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Current Expansion of *Juniperus sibirica* Burgsd. to the Mountain Tundras of the Northern Urals

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Abstract—Ecosystems of high-mountain and high-latitude regions are especially sensitive to changes in climate conditions. A considerable part of recent publications on climatogenic transformation of plant communities deal with the dynamics of the upper treeline, while similar studies on shrub vegetation are scarce. Our study on the age structure of Siberian juniper (*Juniperus sibirica* Burgsd.) thickets in the Northern Urals (the Chuvalsky Kamen Range) has shown that the upper shrubline has shifted up the altitudinal gradient. The establishment of *J. sibirica* in windblown areas with little snow at the summits of slopes began as late as the second half of the 20th century and has gained momentum after the 1970s. An analysis of climatic data has revealed a linear trend toward increase in the magnitude of anomalies in average air temperature over the cold season (November–March) by 1.69°C/100 years (R^2 = 0.57), with precipitation increasing by 67.3 mm/100 years (R^2 = 0.43). The results of correlation analysis between the establishment of *J. sibirica* and average precipitation by 5-year periods show that the strongest correlations occur in areas with little snow at the early cold season (November–January; R = 0.96). Changes in the pattern of snow accumulation in winter could facilitate the current expansion of *J. sibirica* to the mountain tundras of the Northern Urals.

Keywords: snow depth, upper shrubline, *Juniperus sibirica* Burgsd., climate change, Northern Urals

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During the past few decades, the international scientific community has been increasingly discussing the problems of current climate change [1] and its consequences for the world's fauna [2] and flora [3]. Especially sensitive to climate change ecosystems of high-mountain and high-latitude regions [4], where harsh microclimatic conditions create a barrier to the development of tree and shrub species [5]. Changes in the temperature and moisture regime in such regions lead to shifts in the botanical geographic boundaries [6, 7].

The problem of advancement of tree species to the mountains has been actively discussed in the scientific literature. Harsch et al. [4] have analyzed 166 publications dealing with shifts of the upper treeline in different regions of the world and concluded that most significant changes have occurred in the regions where the near-ground air temperature in the cold season has markedly increased during the past century. Similar generalizations are also available for shrub vegetation, but they mainly concern polar regions. Having analyzed more than 60 publications, Myers-Smith and Hik [8] have found only six studies dealing with the dynamics of the shrubline [9–14], with only three of them [11, 13, 14] attempting to reveal a relationship between the observed intensification of growth and expansion of shrub vegetation and the temperature and precipitation of the cold season. Supposedly, the expansion of shrubs may lead to reduction in the biodiversity of mountain tundra and meadow communities (in particular, their alpha and beta diversity) and to changes in the structure of the mountain landscape [15]. Therefore, studies on assessing the expansion of shrub vegetation and predicting future changes in the vegetation of tundra ecosystems are highly relevant under current conditions [16].

Siberian juniper *Juniperus sibirica* Burgsd. is one of the most widespread shrub species in the Ural Mountains, which grows along the entire length of this range and plays an important phytocenotic role in the composition of high-mountain plant communities. Route surveys in the axial part of the Ural Mountains have shown that *J. sibirica* is especially abundant in the Northern Urals (the Olkhovochny, Chuvalsky Kamen, and Molebny Kamen ranges), where it forms a band of vegetation in open and sparse forests and the lower mountain tundra and meadow zone, growing in dense, hardly passable thickets. As shown in recent studies, the 20th century (especially after the 1950s) was marked by intensive *J. sibirica* expansion to mountain tundra on certain peaks of the Southern [17] and Northern Urals [18]. Since studies on shifts in the shrubline are rare [8], no deep insight has yet been gained into the geographic scale and rate of the advancement of shrubs to high-mountain mountain tundra and the driving forces of this process.

