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Contemporary Expansion of Siberian Larch into the Mountain Tundra of the Polar Urals

S. G. Shiyatov and V. S. Mazepa

Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences, ul. 8 Marta 202, Yekaterinburg, 620144 Russia

e-mail: stepan@ipae.uran.ru

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Abstract—The spatiotemporal dynamics of forest–tundra communities growing in the upper treeline ecotone on the eastern macroslope of the Polar Urals (Rai-Iz mountain massif) influenced by centennial and intracentennial climate changes is analyzed in detail. Particular attention is paid to the expansion of Siberian larch into the mountain tundra for the last 110 years due to climate warming and moistening in the summer and winter periods. To date, the upper treeline has not yet reached those high levels where it grew in the Middle Ages, due to a short period of favorable climate and low availability of Siberian larch seeds in tundra area.

Keywords: upper treeline ecotone, climatogenic dynamics of forest–tundra communities, tree-ring analysis, age structure and density of tree stands, modern climate changes, *Larix sibirica* Ledeb., Polar Urals

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INTRODUCTION

Considerable attention is paid to studying the climatogenic dynamics of forest–tundra communities growing in the upper treeline ecotone (Shiyatov et al., 2005; Kapralov et al., 2006; Shiyatov 2009; Kullman, 1990; Körner, 1999; Kharuk et al., 2002; Holtmeier, 2003; Mazepa, 2005; Kirdyanov et al., 2012; Hagedorn et al., 2014; Frost and Epstein, 2014). The aim of these studies was the need to assess the response of forest–tundra and forest–meadow communities to contemporary climate warming and moistening, which began in the late 19th–early 20th centuries and continues today. Studies in mountainous and northern regions are the most promising, because there is a high variability of climatic conditions and tree vegetation grows under extreme conditions. In addition, the influence of anthropogenic factors is minimized in many of these areas.

Within the Ural mountain country, the dynamics of highland tree vegetation at the upper boundary of its growth is the most pronounced in the Polar Urals, where for the last millennium there were significant changes in its composition, structure, and spatial distribution. The most promising area for studying tree vegetation dynamics is the Sob River basin, in particular, the feet of the slopes of the Rai-Iz massif and Chernaya Mountain, where there is a large number of remains of long-dead Siberian larch (*Larix sibirica* Ledeb.) preserved above the modern upper treeline and under a canopy of modern open forests.

This paper presents the quantitative characteristics of the settlement and growth of Siberian larch in the last century in the Ker-Doman-Shor River basin, at the foot of the southeastern slope of the Rai-Iz mountain massif. A characteristic feature of this site of the slope with an area of about 40 hectares is the presence of a large number of well-preserved remains of dead larch trees at the upper part of the ecotone of the upper boundary of tree vegetation (for some of them, diameters reached 40 cm).

MATERIALS AND METHODS

In 1983, an altitudinal transect with an area of 0.86 hectares was established on the southeastern slope of the Rai-Iz massif within an open larch forest that was totally dead by the end of the 19th century. The transect begins at an altitude of 340 m above sea level, where remains of dead trees preserved in the form of dead fallen wood and deadwood are located, and ends near the modern upper boundary of open forests (280 m above sea level). The nearest small outlier of open larch forest is located 200 m southwest of the transect. The slope is protected from strong winter winds, and the snow cover reaches 0.5–1.0 m. The trees growing here have a single-stemmed form of growth. The slope is not very steep (7°–8°), and its surface is covered with mountain tundra soils. The above-ground cover consists of dwarf birch–sedge–forb tundra. Its density is 60–70%. Mosses are absent. The compactness of the lichen cover, consisting mostly of fruticose species, does not exceed 20%. The area of rubbly and earthy spots uncovered by vegetation is around 15%. This slope has an expressed ther-

