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Comparative Reaction of Larch (*Larix sibirica* Ledeb.) Radial Increment on Climate Change in the Forest Steppe and Highlands of Southern Siberia

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Abstract—The influence of climate changes on larch (*Larix sibirica* Ledeb.) radial increment under conditions of a limited (forest steppe) and sufficient (high-altitude Kuznetsk Alatau, floodplain stands) humidification is considered. The relationship between growth index of larch trees ($N = 257$) and ecological and climatic variables is analyzed. In the forest steppe, with the onset of warming, a decrease in the aridity of the climate, an increase in the duration of the growing season (1980s), and an increase in the larch growth index followed by its depression in the 1990s have been observed. Radial-increment depression is caused by an increase in vapor-pressure deficit and arid climate due to a rising air temperature. In the 2000s, radial-increment fluctuations with average values not exceeding those before the beginning of current climate warming period occurred. In the highlands, since the 1970s, there has been a general increase in the larch radial increment closely associated with the main limiting factor of growth—air temperature. At the same time, in arid years, the radial-increment depression of larch trees in highland and floodplain larch forests is also noted. When implementing "hard" climate scenarios (RCP 6.0 and RCP 8.5), it is likely that the larch growth index in a forest steppe will decrease further and its increase in areas of sufficient moisture will be observed.

Keywords: Larix sibirica, climate change, forest steppe, highland forests, growth index, water deficit, drought index, water stress and radial increment

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INTRODUCTION

The most significant impact of climate change on woody plants is observed in transition zones (ecotones) between different types of vegetation cover, where the growth of woody plants is limited by temperature or moisture (Lloyd and Bunn, 2007; IPCC, 2014). In recent decades, the limitation on moisture supply (due to increasing aridity of climate, frequency, and intensity of drought) has been observed in all parts of the boreal zone, which, combined with the activation of biotic influences, led to the shrinking of stands, predominantly evergreen conifers, in the forests of North America (Allen et al., 2009; Millar and Stephenson, 2015), Western and Eastern Europe, and Russia (Fettig et al., 2013; Kharuk et al., 2016; Kolb et al., 2016). In the European part of Russia and Belarus, there is a drying up of spruce (*Picea abies* (L.) H. Karst.) (Chuprov, 2008; Sarnatskii, 2012), and in Siberia the growth conditions of fir and cedar (*Abies sibirica* Ledeb., *Pinus sibirica* du Tour) are deteriorating due to the synergism of water stress and biotic influences (Pavlov et al., 2008; Kharuk et al., 2015, 2016). At present, the shrinking of stands formed by *Pinus silvestris* L., a species relatively drought-resistant, in the forest-steppe zone of Ukraine and in the southwestern part of Belarus is noted (Luferov and Kovalishin, 2017). A limitation on moisture may also be observed in high latitudes (Kharuk et al., 2015).

Larch (*Larix sibirica, L. dahurica* Turcz.), due to its high efficiency of water use, which allows this species to grow at a low (up to 250 mm/year) precipitation level, belongs to the most drought-resistant woody plants in Siberia (Kloeppel et al., 1998). Under the arid climate forecasted in a number of regions and changes in forest conditions, larch may be considered a potential replacement for aridity-tolerant tree species (e.g., *A. sibirica*, *P. sibirica*, and *P. abies*), which are losing some of their areas (Sarnatskii, 2012; Millar and Stephenson, 2015; Kharuk et al., 2016).

The goal of this work was a comparative analysis of the impact of climate change on the radial growth of the Siberian larch tree living in the ecotone of the forest steppe and under conditions of sufficient moisture (high mountains and floodplain stands).

