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Forest–Tundra Larch Forests and Climatic Trends

V. I. Kharuk[a], K. J. Ranson[b], S. T. Im[a], and M. M. Naurzbaev

[a] *Sukachev Institute of Forest, Siberian Division, Russian Academy of Sciences, Akademgorodok, Krasnoyarsk, 660036 Russia;*
e-mail: kharuk@ksc.krasn.ru
[b] *Goddard Space Flight Center, National Aeronautics and Space Administration, United States;*
e-mail: jon.ranson@nasa.gov

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Abstract—Climate-related changes that occurred in the Ary-Mas larch forests (the world's northernmost forest range) in the last three decades of the 20th century have been analyzed. An analysis of remote-sensing images made by Landsat satellites in 1973 and 2000 has provided evidence for an increase in the closeness of larch forest canopy (by 65%) and the expansion of larch to the tundra (for 3–10 m per year) and to areas relatively poorly protected from wind due to topographic features (elevation, azimuth, and slope). It has also been shown that the radial tree increment correlates with summer temperatures ($r = 0.65$, $\tau = 0.39$) and the amounts of precipitation in summer ($r = -0.51$, $\tau = 0$–41) and winter ($r = -0.70$, $\tau = -0.48$), decreases with an increase in the closeness of forest canopy ($r = -0.52$, $p > 0.8$; $\tau = -0.48$, $p > 0.95$), and increases with an increase in the depth of soil thawing ($r = 0.63$, $p > 0.9$; $\tau = 0.46$, $p > 0.9$). The density of undergrowth depends on temperatures in winter($\tau = 0.53$, $p > 0.8$) and summer ($r = 0.98$, $p > 0.99$, $\tau = 0.9$, $p > 0.99$) and the date of the onset of the growing period ($r = -0.60$, $p > 0.99$; $\tau = -0.4$, $p > 0.99$) and negatively correlates with the amount of precipitation in summer ($r = -0.56$, $p > 0.99$, $\tau = -0.38$, $p > 0.99$).

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Key words: larch forests, climatic trends, radial tree increment, remote sensing.

According to recent climatic scenarios, air temperature and the amount of precipitation in the north of Siberia may increase by 4–6°C and approximately 25%, respectively, by the year 2100 (Gordon et al., 2000; *IPCC*…, 2001), and this may entail the displacement of the limit of tree growth to the north. There is an increasing amount of evidence for the expansion of trees to the tundra at both latitudinal and altitudinal limits of tree growth and for an increase in the canopy density and radial tree increment in subtundra forests in the last decades of the 20th century (Vaganov et al., 1999; Suarez et al., 1999; Skre et al., 2002; Lloyd and Fastie, 2002; Kharuk and Fedotova, 2003; Shiyatov, 2003). The response of trees to climatic changes should be more distinct in the zone where temperature is the limiting factor, i.e., in the forest–tundra ecotone at the northern boundary of tree growth. In Asia, this boundary is formed by larch stands, which include the world's northernmost forest range in the Ary-Mas area (72°28′ N, 101°40′ E). Tracing the influence of climatic trends on the dynamics of vegetation involves an analysis of long-term series of observations on test plots combined with dendrochronological data (Shiyatov et al., 2005). Time series of satellite images, with the first of them dating from the 1960s, offer additional opportunities for such an analysis. They allow specialists to reveal changes in plant cover and use the results of on-ground observations for extrapolations at regional and subglobal levels (Myneni et al., 1997; Kharuk et al., 2003).

The purpose of this study was to analyze the response of forest–tundra larch forests (exemplified by the Ary-Mas forest range) to climatic trends using the data of on-ground surveys and satellite images.

OBJECT UNDER STUDY

The study area extends from 72°02′ to 72°40′ N and from 101°15′ to 102°06′ E (a total of approximately 36000 ha) and includes the Ary-Mas forest itself and larch forests on southeastern slopes descending to the Khatanga River (Fig. 1). The distance between them is approximately 34 km, and both forest areas are similar in terms of ecological and site conditions. For convenience, they are hereinafter referred to as the Ary-Mas range. The Ary-Mas forest occupies terraces on the right bank of the Novaya River at elevations of up to 80 m a.s.l. This unique "forest island" was described for the first time by Tyulina (1937). It extends along the river for about 20 km and is 0.5–1.5 km wide, with sparse trees spreading away from the river, along the valleys of streams, for 3–4 km. On the left bank, tree stands occupy a narrow strip along the river. In a swamped lowland lying on the north, small clusters of