The purposes of this study were as follows: to analyze the morphological and age structure of *J. sibirica* thickets and the spatiotemporal dynamics of juniper communities in the mountain tundra belt on the Chuvalsky Kamen Range, in areas with different snow accumulation conditions, and to reveal environmental factors that may contribute to shifts in the upper distribution boundary of this species.

MATERIAL AND METHODS

The Chuvalsky Kamen Range (the Northern Urals) is located in the territory of Vishera State Nature Reserve (Krasnovishersky district, Perm krai; (60°57′38″ N, 58°57′51″ E). It extends for 18 km from north to south and 14. 5 km from west to east, its highest peak is Mt. Zyryanovka (929.4 m a.s.l.). The range is formed of shales, metabasalts, and quartzitic sandstones of the Ordovician Chuval formation [19]. The climate of the study region is continental boreal type. According to long-term data from the Troitsko-Pecherskoe weather station (1888–2018), the annual average air temperature is –1.1°C; average January temperature, –17.7°C (with the absolute minimum of about –50°C); and average July temperature is 16.1°C. The warm season is 160–170 days long. Prevailing wind directions are from southwest, west, and south (in summer, from north and east). Snow cover in the region is deep (50–150 cm according to long-term observations in forest areas); it is formed in the second 10-day period of October and disappears in the third 10-day period of April [20]. According to Gorchakovskii [6], three altitudinal vegetation belts are distinguished on the range: the mountain forest, subgoltzy, and mountain tundra belts. Spruce and fir–spruce forests prevail in the mountain forest belt; the vegetation of the subgoltzy belt is represented by birch, birch–spruce, and birch–fir scrub forests. *Juniper sibirica* thickets grow at elevations above the upper forest boundary. The mountain tundra vegetation extends throughout the top of the range [21].

Two altitudinal transects on the northwestern slope of the Chuvalsky Kamen, above the boundary of spruce–birch sparse forests, and several additional test plots at the Mt. Zyryanovka top were established in 2016. Studies on the transects were performed at three levels: at the upper boundary of closed *J. sibirica* thickets (bottom level), at the upper boundary of open *J. sibirica* thickets (middle level), and at the upper boundary of sparse *J. sibirica* shrubs (top level) (Fig. 1). Two to five permanent test plots (20 × 20 m) established at each level. The transects were laid out so that the top-level plots were located on the axial part of the ridge (at summits). Each *J. sibirica* plant in a plot was examined to record its precise location and determine its height, crown diameter in two perpendicular directions, and age. To determine shrub age, a crosscut sample of wood from the thickest branch at the place of its attachment to the stem was taken and used for subsequent tree-ring dating in the laboratory [22]. The age correction factor for the branch attachment height was determined by studying the course of growth from the hypocotyl of the stem to the place where it split into plagiotropic branches in individual young *J. sibirica* plants. This method was successfully tested in our previous studies [17, 18]. On the whole, morphometric parameters and age were determined for each of 720 *J. sibirica* shrubs growing in a total area of 1.18 ha.

Changes in climate parameters in the study region were evaluated based on the data from the Troitsko-Pecherskoe weather station (62°42′ N, 56°12′ E, 135 m a.s.l.). Long-term series of observations on near-ground air temperature and total precipitation (1888–2018) were analyzed. The data on precipitation were used with corrections for wetting losses and replacement of gauges [23]. The data on monthly average air temperature and precipitation were analyzed as applied to the warm season (June–August), when *J. sibirica* was at the phase of active growth, and the cold season (November–March), when monthly average air temperatures were below zero. Anomalies in average air temperature and precipitation during the warm and cold seasons of each year were revealed by calculating the difference between the current value of a given parameter and its average value in the reference period (1961–1990).

A survey to measure snow depth was conducted in March 2017. No less than 40 measurements with a special prove were made in the locations of rest plots and adjacent slope areas. In each plot, a DS1921 Thermochron iButton logger was inserted in the soil to a depth of 10 cm to determine the minimum soil temperature.