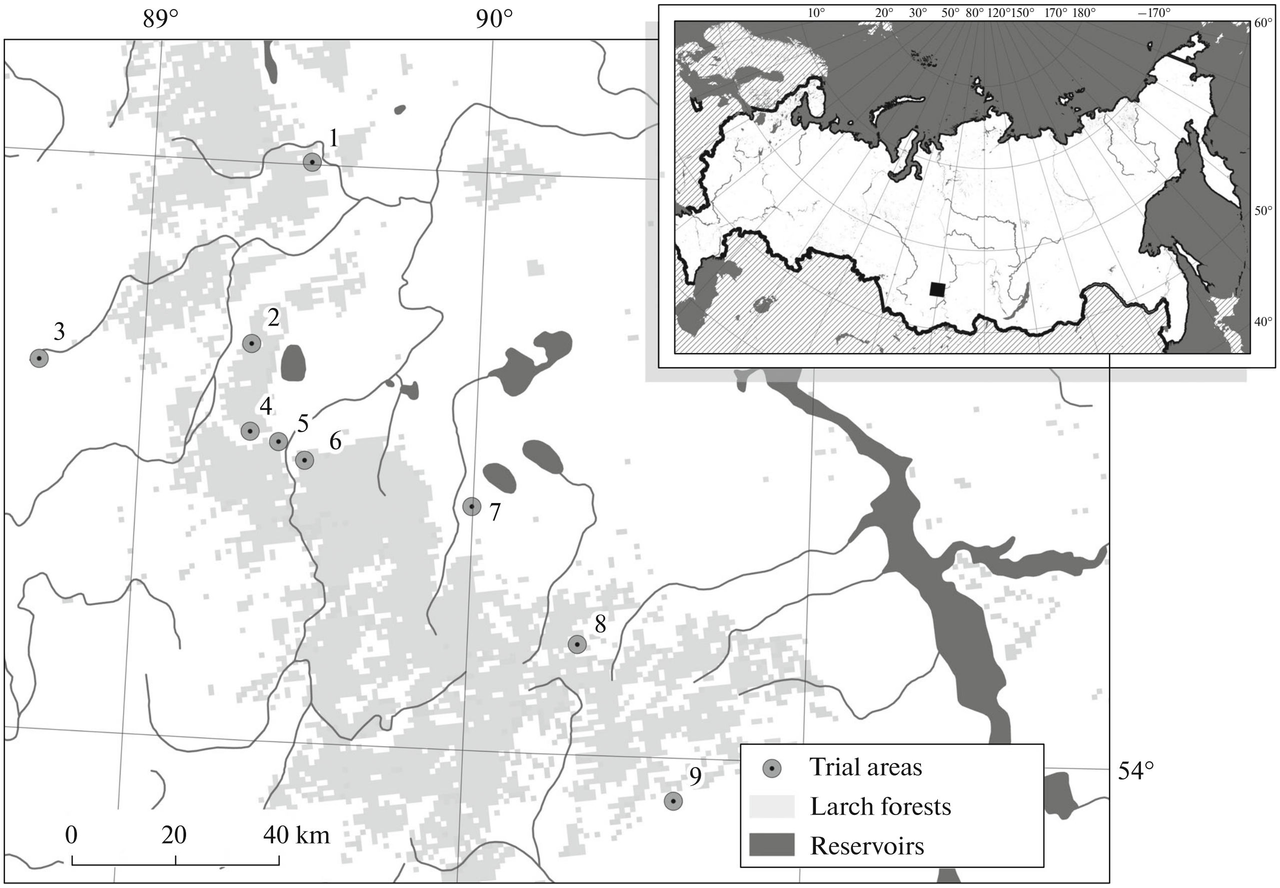

Fig. 1. Map–scheme of trial-area placement (it is marked with a square on the insert). (1, 2, 4, 6–9) Forest steppe, (3) highlands, and (5) floodplain.

MATERIALS AND METHODS

The studies were carried out on Siberian larches (*Larix sibirica* Ledeb.), trees of the forest-steppe ecotone (Middle Siberia and the Minusinsk depression) and the highlands of the Kuznetsk Alatau (Fig. 1). Samples of wood (cores) were selected with increment borer at trial areas (TAs, $n = 9$) located in the forest steppe ($n = 7$), in the floodplain of the river ($n = 1$), and in the highlands ($n = 1$). TAs were either transects on mountain slopes (nos. 1–4, 8, 9; Fig. 1) or sections on a 0.25-ha plain (nos. 5–7). TA characteristics and tree biometrics are shown in Table 1. Transects were laid on the slopes of the southern exposure—from the border of closed stands to the border of the distribution of woody vegetation in the steppe zone (transects nos. 1, 2, 4, 8, and 9) or the boundary of the mountain forest tundra (no. 3). Sampling was carried out with an interval of 10 m in height above sea level. On the TA outside the transect, samples were selected in random order. At each TA, the coordinates of sampling were recorded, a geobotanical description was performed, and the type of soils and exogenous impacts (fires and logging) were determined. The soils were represented by brown steppe type in the forest steppe and brown gravelly forest type in the highlands. In the forest-steppe, undergrowths (tree plants under 30 years old) were represented by single examples; in the highlands the average number of young growths was ~300 pieces/ha. On most TA, impact traces of grassland fires (deposits) were observed. None of the TAs had any trees falling apart.