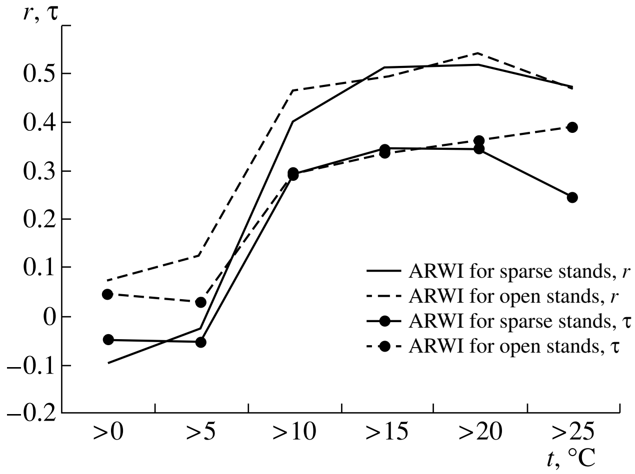

Fig. 1. Dependence of the annual ring width index (ARWI) on the number of days with air temperature above the values shown on the abscissa.

larch trees (mainly prostrate forms) occur in sites protected from wind, such as depressions near lakes, at a distances of up to 50–70 km from the Ary-Mas area. Tree stands consisting of *Larix gmelinii* have the following parameters: crown density reaches 0.5; quality class is 5a–5b; tree height and diameter average 5–8 m and 10–14 cm, reaching 10–12 m and 25 cm. Tree age reaches 50–700 years. Many trees older than 150 years of age are affected by heart rot. Fructification begins when tree age reaches 30 years; cones are abundant and small (1.5–2 cm) and seed germination rate is relatively low. The density of young tree growth varies from 100 to 2000 ind./ha, averaging 260 ind./ha under the forest canopy and 140 ind./ha in open stands; the overall average is 200 ind./ha. The quality of young growth is good: the proportion of dead individuals does not exceed 5% (*Ary-Mas*, 1978).

The study region has a sharply continental climate with the annual precipitation, evaporation, and average air temperature being approximately 250 mm, 50–100 mm, and –15°C, respectively. The greater part of precipitation falls in summer, with a peak in August; the monthly average period with some precipitation is 80–100 h. Relative air humidity in summer is 78%. Fogs are rare, because most days are windy. Approximately one-third of the annual precipitation falls in the winter period, with snow cover lasting for approximately 250 days. It appears in late September, melts on elevated elements of relief in the first ten-day period of June, but is often preserved throughout summer on northern slopes and in depressions. Snow depth reaches a peak in April, being 30–50 cm in open areas and 60–70 cm in sites protected from wind. Air temperature in June may reach +29°C, and its monthly average value is +5°C. The period with above-zero temperatures is about 100 days, but subzero temperatures and snow may occur throughout summer. The depth of the ground layer that freezes in winter and thaws in summer is 50–70 cm in mineralized areas (up to 1 m on steep slopes under open forests or sparse trees) and 10–30 cm under the moss cover. In winter, low temperatures combined with strong winds place the Ary-Mas range among Asia's areas with the severest climate. February is the coldest month, with air temperature having a monthly average of –31°C and an absolute minimum of –59°C. The average wind velocity in winter is about 5 m/s, the number of days with blizzards reaches 50 (in some years, up to 90); on approximately 20 days per year, the wind velocity exceeds 15 m/s (*Ary-Mas*, 1978).

MATERIAL AND METHODS

Data of ground-based observations. The earliest data used in this study, obtained by 1969, include geobotanical, pedological, and taxonometric descriptions, the map of the Ary-Mas range, and characteristics of 12 test plots 0.25 to 1.0 ha in size (*Ary-Mas*, 1978). Subsequent taxonometric surveys were made in 1989–1991 and 2000. Core samples taken in ten test plots were used to construct tree-ring chronologies covering the period from 1900 to 1990. The trend of radial increment (γ) was determined as the tangent of the angle between the abscissa and the regression line of the annual ring width index (ARWI). Data on air temperature and precipitation were obtained from the Khatanga weather station located at a distance of approximately 45 km from the study area. The summer period was assumed to be three months, from June to August; the remaining nine months were conventionally regarded as the winter period. The spring and autumn phenophases were not distinguished because of their short duration and variation in the dates of the onset and end of the growing period.

