UDC 630*111: 630*113: 574.42

Pinus sibirica Du Tour RESPONSE TO CLIMATE CHANGE IN THE FORESTS OF THE KUZNETSK ALATAU MOUNTAINS

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Received 17.04.2019

Climate change has a direct impact on the forest ecosystems of the boreal zone. Temperature increase has a stimulating effect on the advancement of a tree line along the elevation gradient, increase of tree radial increment and stand density. The object of the study was the stands formed by the Siberian pine growing in the forest-tundra ecotone of Kuznetsk Alatau Mountains. The rate of timberline and tree line advancement were estimated using GIS-technology and field research. It has been established, that the beginning of the Siberian pine advancement along the elevation gradient coincides with the period of air temperature increase. Estimated speed of tree line advancement is approximately 0.2–0.3 m/year; timberline ~ 0.5 m/year. The average radial increment after 1980 was 25 % higher than the radial increment over the same period of the previous years. At the same time after a marked increase of the radial increment in the early 1980s, a negative trend is observed up to the local minimum of 1999 (r^2 = 0.52). Dendroclimatic analysis indicates a negative influence of July–September temperatures (*r* = –0.63) and that of winter precipitation (*r* = –0.81) on radial increment, while the amount of July–September precipitation (*r* = 0.54) and root zone wetness content during the vegetation period (*r* = 0.73) show positive correlation with radial increment. During the previous period from 1967 to1982, a negative effect of winter precipitation on radial increment was also noted (*r* = –0.69), whereas May–June temperatures demonstrated a positive effect on radial increment (*r* = 0.66).

Keywords: *mountain forest-tundra, the Siberian stone pine, drought, Southern Siberia, Pinus sibirica, climate change, Kuznetsk Alatau.*

How to cite: *Petrov I. A., Shushpanov A. S., Golyukov A. S., Kharuk V. I. Pinus sibirica* Du Tour response to climate change in the forests of the Kuznetsk Alatau Mountains // *Sibirskij Lesnoj Zurnal* (Sib. J. For. Sci.). 2019. N. 5. P. 43–53 (in English with Russian abstract).

DOI: 10.15372/SJFS20190506

INTRODUCTION

Climate change taking place at the turn of the XXI century affects forest ecosystems over the entire circum-boreal zone causing changes in the ecosystems and redistribution of woody species (Aitken et al., 2008). The advancement of treeline and timberline can be assessed both by dendrochronological and GIS methods. Dendrochronological techniques make it possible to estimate climate influence on local changes of treeline and timberline. However, GIS methods can allow us to approximate these changes on wide scale territory. When applying the combination of dendrochronological and GIS methods, elevational shifts of forest vegetation have been observed in the mountains of the Altai-Sayan region (Kharuk et al., 2017*c*), the Urals (Moiseev et al., 2004; Shiyatov et al., 2007; Devi et al., 2018) and the Alps (Walther et al., 2002), in Sweden (Kullman, 1997, 2002, 2007, 2014; Kullman, Öberg, 2009), USA (Jakubos, 1993; Taylor, 1995; Weisberg, Baker, 1995; Woodward et al., 1995; Lloyd, Graumlich, 1997; Klasner, Fagre, 2002; Munroe, 2003) and Canada (Kearney, 1982; Lavoie, Paeytte, 1992; Masek, 2001).

At the same time, the increase in air temperature might increase aridity, which can lead to the change of radial increment limiting factors (D'Arrigo et al., 2008; Hellmann et al., 2016). In the southeastern part of the Putoran Plateau increased sensitivity of larch radial increment to moisture parameters after 1990 was recorded (Kharuk et al., 2019). Increased aridity has been recorded as a limiting factor for northeastern (Liu et al., 2006; Yang et al., 2013; Liang et al., 2016) and northern Himalayan slopes (Liang et al., 2014) since the 1950s. Water stress brought about the Siberian pine decline after 1985 in the mountains of Baikal region (Khamar-Daban ridge) (Kharuk et al., 2017*a*).

In this study we aimed to analyze the Siberian pine response to climate changes in the Kuznetsk Alatau forest-tundra ecotone. In order to achieve the aim, we planned to answer the following questions:

1. How radial increment rate of the Siberian pine has changed since 1950;
2. How treeline elevation level in the Kuznetsk Alatau Mountains alters under climate change;
3. What major limiting factors for radial increment of the Siberian pine are; if any change in limiting factors for the Siberian stone pine radial increment has occurred.