Correlations were analyzed between the numbers of *J. sibirica* plants emerged during 5-year periods and the average values of climatic parameters in different time intervals of the year (individual months and cold and warm seasons) over the current and previous 5-year periods. Correlation strength was estimated using Spearman's correlation coefficient (R), since data distribution differed from normal (Shapiro–Wilk test) and sample size was relatively small. Data grouping by 5-year periods is explained by the fact that the formation of cone berries in *J. sibirica* takes 2–3 years [25], and seedlings emerge 2–3 years still later because of delayer seed germination [26]. The data on correlations are presented for the top and middle levels. These data for the bottom level were not included in analysis because of the absence of *J. sibirica* regeneration after the 1970s, which could be explained by the absence of areas suitable for the establishment of new plants, in particular due to the high canopy closure of mature shrubs.

Table 1. Morphometric (mean ± *SE*) and areal parameters of *J. sibirica* shrubs in altitudinal transects

Parameter	Transect I			Transect II			Mount Zyryanovka top
Altitudinal level	bottom	middle	top	bottom	middle	top	
Average shrub height, cm	88.5 ± 3.4	55.7 ± 2.1	35.8 ± 1.7	82.2 ± 2.3	39.4 ± 1.7	39.7 ± 1.4	28.5 ± 1.1
Average crown diameter, cm	384.3 ± 23.5	154.6 ± 8.3	87.2 ± 4.9	362.8 ± 17.2	117.1 ± 5.4	117.9 ± 5.9	99.6 ± 5.5
Average age, years	102 ± 4	68 ± 3	40 ± 2	95 ± 3	51 ± 2	46 ± 2	37 ± 2
Shrub density, ind./ha	420	1600	614	476	1366	510	397
Crown projective cover, m^2/ha	5127	4094	471	5058	1944	695	463

RESULTS

As follows from the data in Table 1, the average morphometric and areal characteristics of *J. sibirica* shrubs consistently decreased upon transition from the bottom to the top level of the transects. Thus, the average shrub height decreased by a factor of 2–2.5, depending on site conditions; crown diameter, by a factor of 2–4; and the sum of crown projections, by a factor of 4–12. The number of shrubs reached a peak at the middle level, where conditions for their growth were apparently more favorable than at other levels. The average age of shrubs decreased along the altitudinal gradient from 102 to 40 years on transect I and from 95 to 46 years on transect II.

Analysis of the age structure of *J. sibirica* thickets on the Chuvalsky Kamen slopes (Fig. 2) showed that the establishment of this species on transect I began in the mid-19th century. Regeneration of *J. sibirica* at the bottom level was most active between 1885 and 1935, when about 70% of currently growing plants had emerged. The first *J. sibirica* plants at the middle level appeared in the 1870s, but their establishment on a large scale occurred in the period from 1935 to 1975 (65%). At the top level, mass colonization by *J. sibirica* began as late as the second half of the 20th century, and 55% of currently growing shrubs emerged between 1965 and 1985.

In transect II, the establishment of *J. sibirica* at the bottom level followed a similar scenario: this process reached a peak between1905 to 1915, with 30% of currently growing plants having emerged during this period. The first *J. sibirica* plants at the middle level appeared in 1905 (later than on transect I), and their large-scale establishment continued throughout the century. At the top level, the first *J. sibirica* plants appeared in the 1930s, but their active expansion began after 1965, as on transect I (50% of currently growing plants). The establishment of *J. sibirica* in additional test plots at the Mt. Zyryanovka top began after the 1970s.