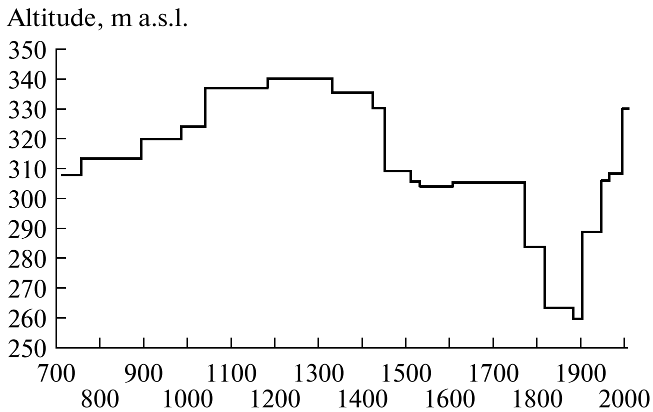

Fig. 1. Dynamics of upper boundary of spread of tree vegetation during past 1300 years on Rai-Iz mountain massif (Polar Urals).

mal type of upper forest boundary, so a steady shift of the upper boundary of growth of forest–tundra communities is observed here under the influence of centennial and intracentennial climate changes.

A rectangular altitudinal transect with a length of 430 m and a width of 20 m was divided into 86 quadrats measuring 10 × 10 m, two quadrats per row. Stone pills were set at the corners of sites. The left row of columns was numbered from top to bottom (from 1 to 44). The geographical coordinates of the upper left corner of the transect are as follows: 66°51′19″ N, 65°38′57″ E, 340 m above sea level; of the lower, 66°51′08″ N, 65°38′51″ E, 280 m above sea level.

In 1983, 252 wood remains of varying degrees of digestion and 19 live larches were mapped and described within the transect. Cross cuts were taken from each wood remain in order to determine the calendar lifetime of trees using the dendrochronological method. Since these remains were still in their place of growth, it was possible to reconstruct the displacement of the upper boundaries of forest–tundra communities with a high degree of accuracy.

One of the goals for laying the transect was to monitor the formation process of forest–tundra communities in tundra areas, where tree vegetation had grown until the middle of the 19th century. This process is observed due to the improvement of forest conditions caused by modern climate warming and moistening. In 1983, 2004, and 2014, mapping was performed and larch trees were described at all quadrats of the transect. Each living tree was measured and determined for such indicators as height, diameter at the base of the trunk and at a height of 1.3 m, age, and vitality. In 2004, moreover, apical shoot growth was measured, and in 2014, those for the horizontal projection of the crown.

When forest–tundra communities are assigned to a particular type, such an indicator as tree canopy density is commonly used. Thus, communities with the forest stand canopy density of 0.1–0.3 are referred to an open forests, and those with canopy density of less than 0.1, to sparse forests (Abaimov et al., 1997).

The tree canopy density reached 0.1–0.2 at some sites of the transect, but it was lower at most sites, although the tree density, including undergrowth, was high (up to 2000–2200 pcs./ha). Due to the fact that young individuals with small horizontal crown projections grow predominantly in the transect, we used such indicators as the average distance between individuals in attributing forest–tundra communities to a particular type. Communities where the distance between individuals ranged from 7–10 to 20–30 m were attributed to open forests; from 20–30 to 50–60 m, to sparse forests; and those with more than 50–60 m, to tundra with single trees.

The landscape was rephotographed in the transect and surrounding areas of the slope in 1977, 1983, 1996, 2004 and 2014 in order to visually illustrate changes in tree vegetation.

RESULTS

The results of dendrochronological dating of wood remains in the transect showed that from the 8th to the 14th centuries, i.e., during Medieval climate warming, the upper tree-line increased gradually high in the mountains and reached a maximum height (340 m) in the 13th century (Fig. 1). Then the Little Ice Age (from the 14th to the 20th century) arrived, when there was mass extinction of trees, leading to a reduction in the upper growth boundary of tree vegetation to 260–280 m above sea level. The most intense decrease in this boundary was observed in the 15th and 19th centuries (Shiyatov, 1993; Mazepa et al., 2011). At the end of the 19th century, there was no single living tree in the transect. The situation changed at the beginning of the 20th century, when viable undergrowth began to appear in the transect.

Figure 2 presents data on the locus of every living larch individual along the length of the transect and the time of their lives, as well as the distribution of types of forest–tundra communities in the transect in 1983, 2004, and 2014.