MATERIALS AND METHODS

Field studies. The field studies have been carried out on the eastern macro slope of the Kuznetsk Alatau (Fig. 1).

The objects of the study were the Siberian pine trees growing in the mountain forest-tundra ecotone. Sampling was carried out along two elevational transects (1410–1445 and 1370–1390 m above sea level) on the southwestern and southern slopes.

The beginning of the transect corresponds to the boundary of closed stands (closeness > 0.3), whereas the end of the transect correlates with the upper elevation level of regeneration. Temporary 3 × 3 m test plots (TP) were established along the elevation gradient with an interval of 10 meters in elevation along the transect. Within TP regeneration quantity, height, viability and age were determined by the number of annual rings at the level of root collar. In addition, exogenous effects (for example, fires or cuttings) were described. Model trees grew on local southern or southwestern slopes with a steepness from 9° to 18° on well-drained brown-mountain soils (Buko, 1999). Samples were taken within the transect using a 5-mm diameter increment borer. For a more accurate tree age determination the samples were taken as close to the root collar as possible.

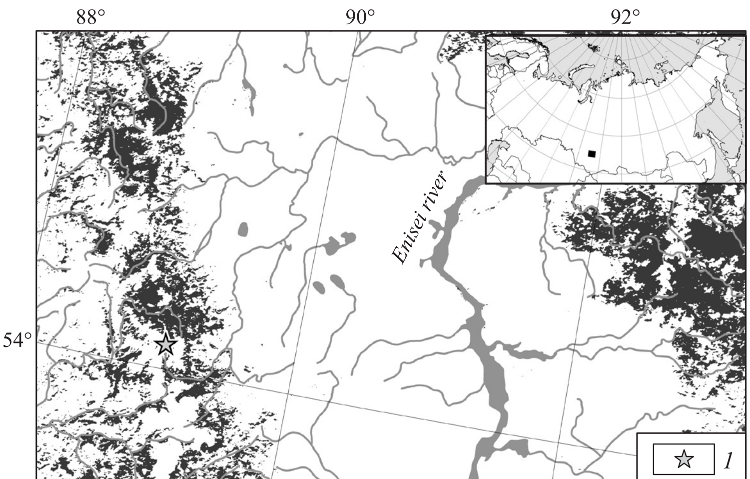

Fig. 1. Geographical location of the studied area (*1* – test plot, *2* – rivers and lakes, *3* – dark needle conifer stands).

For each tree the coordinates and elevation above sea level were recorded and morphometric characteristics (tree height, diameter at breast height) were described.

Dynamics of ecological-climatic variables. The average annual temperature in the Kuznetsk Alatau Mountains is –2.1 °C. The coldest month is January (–15.3 °C), the warmest one is July (13.4 °C). During the year, the average total amount of precipitation is 1600 mm (in summer 380 mm, in winter – 330 mm).

The early 1970s was characterized by a decrease of air temperature during the growing season, particularly in May–June (Fig. 2, *a*).

Major climatic changes occurred in the period from the early 1980s to the early 2000s. During this time, warm period (May–September) temperature (Fig. 2, *a*) and amount of cold period (November–Mach) precipitation has increased (Fig. 2, *b*). The temperature in the cold period increased on the average by 1.7 °C (Fig. 2, *a*).

At the same time, there was a decrease in root zone wetness (Fig. 2, *c*). In 1998–1999, a strong soil drought (Fig. 2, *c*) was observed. In the beginning of the 2000s, the temperature of the growing season decreased, while the frequency and strength of soil droughts increased (Fig. 2, *a*, *c*).

GIS analysis. Remote sensing data included images of medium (Landsat, 60 and 30 m; http://glovis.usgs.gov) and ultra-high (WorldView, GeoEye; 0.41–0.46 m; www.google.com/maps; www.bing.com/maps) spatial resolution and digital elevation model SRTMGL 1 (30 m spatial resolution, https://lpdaac.usgs.gov).

