Russian Journal of Ecology, Vol. 36, No. 2, 2005, pp. 69–75. Translated from Ekologiya, No. 2, 2005, pp. 83–90.

Spatiotemporal Dynamics of Forest–Tundra Communities in the Polar Urals

S. G. Shiyatov, M. M. Terent'ev, and V. V. Fomin

Institute of Plant and Animal Ecology, Ural Division, Russian Academy of Sciences, ul. Vos'mogo Marta 202, Yekaterinburg, 620144 Russia

Received October 10, 2004

Abstract—The spatiotemporal dynamics of forest–tundra communities in the 20th century have been studied in the timberline ecotone of the Polar Urals. Maps reflecting the distribution of different types of forest–tundra communities have been made, and data on the morphological and age structure of tree stands have been obtained for three time sections (the mid-1910s, 1960s, and 2000s). They show that open and closed forests have markedly expanded due to natural afforestation of the tundra and increase in the density and productivity of existing forest stands. The unidirectional pattern of plant community transition (from the tundra to closed forests) and meteorological data provide evidence that this transition has been conditioned by climate warming and increasing humidity recorded during the past 90 years.

Key words: timberline ecotone, spatiotemporal dynamics of forest–tundra communities, geobotanical mapping, climate warming, geographic information system.

Recently, studies on the spatiotemporal dynamics of highland forest–tundra and forest–meadow communities have attracted increasing attention due to the necessity of assessing their response to current and future climate changes (Kullman, 1990; Körner, 1999; Bugmann and Pfister, 2000; Holtmeier, 2003; Shiyatov, 2003). Of particular interest are the communities of high latitudes, as the most significant changes in climatic conditions occur in the corresponding regions (*Climate Change…*, 2003).

The Polar Urals is a promising mountain region for analyzing the response of the biota to climate change (Shiyatov, 1965, 2003; Shiyatov *et al.*, 2002). Climatic conditions assessed on different time scales are highly variable (Shiyatov, 1986), and highland vegetation does not suffer from the anthropogenic impact. The zone at the timberline is under tree stands of relatively simple composition (mainly of Siberian larch), which facilitates analysis of their climate-conditioned dynamics. Moreover, abundant data characterizing the composition and structure of forest–tundra vegetation in this region have been accumulated over the past 40–50 years, and, hence, direct evidence is available for assessing changes that have occurred in this period.

To quantitatively assess changes in the composition, structure, and spatial distribution of forest–tundra communities over the past 90 years, we performed large-scale on-ground mapping and description of forest–tundra communities growing within the timberline ecotone. Following Körner (1999), we apply this term to the transitional belt of mountain vegetation between the upper limit of single tree growth in the tundra and the upper limit of closed forests. This ecotone is wider than the subgoltsy belt, because it covers the lower part of the mountain tundra belt, where solitary woody plants are found.

This study deals with the results of studies on the transition between different types of forest–tundra communities under the effect of climate warming and increasing humidity over the past 90 years. Changes in the composition and structure of tree stands are not considered in detail.

OBJECTS AND METHODS

The study region is on the eastern macroslope of the Polar Urals, in the Sob River basin (66°46′–66°55′ N, 65°22′–65°49′ E). The major part of its area (with the highest elevations) is occupied by the Rai-Iz massif, which is composed of peridotites and extends from the Sob River on the east to the Makar-Ruz' River on the west (Fig. 1). The highest part of the Rai-Iz is a large plateau (800–1100 m above sea level) with several sharp peaks (1260–1290 m) on the north. A chain of mountains composed of gabbro extends along the southern margin of the massif. Mounts Tchernaya and Malaya Tchernaya (1030 and 594 m, respectively) are the highest in this chain. At some distance, there is another chain of lower coniform mountains (294, 312, and 359 m). The Engayou and Kerdomanshor rivers have their sources in the northern part of the Rai-Iz. Large areas in their valleys are covered with moraine debris deposited during the last glaciation and abound with lakes. The northern and eastern slopes of the Rai-Iz

1067-4136/05/3602-0069 © 2005 Pleiades Publishing, Inc.

