ISSN 1067-4136, Russian Journal of Ecology, 2007, Vol. 38, No. 4, pp. 223–227. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © S.G. Shiyatov, M.M. Terent'ev, V.V. Fomin, N.E. Zimmermann, 2007, published in Ekologiya, 2007, Vol. 38, No. 4, pp. 243–248.

Altitudinal and Horizontal Shifts of the Upper Boundaries of Open and Closed Forests in the Polar Urals in the 20th Century

S. G. Shiyatov [a], M. M. Terent'ev [a], V. V. Fomin [a], and N. E. Zimmermann [b]

[a] *Institute of Plant and Animal Ecology, Ural Division, Russian Academy of Sciences, ul. Vos'mogo Marta, 202, Yekaterinburg, 620144 Russia; e-mail: stepan@ipae.uran.ru*

[b] *Swiss Federal Research Institute WSL, Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland; e-mail: niklaus.zimmermann@wsl.ch*

Received April 7, 2006

Abstract—In the Polar Urals (the Rai-Iz massif and Mounts Tchernaya and Malaya Tchernaya), altitudinal and horizontal shifts of the upper boundary of open and closed larch forests in the 20th century have been studied. Spatiotemporal parameters of these shifts have been assessed with the aid of the ARC/INFO geographic information system (ESRI Inc., United States), using our original large-scale geobotanical maps showing the distribution of different types of forest–tundra communities in the early 1910s and 2000s. The results show that tree vegetation has been actively expanding to higher elevations over the past 90 years. On average, the upper boundaries of open and closed forests have ascended 26 and 35 m and shifted horizontally 290 and 520 m, respectively. These shifts have been conditioned by climate warming and increasing humidity observed since the 1920s.

DOI: 10.1134/S1067413607040017

Key words: timberline ecotone, altitudinal and horizontal shifts of upper boundaries of open and closed forests, climate warming, increasing humidity, geographic information system, *Larix sibirica*, the Polar Urals.

In a previous study, we analyzed the spatial distribution of different types of tundra communities (individual trees in the tundra, sparse tree growth, open forest, and closed forests) in the Polar Urals in the 1910s, 1960s, and 2000s (Shiyatov et al., 2005). During the past 90 years, open and closed forests in the timberline ecotone have markedly expanded due to natural afforestation of the tundra and increase in the density and productivity of existing forest stands. The upper boundaries of sparse tree growth, open forests, and closed forests on many mountain slopes have ascended, but accurate data on the extent and rate of their displacement is absent.

The purpose of this study was to quantitatively assess the altitudinal and horizontal shifts of the upper boundaries of pure larch (*Larix sibirica* Ledeb.) open and closed forests between 1910 and 2000, i.e., in the period with favorable climatic conditions for tree growth. Areas with sparse tree growth and individual trees in the tundra were not considered because of difficulties in determining their boundaries in the field. The mapped area included in the analysis (approximately 50 km^2) is in the timberline ecotone, extending from the eastern spur of the Rai-Iz massif in the north to the Orekh-Yugan stream in the south. Low-angle slopes prevail there, and the position of the timberline is determined mainly by climatic factors and, in particular, wind at the foothills of Mts. Tchernaya and Malaya Tchernaya, and ambient temperature on the southern slope of Rai-Iz (Shiyatov, 1970).

We apply the term "timberline ecotone" to the transitional belt of mountain vegetation between the upper limit of closed forests and the upper limit of single tree growth in the tundra. Today, this ecotone in the study region lies at elevations ranging from 140 to 560 m a.s.l. Closed and open larch forest grow at the bases and in the middle parts of slopes, with their upper boundaries passing at the average elevations of 230 and 260 m, respectively. According to our classification, these terms refer to communities in which the average distances between trees are less than 7–10 m and from 7–10 to 20–30 m, respectively. More detailed data on the study region and cartographic methods were published previously (Shiyatov et al., 2005).