The satellite images of Landsat analyzed in this work cover the time span from 08/20/1976 (Landsat 2) to 06/29/2015 (Landsat 8). To analyze the dynamics of the closed forest area in the Kuznetsk Alatau Mountains a site with total area of ~ 65 thousand hectares was chosen (coordinates of the scene angles are top left: 88°47´0´´ E, 54°11´30´´ N; bottom right: 89°15´0´´ E, 54°0´0´´ N). Initially the images were pretreated, corrected in terms of topography normalized (Riano et al., 2003) and processed in the Erdas Imagine software package (http://www.hexagongeospatial.com). For each image, a mask of closed forest (closeness > 0.3) was formed by maximum likelihood method using the threshold func-

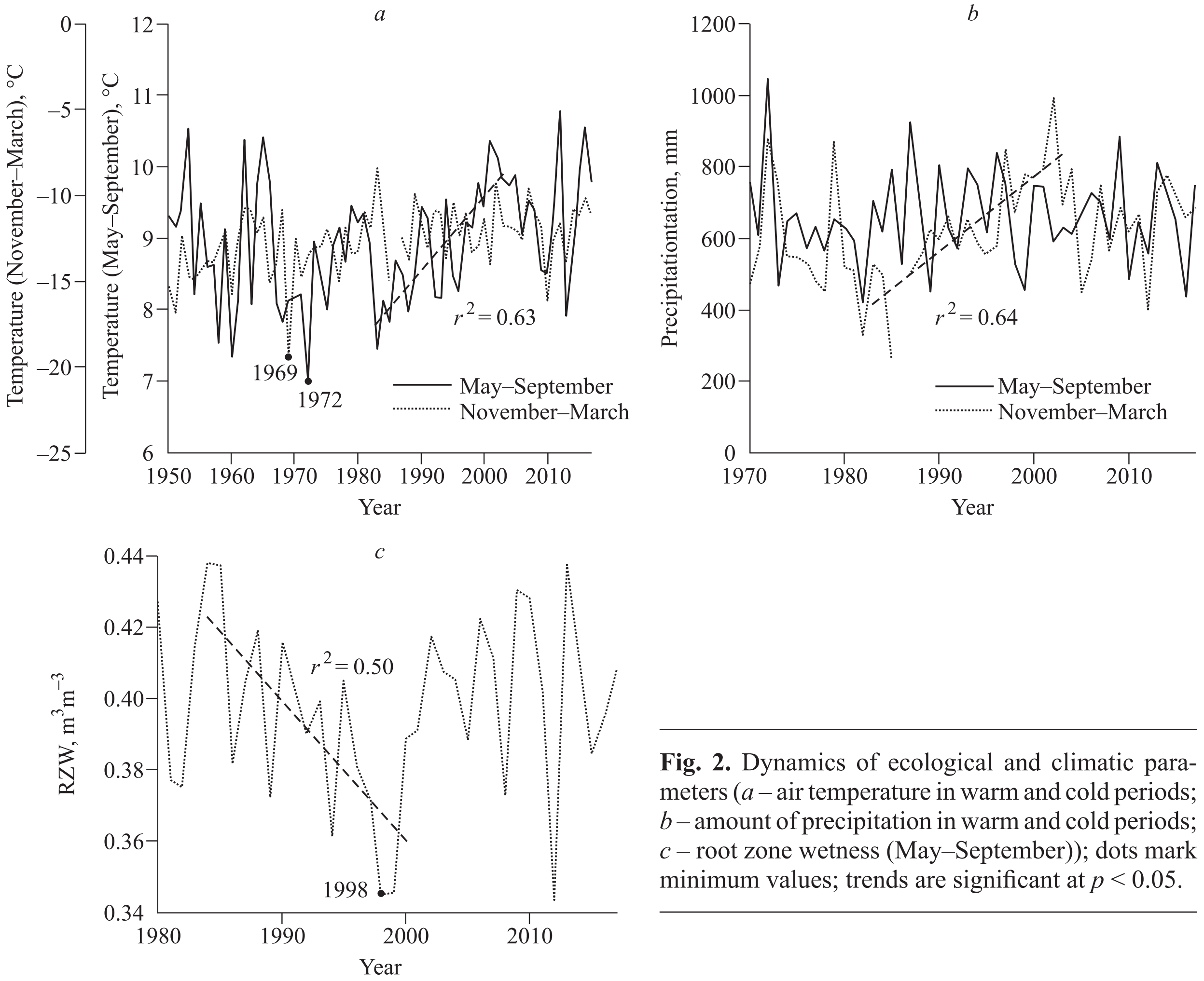

Fig. 2. Dynamics of ecological and climatic parameters (*a* – air temperature in warm and cold periods; *b* – amount of precipitation in warm and cold periods; *c* – root zone wetness (May–September)); dots mark minimum values; trends are significant at $p < 0.05$.

tion. Test samples were created by the method of increasing area according to the topographic maps of the 1980s (scale 1 : 100.000), field data (2014 and 2016) and ultra-high spatial resolution images (2013) from open sources. For each year, two classes were created: closed forest and background areas. Then, the distribution of closed forest class via the elevation above sea level was obtained in the ArcGIS software package (2019) for the maps of 1976 and 2015. Estimation of the advance of the upper limit of closed stands was carried out by comparing the calculated median values of elevation above sea level (Fig. 4, *a*) for the class of closed stands.