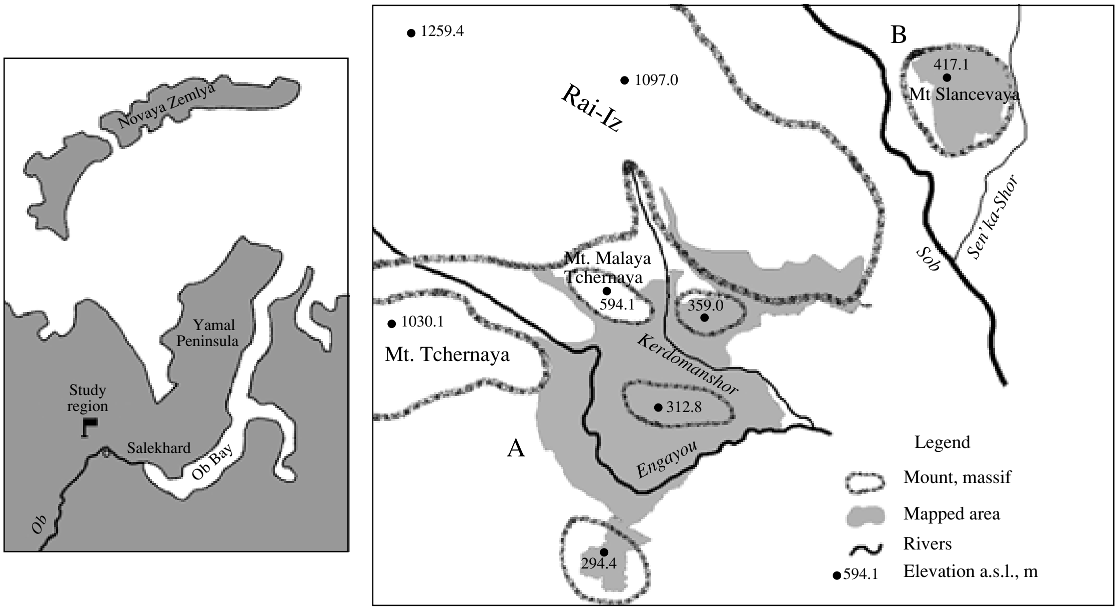

Fig. 1. Map of the study region: (A) vicinity of the Rai-Iz massif and Mounts Tchernaya and Malaya Tchernaya, and (B) vicinity of Mount Slancevaya (the mapped area is shown in gray).

are surrounded by mountains (400–880 m) composed of crystalline shales, including mounts Slancevaya, Yar-Keu, and Pour-Keu. Mount Slancevaya has three peaks (363, 412, and 417 m) and is separated from the Rai-Iz by the Sob valley.

The study region is in the southern part of the forest–tundra zone. Vegetation belts distinguished on mountain slopes are as follows: the mountain taiga, subgoltsy, mountain tundra, and cold goltsy deserts (Gorchakovskii, 1975). Pure larch (*Larix sibirica*) forest–tundra communities prevail in the timberline ecotone, with open larch forests and larch forests with Siberian spruce (*Picea obovata*) and birch (*Betula tortuosa*) occurring in its lower part.

Mapping was performed from 2000 to 2004. Field work was aimed at delimiting forest–tundra compartments (sites) internally uniform with respect to the composition and structure of the tree and ground vegetation layers and the main parameters of microclimate and soil. To mark their boundaries, we used topographic maps (scale 1 : 25000) and black-and-white and color aerial photographs (1 : 25000 to 1 : 40000). The smallest compartment was 30 × 30 m in size. A total area of 5407 ha at the base of mounts Tchernaya and Malaya Tchernaya, on the southern slope of the Rai-Iz massif, and on Mount Slancevaya was mapped (gray area in Fig. 1).

Descriptions of the present-day and former forest–tundra vegetation were made using our original method. First, the phytocenotic type of forest–tundra community was determined for each site. Taking into account the region and objects of study, we distinguished the following main types: the tundra with single trees, sparse tree growth, open forests, and closed forests. Stand density estimated from the average distance between trees served as a criterion for attributing a phytocenosis to a certain type. For larch communities of the Polar Urals, these indicator distances were chosen as follows: less than 7 (10) m, closed forest; 7 (10) to 20 (30) m, open forest; 20 (30) to 50 (60) m, sparse tree growth; and more than 50 (60) m, the tundra with single trees. Greater distances (in parentheses) were used when the stand consisted of large and old trees.