To select a measure characterizing the length of the growing period, the following parameters were considered: (1) the number of days with air temperatures exceeding 0, 5, 10, 15, 20, or 25°; and (2) the sum of temperatures accumulated on the days when air temperature exceeded these values. According to the results of our analysis, ARWI most strongly correlated with the number of days with temperatures above 15°C (Fig. 1), and the same was true for the sum of temperatures exceeding this threshold. Hence, the number of days on which temperature rose above 15°C was chosen as a measure of the length of the growing period. As a criterion of the onset of the growing period, we considered the date on which air temperature first rose above 0, 5, or 10°C and the date on which the sum of above-zero temperatures exceeded 100 or 300°C. The response of tree plants (with respect to ARWI and the density of young growth) was observed when the latter parameter exceeded 300°C.

Remote-sensing data included (1) images from the Landsat-MSS satellite (L-MSS, pixel size 57 × 57 m) obtained on July 26, 1973, and from the Landsat-7 satellite (L-7, pixel size 30 × 30 m) obtained on August 3,

Table 1. Dynamics of land classes in the Ary-Mas range from 1973 to 2000

Class	S_1, ha (t_1, 1973)	S_2, ha (t_2, 2000)	$\Delta_1(S_2 - S_1)$, ha	$\Delta_2[(S_2 - S_1)/S_1]$, %	$\Delta_2/(t_2 - t_1)$, % per year
Sparse stands (L_1)	17883	19264	1381	+8	0.29
Open stands (L_2)	13887	16133	2245	+16	0.60
Normal stands (L_3)	9415	15601	6186	+66	2.43
Background	51654	41842	–9812	–19	–1.12

2000; (2) a panchromatic image made by the Corona system on February 28, 1965 (pixel size 7 × 7 m); and (3) panchromatic aerial photographs made on July 31, 1970, (scale 1 : 35000) and on July 27, 1984 (scale 1 : 15000). The Corona KH-4A system operated from August 1963 to October 1969, scanning a strip 19.6 km wide and 267 km long with a resolution of 2.7 m. All images and maps were converted into the same autogonal conical Lambert projection and referred to control topographic points. The L-MSS and L-7 images were resampled to the same resolution (60 × 60 m) and classitied using a supervised maximum likelihood method. The position of the forest–tundra boundary was determined from the image made by the Corona system, in which trees stood out against the background of snow due to the shadow they cast, especially at a low sun angle. A matrix of elevations was used to exclude from analysis the areas lying beyond the altitudinal limits of larch growth (below 5 m and above 80 m a.s.l.).

Learning samples and classification. To generate learning and control samples, we used the map of larch forest types in the Ary-Mas range and aerial photographs. Because of uncertainty in determining the "forest boundary" in the forest–tundra ecotone (Hustich, 1953), we classified forest areas by the index of canopy density (CD): (1) sparse stands (L_1, CD < 0.1), (2) open stands (L_2, 0.1 < CD < 0.3), and (3) "normal" stands (L_3, CD ≥ 0.3). Larch stands of the Ary-Mas range are typologically diverse. According to the results of on-ground surveys, they belong to 18 different classes represented on the initial map by 88 categories, each with taxonometric and geobotanical descriptions. In addition to larch stands, eight classes of tundras, four types of bogs, and five classes of dwarf-birch and willow coppice were distinguished in this range. However, as the total area of tundras and bogs on this map was relatively small, the learning samples of the corresponding classes were generated using topographic maps (scale 1 : 100000), on which tundras and bogs were better represented. On the whole, we initially distinguished 35 classes, which were subsequently generalized. The resultant classes were as follows: (1) sparse larch stands (L_1); (2) open larch stands (L_2); (3) normal larch stands (L_3); (4) background areas usually devoid of trees, such as tundras, bogs, and open woodland; (5) sand or pebble banks; and (6) water areas. Images were analyzed with regard to both spectral channels and layers corresponding to the slope (α), elevation (*h*), and azimuth (az) of different elements of relief. The slope α proved to be the most informative parameter.

The accuracy of classification was estimated on the basis of a matrix of errors and κ-statistics (Rosenfield and Fitzpatric-Lins, 1986). In addition to regression analysis, we used Kendall's nonparametric τ parameter (*Nonparametric Statistics*, 2003). The τ parameter may assume values from the interval [–1, +1] and is calculated as τ = (the number of coincidences – the number of noncoincidences) / (the total number of pairs compared). The zero value of τ indicates the absence of correlation, and values of +1 and –1 correspond to a complete synchrony and asynchrony of the series compared, respectively.