Statistical analysis of the data was carried out with the following software packages – Microsoft Excel (2019) and StatSoft Statistica (2019).

Dendrochronology analysis. For dendrochronological analysis, cores were selected from 50 model the Siberian pine trees using an increment borer. Each core was glued to a wooden backing, sanded and treated with contrasting powder. The measurements were carried out on the LINTAB-3 platform with the accuracy of 0.01 mm. The quality of cross dating was evaluated using COFECHA program (Holmes, 1983). The absolute chronologies were indexed and detrended in the ARSTAN program (Cook, Holmes, 1986) by means of the negative exponent method or linear regression with a negative slope (Rinn, 1996; Speer, 2010).

In dendroclimatic analysis the ecological and climatic parameters were used: temperature, total precipitation and root zone wetness (RZW). Pearson's correlation coefficients (including running 11-yr correlation) were used in dendroclimatic analysis. Multiple regression analysis was used for studying the relationship of growth index (GI) and climatic variables (temperature and precipitation).

The series of average monthly temperatures and precipitation values were obtained from the nearest to TPs weather station «Nenastnaya» (WMO index 29 752; ~ 65 km to TP, 1186 m a. s. l.).

Root zone wetness (average/estimated amount of water at a depth of 1 m taken equal to 0–100 cm) was obtained from the MERRA-2 database (2016) (spatial resolution 0.5°× 0.625°).

RESULTS AND DISCUSSION

Estimation of tree line advancement rate. The advancement of trees along the elevation gradient is observed for both the tree line and timberline. According to the tree ages, it has been established that since the 1960s the Siberian pine trees have appeared at elevations, which were not previously occupied by woody plants (Fig. 3).

On the average, the distribution limit has advanced 15–30 meters in comparison to the first half of the twentieth century, which makes it possible to estimate the rate of advancement as 0.2–0.3 m/year.

At the same time, the timberline is moving faster (0.5 m/year). According to remote sensing data, the area of closed stands from 1976 to 2015 has increased from 26.4 thousand hectares up to 28.7 thousand hectares (Fig. 4, *a*); thus the overall increase of closed stands in the area under study was ≈ 8.3 % (2.3 thousand hectares).

Median values change corresponds with the dynamics of overall advancement of closed stands and was approximately (19 ± 0.3) m in elevation from 1976 to 2015.

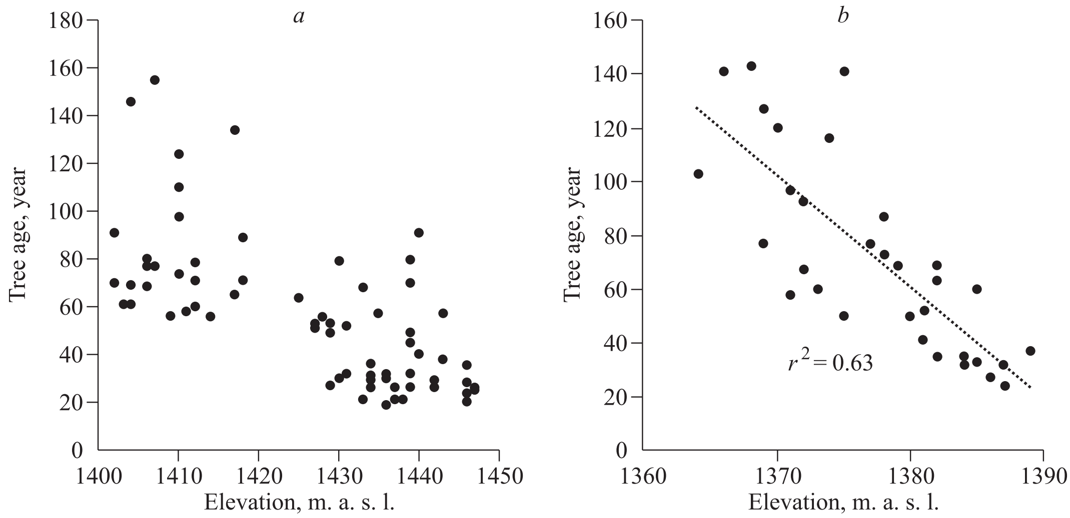

Fig. 3. Age of the Siberian pine trees *vs* elevation on southwestern (*a*) and southern (*b*) slopes.