During the establishing of the transect in 1983, 19 live larches and a dead one were found in the lower half of the transect. The first living larch appeared in 1903 and had a height of 4 m at age 80. The crown had already a small number of cones. The next two larches were only 40 and 45 years old (in 1943 and 1948.). More intense regrowth of larches occurred from 1963 to 1975: by that time there were 16 young larch trees, which had heights from 15 to 70 cm in 1983. Most of these larches appeared in the lower part of the transect near the 80-year-old fruit-bearing larch. Four larch trees appeared in the middle part of the transect (see Fig. 2).

Next, living larch trees were counted in the transect in 2004, i.e., after 21 years. During this time, 129 young

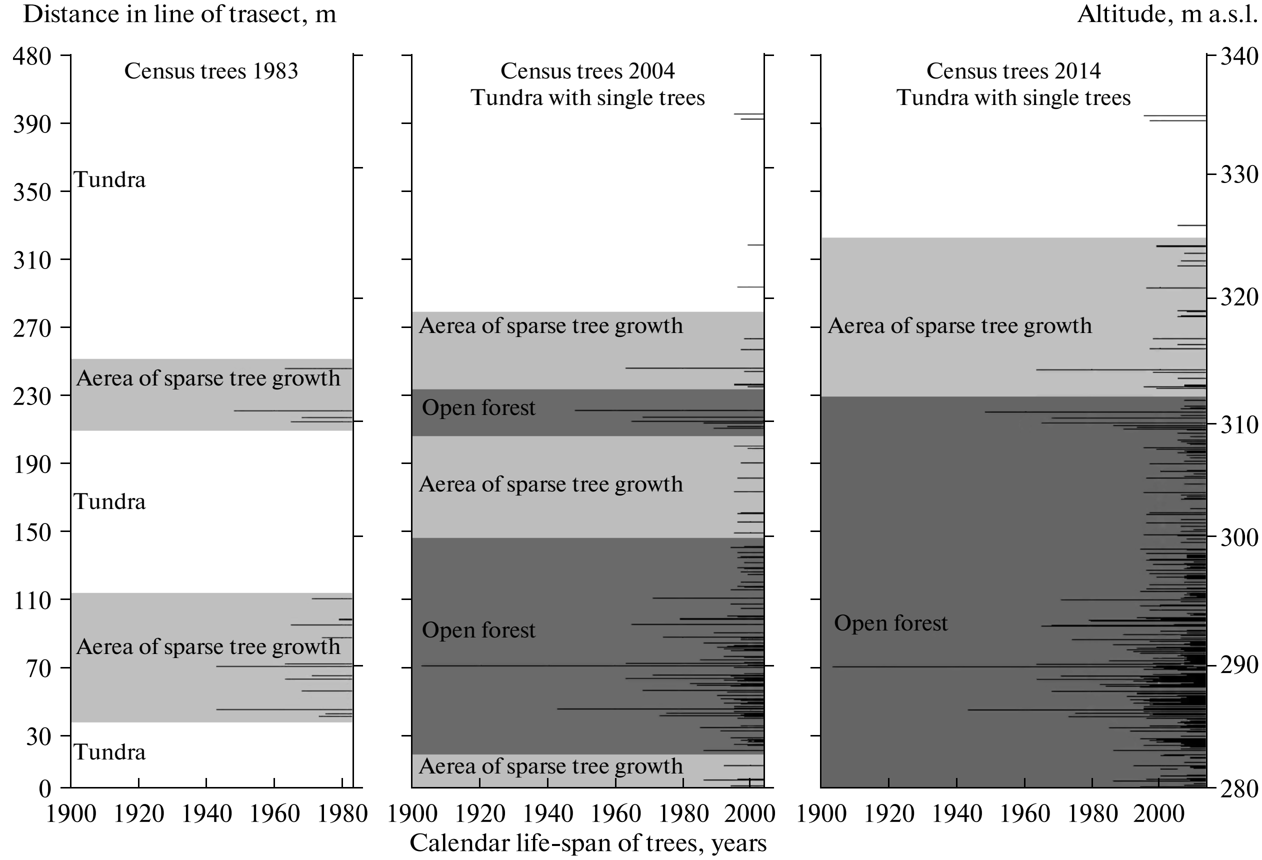

Fig. 2. Location and life-span of appearance of living larches and formation of various types of forest–tundra communities in transect in 1983, 2004, and 2014.

