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Changes in the Composition, Structure, and Altitudinal Distribution of Low Forests at the Upper Limit of Their Growth in the Northern Ural Mountains

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Abstract—Changes in the composition, structure, and altitudinal distribution of low forests at the upper limit of their growth over the past 50 years have been studied in the Tylaisko-Konzhakovsko-Serebryanskii Massif (the Northern Urals). The qualitative and quantitative assessment of these changes has been made on the basis of descriptions, photographs, and maps made in 1956 and 2005. The results show that the upper boundary of low forests on the majority of slopes has ascended. Considerable changes have occurred in the composition, density, and height of the tree layer in the communities that formed the upper low-forest boundary in 1956. Among a fairly large number of tree species growing in the subgoltzy belt (*Picea obovata, Larix sibirica, Pinus sibirica,* and *Abies sibirica*), the birch *Betula tortuosa* has expanded most actively, whereas the proportions of *P. obovata* and especially *L. sibirica* in low forests have decreased. These changes are explained by climate warming and increasing humidity.

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Key words: upper low-forest boundary, stand composition and structure, climate warming and increasing humidity, geographic information system, the Northern Urals.

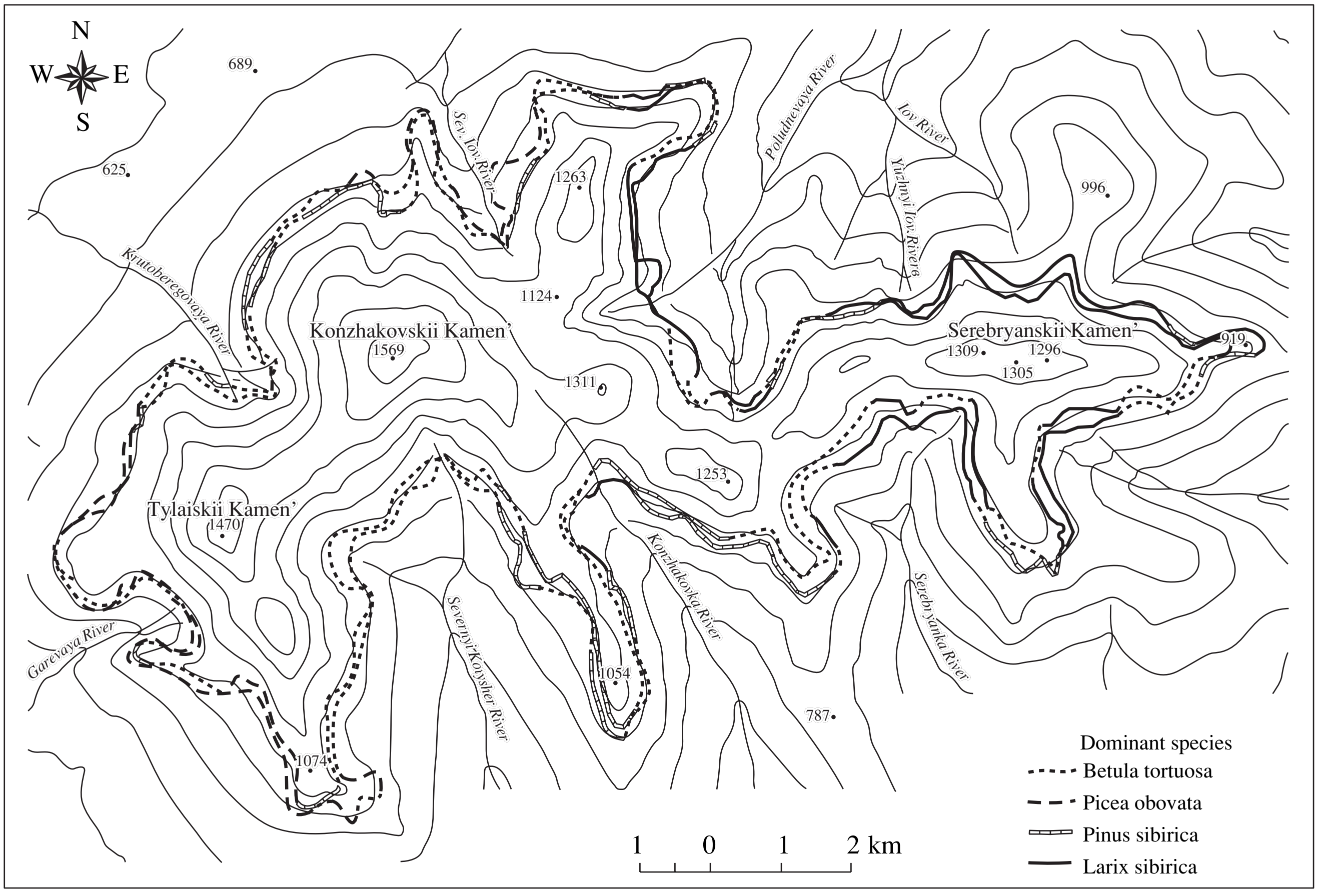
Studies on the dynamics of forest communities and their components under the effect of recent climatic changes are receiving increasing attention. It is expedient to perform such studies in high mountains, where tree grow under extreme soil and climatic conditions and the responses of forest ecosystems to climatic changes are more distinct (Shiyatov, 1993; Körner, 1999; Holtmeier, 2003; Kullman, 2003; Moiseev et al., 2004; Shiyatov et al., 2005). Of special interest are regions in which high-mountain vegetation has not been exposed to significant influences of anthropogenic factors. In particular, high-mountain regions of the Ural Mountain Range, which extends from the tundra zone in the north to the steppe zone in the south, appear to be promising in this respect.