Analysis of the data from the Troitsko-Pecherskoe weather station (Fig. 3) revealed linear trends toward increase in the values of anomalies in the average air temperature and precipitation of the cold season at the respective rates of 1.69°C/100 years (R^2 = 0.57) and 67.3 mm/100 years (R^2 = 0.43). Climatic parameters of

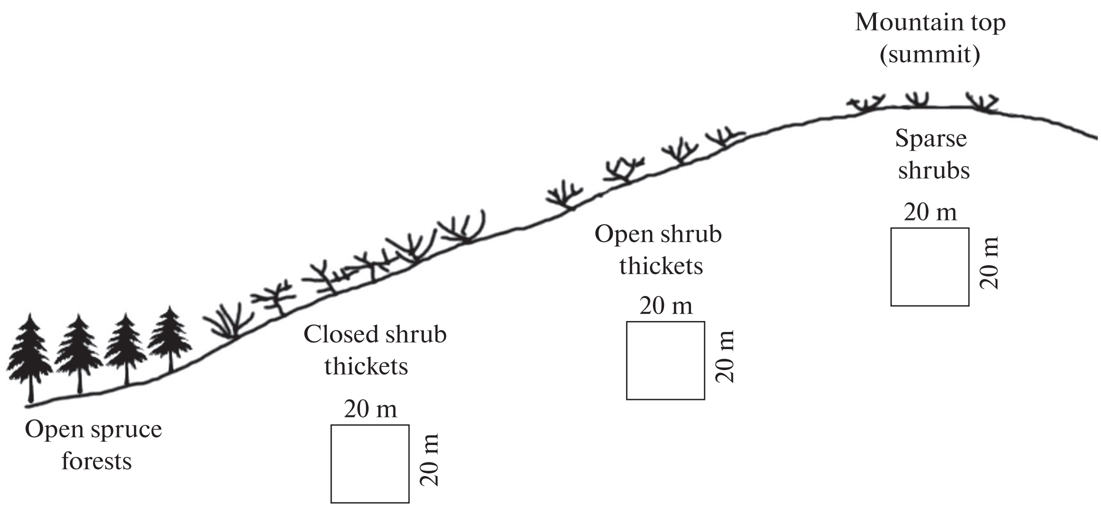

Fig. 1. Scheme of changes in vegetation along an altitudinal transect.