Dendrochronological analysis was performed on the basis of sampling larch trees (forest steppe $N = 160$, highlands $N = 57$, and floodplain $N = 40$). Measurements of the wood cores were carried out on the LINTAB 3 platform with an accuracy of 0.01 mm (Rinn, 1996). As a result, absolute individual chronologies for each tree (mm) were obtained. To verify the quality of dating, TSAP and COFECHA programs (Holmes, 1983) were used. To eliminate the age trend, a standardization procedure was applied, which may convert the time series of the width of annual rings to the time series of dimensionless indices with an average of 1.0 and a relatively constant variance (Speer, 2010).

To obtain indexed generalized tree-ring chronologies of a specific trial area (TA), the growth indices of individual trees were averaged. For each TA, standardized and "residual" (derived from the standardized by minimizing the autocorrelation component) chronologies in the ARSTAN program were constructed; the linear regression, or negative exponential curve, was

Table 1. Taxation characteristics of trees on the TA

No.	TA, height above sea level (max–min), m	Transect length, m	Tree age, years	Tree height, m	Tree diameter, cm
1	629–549	255	53 ± 10	11.9 ± 0.4	22.7 ± 1.7
2	630–590	150	46 ± 3	9.8 ± 0.6	18.4 ± 1.4
3	1350–1290	200	138 ± 12	4.2 ± 0.3	15.0 ± 2.1
4	685–655	115	55 ± 3	10.3 ± 0.7	17.3 ± 1.4
5	479	–	65 ± 4	19.8 ± 1.0	37.5 ± 1.4
6	673	–	60 ± 1	17.0 ± 1.0	35.0 ± 3.5
7	541	–	99 ± 6	6.0 ± 1.0	18.0 ± 2.5
8	777–730	174	61 ± 13	14.1 ± 0.5	21.7 ± 2.1
9	725–715	70	77 ± 20	10.5 ± 1.1	23.6 ± 3.6

Table 2. Statistics of individual chronologies

No. TA	Number of samples	Average radial increment	Maximal radial increment	Interserial correlation	Standard deviation, Σ	Sensitivity coefficient
1, 2, 4, 6, 7, 8, 9	160	1.39	11.68	0.59	1.05	0.46
3 (highlands)	57	0.57	4.70	0.62	0.38	0.44
5 (high-water bed)	40	2.13	9.86	0.42	1.27	0.31

carried out (Cook and Kairiukstis, 1990). The dendroclimatic analysis, which included the "residual" chronologies, represented by dimensionless growth index, was used. The choice of "residual" chronologies was due to the absence of an autocorrelation component in the latter, which significantly enhanced the climatic signal. Statistics of individual chronologies are shown in Table 2.

The growth index was considered in connection with the following environmental and climatic variables: air temperature, precipitation, water-vapor pressure deficit (VPD), drought index SPEI, humidity of the root layer (HRL), the sum of the active temperatures ($t \geq 5$°C), and the duration of the vegetation period (days with $t \geq 5$°C). As shown by Rossi et al. (2008), the xylogenesis of conifers is observed when the air temperature rises to 4–5.8°C. Climatic variables were obtained from the data of local Svetlolobovo (forest steppe, distance to the TA ~90 km) and Nenastnaya (highlands, distance to the TA ~10 km) weather stations.

The humidity of the root layer (assumed to be 0–100 cm) was obtained from the MERRA2 database (the ground resolution is 0.5° × 0.625°; https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2).

The aridity of climate was estimated from the SPEI dryness index, representing the difference (D_i) between precipitation values (P_i) and potential evapotranspiration (PET_i):

$$D_i = P_i - PET_i, \quad (1)$$

where i is the month (the spatial resolution is 0.5° × 0.5°; http://sac.csic.es/spei).