larches had appeared (see Fig. 2). Their settlement occurred mainly in the lower and middle parts of the transect. Two larches (8 and 10 years old) were at the top of the transect at an altitude of 335 m above sea level, i.e., near the remains of the topmost trees that grew on the upper tree-line in the 13th century. More than 80% (105 pcs.) of larch trees currently have a good living condition; 20 pcs., satisfactory; and 4 pcs., poor. Most larches (12 pcs.) that settled before 1983 started to bear fruit.

Finally, larch trees were counted in 2014, i.e., after 10 years. In a short period of time (7 years), 220 young larch trees had appeared (1- to 3-year-old seedlings were not taken into account). During this time, nine of the larch trees that appeared between 1983 and 2004 dried up, i.e., 7% of the total amount. Currently, 359 larch trees of different ages and heights are growing in the transect (see Fig. 2). Their resettlement is concentrated mainly in the lower and middle parts of the transect. The density of individuals for the entire transect is 415 pcs./ha; in the lower and middle parts of the transect, the density of larch trees reaches 750–900 pcs./ha; and in some quadrats, 2000–2200 pcs./ha.

Figure 3 shows the time of appearance and number of new individuals of Siberian larch in the transect from 1983 to 2011. The nature of the reforestation dynamics is uneven: there were boom and bust periods. The intensity of seed formation and the conditions for the survival of seedlings in different years could be as the reasons for this unevenness. However, an increase in the intensity of regeneration of Siberian larch is clearly visible for the entire observed period.

The main stages of expansion of tree vegetation beginning from the treeless tundra (1977), single trees in the tundra (2004), and young sparse forest (2014) are clearly visible in the landscape photographs (see Fig. 4) taken in the middle part of the transect from the same point at different times.

Good living conditions of larches growing on both transect and in adjacent areas of the slope are noteworthy. Trees of single-stemmed form dominate. Flaglikeness of crowns is weakly pronounced. This indicates that there are no severe wind conditions on this slope in winter. No less than 50 cm of snow cover is deposited there, which protects the soil and root system of woody plants from low temperatures. The magnitude of larch growth in height indicates favorable habitat conditions in the transect. In 2004, annual api-

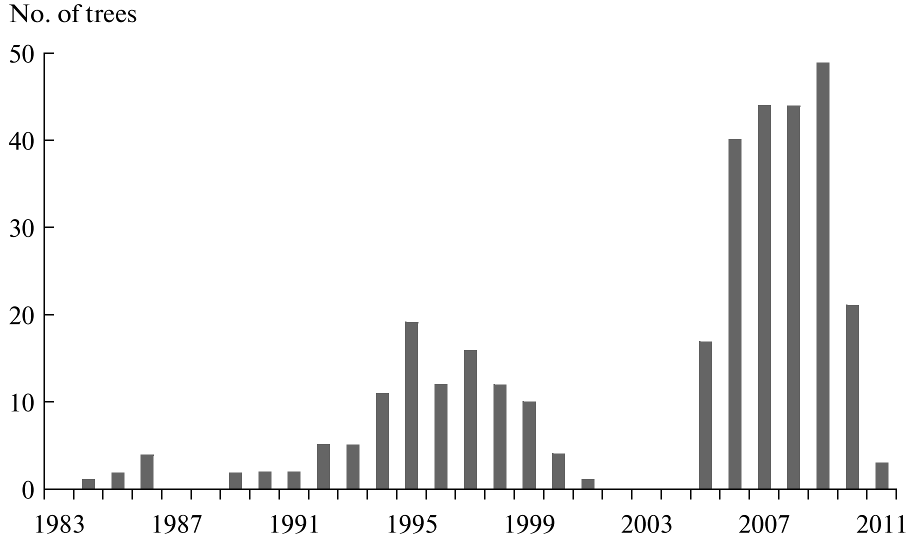

Fig. 3. Time of occurrence and number of individuals of Siberian larch in transect from 1983 to 2014.

cal shoot growth was measured for all individuals: the height increment ranged from 1 to 9 cm (mean 5.4 cm) for larch trees under an age of 8 years; from 5 to 27 cm (average 13 cm) for those aged from 9 to 15 years; from 25 to 35 cm (average 30 cm) for trees aged from 15 to 20 years; and 10 to 17 cm for the oldest larch trees. Currently, the height of the oldest larch (112 years old) is 10 m. The height of trees that settled between 1943 and 1983 ranges from 2.8 to 8.5 m.