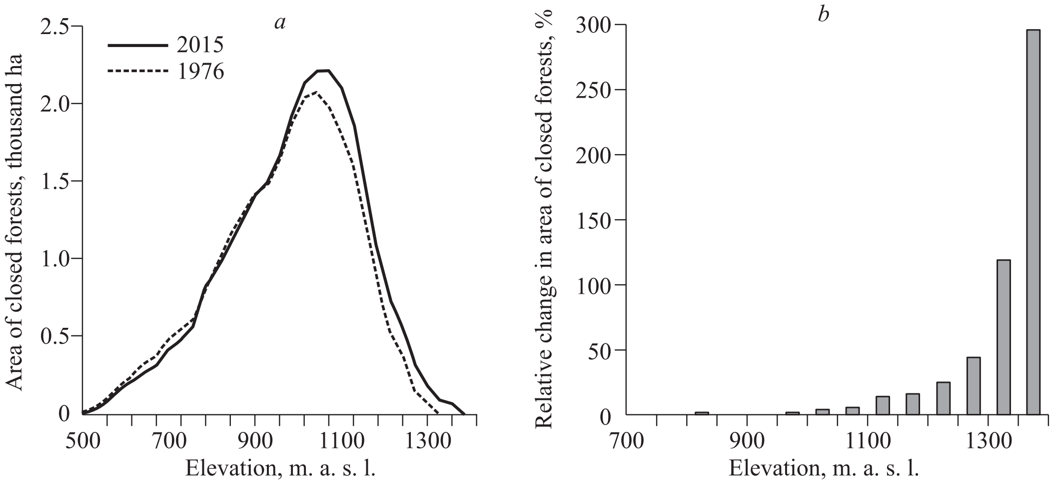

Fig. 4. Advancement dynamics of closed tree stands along the elevation gradient (*a* – absolute values, *b* – relative values).

Fig. 4, *b* shows a relative change in the area of closed tree stands along the elevation gradient with a step of 50 m. A reliably distinguishable increase of the closed tree stands area is observed at elevation of more than 1000 meters a. s. l. The highest increase of the closed tree stands area is observed in the mountain forest-tundra ecotone.

The process of tree line advancement is characterized by several stages. At the first stage, individual trees occupy the most favorable places in microtopography, creating protection from snow abrasion and desiccation (Batllori et al., 2009; Benavides et al., 2016; Vitali et al., 2019). Subsequently these trees become nurse plants for new seedlings, contributing to the advance of new trees into the mountain forest-tundra zone. Thus, the so-called «hedges» are gradually formed (Holtmeier, 2009) – structures consisting of several individual trees and oriented in the direction of prevailing winds (Holtmeier, Broll, 2010). As growing conditions are transformed and mitigated, the areas between the «hedges» overgrow, «hedges» also grow and the crowns gradually merge leading to the advancement of timberline. It is worth noting that, having equal mitigation of growing conditions, the emergence of woody plants in a previously unoccupied area is slower than timberline advancement (e. g., Camarero, Gutiérrez, 2004), which is mainly due to the seed propagation rate. In the case of the Siberian pine, which is a zoohore species, the rate of propagation depends on the activity of a distributor – the Siberian nutcracker *Nucifraga caryocatactes* L. (Kajimoto et al., 1998; Tomiolo, Ward, 2018). Warming observed since 1950s (an increase in average annual temperature) has stimulated tree line and timberline advancement. In Altai region, during recent warming (since the 1980s) the increase and advancement of Siberian pine regeneration were observed (Timoshok et al., 2009, 2014, 2016; Kharuk et al., 2017*c*). Similar advances of woody plants and increase in crown density are also recorded for Europe and North America (Theurillat and Guisan, 2001; Baker, Moseley, 2007; Kullman, 2007, 2014; Lenoir et al., 2008; Fagre, 2009).

Dendrochronology analysis. The average interserial correlation coefficient of the developed tree-ring chronology is 0.55. The expressed population signal level (EPS) is 0.98. Mean tree-ring width is 1.23 mm; mean sensitivity of individual series is 0.24, mean age of model trees is 82 years (minimum 50 years, maximum 155 years, standard deviation is 27).

On the curve of tree-ring chronology, two main periods were considered (Fig. 5).

The period from 1982 to 2001 demonstrates a high increment followed by a negative trend. At the same time, the average radial increment after 1980 is 25 % higher than the same for the previous period. The previous period (1967–1981) shows a decline of the increment with a minimum in 1973, followed by a recovery of growth index to the level of 1967–1969.