Statistical analysis was performed in the StatSoft Inc. program (2013).

RESULTS

Dynamics of Ecological and Climatic Variables

In the forest-steppe zone, the mean annual temperature, the mean summer temperature, and the mean winter temperature are 0.2, 16.3, and –17.2°C, respectively. The mean temperature in January is –19°C and it is 18.1°C in July. The average annual total precipitation is 331 mm, and it is 183 mm in summer. In the highlands, the average annual temperature, the mean summer temperature, and the mean winter temperature are –2.2, 12, and –15°C, respectively. The temperatures of January and July are –15 and 13°C, respectively. The average annual total precipitation is 1600 mm and 380 mm in summer.

Positive air temperature trends have been observed since the 1970s (for the hydrological year) and from the 1980s (for the period May–September) to the early 2000s without significant trends in the future (Fig. 2a). The sum of active temperatures increased during the period from 1980 to the early 2000s; the duration of the vegetative period increased throughout the entire period of observation (Fig. 2b). The amount of precipitation in the "warm period" has increased since the 1970s, with a subsequent declining trend in the 1990s (Fig. 2c). The deficit of water-vapor pressure increased in 1980–2000 without significant trends in the future (Fig. 2d). The aridity of climate (estimated by SPEI) decreased in 1975–1990. In the future, the trend of minimal values of SPEI was observed: the intensity of droughts increased (Fig. 2e). The humidity of the root layer decreased until the early 2000s without significant trends in the future (Fig. 2f).