Data enumeration performed in 2014 indicate vigorous growth in height: the height of some larch trees that appeared 8–10 years ago reaches 130–150 cm; the average annual linear increase in height was 13–15 cm. Judging from the wood residues, trees growing in the transect in the Medieval warming period (8th–13th centuries) had high height and diameter increments.

The table presents data on the distribution of areas occupied by tundra and forest–tundra communities in the transect in 1983, 2004, and 2014. In 1983, the largest area was occupied by tundra communities (72%). In the bottom half of the transects, there were two small areas of open larch forests, the total area of which was 28%. In 2004, the distribution of different types of forest–tundra communities changed significantly: two sites of sparse larch forest formed instead of open forest, the total area of which was 35%; a significant area was occupied by three sites of open forest (30%); the area covered by tundra decreased by more than three times (from 72 to 20%). The most intense expansion of tree vegetation occurred in the last 10 years, resulting in a significantly increased area occupied by sparse larch forest (53%).

Distribution of areas covered with tundra and forest--tundra communities in transect at different times

Type of community	Year					
	1983		2004		2014	
	m^2	%	m^2	%	m^2	%
Tundra	6200	72	1700	20	1300	15
Tundra with single trees	–	–	1300	15	700	8
Sparse forest	2400	28	2600	30	2000	24
Open forests	–	–	3000	35	4600	53

The photograph (see Fig. 4) taken in 2014 shows a young sparse forest growing in the middle part of the transect. It is clear that there is an active settlement of the single-stemmed form of larch. To date, a fairly large site of sparse forest 2000 m^2 in area (24%) formed in the upper half of the transect. The area occupied by the tundra community decreased to 15%, and the area of tundra with single trees, up to 8% (see table).

The counting of living larch trees in different time periods made it possible to quantify the displacement of the upper boundary of growth of different types of forest–tundra communities (tundra with single trees, sparse forests, open forests) in the last century. The first living larch tree appeared in the transect in 1903; as a result, the upper boundary of single trees rose to 290 m. The next larch, which grows up on the hill, was only 45 years old (in 1948 at an altitude of 311 m). Subsequently, single larch trees settled in 1963 and 1995 at altitudes of 314 and 335 m (Fig. 2). The upper boundary of growth of single larches rose vertically by 46 m (from 290 m to 335 m) from 1903 to 1995, almost reaching the height of single trees in the 13th century. The rate of vertical advance of the upper boundary of single trees averaged 2 m per year.

The first sparse larch forest in the transect, consisting of 16 individuals, formed in 1963–1983 at an altitude from 286 to 295 m above sea level near the oldest