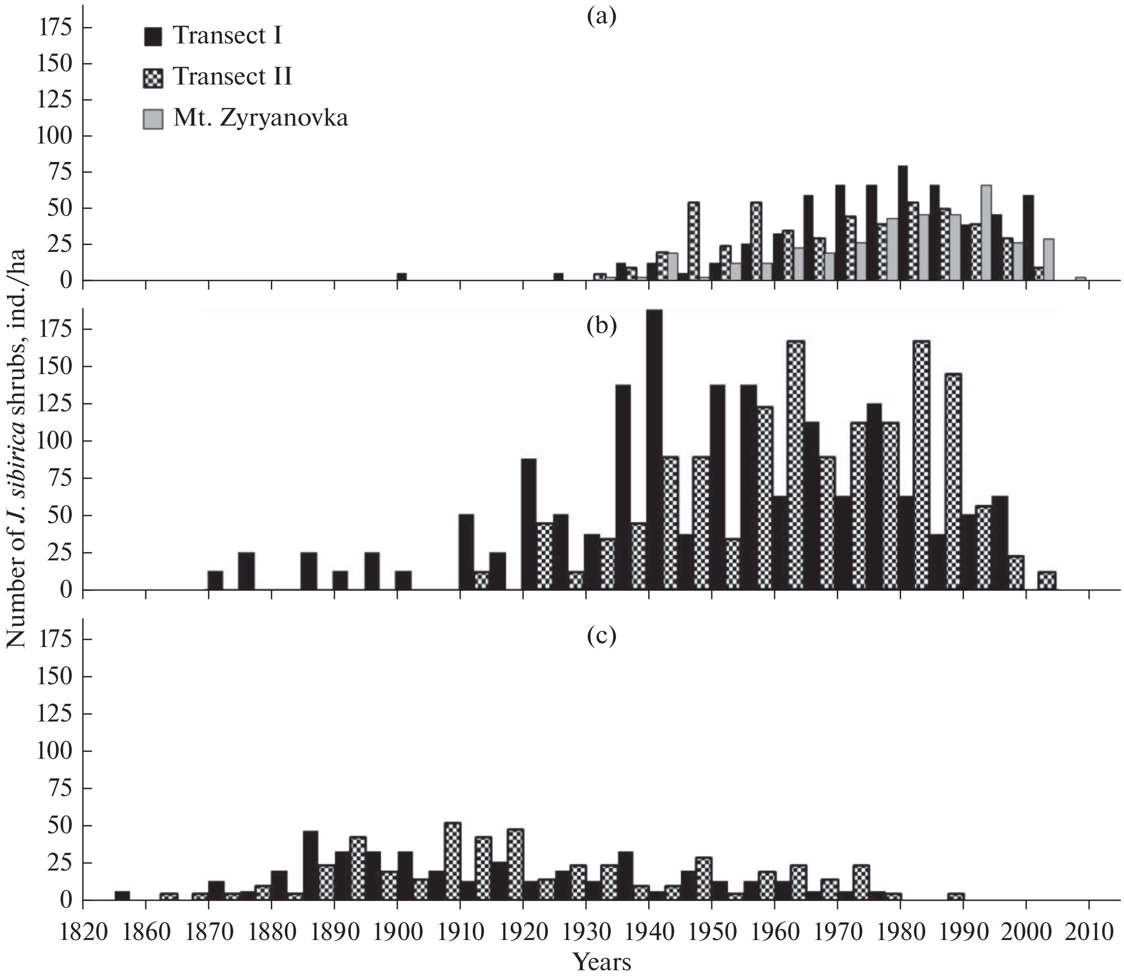

Fig. 2. Distribution of *Juniperus sibirica* Burgsd. shrubs (ind./ha) at (a) top, (b) middle, and (c) bottom altitudinal levels.

the warm season showed no significant trends over time.

The results of snow survey on the transects showed that the depth of snow cover averaged 73 ± 9 cm at the top level, 87 ± 17 cm at the middle level, and 122 ± 14 cm at the bottom level, with the minimum soil temperature ranging from –1…0°C at the bottom level to –10°C at the top level.

As follows from the results of correlation analysis (Table 2), the establishment of *J. sibirica* was positively correlated with precipitation. This correlation was especially strong in test plots at the top level of the transects. It is only at this level that the establishment of *J. sibirica* was found to correlate with precipitation in the warm season of previous 5-year periods, which could contribute to the improvement of reproductive functions. Statistically significant coefficients were also obtained for correlation of *J. sibirica* establishment at the middle level with precipitation during the previous 5-year period and temperature during the current 5-year period.

DISCUSSION

The results obtained on the Chuvalsky Kamen Range provide evidence for intensive expansion of shrub vegetation (in particular, *J. sibirica*) to mountain tundra communities in the Northern Urals. This process began in the mid-19th century, but large-scale *J. sibirica* establishment at the topmost hypsometric levels (at summits) occurred only after the 1970s. The unidirectional expansion of *J. sibirica* over the past 150 years (most active since 70–40 years ago) on slopes differing in stone content, wind loading, and snowiness indicates that conditions for the growth and development of shrub vegetation have been improved under the effect of factors common for the study region. In our opinion, these are primarily climatic factors. As follows from analysis of meteorological data, the climate of the Northern Urals has become warmer and more humid during the past 130 years, with changes in the temperature and moisture regime of the cold season being most significant.

Route survey of the study region in winter and snow measurements have shown that the distribution