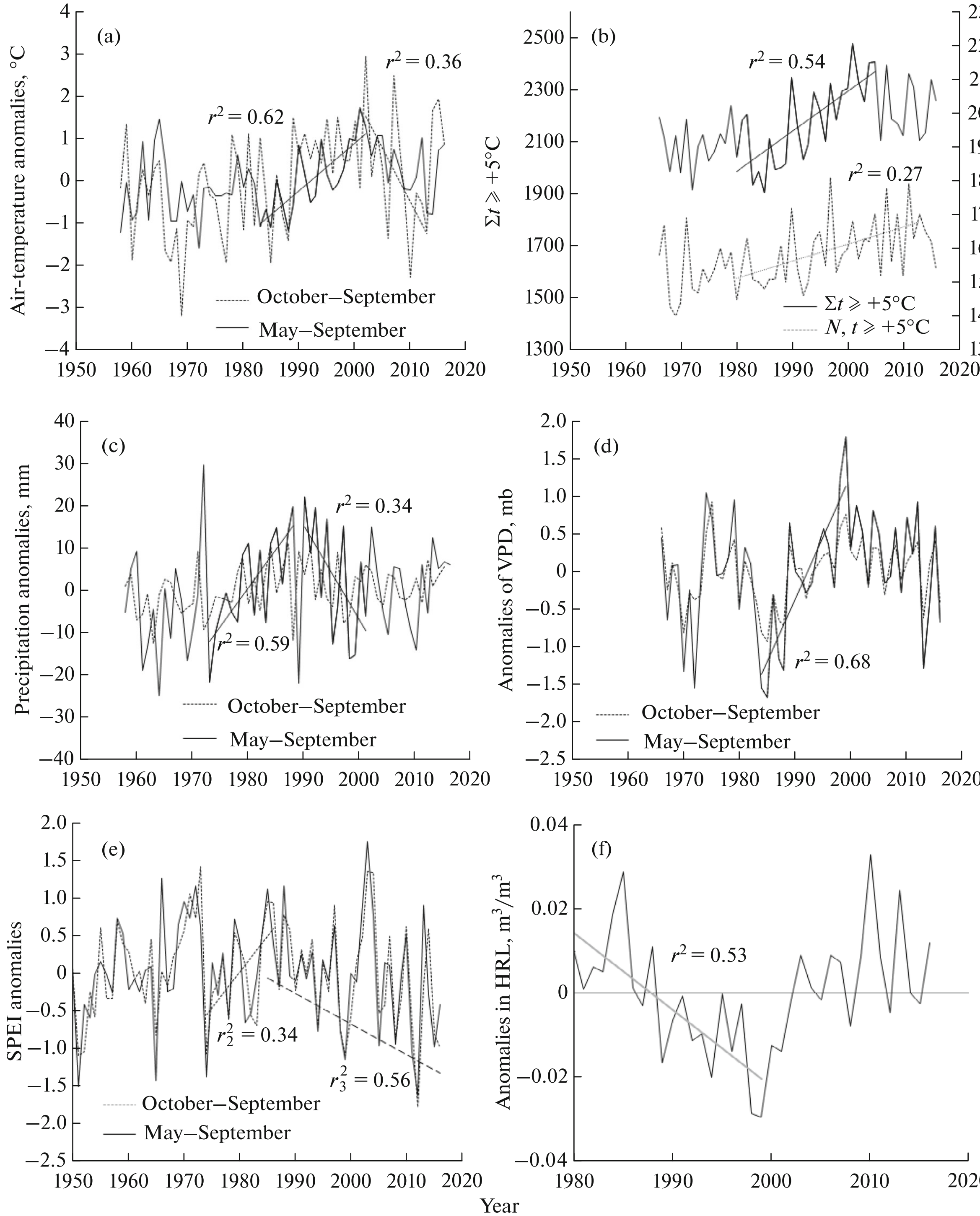

Fig. 2. Dynamics of ecological and climatic variables in the forest-steppe zone. (a) Air-temperature anomalies, (b) dynamics of the sum of active temperatures and the duration of the vegetation period (number of days, N, with $t \geq 5°C$), (c) precipitation anomalies, (d) anomalies of water vapor pressure deficit (VPD), (e) SPEI anomalies, and (f) anomalies in the humidity of the root layer (HRL). The data are presented for the "warm period" (May–September) and the hydrological year (October–September). Trends are significant for $p < 0.05$. Note: a decrease in SPEI indicates an increase in aridity.

Radial Increment of Larch Tree and Ecological and Climatic Variables

The radial increment of the larch tree in the forest-steppe zone increased starting in the 1980s, with a subsequent depression in the 1990s. In the 21st century, there have been fluctuations in the value of radial increment without significant trends (Fig. 3a). The growth of trees under sufficient soil moistening

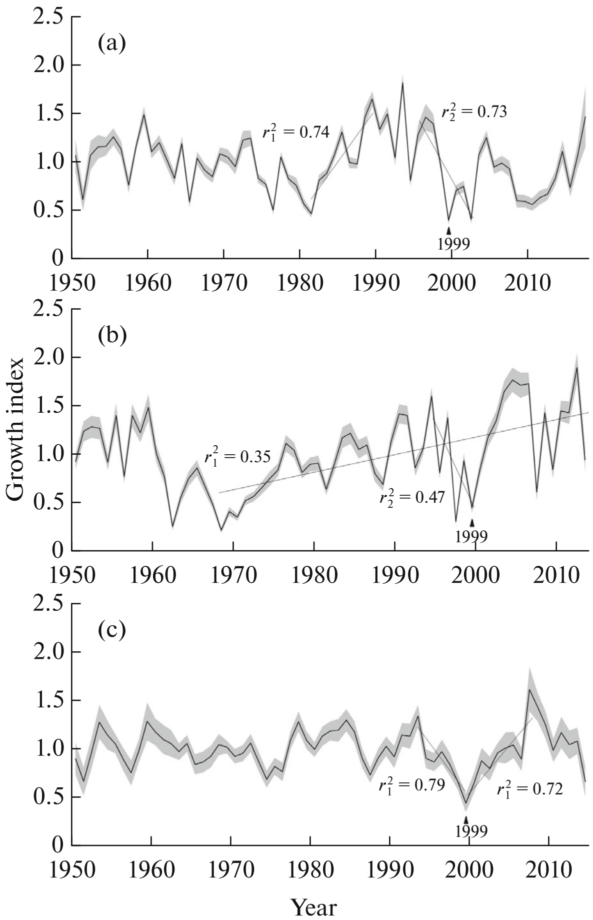

Fig. 3. Dynamics of growth index of larch trees in (a) forest steppe ($N = 160$), (b) highlands ($N = 57$), and (c) floodplain ($N = 40$). Years of drought are marked with arrows.