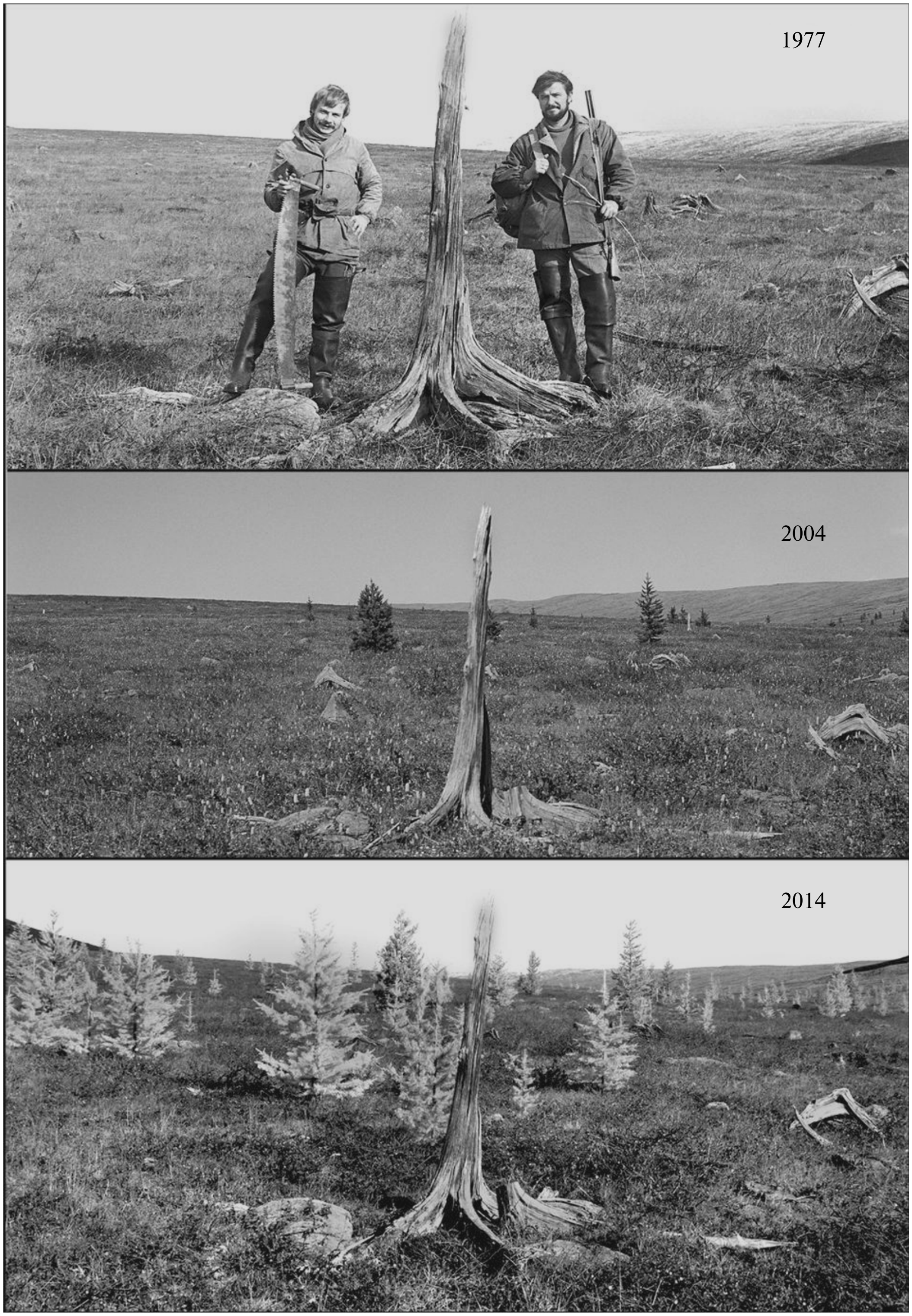

Fig. 4. Landscape photos taken in middle of transect from same point at different times (Rai-Iz mountain massif, Polar Urals).

fruit-bearing larch. Between 1983 and 2004, three sparse forests isolated from each other (see Fig. 2) formed in different parts of the transect: one site of sparse forest, consisting of four individuals, formed in the bottom of the transect at an altitude from 280 to 283 m above sea level; two other sites of sparse forests, consisting of nine and six individuals, formed in the middle part of the transect at altitudes of 300–309 m