METHODS

The altitudinal and horizontal shifts of the upper boundaries of open and closed forests were quantitatively assessed using the ARC/INFO geographic information system (GIS) (ESRI Inc., United States) with the AML language and field-derived thematic geobo-

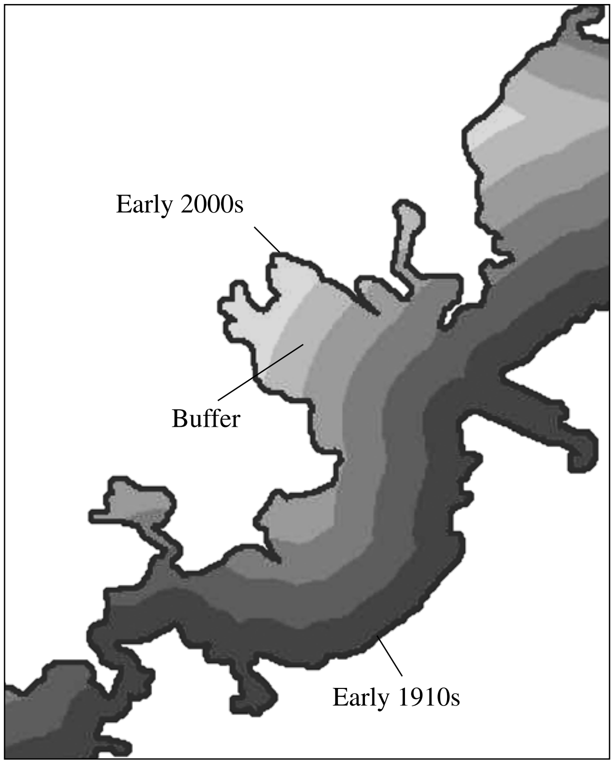

Fig. 1. Scheme of plotting buffer areas.

tanical maps (scale 1:25000) showing the distribution of different types of forest–tundra communities in the early 1910s and 2000s.

These shifts were calculated as follows. The study region is characterized by an insular distribution of forest–tundra communities, especially in the upper part of the timberline ecotone. Therefore, to obtain continuous contours showing the upper boundaries of open and closed forests in the above periods, we drew lines directly connecting the frontal edges of the uppermost forest islands or areas. Small islands of open forests at the bases of Mts. Tchernaya and Malaya Tchernaya, 0.5–2.0 km away from these boundaries, were not taken into account. When the part of the slope above the limit of closed forest was free from open forest, the frontal boundaries of these communities coincided.

The line coverages reflecting the positions of these boundaries in the early 1910s and 2000s were converted into a raster format (each line was represented by a set of cells 10 × 10 m in size) and superimposed on a 10-m digital elevation model of the study region in the GIS. Thus, information on altitudinal position above sea level was obtained for each raster cell. On this basis, we plotted histograms showing the distributions of elevations at the upper boundaries of open and closed forests at the beginning and at the end of the period studied. Statistics of these distributions were used to assess their altitudinal shift.

The horizontal shift of the upper boundaries of open and closed forests was estimated in the GIS as follows. The initial (1910) position of each boundary was used as a baseline for plotting buffer regions, each 10 m wide, lying parallel to it (Fig. 1). As a result, a layer of consecutive buffer regions was obtained, and the layer showing the present-day (2000) boundary was superimposed on it. Thus, we obtained information on the magnitude of horizontal shift of both boundaries and calculated the corresponding distribution histograms. As the resulting distributions of the altitudinal and horizontal shifts differed from the normal distribution, the median rather than mean was used for the assessment of these shifts.

Statistical processing and analysis of data were performed using the R program package (R Development Core Team, www.r-project.org).

RESULTS AND DISCUSSION

Figures 2 and 3 show maps of the upper boundaries of open and closed forests in the 1910s and 2000s, and Tables 1 and 2 contain statistical data characterizing the magnitude of their altitudinal and horizontal shifts over the corresponding period. It can be seen that, throughout the study region, both boundaries have moved to higher elevations. However, the distances of their upward shift in different parts of slopes are not equal, which may be explained by unfavorable conditions for tree growth in some habitats (in most cases, steep rocky slopes or windswept areas). An analysis of Figs. 2 and 3 and Table 1 shows that a downward shift of forest boundaries has not occurred anywhere in the study region.