For each site, we visually estimated the composition and structure of present-day vegetation and basic microclimatic and soil conditions (moistening, amount of snow, wind conditions, stoniness, exposure, and slope). Morphometric parameters of tree stands were determined, including average tree height and diameter, average distance between trees, crown density, percent ratio of the forms of tree growth, timber volume, and the presence or absence of undergrowth. As shown previously (Shiyatov, 1965), open larch forests of the Polar Urals have a stepped age structure conditioned by centennial climatic fluctuations. The present-day tree stands consist of overmature (310–370 years), middle-aged (150–220 years) and young (up to 80–90 years) generations, which are well differentiated by morphological characters (tree height and diameter and crown shape). On the whole, more than 900 sites were described and mapped.

In addition, the composition and structure of tree stands as of the early 1910s and 1960s were reconstructed for each site. The first time section corresponded to the end of a cold period and the onset of formation of the young tree generation, and the second, to the early period of intensive studies on forest–tundra communities in this region (Shiyatov, 1965). Recon-

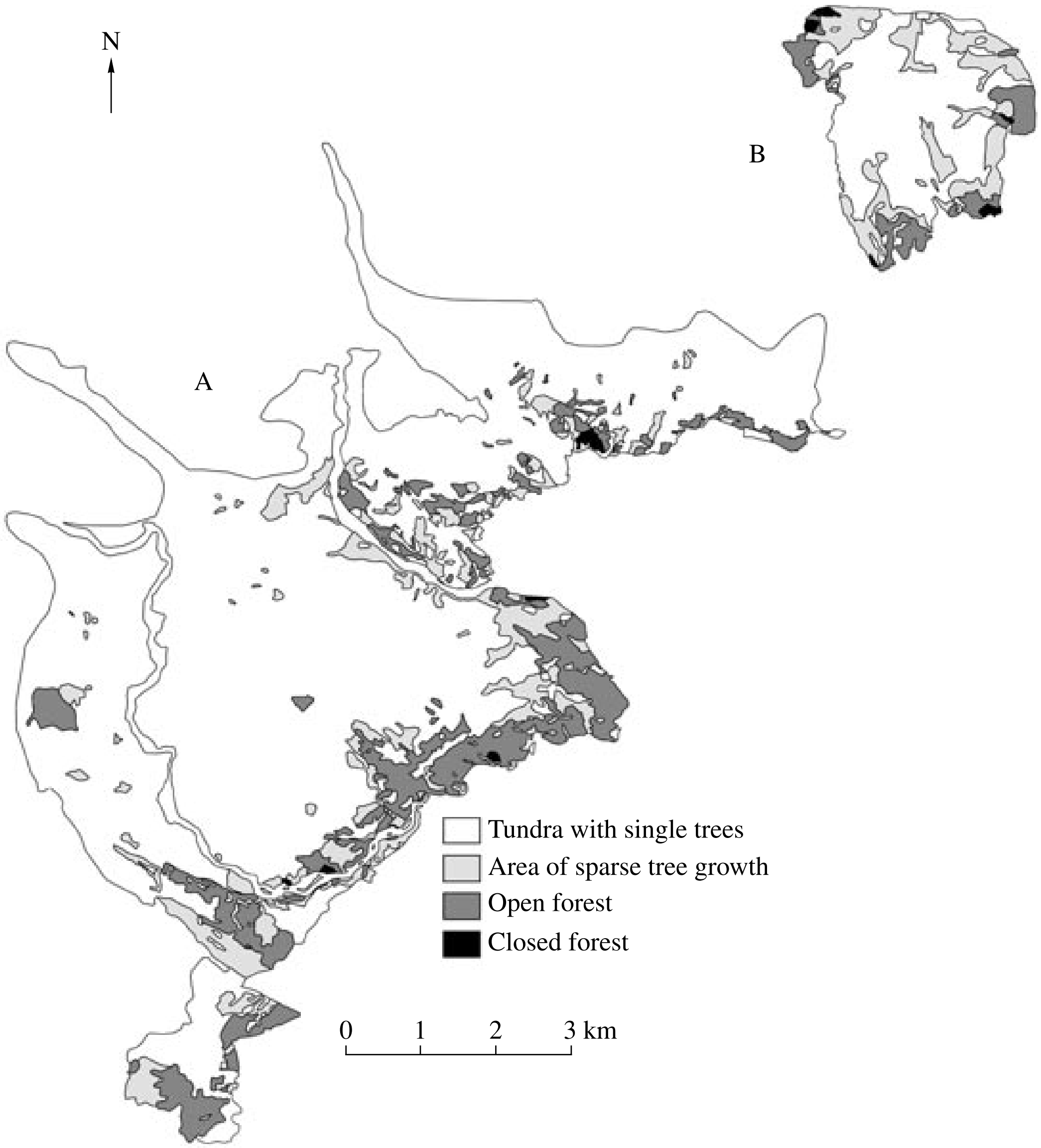

Fig. 2. Distribution of different types of forest–tundra communities in the early 1910s: (A) vicinity of the Rai-Iz massif and Mounts Tchernaya and Malaya Tchernaya, and (B) vicinity of Mount Slancevaya.