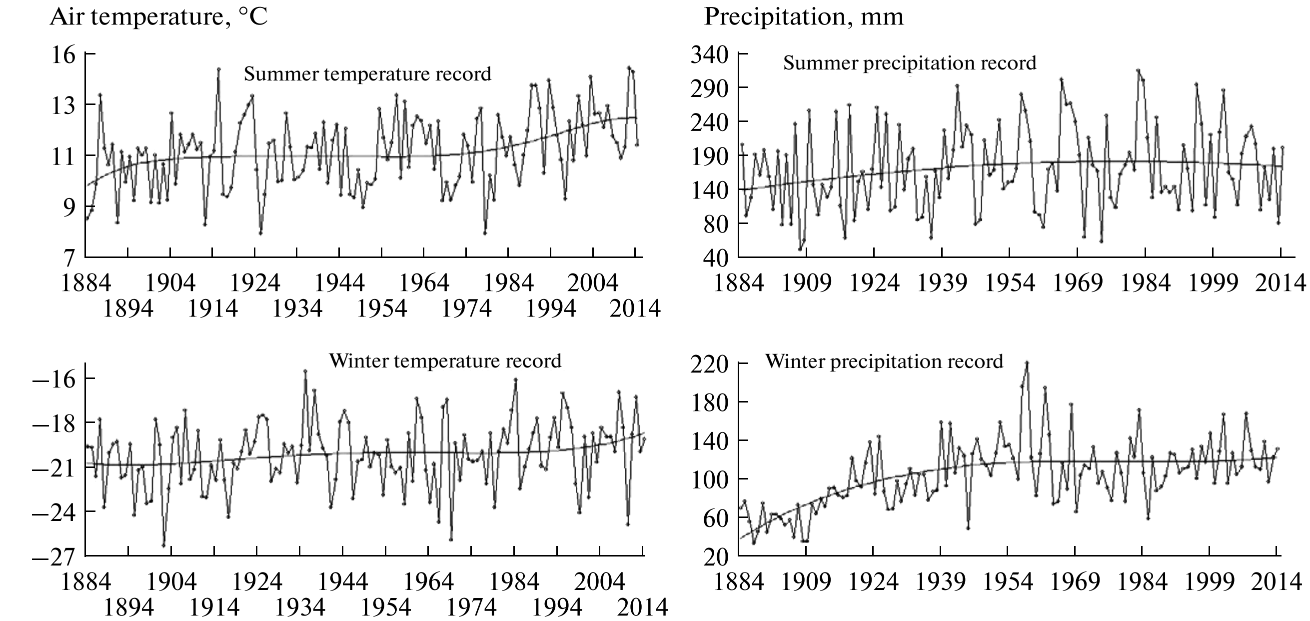

Fig. 5. Summer (June–August) and winter (November–March) average air temperatures and precipitation for Salekhard weather station (WMO # 2012333000, 66°31′ N, 66°36′ E, 35 m above sea level).

and 313–316 m. The enumeration in 2014 revealed the presence of a fairly large portion of sparse larch forest at an altitude from 312 to 324 m, consisting of 19 individuals.

During the last decade, there was a significant increase in the area occupied by larch forests in the lower half of the transect at an altitude from 280 to 312 m above sea level (see table and Fig. 2). The average rate of expansion of the upper boundary of sparse larch forests high in the mountains for the past 25 years was 1.3 m per year.

DISCUSSION

Since the beginning of the last century to the present, there has been an expansion of tree vegetation in mountain tundra in the area of the slope on which productive sparse larch forests grew during the Medieval climate warming (8th–13th centuries). All the trees dried up on this slope during the Little Ice Age (14th–19th century), while the upper tree-line decreased from 340 to 260 m above sea level (see Fig. 1). At the end of the 19th century, there was no single living tree in the transect. The process of larch settlement in the mountain tundra began in the first decade of the 20th century. Single trees appeared in the lower and middle parts of the transect. In 1960s–1980s, the number of living larch trees increased noticeably. Two sparse larch forests formed during this period. Between 1983 and 2004, the intensity of reforestation increased dramatically, and juveniles appeared in the upper part of a transect. The most intense resumption of larch happened over the last 10 years, when there were over 219 young larches and a sparse larch forest formed in the bottom half of the transect.