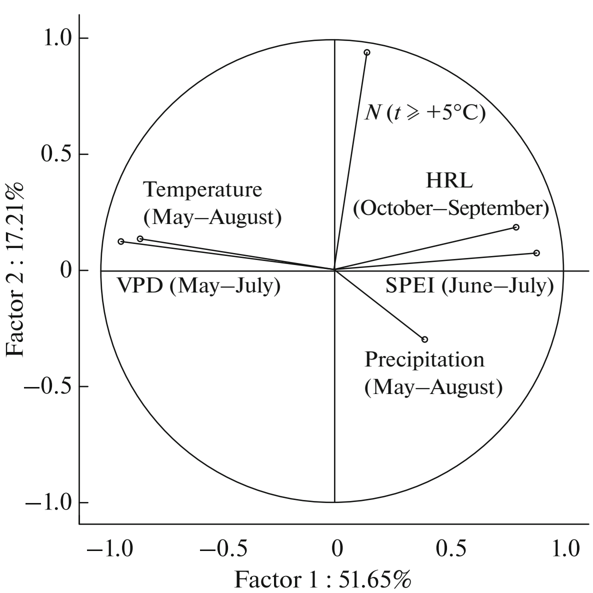

Fig. 4. Diagram of the principal components of climatic factors (forest steppe). VPD, water-vapor pressure deficit; HRL, humidity of the root layer; and N ($t \geq 5°C$), duration of the vegetation period (number of days with $t \geq 5°C$).

(floodplain and highlands) also decreased in dry years (the late 1990's; Figs. 3b, 3c). However, in the highlands, unlike the forest-steppe, there was a general positive trend of radial increment during the whole period of observations (Fig. 3b).

The positive trend in the radial increment of the larch tree of the forest-steppe was due, as follows from Eq. (2), by a decrease in aridity and an increase in the duration of the vegetation period:

$$G = 0.21(\mathrm{SPEI}) + 0.02N - 0.1(\mathrm{VPD}) - 1.27; \quad \left(R^2 = 0.86\right), \tag{2}$$

where G is the index of radial increment, N is the number of days with $t \geq 5°C$, and VPD is the water vapor pressure deficit.

The subsequent depression of radial increment (1987–2003) is mainly due to the negative influence of air temperature and water-vapor pressure deficit:

$$G = -0.3t - 0.06\ (\mathrm{VPD}) + 6.02; \quad \left(R^2 = 0.57\right). \tag{3}$$

An analysis of the main components of the variables that affect the radial increment showed that the first component is determined mainly by the temperature and moisture supply (VPD, SPEI, HRL, and precipitation); the second component is the duration of the vegetation period (Fig. 4).

Particular correlations (Fig. 5) show that, in the forest-steppe zone, the radial increment negatively reacts to the temperature, and the water-vapor pressure deficit ($r = -0.63$, $r = -0.57$, respectively; Figs. 5a, 5d). A positive correlation was found with the drought index ($r = 0.63$), humidity of the root layer ($r = 0.62$) and the duration of the vegetation period ($r = 0.55$; Figs. 5b, 5c, 5e). In contrast to the forest steppe, the increment in the highlands was positively correlated with the main growth factor, i.e., the temperature ($r = 0.74$; Fig. 5a); correlations with the rest of the variables were insignificant. However, in the droughty period (the late 1990s), the radial increment depression was also observed in the areas of sufficient moistening—highland and floodplain stands (Figs. 3b, 3c). During this period, the radial increment in floodplain larch forests correlated with the drought index ($r = 0.55$), the deficit of water-vapor pressure ($r = -0.56$), and the humidity of the root layer ($r = 0.63$).

At the same time, the sufficient humidity of the root layer may not compensate for the effects of atmospheric drought (described by VPD and SPEI), which was also noted by Novick et al. (2016).