The purpose of this study was to analyze qualitative and quantitative changes in the composition, structure, and altitudinal distribution of low forests at the upper limit of their growth in the Tylaisko-Konzhakovsko-Serebryanskii Massif (the Northern Urals) that occurred in the second half of the 20th century.

STUDY REGION

The Tylaisko-Konzhakovsko-Serebryanskii Massif (59°30′–59°40′ N, 59°00′–59°20′ E), located in the axial watershed zone of the Northern Urals, extends in a west–east direction for 20 km and comprises three mountains: Tylaiskii Kamen' (1470 m a.s.l.), Konzhakovskii Kamen' (1569 m), and Serebryanskii Kamen' (1306 m). Numerous spurs extend southward and northward from its central axis (figure). The massif is composed of pyroxenites, dunites, and gabbros. It serves as a watershed: the Kos'va River (a tributary of the Kama River) flows from its northwestern slopes, whereas other slopes contain the headwaters of the Lobva River (a tributary of the Sos'va River). Mountain slopes above the upper low-forest boundary are usually steep, with large-stone screes (rock streams).

Foothills at elevations of up to 850–900 m are in the mountain forest belt with the prevalence of dark conifer forests dominated by Siberian spruce (*Picea obovata* Ledeb.), Siberian fir (*Abies sibirica* Ledeb.), and Siberian stone pine (*Pinus sibirica* Du Tour). In the eastern part of the massif and in the vicinity of Kytlym, pine (*Pinus sylvestris* L.) and birch (*Betula pubescens* Ehrh.) forests are widespread. At higher elevations, in the subgoltzy belt, there are low (crooked and open) forests made up of the aforementioned tree species (except *P. sylvestris*). In the eastern part of the massif, they are supplemented with open Siberian larch (*Larix sibirica* Ledeb.) communities. *Betula pubescens* is sub-



Map of the study region and positions of the upper low-forest boundary in 1956 (lower line) and 2005 (upper line) with regard to dominance of different tree species.

stituted by *Betula tortuosa* Ledeb., a closely related species. *Abies sibirica* occurs as an admixture, mainly in the prostrate or multistemmed growth forms. The mountain tops (above 900–1000 m) are in the mountain tundra belt.

The massif is far from large industrial centers and highways (60 km from Karpinsk and Krasnotur'insk, 80 km from Serov, and 135 km from Berezniki), and forest vegetation on its slopes is not exposed to technogenic pollution. In lower parts of the slopes, forests suffer from mining, tree cutting, and fires. In high-mountain areas, recreational load is the main anthropogenic factor, but it has not yet produced any significant effect on the composition and structure of low forests.