After 2002 there are fluctuations of radial increment with depression in the 2010s.

Tree-ring width and ecological variables. In the mountain forest-tundra ecotone the temperature and precipitation during both warm (months with consistently positive mean monthly temperatures) and cold (months with consistently negative temperatures) periods of the year have a considerable effect on radial increment (Fig. 6).

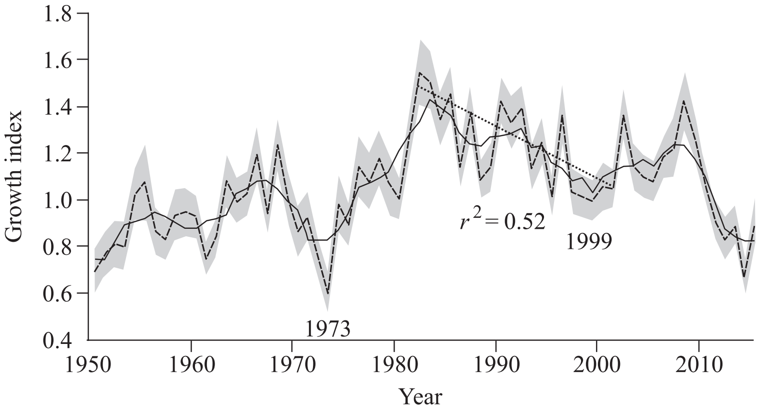

Fig. 5. Dynamics of the Siberian pine radial increment in the Kuznetsk Alatau mountain forest-tundra ecotone. Grey background – confidence interval ($p < 0.05$).

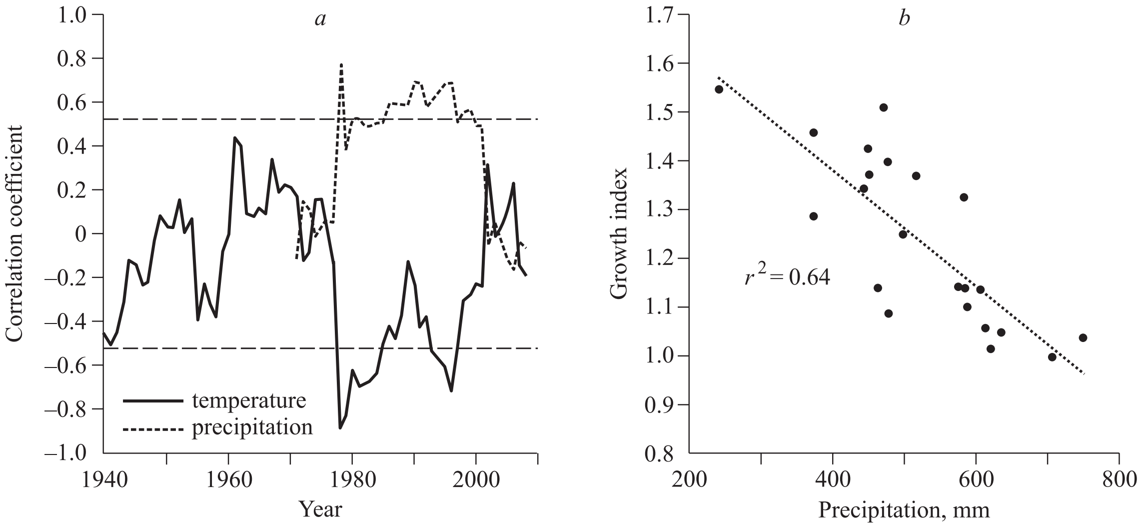

Fig. 6. *a* – running 11-yr correlation coefficients between growth indices and meteorological parameters (July–September); *b* – relationship between growth indices and precipitation in November–February. Dotted line – significance level at $p < 0.05$.

The relationship between radial increment (in growth indices – GI) and precipitation in November–February is consistently negative over the entire period of observation ($r = -0.37$). In the period between 1967 and 1982 the correlation was $r = -0.69$, in the period between 1982 and 2001 $r = -0.81$.

During the decline of radial increment between 1967 and 1982 GI correlated positively and significantly with the temperature of May–June ($r = 0.66$).

The decline in radial increment with its subsequent increase in the late 1960s and early 1980s corresponds with the decrease of air temperature at the beginning of the growing season (May–June). The multiple regression equation for this period indicates positive effects of May–June temperatures and negative effects of November–February precipitation (3).