DISCUSSION

Since the 1970s, there has been an increase in the growth index of larch trees in the forest-steppe, which was replaced in the 1990s by its depression. The increase in the radial increment was facilitated by a

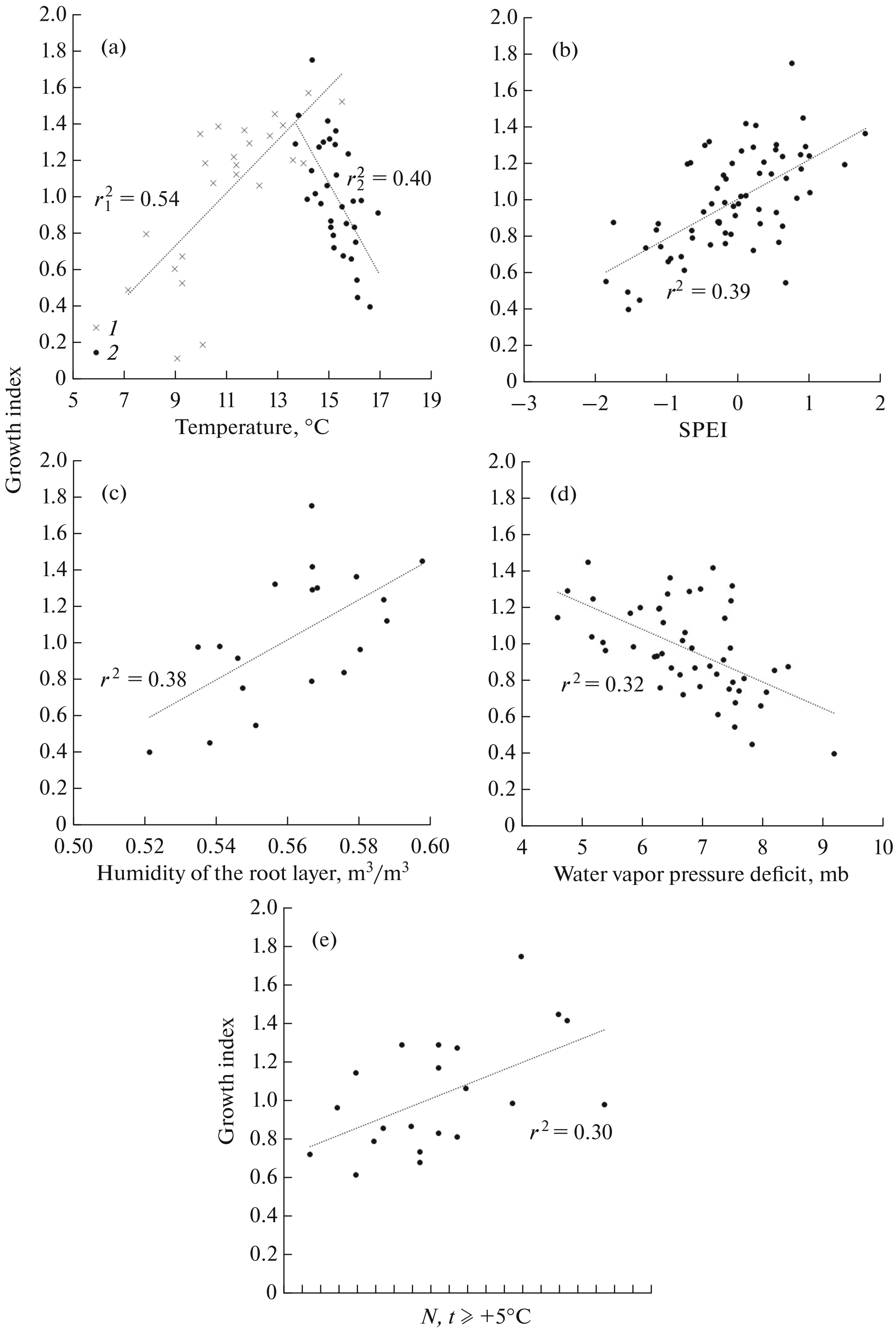

Fig. 5. Dependence of the growth index on (a) air temperature: (*1*) highlands and (*2*) forest steppe; (b) SPEI (index aridity); (c) humidity of the root layer; (d) water-vapor pressure deficit; and (e) duration of the vegetation period. The time interval corresponds to the maximum r^2. Note: a decrease in SPEI indicates an increase in aridity.

decrease in the arid climate and an increase in the vegetative period, when the duration increased by 8–10 days. The depression of the radial increment was due to an increase in temperature and water-vapor pressure deficit (Eqs. (2), (3)). Along with this, the humidity of the root layer decreased (Fig. 2f). At the same time, there is no significant relationship between radial increment and precipitation. This paradox is explained by the growing demand of plants in moisture due to the increase in the level of evapotranspiration (equation (1)). Babushkina et al. (2017) also indicated a weak relationship between radial increment and precipitation.