OBJECTS AND METHODS

The composition and structure of low forests and the altitudinal position of their upper boundary in the Tylaisko-Konzhakovsko-Serebryanskii Massif were studied by S.G. Shiyatov in 1956 (see Gorchakovskii and Shiyatov, 1970). This boundary was understood as the line to which forest communities with a crown density of no less than 15–20% can ascend. Its position was determined using barometric surveying and a topographic map (scale 1 : 100000). In parallel, visual analysis and description of tree stands near this boundary (in the upper 50- to 100-m band) were performed. The following parameters were recorded: stand composition (by timber stock), crown density, average tree diameter and height (for the entire stand and for individual tree species), and the direction to which asymmetrical (flaglike) tree crowns were extended. The upper low-forest band was divided along the slope into sites differing in the composition of the tree stand by one or more units (the composition and structure of the tree stand within each site were uniform). A total of 124 sites were described, with absolute elevations being determined at 136 points.

In 2005, D.S. Kapralov and P.A. Moiseev performed field studies in the same area in order to assess changes in the composition, structure, and altitudinal distribution of low forests over the past 50 years. For this purpose, they used a digitized topographic map (scale 1 : 25000) that contained information obtained in 1956, including the altitudinal position of the upper low-forest boundary, boundaries of sites, the composition of tree stands, and elevations at the points of barometric

Table 1. Changes of dominant tree species in stands growing at the upper low-forest boundary between 1956 and 2005

Mountain	Length of the upper low-forest boundary in 1956, km	Year	Dominant of tree layer							
			Betula tortuosa		*Pinus sibirica*		*Picea obovata*		*Larix sibirica*	
			km	%	km	%	km	%	km	%
Tylaiskii Kamen'	16.82	1956	7.70	46	0.36	2	8.76	52	–	–
		2005	8.70	52	0.74	4	7.38	44	–	–
Konzhakovskii Kamen'	28.33	1956	15.09	53	3.60	13	4.91	17	4.73	17
		2005	17.78	63	4.17	15	2.15	7	4.23	15
Serebryanskii Kamen'	25.84	1956	4.30	17	6.78	26	–	–	14.76	57
		2005	11.44	44	5.84	23	–	–	8.56	33
Total	70.99	1956	27.09	38	10.74	15	13.67	19	19.49	28
		2005	37.92	53	10.75	15	9.53	14	12.79	18

measurements. In the field, positions of these sites and points were determined with the aid of a topographic map, a barometric pressure gauge, and a GPS receiver. Repeated descriptions of low forests at the sites surveyed in 1956 showed that the upper boundary of stands with a crown density exceeding 15–20% has ascended since then on the majority of mountain slopes. Hence, it was decided to repeat studies on mapping and describing the present-day low-forest boundary by the methods used in 1956 and to compare the results. Changes in high-mountain vegetation were estimated using numerous landscape photographs from the same points as those made by Shiyatov in 1956, 1957, and 1969.

The data of field studies performed in 1956 and 2005 were put into the ARC/INFO geographic information system (GIS) (ESRI, United States) to make digital vector maps that allow us to show the altitudinal position of the upper low-forest boundary and other attributive parameters. A digital elevation model (DEM) of the study region was created, and, on this basis, rasters providing information on slope and aspect were calculated. To assess changes in the composition, structure, and the upper boundary of low forests, digital thematic maps were converted into the special GRID raster format, in which raster cells contain information from the attribute tables of vector thematic maps. In this data format, it was possible to perform cell-based analysis and compare the results with respect to different parameters.

An analysis of the altitudinal position of the upper low-forest boundary was performed in the GIS by superimposing the rasters containing information about the configuration of sites and dominant tree species upon the DEM of the study region.