structions were based on the analysis of morphological parameters and age structure of tree stands and on descriptions and calculations made in permanent test plots established between 1960 and 1962. Analysis of landscape photographs made 35–40 years age proved to be especially useful. The contribution of each tree generation was estimated for all time sections, which allowed us to obtain data on the dynamics of tree stand as a whole and of individual generations over the past 90 years.

The ARC/INFO geographic information system (GIS) (ESRI Inc., United States) and the ERDAS Imagine program package for processing aerial and satellite images (ERDAS Inc., United States) were used to make maps reflecting the distribution of different types of forest–tundra communities in the early and mid-20th century and the early 21st century. In Figs. 2–4, mapped area B (Mount Slancevaya) is placed closer to area A (the Rai-Iz massif) to save space. The topographic map of the study area (1 : 25000) was digitized to make electronic coverage with isolines, elevations, and hydrological objects. The TOPOGRID algorithm was used to create a hydrologically correct digital elevation model (DEM), which, in turn, was used for orthotransformation of color aerial photographs in different spectral zones (1 : 40000) made in 2002 and 2003. As a result, we obtained a mosaic of images of the study region, which was used as a reference in order to more accurately reflect the configuration of the sites of vector coverage

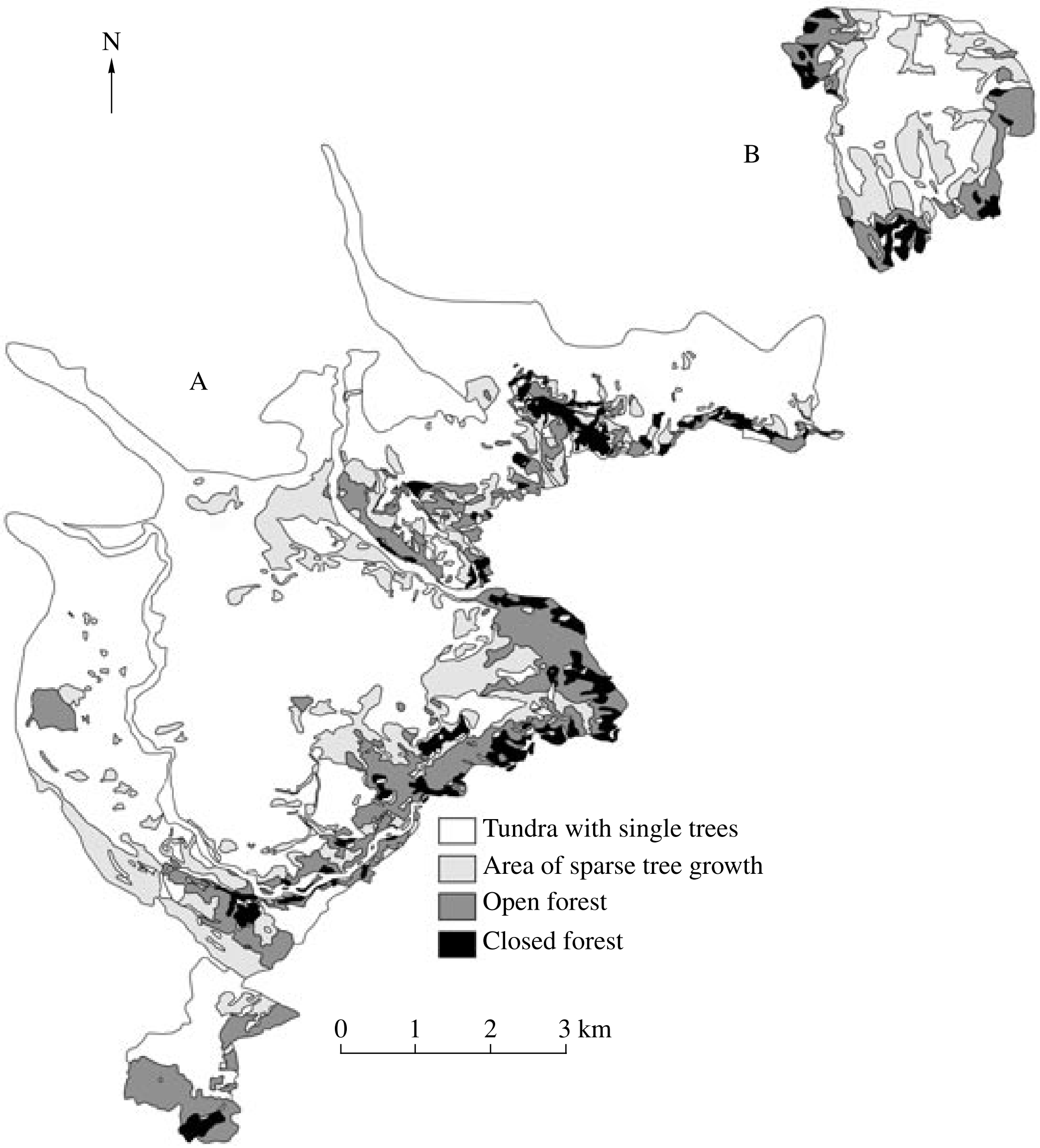