For 1967–1982:

$$GI = 0.68 * T_{May–June} - 0.5 * P_{November–February} - 0.52 \quad (r^2 = 0.71), \qquad (3)$$

where, *GI* – growth index; *T* – temperature; *P* – precipitation.

The decrease of May and June temperatures inhibits radial increment at the beginning of the growing season and together with a large amount of winter precipitation slows down melting process and shortens the length of the growing season, leading to a decrease in radial increment. Earlier (Vaganov et al., 1999) it was shown that increased winter precipitation causes shortening of the growing season and, consequently, decrease in the width of annual rings. Also, for the Altai Mountains, it was shown based on the Siberian larch *Larix sibirica* Ledeb.

trees (Fonti et al., 2013) that warmer early-growing season promotes a higher water conduction capacity by increasing the number and size of early wood tracheids.

After 1982 and up to 2001 radial increment responds positively to the precipitation in July–September (r = 0.54) with an increase in correlation during the period of root zone wetness decrease (Fig. 2, *c*). In the same period the correlation with July–September temperature becomes negative (r = –0.63). There is also a positive correlation with the temperature of a cold period (the strongest is the correlation with November–December temperatures of the previous year; r = 0.52).

The period from 1982 to 2001 is characterized by a strong increase in GI with a subsequent negative trend. The equation of multiple regressions, as in the previous case, indicates the negative effect of winter precipitation. However, there is a positive correlation with the precipitation during the second half of the growing season and a negative correlation with the temperature of the same period (4).

For 1982–2001:

$$GI = 0.49 - 0.36 * T_{July–September} - 0.56 * P_{November–February} + 0.26 * P_{July–September} \quad (r^2 = 0.81), \qquad (4)$$

where, GI – growth index; T – temperature; P – precipitation.

The manifestation of a significant correlation between radial increment and precipitation in July–September, as well as a change in the reaction of the Siberian pine radial increment from a positive correlation with May–June temperatures to a negative one with July–September temperatures coincides in time with a gradual increase in soil aridity.

The minimum root zone wetness occurs during 1998–1999 and coincides with the minimum of radial increment (Fig. 2, *c*, 5). Taking into consideration that the Siberian pine trees grow on thin, well-drained soils, occurrence of soil drought can produce a negative effect on radial increment (correlation between GI and RZW 0.73) (Fig. 7). In addition, as air temperature increases the rate of evapotranspiration also rises. A similar phenomenon was recorded for North America when the increase in air temperature led to the decrease in radial increment of Douglas fir *Pseudotsuga menziesii* (Mirb.) Franco due to the increased atmospheric aridity (Restiano et al., 2016), and in Baikal region, when the decrease in soil and atmospheric moisture caused the Siberian pine (Kharuk et al., 2017*a*) and the

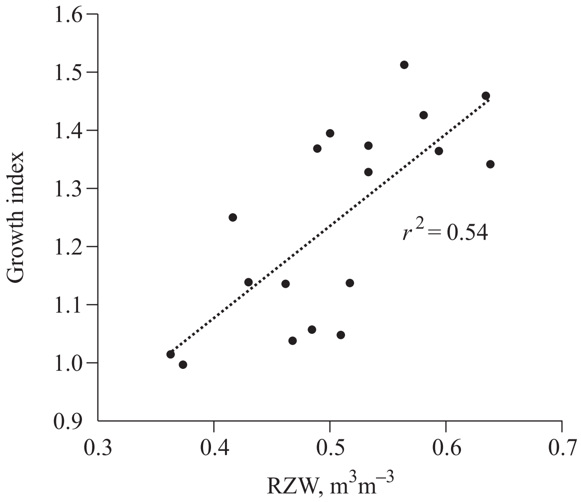

Fig. 7. GI *vs* root zone wetness (July–September).

Siberian fir *Abies sibirica* decline (Kharuk et al., 2017*b*).

The decrease in radial increment after 2007 may have been caused by a decrease of winter or May–June temperatures; however, a short length of the series does not allow to estimate the influence of climate on the chronology.