The horizontal displacement of the upper low-forest boundary between 1956 and 2005 was estimated in the GIS by a special algorithm that we developed for this purpose. Using the 1956 low-forest boundary as a baseline, we calculated and plotted buffer regions in the form of polygon coverages with boundaries lying parallel to the baseline at distances equal to multiples of the cell size in the DEM of the study region. As a result, a layer consisting of consecutive buffer regions was obtained. After rasterization of this layer, the raster coverage reflecting the position of the low-forest boundary in 2005 was superimposed on it. Thus, each cell corresponding to the 2005 low-forest boundary had its counterpart in the buffer layer, which showed the horizontal displacement of this boundary relative to its position in 1956.

In addition, we analyzed long-term climatic data (1881–1996) from the nearest weather stations Karpinsk (187 m a.s.l.) and Biser (408 a.s.l.) located at distances of 60 and 125 km from the study region, respectively.

RESULTS

Table 1 shows data on changes of dominant tree species in stands that formed the upper 50- to 100-m band of low forests in 1956. A noteworthy fact is a sharp increase in the dominance of *B. tortuosa*: in the massif as a whole, the length of sites dominated by this species along the low-forest boundary (relative to its total length) increased from 38% in 1956 to 53% in 2005 (i.e., by 15%), and the corresponding increase on Serebryanskii Kamen' reached 27% (from 17 to 44%). On Konzhakovskii Kamen' and Tylaiskii Kamen', where birch stands at the upper low-forest boundary were well represented in 1956 (53 and 46%), the relative length of sites dominated by *B. tortuosa* also increased by 10 and 6%, respectively.

The dominance of conifers in sites described in 1956 either decreased or remained at the same level. In general, the relative length of sites dominated by *P. obovata* and, especially, *L. sibirica* decreased by 5 and 10%, respectively, whereas the degree of dominance of *P. sibirica* remained unchanged (15%). The proportion of larch in tree stands markedly decreased

Table 2. Lengths of the upper low-forest boundary in 1956 and 2005 with regard to dominance of different tree species

Mountain	Year	Length of the upper low-forest boundary in 1956, km	Dominant of tree layer							
			Betula tortuosa		*Pinus sibirica*		*Picea obovata*		*Larix sibirica*	
			km	%	km	%	km	%	km	%
Tylaiskii Kamen'	1956	16.82	7.70	46	0.36	2	8.76	52	–	–
	2005	16.16	9.40	58	1.42	9	5.34	33	–	–
Konzhakovskii Kamen'	1956	28.33	15.09	53	3.60	13	4.91	17	4.73	17
	2005	28.25	17.49	62	7.36	26	0.44	2	2.95	10
Serebryanskii Kamen'	1956	25.84	4.30	17	6.78	26	–	–	14.76	57
	2005	25.38	10.92	43	3.60	14	–	–	10.86	43
Total	1956	70.99	27.09	38	10.74	15	13.67	19	19.49	28
	2005	69.79	37.82	54	12.38	18	5.78	8	13.81	20

Table 3. Average (above the line) and highest (below the line) elevations of the upper low-forest boundary in 1956 and 2005 with regard to dominance of different tree species, meters above sea level

Dominant of tree layer	1956				2005			
	Tylaiskii Kamen'	Konzhakovskii Kamen'	Serebryanskii Kamen'	total massif	Tylaiskii Kamen'	Konzhakovskii Kamen'	Serebryanskii Kamen'	total massif
Betula tortuosa	933/1005	928/1032	940/993	932/1032	964/1049	947/1083	983/1070	962/1083
Pinus sibirica	925/940	915/997	933/1012	925/1012	945/1008	984/1089	991/1054	981/1089
Picea obovata	942/1052	906/1009	–	929/1052	1002/1081	990/1005	–	999/1081
Larix sibirica	–	878/977	934/1024	919/1024	–	899/984	975/1066	960/1066

on Serebryanskii Kamen' (by 24%). Changes were especially significant in larch and birch–larch forests prevailing in this area, in which the proportion of *B. tortuosa* became significantly greater. The relative length of sites dominated by *P. obovata* on Konzhakovskii Kamen' and Tylaiskii Kamen' decreased by 10 and 8%, respectively; dominance of *P. sibirica* increased by 2% on both these mountains but decreased by 3% on Serebryanskii Kamen' (Table 1).