A similar growth dynamics (increase in the 1980s with subsequent depression due to increased water stress) was also noted for *P. sibirica* and *A. sibirica* in the Baikal region and East Sayan (Kharuk et al., 2017a, 2017b). Note that the absence of a positive relationship between radial increment and air temperature (the "divergence phenomenon") was previously described for other parts of the boreal zone (eg., Andreu-Hayles et al., 2011), which was probably also due to the increased water stress. The latter is confirmed by the data of Restaino et al. (2016). The authors showed that temperature increase led to a decrease in radial increment of Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) in the west of the United States due to the growing deficit of water-vapor pressure. Based on the data in Figs. 2d and 3a, it was possible to estimate the critical value of the water-vapor pressure deficit, the excess of which resulted in a decrease in radial increment (7–9 mb). However, the increase in the aridity of climate did not lead to the drying up of the larch forests of the forest steppe, while at the time in the southern taiga subzone there was a drying out of stands formed by moisture-loving Siberian pine cedar and fir (Kharuk et al., 2016). In the 2000s, there were fluctuations in radial increment with average values not exceeding those before the onset of warming.

In the highlands, where larch growth is primarily limited by temperature, there was a general trend of increasing radial increment. Earlier, (Petrov et al., 2015) showed a significant (>50%) increase in the increment of the larch tree in modern conditions when compared with that in the early 20th century. At the same time, during periods of severe droughts, when the seasonal distribution of precipitation is disturbed, a decrease in radial increment occurs under conditions of the excess annual average (>1500 mm) humidification of highlands, as well as in floodplain larch forests. Another documented effect of warming in the highlands is the advancement of the altitudinal boundaries of woody vegetation, woodlands, and closed stands (Kharuk et al., 2017c). At the same time, in the highlands of the south of the Altai-Sayan region (ASR), the increment is limited not only by temperature, but also by the conditions of moisture supply, which may lead to the regression of the upper boundary of woody vegetation. According to (IPCC, 2014) forecasts, in southern Siberia, especially under "tough" climate scenarios (RCP 6.0, RCP 8.5), the aridity of climate will increase, as is evidenced by the trend of increasing drought intensity in the region under study (Fig. 2e). In this regard, we should expect a decrease in the radial increment of larch trees of the forest steppe and probably in the mountains of the southern part of the ASR, while under conditions of sufficient moistening (Kuznetsk Alatau, Western Sayan), a further increase in the larch-tree increment will be observed.

In conclusion, we note that the high (when compared with other forest-forming Siberian breeds) drought resistance of larch allows us to recommend this species for reforestation in zones of the climatically induced desiccation of dark coniferous (Kharuk et al., 2016). Siberian larch may also be considered a probable replacement of spruce (*P. abies*) in the shrinking stands of the European part of Russia and in Europe, as well as possibly also in pine stands (*P. sylvestris*), whose drying is noted in the southern part of the forests of Ukraine and Belarus (Sarnatskii, 2012; Kharuk et al., 2015; Lufferov and Kovalishin, 2017).

SUMMARY

(1) The warming that began in the 1980s, the decrease in the aridity of the climate, and the increase in the duration of the vegetative period were accompanied by an increase in the index of larch radial increment in the forest-steppe. In the early 1990s, the increase in growth was replaced by its depression due to an increase in the deficit of water-vapor pressure and the aridity of climate, caused by the rising air temperature. In the 2000s there were fluctuations in the increment with average values not exceeding those before the beginning of the period of modern climate warming.

(2) In the highlands, since the 1970s, there has been a general trend of an increase in larch radial increment due to the increase in the main growth factor: air temperature. At the same time, in arid periods, the increment depression was also noted in humid places (highland and floodplain larch forests).

(3) When implementing "hard" (RCP 6.0 and RCP 8.5) climate scenarios, it is likely that the larch growth index in the forest steppe will decrease further and increase in areas of sufficient moisture.

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