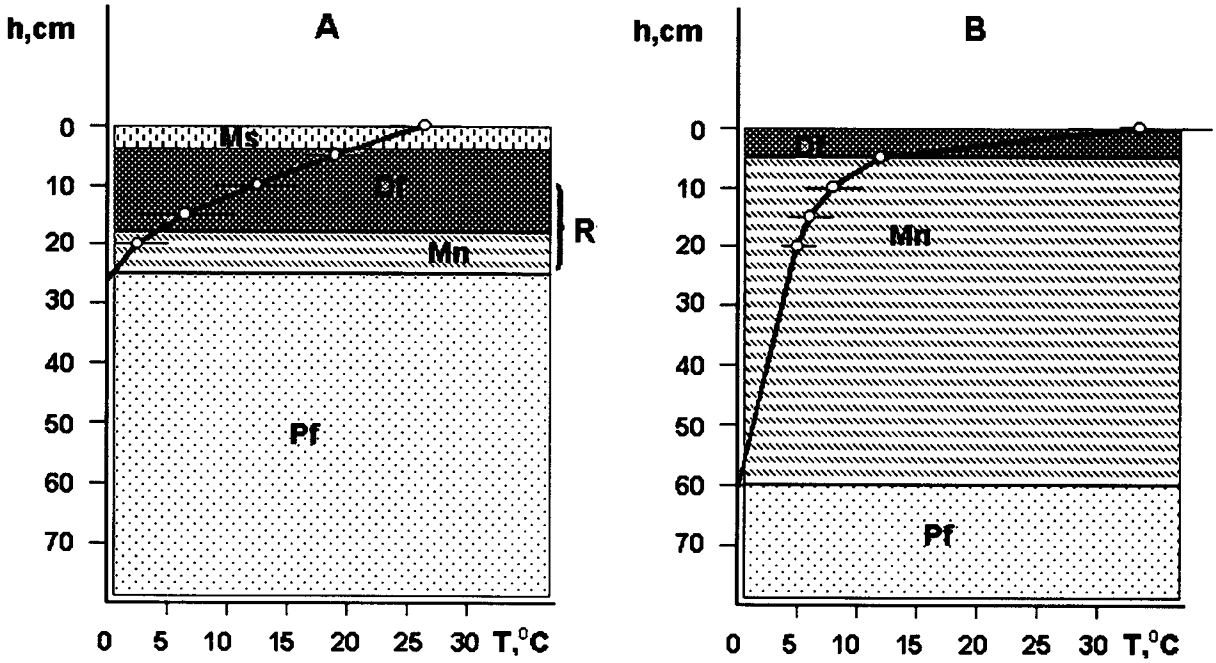

Fig. 3. Vertical soil profiles and soil temperatures in the two experimental plots of *L. gmelinii* forests near Tura, (A) plot II-5 (not-burnt forest) and (B) plot II-4 (burnt site by 1994 surface fire).

T: temperature (mean plus standard deviation), h: depth, Ms: moss, Df:duff, Mn: melted mineral soil, Pf: frozen soil (permafrost), and R: rooting layer.

Table 4. Coverage area and average thickness of prime conductors of burning (PCB), total organic layer thickness (TOL), and summer soil thawing depth (STD) in three experimental plots on the distant site (90 km west) of Tura.

	Plots		
	P1	P2	P3
Coverage area (%)			
Lichen [1]	–	–	23
Green mosses [2]	68	74	44
Mixture of mosses and lichen	26	4	30
Litter (α-layer)	2	8	–
Duff [3]			
F-layer	94	–	95
H-layer	86	83	92
Bare ground	4	14	3
Thickness (cm) [4]			
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 total organic layer (TOL) (cm) [5]	21.2±3.8	17.7±3.6	18.8±2.0
Soil thawing depth (STD) (cm) [6]			
In late July (normal condition)	46	39	44
In late July (drought condition)	44	44	50
Correlation of STD with TOL [7]			
STD (normal condition)	-0.22	-0.18	-0.07
STD (drought condition)	-0.19	-0.04	0.44 *

1) *Cladina* species. 2) *Pleurocium - Schreberi prevails.*

3) Duff was separated into two components; dead-out moss (F-layer) and decomposed moss (H-layer).

4) Average and standard deviation for each component of organic layers.

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

6) Soil thawing depths measured under two moisture conditions (normal and drought) in late July; each value shows average of all measurement points along the transect (40 m in length).

7) Simple correlation coefficient (r) of the relationships between TOL (absolute value) and STD using the all data at each measurement point; correlation was significant at p=0.05 (*).