Along with changes in the composition of tree stands, the crown density in them increased, on average, by 11% (from 49 to 60%). This increase was most prominent in sites dominated by *P. sibirica* (26%, from 46 to 72%), whereas the crown density in *P. obovata* sites remained almost the same. The average tree height increased by 0.6 m (from 4.8 to 5.4 m).

The figure shows altitudinal positions of the upper low-forest boundary in 1956 (lower line) and 2005 (upper line). It can be seen that the boundary has obviously ascended, remaining on the same position only in small areas of steep slopes and windswept mountain passes. This is an unexpected result, as steep rocky slopes prevail in the upper part of the massif. An analysis of the distribution of low forests that has appeared since 1956 shows that they are usually confined to numerous mountain terraces where fine earth accumulates and primitive mountain-tundra soils are being formed. Therefore, the present-day low-forest boundary differs from the former boundary in the increasing area of woodless sites with rock streams located between large and small crooked and open forests. In addition, the figure provides information on dominance of different tree species along the low-forest boundary in 1956 and 2005, which shows that the change of dominants has occurred on certain mountain slopes.

Quantitative data on dominance of different tree species along the upper low-forest boundary are shown in Table 2. They provide evidence for the expansion of *B. tortuosa* to mountain tundras over the past 50 years. As the upper forest boundary has ascended since 1956, its total length in the massif has decreased by 1.2 km (to

69.79 km), but the relative length of its segments dominated by *B. tortuosa* has increased from 38 to 54%. This species has expanded most actively on Serebryanskii Kamen': in 1956, larch stands prevailed there (57%), whereas their present-day proportion along the upper forest boundary is equal to that of stands dominated by *B. tortuosa* (43% each). The proportion of birch stands at the upper low-forest boundary has also increased on Tylaiskii Kamen' (by 12%) and Konzhakovskii Kamen' (by 9%). The proportion of stands dominated by *P. obovata* in the entire massif, Tylaiskii Kamen', and Konzhakovskii Kamen' has decreased by 11, 19, and 15%, respectively. In the case of *P. sibirica*, this proportion increased by 3% in the entire massif, by 7% on Tylaiskii Kamen', and by 13% on Konzhakovskii Kamen' but decreased by 12% on Serebryanskii Kamen'.

We also calculated changes in the average and highest elevations of the upper low-forest boundary with regard to dominance of different tree species in the massif as a whole and on individual mountains (Table 3). In 2005, as in 1956, the average elevation of the upper forest boundary with stands dominated by *B. pubescens, P. sibirica*, and *L. sibirica* was higher on Serebryanskii Kamen' and that with stands dominated by *P. obovata* was higher on Tylaiskii Kamen'. Low forests ascending to the highest elevations in 1956 (on average, 932 m a.s.l.) were dominated by birch, whereas low forests that ascended even higher in 2005 (999 m) were dominated by spruce. The upper low-forest boundary with stands dominated by *L. sibirica* was located at relatively low elevations: on average, 919 m in 1956 and 960 m in 2005.

The highest elevation of the upper low-forest boundary does not always coincide with its average elevation, because small areas in different parts of the massif provide especially favorable conditions for the growth of certain tree species. In 1956, the upper forest boundary reached the highest elevation due to stands dominated by *P. obovata* on Tylaiskii Kamen' (1052 m). To date, low forests dominated by *P. sibirica* on Konzhakovskii Kamen' ascended even higher (1089 m).

As follows from Table 3, the upper boundary of low forests dominated by any species has ascended over the past 50 years an average of 41 m, with the average upward shift ranging from 30 m (from 932 to 962 m) in stands dominated by birch to 70 m (from 929 to 999 m) in stands dominated by spruce. The horizontal shift of the upper low-forest boundary in the massif averaged 113 m, reaching the highest values in the upper reaches of the Severnyi Iov and Poludnevaya rivers (420 and 330 m, respectively).

DISCUSSION

The above data show that tree vegetation in the Tylaisko-Konzhakovsko-Serebryanskii Massif has actively expanded during the past 50 years both within the subgoltzy belt and to the lower part of the mountain tundra belt. The density and height of existing stands have increased, and the upper low-forest boundary has ascended on the majority of slopes. The improvement of conditions for the growth of different tree species within the massive as a whole and in individual habitats can be accounted for only by climatic changes.