Table 1. Altitudinal shift of the upper boundaries of open and closed forests between 1910 and 2000

Statistic	Open forests			Closed forests		
	elevation a.s.l., m		shift, m	elevation a.s.l., m		shift, m
	1910	2000		1910	2000	
Median	231	257	26	195	230	35
Minimum	153	194	41	131	154	23
Maximum	332	410	78	292	348	56

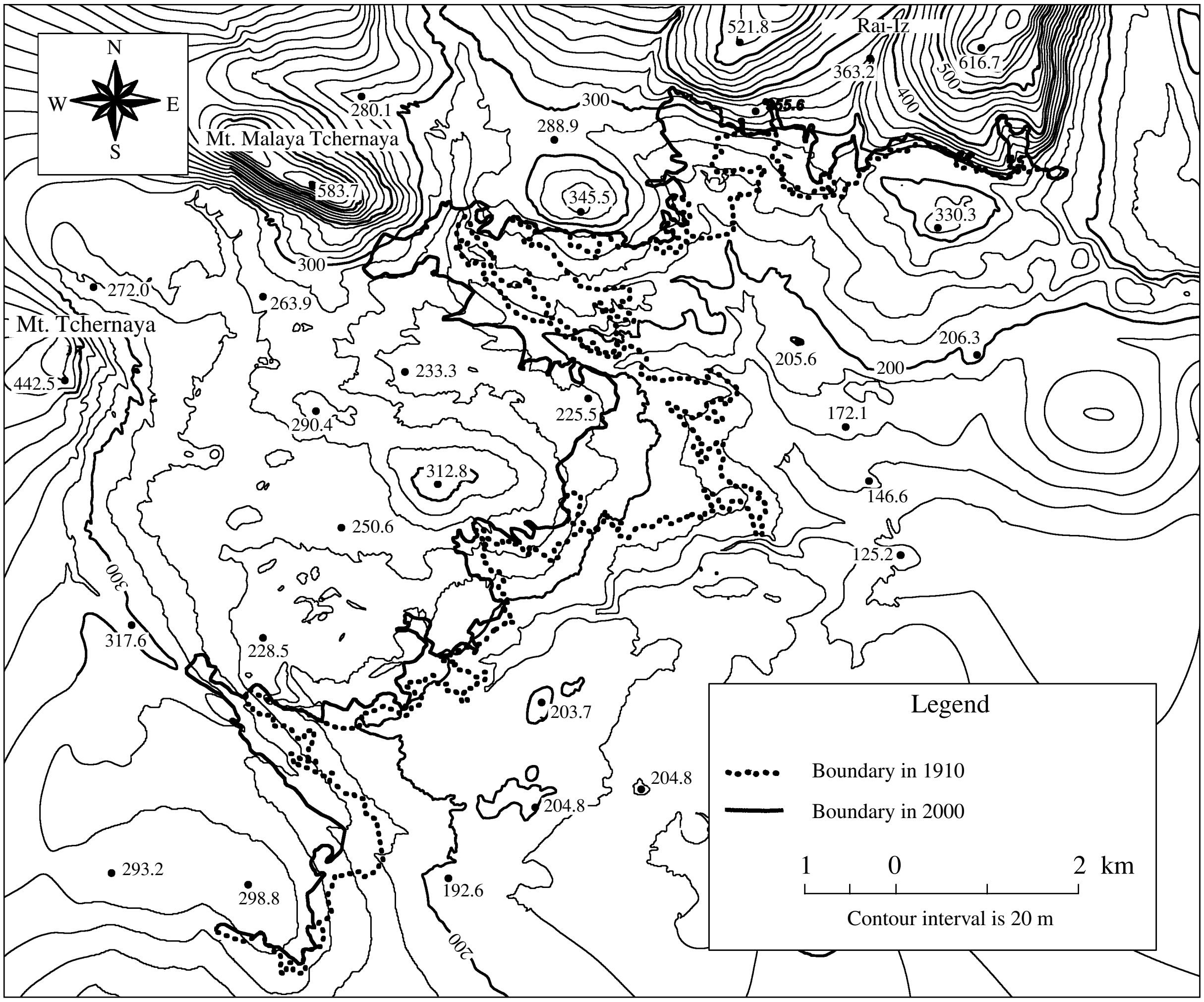

Fig. 2. Map of shift of the upper boundary of open forests over the past 90 years.