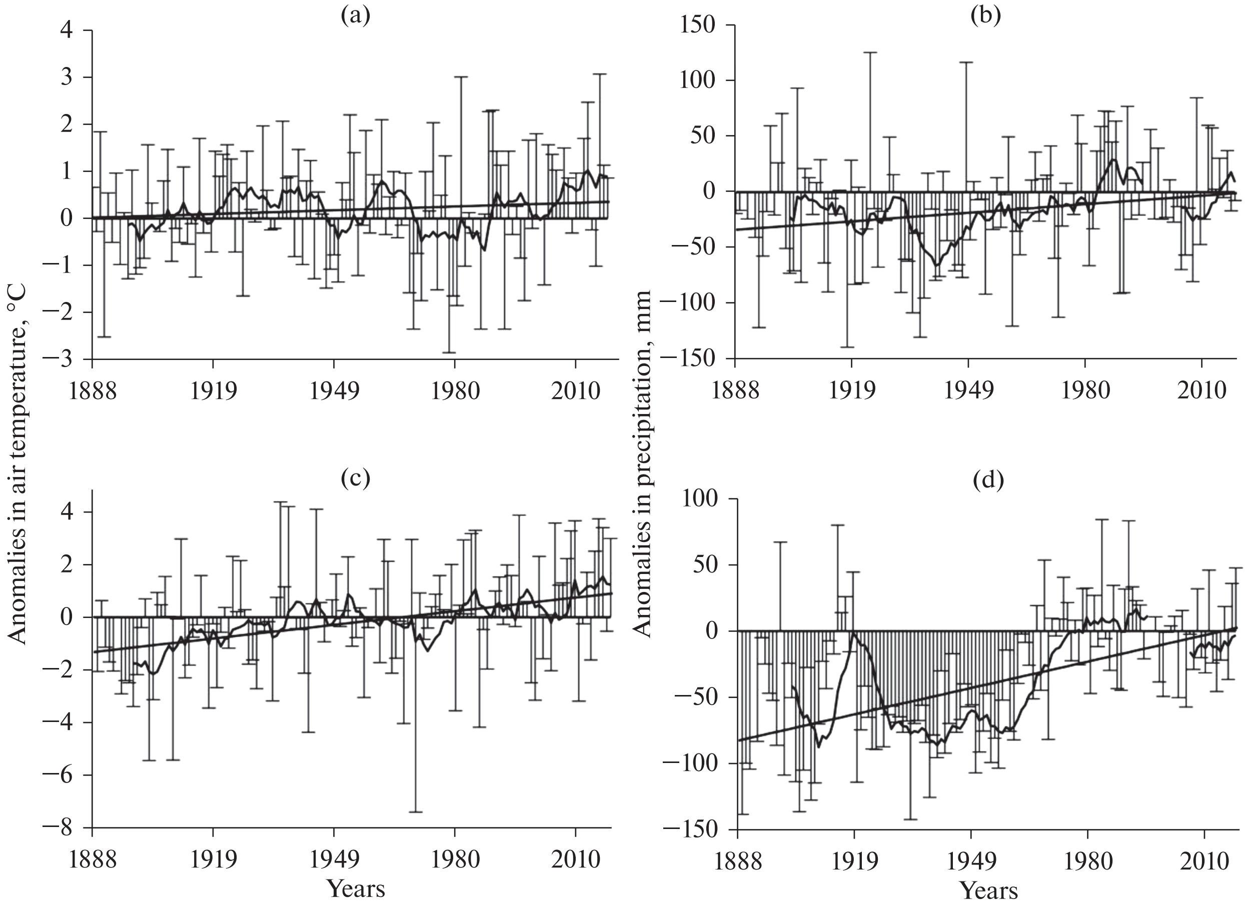

Fig. 3. Time series of anomalies in average near-surface air temperature and total precipitation during (a, b) warm period (June–August) and (c, d) cold period of the year (November–March) according to data from Troitsko-Pecherskoe weather station (1888–2018). Parameters in the period from 1961 to 1990 were taken as normal. The bold line shows a moving average with 10-year smoothing period.

and height of *J. sibirica* shrubs are correlated with snow distribution over the slope and the depth of snow cover. This species does not occur either in mountain areas where snow is almost absent or in areas with deep snow cover and snow piles over 2 m high (usually close to the forest boundary). test plots at the topmost (summit) levels of the transects and additional plots accumulate minimum amounts of snow, with its average depth and soil temperature increasing with a decrease in elevation. In summer, no *J. sibirica* shrubs with traces of snow corrasion (abrasion of the bark and branches by drifting snow [10]) have been found in the study region, although such a phenomenon in often observed in trees, leading to the formation of two crowns: one under the snow cover (skirt) and the other above the level of snow corrosion.