Fig. 3. Distribution of different types of forest–tundra communities in the early 1960s: (A) vicinity of the Rai-Iz massif and Mounts Tchernaya and Malaya Tchernaya, and (B) vicinity of Mount Slancevaya.

upon digitization in the GIS. Attributive data on the aforementioned parameters were entered for each site.

RESULTS AND DISCUSSION

Figures 2–4 show the distribution of different types of forest–tundra communities in the early 1910s, 1960s, and 2000s. For clarity, lakes and rivers are not shown on these maps.

The upper boundary of the timberline ecotone is the line connecting the uppermost single trees of different growth forms (single-stemmed, multistemmed, or prostrate) that continue growing. To determine its location in the middle and, especially, early 20th century is impossible because of the short life span of such trees and difficulties in determining their age. Hence, we considered this boundary to be fixed throughout the corresponding period. As follows from Figs. 2–4, it is sinuous and forms long lobes extending far to the mountains along river valleys. Its lowermost location is in the Engayou River valley (270 m), which is waterlogged and exposed to strong winds, and the uppermost location is on the stony eastern brow of the Rai-Iz massif (560 m). On Mount Slancevaya, single prostrate trees grow even at the highest elevations, so that the whole mountain top is within the timberline ecotone.

The lower boundary of the timberline ecotone lies at the base of the Rai-Iz southern slope and, farther south, at the bases of cone mountains located 3–5 km away from mounts Tchernaya and Malaya Tchernaya (Fig. 1).