Expansion of larch in the mountain tundra was due to forest conditions that improved after climate warming and moistening both in the summer and winter periods. This is confirmed by analysis of instrumental data for the last 130 years from the weather station in Salekhard, located 55 km east of the transect (see Fig. 5). According to these data, there was significant warming and moistening of the climate in 1920 that continues to this day. In 1883–1920, the average temperature in the summer months (June–August) was 10.6°C, and in 1921–2004, 11.2°C; i.e., it increased by 0.6°C. The temperature of winter months (November–March) for the same period increased by 1.1°C (from –20.6 to –19.5°C). Average rainfall in the summer months in 1891–1920 amounted to 147 mm, and in 1921-2004, 179 mm; i.e., it increased by 32 mm. In the winter months it increased from 67 to 114 mm, i.e., by 47 mm. The last decade was the warmest for the entire period of meteorological observations. The temperature in the summer months increased by 1.1°C compared with the period of 1921–2004, and for the winter months, by 0.8°C. Rainfall in the summer months did not change for 2005–2014 in comparison with 1921–2004, and winter precipitation increased by 8 mm.

Comparison of the summer temperatures reconstructed according to ring width of larch in different parts of the Siberian Subarctic (Vaganov et al., 1996) showed that the most significant warming happened in the Polar Urals in the 20th century in comparison with northwestern Siberia and Taimyr. An early start of the growing season was essentially significant for the intense expansion of tree vegetation, as is evidenced by the increase in May temperatures. In 1883–1920, it was –2.4°C; in 1921–2004, it rose to –1.1°C; and in 2005–2014, to –0.1°C. That is, it increased by 1.3 and 1.0°C respectively. As a result, the length of the growing season increased by 5–7 days during daytime and nighttime solar illumination.

The high-altitude temperature gradient of summer months in the Polar Urals is 0.7°C. The temperature boundary at which the existence of tree vegetation is now possible rose higher in the mountains for more than 100 m. In fact, the upper boundary in the transect increased vertically by only 55–60 m. Thus, the upper growth boundary of tree vegetation has not yet reached the climatically specified limit and the altitude level to which it had increased during the Medieval warming.

Our materials confirm the earlier conclusion (Shiyatov, 1966) that the process of larch settlement higher in the mountains is constrained by the lack of larch seeds. In this area, the departure of seeds from cones occurs a year after their formation. All winter the seeds are in the cones, and only with the onset of next year's warm and sunny weather do the cones open and begin a massive departure. This usually occurs in June and July. Larch seeds are carried by the wind and fall no more than 40–60 m from 10–13- m-high fruit trees, settling in the above-ground cover and litter. Further spread of fallen seeds, especially uphill, does not occur. Larch in the research area bears fruit almost every year, providing a sufficient amount of seeds to tundra areas, sparse forests, and open forests near fruit-bearing individuals, as well as under their canopy. According to N.B. Koshkina (2008), laboratory germination of larch seeds in different types of forest–tundra communities in the Polar Urals is quite high: from 17 to 39%. Seeds are rarely recorded in tundra areas more than 60 m from fruit-bearing species, so many tundra areas suitable for growth of tree vegetation are still treeless. The data on enumeration and mapping of larches in the transect confirm the conclusion on the importance of seed supply to tundra areas in order to form forest–tundra communities. More intense resumption of larch in the transect occurred around fruiting individuals. The significant increase in the area of sparse larch forest for such a short time period (10 years) was due to the fact that a fairly large number of individuals aged from 15 to 110 years began to bear fruit. In addition, the climatic conditions during this period were favorable for the growth and development of larch.

CONCLUSIONS

The analysis of the appearance and growth of larch trees in the transect established on the southeastern slope of the Rai-Iz massif showed that over the past 110 years, there was continuous settlement of larch in the mountain tundra. The initial stages of resettlement were slow. In the first half of the 20th century, there were single trees and small areas of open forests. Over the past two decades, the formation process of forest–tundra communities accelerated greatly. Currently, most of the transect is occupied by young sparse larch forests and open forests, and the upper boundary of individual trees rose almost to the altitude level at which they grew in the 13th century. Modern expansion of tree vegetation into the mountain tundra was caused by climate warming and increased humidity in the summer and winter periods. Accelerated afforestation of the transect, which occurred over the last 20 years, was due to better availability of larch seeds. To date, the upper growth boundary of tree vegetation on the slope of the transect has not yet reached the levels of the 13th century because of the short period favorable for tree vegetation growth. We believe that if the current climatic conditions persist, the uppermost young larches will begin to bear fruit over the next 15–20 years, and the gap between the actual and the climate-caused upper boundary of tree vegetation will be reduced.

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