The negative effect of aridity increase on the Siberian stone pine vital status in the Kuznetsk Alatau Mountains was shown earlier. V. I. Kharuk et al. (2013) demonstrated the Siberian pine declining at elevation up to 900 meters a. s. l., caused by a decrease in the level of atmospheric moistening. It was noted that the declining began in the areas of greatest water stress risk (steep southern slopes with thin, well-drained soils). On the territory of Khamar-Daban Range (Kharuk et al., 2017*a*), the decrease in soil (RZW) and atmospheric moisture caused the Siberian pine and the Siberian fir decline and mortality, making them more susceptible to various pathogens. High aridity, the increase of frequency and intensity of droughts led to a significant damage of the Siberian fir in the Eastern Sayan Mountains (Kharuk et al., 2017*b*). In the Czech Republic an increase in the sensitivity of the European spruce *Picea abies* L. to moisture was noted and it was also established that the excess of average June temperatures above 13.5 °C leads to the change from the stimulating effect of the temperature on radial increment to the inhibitory one (Tumajer et al., 2017). An increase in the aridity of the climate led to a massive decline and mortality of the Siberian spruce *Picea obovata* Ledeb. in the European part of the continent (Martínez-Vilalta et al., 2012; Sazonov et al., 2013).

Although in a high mountain environment the increase in the aridity of climate does not affect the vital status of the Siberian pine due to the increase of temperature (e. g. Demidko, 2006) and modern warming has a stimulating effect on Siberian pine advancement along the elevation gradient (Timoshok et al., 2009, 2014, 2016; Kharuk et al., 2017*c*), in the areas with a high risk of water stress the radial increment responds to the decrease of soil humidity.

CONCLUSIONS

1. The reaction of the Siberian pine to a climate warming in the Kuznetsk Alatau Mountains indicated the phase of stimulating radial increment and its subsequent depression in 1980–2000.

2. During the phase of increasing radial increment it was correlated with the increase in air temperature at the beginning of the growing season (May–June). A further increase in temperature, resulting in water stress, led to a decrease of radial increment after 1983–1984. In the depression phase, the radial increment negatively correlated with the air temperature and positively with the moisture parameters (root zone wetness, precipitation).

3. The increase in air temperature contributed to the advancement of tree line and timberline (the rate of advancement was 2–3 m/10 years and 5 m/10 years, respectively).

The Russian Science Foundation (17–74–10113) supported dendrochronological and dendroclimatic analysis.

The Russian Foundation for Basic Research supported a part of analysis of ecological and climatic variables (grant 18–45–240003).

The authors thank two anonymous reviewers for helpful comments on the previous version of the manuscript.

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УДК 630*111: 630*113: 574.42

ВОЗДЕЙСТВИЕ ИЗМЕНЕНИЙ КЛИМАТА НА РАДИАЛЬНЫЙ ПРИРОСТ *Pinus sibirica* Du Tour В ГОРНЫХ ЛЕСАХ КУЗНЕЦКОГО АЛАТАУ

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Поступила в редакцию 17.04.2019 г.

Климатические изменения оказывают непосредственное влияние на лесные экосистемы бореальной зоны. Возрастание температуры оказывает стимулирующий эффект на продвижение древесной растительности по градиенту высоты, возрастание радиального прироста деревьев и сомкнутости древостоев. Исследовали древостои, сформированные *Pinus sibirica* Du Tour (сосной кедровой сибирской, кедром сибирским), произрастающие в экотоне горной лесотундры Кузнецкого Алатау в Южной Сибири. С помощью ГИС-технологий и наземных исследований проведена оценка скорости продвижения границы сомкнутых древостоев и верхней границы леса. Установлено, что начало продвижения кедра сибирского по градиенту высоты совпадает с периодом возрастания температуры воздуха. Оценочная скорость продвижения верхней границы леса составляет 2–3 м/10 лет, сомкнутых древостоев – 5 м/10 лет. Средний радиальный прирост (РП) после 1980 г. на 25 % превышает радиальный прирост за аналогичный предшествующий период. При этом после резкого пика РП в начале 1980-х гг. наблюдается отрицательный тренд до локального минимума 1999 г. ($r^2 = 0.51$). Проведенный дендроклиматический анализ указывает на отрицательное влияние температуры июля–сентября ($r = –0.65$) и суммы зимних осадков ($r = –0.75$), в то время как с суммой осадков июля–сентября ($r = 0.51$) и влагосодержанием корнеобитаемого слоя периода вегетации корреляции ($r = 0.62$) РП значимо положительные. В предшествующий период (1967–1982 гг.) также отмечено отрицательное влияние на прирост зимних осадков ($r = –0.67$), в то время как температура мая–июня влияет на РП положительно ($r = 0.66$). И хотя в высокогорьях не наблюдается изменения жизненного состояния кедра сибирского, для Кузнецкого Алатау зафиксирована смена тенденций как РП кедра сибирского, так и лимитирующих РП факторов.

Ключевые слова: *горная лесотундра, сосна кедровая сибирская, засуха, Южная Сибирь, Pinus sibirica, изменения климата, Кузнецкий Алатау.*