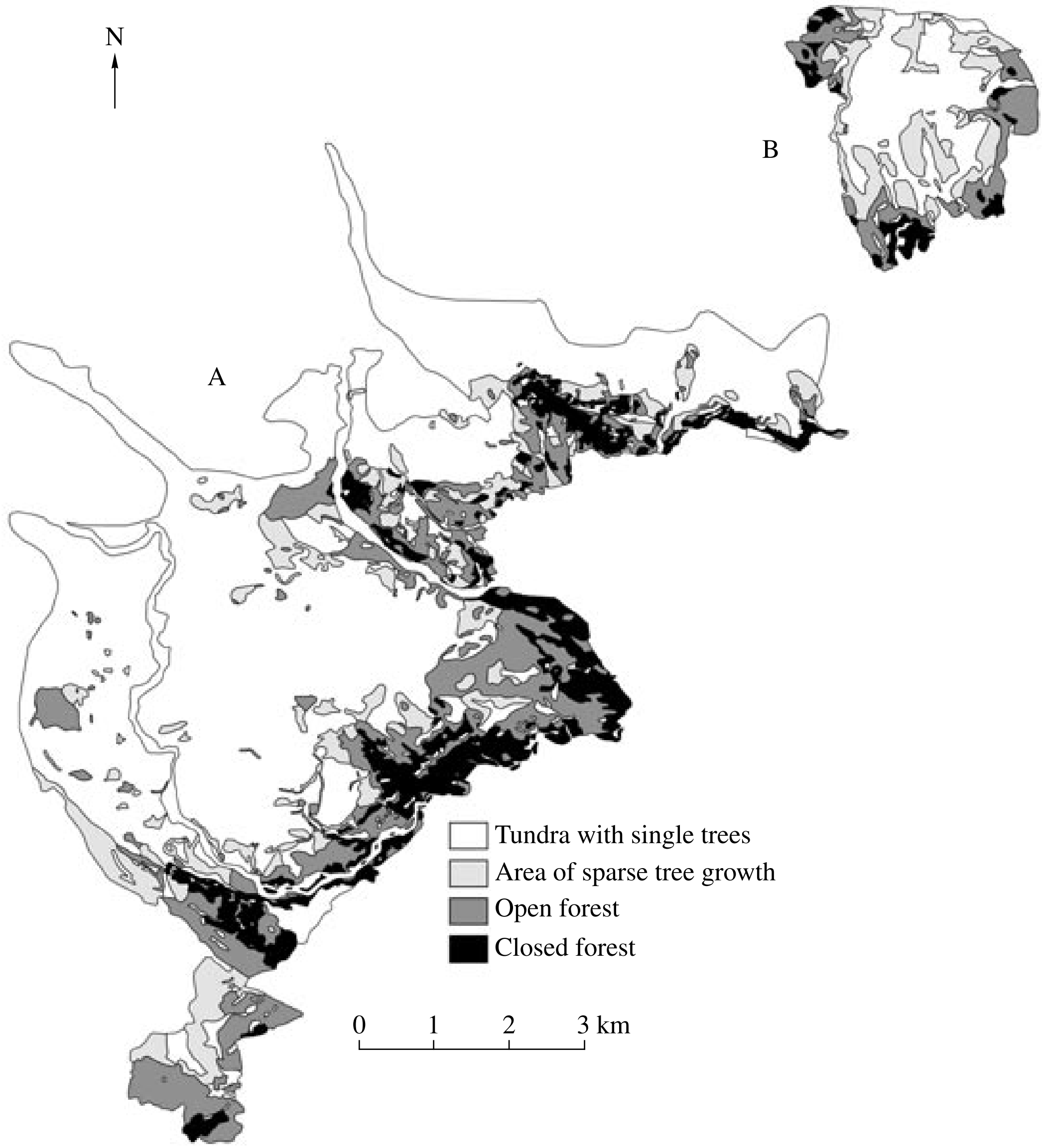

Fig. 4. Distribution of different types of forest–tundra communities in the early 2000s: (A) vicinity of the Rai-Iz massif and Mounts Tchernaya and Malaya Tchernaya, and (B) vicinity of Mount Slancevaya.

On Mount Slancevaya, it rises to the middle of the western and southern slopes. The corresponding elevations vary from 140 to 230 m, i.e., within a much narrower range than in the case of the upper boundary.

The width of the ecotone depends mainly on wind conditions and the slope of the terrain. It reaches 7–9 km in the Engayou–Kerdomanshor interfluve and decreases to the minimum at the eastern margin of the Rai-Iz massif.

A comparison of Figs. 2–4 shows that the degree of afforestation in the ecotone has markedly increased during the past 90 years. In both the first and second halves of the 20th century, open and closed forests markedly expanded, whereas tundra areas decreased. The upper boundaries of the areas of sparse tree growth, open forests, and close forests on many slopes shifted to higher elevations. The maximum shift observed in the Engayou–Kerdomanshor interfluve was 50, 77, and 80 m, respectively. On Mount Slancevaya, this shift was smaller (35 m for closed forests and 45–50 m for communities of the other two types), because this mountain is lower and is exposed to strong wind impact.

Table 1 shows the absolute and relative areas covered by different types of forest–tundra communities in the early 1910s, 1960s, and 2000s. The tundra with single trees prevailed in the timberline ecotone throughout this period, because large areas of the ecotone (especially in its upper part) are unsuitable for tree growth and the amount of seeds is insufficient for natural affor-

Table 1. Distribution and ratio of areas under different types of forest–tundra communities

Type of community	Early 1910s		Early 1960s		Early 2000s	
	ha	%	ha	%	ha	%
Tundra with single trees	4125	76	3464	64	3189	59
Area of sparse tree growth	642	12	950	18	733	13
Open forest	618	11	755	14	951	18
Closed forest	22	1	238	4	534	10
Total	5407	100	5407	100	5407	100

Table 2. Matrix of transition between the areas (ha) under different types of forest–tundra communities: (1) tundra with single trees, (2) area of sparse tree growth, (3) open forest, and (4) closed forest