3. Influence of fires on larch trees growth

Fig. 4 shows examples of diameter growth curves of the larch sample trees taken from the old burnt site (plot TB-1) of Tura where a surface fire occurred in 1910. Growth rates of younger trees (No.4 and 5) were relatively high during the early growth stage, but decreased gradually for 30-40 years after the regeneration. As for two older trees (Nos.2 and 3; ca. 200 yrs-old), which regenerated before the fire, their growth rates were also reduced for several decades after the regeneration of each tree. However, the growth rates recovered again after that depressed growth stage (i.e., 110 - 150 years after each regeneration). This growth recovery ("rejuvenation phenomena") occurred just after the 1910 fire. Likewise, another older tree (No.1, ca. 220 yrs-old) also showed a growth recovery after the 1910 fire (Fig. 4). These facts suggest that growth activities of the larch trees are often enhanced by ground fire, if they can escape serious damage. The post-fire growth recovery might be primarily a result of the amelioration of the soil-temperature due to the burning of thermal insulating organic layers (Table 4). 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 in part to the rejuvenation phenomena of the surviving larch trees.

Figure 4 also indicates that the older trees grew up to

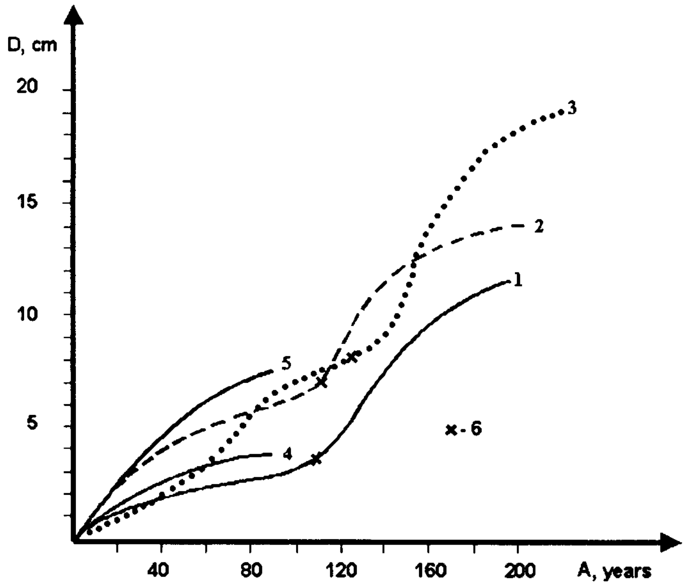

Fig. 4. Examples of stem diameter (D) growth curves for the *L. gmelinii* trees of the old burnt site (TB-1) near Tura settlement. Three trees (No.1-3) of older age-group regenerated before 1910 surface fire, and two trees (No.4-5) of younger age-group regenerated after the fire. Cross mark (x) plotted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

The value of x-axis (A) was expressed as the years after regeneration for each tree.

double the size (10-20cm in diameter) of what they were before the fire (less than 7-8cm). This basically supports the results of a previous study by 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 in Siberia, and showed that diameter growth rates were 1.25-1.52 times higher than those before a fire disturbance. Likewise, such a positive effect of fire disturbance on individual growth rates was observed for the mature larch trees (150, 170 and 250 years-old) in Central Evenkia (Abaimov *et al.* 1997; original data from M.K. Arbatskaya).

According to our data and these previous findings, the growth pattern of *L. gmelinii* in Central Evenkia might be characterized by two distinct growth stages. The early stage just after regeneration has relatively high growth rates (both in diameter and height) and the subsequent stage shows several decades of conspicuous growth reduction. 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 post-fire recovery of moss and lichen layers occurs, and the active layer depth returns to the original level within 25-50 years following a fire disturbance (Viereck 1982, Dyrness *et al.* 1986).

Our field study showed that moss-lichen layers functioned as an important "thermal insulator," and predetermined conditions of the summer soil temperature in the larch forest ecosystem of Central Evenkia. It was also suggested that the function of the moss-lichen cover was initialized by periodic fire disturbances, by which growth rates of the surviving larch trees were enhanced again. In terms of forest management in this region, our findings lead us to conclude a possibility that prescribed fire, in other words artificial ground surface fire, may be a useful way of increasing timber production of individual trees by eliminating the thermal insulator and ameliorating soil temperature and nutrient conditions. There are, however, some problems that should be taken into consideration before applying an artificial fire treatment. For example, we need to calculate and/or select optimal conditions of prescribed fires carefully by noting the fact that the *L. gmelinii* is a fire-resistant species and the extent of fire damage is largely dependent on tree size (Sofronov and Volokitina 1990).

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