On the median, the altitudinal shift reached 26 m for open forests (from 231 to 257 m a.s.l.) and 35 m for closed forests (from 195 to 230 m); the horizontal shift reached 290 m for open forests and 520 for closed forests (Tables 1, 2). Thus, the respective rates of altitudinal displacement over 90 years were 3 and 4 m per decade, and those of horizontal displacement were 32 and 58 m per decade. It is apparent that closed forests have moved more rapidly than open forests, which is explained by the fact that open forest communities under favorable conditions readily transform into closed forests due to more abundant seed supply from trees growing in open forest areas. As shown previously (Shiyatov, 1966), seed dispersal from larch cones in the study region takes place in summer, when snow disappears. Heavy larch seeds are carried by wind no farther than 40–60 m from maternal plants and, after settling, are retained in the litter. Hence, larch regeneration in more distant tundra areas proceeds very slowly, and the formation of more or less dense tree stands may take much time.

The maximum altitudinal shifts of open and closed forests between 1910 and 2000 reached 78 and 56 m, and the horizontal shifts reached 1190 and 2030 m, respectively (Tables 1, 2). The most significant displacement of forest boundaries took place on the southern slope of the Rai-Iz massif, along the left bank of the Kerdomanshor River, on the eastern slope of a cone mountain 312.8 m high, and along the right bank of the Engayou River. The advancement of closed forests for more than 2 km along the Kerdomanshor River is most impressive. In the 1910s and even in the 1960s, there were mainly single or sparse trees, with a narrow strip

Table 2. Horizontal shift of the upper boundaries of open and closed forests between 1910 and 2000, m

Statistic	Open forests	Closed forests
Median	290	520
Minimum	70	10
Maximum	1190	2030