Time section	Early 1910s				
	Type of community	1	2	3	4
Early 1960s	1	3464	–	–	–
	2	581	370	–	–
	3	72	251	432	–
	4	8	21	186	22
	Early 1960s				
Early 2000s	1	3189	–	–	–
	2	245	486	1	1
	3	29	453	468	1
	4	1	11	286	236

estation. However, the absolute area of the tundra became almost 1000 ha smaller, and its proportion decreased from 76 to 59%. The area with sparse trees abruptly expanded from 642 to 950 ha in the first half of the 20th century but decreased in the second half. Today, this area is only 91 ha greater than in the 1910s, because sparse trees at some sites have changed into open or closed forests. Open forests gradually increased in area from 618 to 951 ha over 90 years. Closed forests deserve special attention: compared to the early 1910s, when they were confined to ten small sites (a total of 22 ha), their area in the ecotone has increased almost 25-fold, reaching 534 ha (Table 1). The expansion of closed forests has been especially active on the southern slope of the Rai-Iz massif (Fig. 4), where conditions for the growth of larch are more favorable: the ground vegetation layer poorly develops on peridotites, and the terrain is protected from winds.

As follows from Table 1, only the tundra area with single trees has decreased during the past 90 years, whereas all other types of forest–tundra communities have expanded. It was interesting to discover what types of communities gave rise to the present-day communities. The results of calculations made for this purpose are shown in Table 2. Analysis of these data indicates that the most common transformations were those of the tundra into the area of sparse tree growth, of the area of sparse tree growth into open forest, and of open forest into closed forest. In the first half of the 20th century, a large area with sparse trees (581 ha) appeared in the tundra, 251 ha of the area with sparse trees transformed into open forests, and 186 ha of open forests entered the category of closed forests. The same trend was observed in the second half of the 20th century, except that open and closed forests expanded to a greater extent than the area with sparse trees (453 and 286 ha vs. 245 ha, respectively). Direct transformation of the tundra into open or closed forest and of the areas with sparse tree growth into closed forest occurred on a much smaller scale (Table 2). As a rule, such transformations (without intermediate stages) took place in the areas well supplied with high-quality larch seeds.

Degradation of the tree layer in the second half of the 20th century occurred only in several small areas: closed forest (2 ha) degraded into a suppressed open stand and area with sparse trees; 1 ha of open forest also transformed into an area of sparse tree growth. This was caused by the accumulation of huge snowdrifts (up to 6 m high) in the cold season, which began in these areas a few decades ago due to an increase in the density and height of tree stands growing on their windward side. The stems and branches of trees buried under snow bend and break; moreover, the snow cover disappears two to three weeks later than in other areas, which markedly reduces the duration of the growing season. Such conditions are extremely unfavorable for trees, and forests gradually die off to be replaced by tundra and meadow communities.

As follows from Table 1, the total area under sparse trees, open forests, and closed forests was 1282 ha (24% of the ecotone area) in the early 1910s and 1944 ha (36%) in the early 1960s, compared to 2218 (41%) in the 2000s. Therefore, the degree of afforestation in the ecotone has increased almost twofold.

Thus, plant community transition from the tundra to closed forests and increase in the degree of afforestation were characteristic of the timberline ecotone during the past 90 years. The unidirectional pattern of these changes on slopes differing in exposure indicates that they were determined by the same factor. As the anthropogenic impact on forest–tundra communities of the study region is insignificant, the climatic factor is the only candidate for this role. In our opinion, the expansion of trees is related to a significant improvement in the conditions for their growth. This conclusion is confirmed by data recorded at the Salekhard weather station (55 km east of the study region) over the past 120 years. They show that significant climate warming and increase in humidity occurred in the 1920s. The average summer temperature (June–August) increased by 0.7°C, from 10.7°C in 1883–1920 to 11.4°C in 1920–2004, while the average winter temperature (November–March) increased by 1.1°C, from −20.8 to −19.7°C. The amount of precipitation increased by 32 mm in summer (from 147 to 179 mm) and by 46 mm in winter (from 67 to 113 mm).

Climate warming in the Polar Urals in the 20th century was more significant than in the northern regions of western Siberia and Taimyr. This follows from the comparison of summer temperatures in different subarctic regions of the Northern Hemisphere, which were reconstructed by Vaganov *et al.* (1998) by analyzing the width of tree rings in larch. The expansion of trees could be markedly promoted by the earlier onset of the growing season, because the average air temperature in May increased by 1.3°C, from –2.4°C in 1883–1920 to –1.1°C in 1920–2004. As the vertical gradient of summer air temperature in the Polar Urals is 0.7°C, the temperature-dependent upper boundary of the zone suitable for tree growth could be raised by approximately 100 m.