An analysis of data from the Karpinsk and Biser weather stations in the Northern Ural foothills showed that the average temperature of the warm season (May–September) has increased in the past 40 years by 0.4°C (from 12.1 to 12.5°C), that of the cold season (October–April) has increased by 2.0°C (from –9.9 to –7.9°C), and the amount of precipitation has increased by 72 mm (from 360 to 432 mm) and 105 mm (from 302 to 407 mm), respectively. The improvement of heat supply and more abundant precipitation in the cold period are noteworthy, because these factors in high mountains are of special significance.

These climatic data provide a basis for explaining the active expansion of tree species, especially *B. tortuosa.* Birch is known to dominate at the timberline and at the northern forest boundary in maritime regions, where precipitation is abundant. Therefore, the increase of summer and winter precipitation in the study area is apparently a major factor providing for more active expansion of *B. tortuosa*, compared to conifers. No less important in this respect are ecological and biological properties of this species: it is light-loving; can settle on steep rocky slopes in patches of fine earth accumulated between stones; successfully grows in habitats with abundant snow and a short growing period; and produces a great number of seeds, which easily disperse. Conditions for birch expansion proved to be most favorable on Serebryanskii Kamen', where birch formed a dense understory in open larch stands. As a consequence, snow cover in these stands became deeper and natural reproduction of larch ceased. Active expansion of *B. tortuosa* to tundra and meadow communities in snowy habitats was observed by Shiyatov in the Subpolar Urals, near Neroiki Mountain in 1970 (unpublished data). Much attention to this process in the mountains of Scandinavia was devoted by Kullman (1979, 1993, 2001, 2002, 2003), who obtained ample data confirming that small clusters of birch trees grow into large forest islands and that crooked birch forests expand to the tundra. Thus, recent climate warming and increase in humidity promote the expansion of *B. tortuosa* at the upper limit of its growth.

The role of *P. sibirica* in tree stands forming the upper low-forest boundary has changed insignificantly during the past 50 years. In our opinion, this may be related to regular transfer of its seeds to mountain tundras by the Eurasian nutcracker (*Nucifraga caryocatactes*). In tundra habitats with little snow, *P. sibirica* grows in the form of suppressed prostrate plants that produce vertical stems only after a certain period of time, upon the improvement of climatic conditions or an increase in snow depth. In the subgoltzy belt, however, *P. sibirica* trees are among the largest, reaching 15–17 m in height and 30–40 cm in diameter.

The decreased proportion of *P. obovata* in tree stands at the present-day upper low-forest boundary is explained by extreme conditions for its growth and, hence, poor reproduction. In particular, this species forms the climatically determined low-forest boundary on the western slope of Tylaiskii Kamen', where spruce stands and young growth are strongly suppressed. In most cases, the growth and expansion of *P. obovata* depend primarily on the amount of snow that protects plants from cold in winter. This is why the segments of the low-forest boundary dominated by this species ascend very slowly, with dominance on steeper and stony slopes gradually passing to *B. tortuosa*.

Larix sibirica, which forms the upper low-forest boundary only in the eastern part of the massif, has partially lost dominance due to the expansion of *B. tortuosa.* However, it successfully reproduces and shares dominance with birch (43% each) on northern and southern slopes of Serebryanskii Kamen'. Larch is well established in dry, windswept, and almost snowless habitats where competition with other tree species is insignificant. It is noteworthy that, due to the improvement of heat supply, young larch trees are mainly of the normal single-stemmed form and have high vitality, whereas old trees are suppressed, with many of them being of semiprostrate or multistemmed growth forms.

Thus, the data presented above provide evidence for the expansion of tree vegetation in high-mountain regions of the Northern Urals during the past 50 years under the effect of climate warming and increase in humidity. In particular, this process manifests itself in the change of dominant species, increasing crown density and productivity of tree stands growing in the subgoltzy belt, and a significant upward shift of the upper low-forest boundary. Tree species differ in their response to recent climatic changes, but the expansion of *B. tortuosa* has been most active.

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