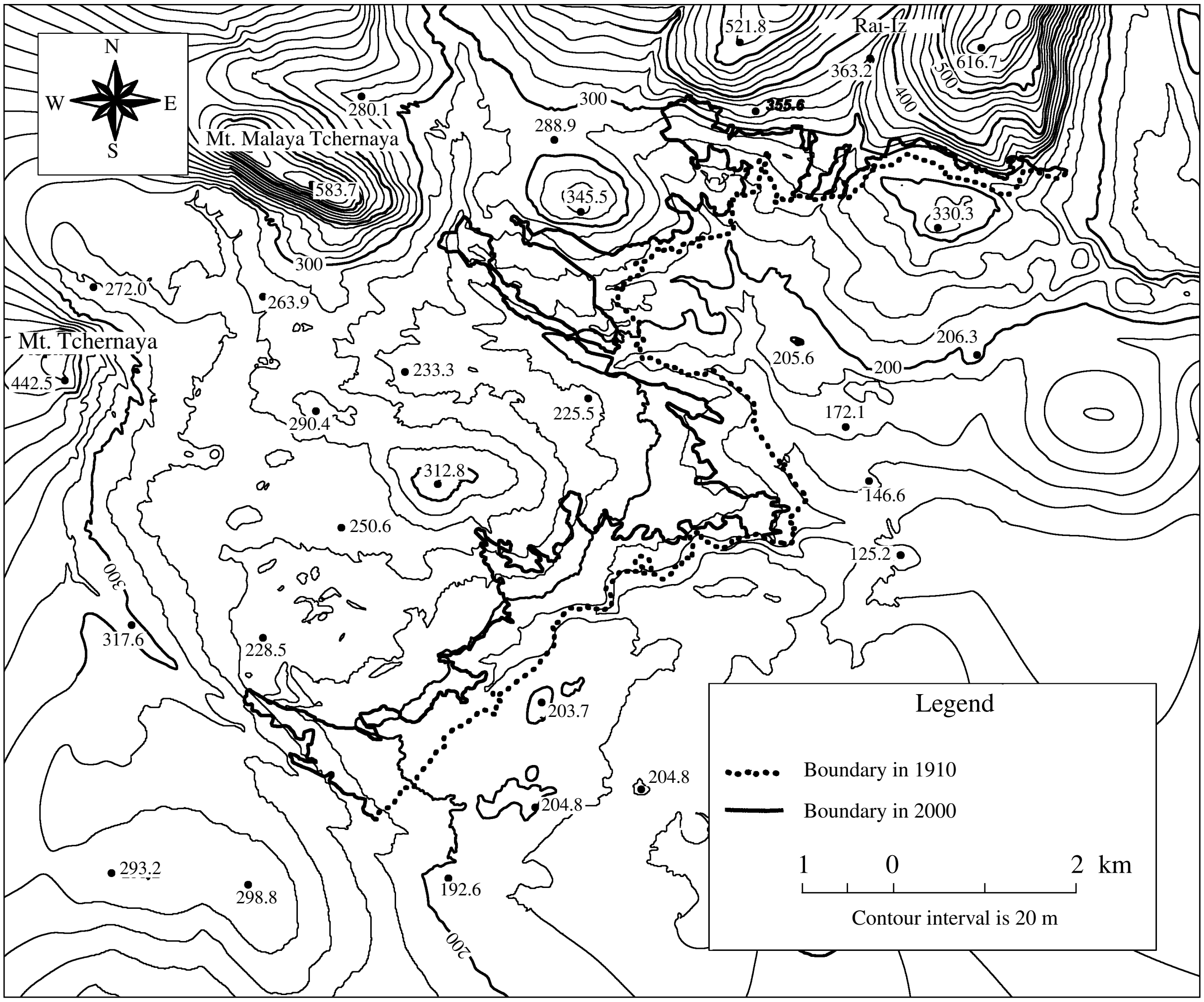

Fig. 3. Map of shift of the upper boundary of closed forests over the past 90 years.

of open forests extending along the steep left bank facing south. To date, most of these communities have become closed forests (Fig. 4).

The upper boundary of open forests has markedly shifted both on slopes exposed in winter to strong westerly winds (the Kerdomanshor–Engayou interfluve) and in the areas where summer temperatures are the main limiting factors (the southern slope of the Rai-Iz massif). This is evidence that the pattern of winds and the temperature conditions have become more favorable for the growth of trees over the past 90 years. The growing period begins earlier, and its duration has increased, and this allows young larch shoots to complete the cycle of their growth and development and to prepare themselves for wintering under severe conditions. Before the recent climate warming, larch in windswept habitats with little snow was represented only by prostrate growth form. To date, prostrate plants have transformed into multistemmed trees up to 5–6 m high and young trees aged up to 50–60 years are mainly single-stemmed.

These data on the magnitude of altitudinal and horizontal shifts in the upper boundaries of open and closed forests in the Polar Urals confirm our previous findings concerning the expansion of tree vegetation to higher elevations due to climate warming and increasing humidity in the 20th century (Shiyatov et al., 2005). According to data from the Salekhard weather station located 55 km east of the study region, the average air temperature in summer (July–August) between 1920 to 2004 was 0.7°C higher and that in winter (November–March) was 1.1°C higher than between 1883 and 1919, and the amount of precipitation also increased by 32 mm in summer (from 147 to 179 mm) and by 46 mm in winter (from 67 to 113 mm). As the elevational lapse-rate of summer air temperatures in the Polar Urals is 0.7°C, the climate-dependent upper boundary of the zone suitable for tree growth could ascend approximately 100 m. This value is almost three times greater than the actual altitudinal shift of the upper boundary of open and closed forests. In other words, tree vegetation has not yet expanded to the climatic limit because of

Fig. 4. Development of relatively dense and open larch forests on the left bank of the Kerdomanshor River.

insufficient supply of larch seeds to tundra areas in the upper part of the timberline ecotone, although it is already close to this limit on some slopes.

Thus, the analysis of vertical and horizontal shifts in the upper boundaries of open and closed forests on the eastern macroslope of the Polar Urals provides evidence for widespread and active expansion of tree vegetation to higher elevations over the past 90 years, which is apparently explained by favorable changes in climatic conditions.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research (project nos. 05-04-48466 and 06-04-49359) and INTAS (grant no. 01-0052) and received technical support from the computer software companies ESRI Inc. and Leica Geosystems (United States).

REFERENCES

Shiyatov, S.G., The Time of Seed Dispersal in Siberian Larch in the Northwestern Part of Its Range and the Role of This Factor in Relationships between Forest and Tundra, in *Voprosy fiziologii i geobotaniki* (Problems in Physiology and Geobotany), *Zap. Sverdlovsk. Otd. Vses. Bot. O–va,* Sverdlovsk, 1966, issue 4, pp. 109–113.

Shiyatov, S.G., On Types of the Timberline and Its Dynamics in the Polar Urals, in *Biologicheskie osnovy ispol'zovaniya prirody Severa* (Biological Foundations of Nature Resource Use in the North), Syktyvkar, 1970, pp. 73–81.

Shiyatov, S.G., Terent'ev, M.M., and Fomin, V.V., Spatiotemporal Dynamics of Forest–Tundra Communities in the Polar Urals, *Ekologiya*, 2005, no. 2, pp. 83–90.