On the majority of slopes, however, trees failed to expand to this boundary due to insufficient seed supply to the tundra areas located in the upper part of the ecotone. As shown previously (Shiyatov, 1966), larch seeds in this region fall out of cones in June or July, when the snow cover disappears, and are carried by wind no farther than 40–60 m away from the maternal tree, so that the spread of seeds up the slope is insignificant. This is why many habitats suitable for tree growth remain vacant. This line of reasoning may also be used to explain more active natural afforestation of the tundra and transformation of sparse stands into closed forests in the lower part of the timberline ecotone, where not only microclimatic and soil conditions are more favorable, but seed supply is also greater.

The expansion of single trees and forests was accompanied by a marked increase in the vertical and radial tree increment, crown density, and productivity of tree stands. The ratio of single-stemmed, multistemmed, and prostrate trees also changed significantly. In the lower part of the ecotone, Siberian spruce successfully regenerates under the canopy of larch stands. These facts are not considered in more detail because of restrictions on the volume of this paper, but they provide additional evidence that conditions for tree growth have markedly improved.

Based on the above data on the climate-conditioned spatiotemporal dynamics of different types of forest–tundra communities in the Polar Urals over the past 90 years, we developed mathematical models employing GIS technologies with the purpose of predicting the development of these communities according to different scenarios of climate change.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research, project nos. 99-04-48984 and 02-04-48148; INTAS grant no. 01-0052; and OOO DATA+, official representative of the software companies ESRI Inc. and ERDAS Inc., United States.

REFERENCES

Bugmann, H. and Pfister, C., Impacts of Interannual Climate Variability on Past and Future Forest Composition, *Reg. Environ. Change*, 2000, no. 1, pp. 112–125.

Climate Change 2001: Synthesis Report. Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Watson, R.T., Ed., Geneva: WMO-UNEP, 2003.

Gorchakovskii, P.L., *Rastitel'nyi mir vysokogornogo Urala* (The Plant World of the High-Mountain Urals), Moscow: Nauka, 1975.

Holtmeier, F.-K., *Mountain Timberlines. Ecology, Patchiness, and Dynamics*, Dordrecht: Kluwer, 2003.

Körner, Ch., *Alpine Plant Life*, Berlin: Springer, 1999.

Kullman, L., Dynamics of Altitudinal Tree-Limits in Sweden: A Review, *Norsk. Geografisk Tidsskrift.*, 1990, vol. 44, pp. 103–116.

Shiyatov, S.G., Age Structure and Tree Stand Formation in Open Larch Forests at the Timberline in the Sob River Basin (the Polar Urals), *Geografiya i dinamika rastitel'nogo pokrova* (Plant Cover Geography and Dynamics): *Tr. Inst. Biol. Ural. Fil. Akad. Nauk SSSR*, 1965, no. 42, pp. 81–96.

Shiyatov, S.G., Time of Dispersal of Siberian Larch Seeds in the Northwestern Part of Species Range and the Role of This Factor in Forest–Tundra Interactions, *Voprosy fiziologii i geobotaniki* (Problems in Physiology and Geobotany): *Zap. Sverdlovsk. Otd. Vses. Bot. O–va*, 1966, no. 4, pp. 109–113.

Shiyatov, S.G., *Dendrokhronologiya verkhnei granitsy lesa na Urale* (Dendrochronology of the Timberline in the Urals), Moscow: Nauka, 1986.

Shiyatov, S.G., Rates of Change in the Upper Treeline Ecotone in Polar Ural Mountains, *PAGES News*, 2003, vol. 11, no. 1, pp. 8 –10.

Shiyatov, S G., Mazepa, V. S., and Chekhlov, O. Yu., Climate Change and Dynamics of Forest–Tundra Ecosystems in the Polar Urals in the 20th Century, *Nauch. Vestn.*, 2002, no. 11, pp. 28–35.

Vaganov, E.A., Shiyatov, S.G., Hantemirov, R.M., and Naurzbaev, M.M., Variation of Summer Air Temperature at High Northern Latitudes over the Past 15 Centuries: Comparative Analysis of Data Derived from Tree Rings and Ice Cores, *Dokl. Ross. Akad. Nauk*, 1998, vol. 358, no. 5, pp. 681–684.