Thus, snow cover is the main factor in the formation of *J. sibirica* in the Ural Mountains, which per-

Table 2. Spearman's correlation coefficients of the number of *J. sibirica* shrubs emerged over 5 years with climatic parameters of different periods of the year during the current and previous half-decades (t_5 and t_{-5}). Boldface indicates statistically significant coefficients ($p > 0.05$)

Parameter	Altitudinal level	November–January		November–Marchт		July–August	
		current (t_5)	previous (t_{-5})	current (t_5)	previous (t_{-5})	current (t_5)	previous (t_{-5})
Precipitation	Top	**0.96**	**0.83**	**0.85**	**0.86**	0.28	**0.55**
	Middle	0.3	0.35	0.31	**0.46**	0.32	0.24
Air temperature	Top	–0.19	–0.33	0.37	0.16	0.11	–0.17
	Middle	0.35	0.03	**0.71**	0.17	0.49	–0.16

forms a protective function [27, 28]. The establishment of single trees in the snowless mountain tundra contributes to snow retention and redistribution over slopes, which allows a lower degree of soil freezing [28] and thereby creates more favorable conditions for the establishment and survival of trees in previously woodless areas. It should be noted that trees on the transects are absent.

According to correlation analysis, the establishment of *J. sibirica* is most strongly correlated with precipitation in the cold season (November–March) at the top level of the transects. Correlation coefficients with data for current 5-year periods are higher for the early cold season (November–January; $R = 0.96$) a, and those with data for the previous 5-year periods are high for the entire cold season ($R = 0.86$).

A probable explanation to the results obtained for the current 5-year periods is that solid precipitation falling during the early cold season forms a snow layer that protects seedlings and young shrubs from cold and wind desiccation, thereby facilitating the survival of *J. sibirica* at the top altitudinal level (at summits, where the smallest amount of snow is accumulated) [27–29]. High correlations with data on the previous 5-year reflect a positive effect of snow cover on mature, fruiting shrubs in which the cycle of cone berry formation is 2–3 years. If soil–climate conditions are unfavorable, their seed reproduction is often impaired or absent [30].

Similar results were obtained in our previous study on the Kvarkush Range, where the establishment of *J. sibirica* at the top altitudinal level over 5 years showed correlation with precipitation of the early cold season (November–January) in the current 5-year period ($R = 0.84$) [18]. A positive effect of snow cover and winter precipitation on the growth of shrubs have also been noted by other researchers. Studies by Hallinger et al. [11] in high-mountain tundras of northern Sweden showed that shrubs growing at top elevations were younger and their radial increment was increased, compared to shrubs at lower elevations. Rundqvist et al. [13] note that climate warming and increase in snow depth over the past century could contribute to increase in the area of shrubs and tree stands in subarctic regions of Sweden.

CONCLUSIONS

Unidirectional advancement of the upper distribution boundary of shrub vegetation, including Siberian juniper (*Juniperus sibirica* Burgsd.), to higher elevations has occurred in the Northern Urals (Chuvalsky Kamen Range) against the background of current change in climatic parameters of the environment, particularly an increase in the amount of precipitation in winter. The rate and specific features of *J. sibirica* expansion in mountain tundras differed depending on local site conditions, primarily the depth of snow cover. Large-scale establishment of *J. sibirica* in areas with little snow began after the 1970.

The results of this study are important for gaining an insight into the mechanisms and rates of transformation of the natural environment under pessimal conditions. They can qualitatively improve the models of biota responses to current climate change by complementing them with data on local processes and allow more reliable prediction of future changes in the environment.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

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Translated by N. Gorgolyuk

SPELL: 1. OK