RESULTS

Analysis of the dynamics of the forest–tundra ecotone. The map in Fig. 2 shows changes that occurred in the Ary-Mas range between 1973 and 2000. In particular, this concerns the increment (Δ) of areas under sparse + open and normal larch stands. The accuracy of classification could be regarded as satisfactory: 60% (κ = 0.47) for the L-MSS image (1973) and 66% (κ = 0.49) for the L-7 image (2000). Tables 1 and 2 show numerical indices characterizing the dynamics of classes L_1–L_3 during the same period. The most significant changes were observed in the class of normal larch stands (CD ≥ 0.3): their area increased by 66% (Table 1). The areas of open and sparse forests (0.1 < CD < 0.3 and CD < 0.1) increased by 16 and 8%,

Table 2. Dynamics of transitions between land classes in the Ary-Mas range from 1973 to 2000

Class in 1973 (MS composite)	Areas of classes in 2000 relative to those in 1973, %			
	Normal stands (L_3)	Open stands (L_2)	Sparse stands (L_1)	Background
Normal stands (L_3)	40.4	11.5	2.1	2.0
Open stands (L_2)	17.2	34.4	12.5	7.7
Sparse stands (L_1)	5.4	16.5	29.1	21.0
Background	36.9	37.6	56.3	69.3
Total	100	100	100	100

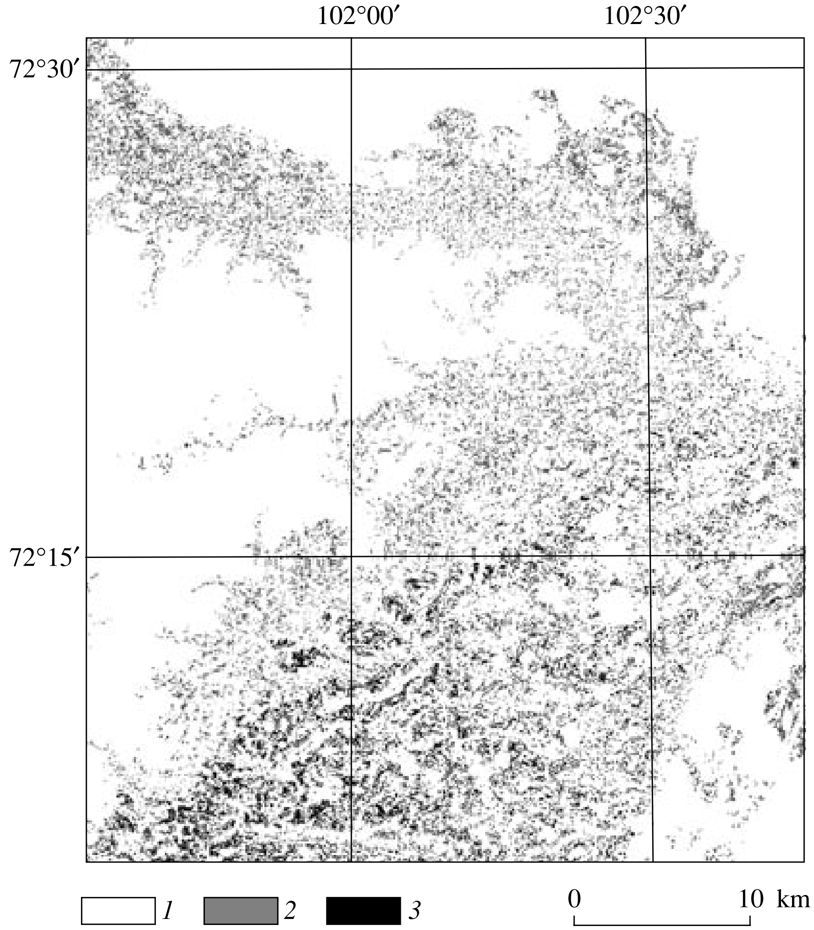

Fig. 2. Subtraction map of the Ary-Mas range (the 2000 map minus the 1973 map): (*1*) background areas, (*2*) increment in the area of sparse and open larch stands, and (*3*) increment in the area of normal larch stands.

respectively, whereas the background area became 19% smaller.

Table 2 shows a matrix of transitions between the classes for the period between 1973 and 2000, with their areas in the 2000 map shown as percentages of those in the 1973 map. For example, the area of class "normal stands" in the 2000 map consists of the following classes delimited in the 1973 map: normal stands, 44.4%; open stands, 17.2%; sparse stands, 5.4%; and background areas, 36.9%. This is indicative of a transition to stands with increasing density (from sparse to open and from open to normal stands), with background areas turning into sparse stands. However, a considerable proportion of class "normal stands" in the 2000 map (36.9%) originated from the background class of the 1973 map. This could not be attributed to a classification error alone, as the background class in the 2000 map included only 2% of the normal stand class delimited on the 1973 map. Apparently, the background class (tundras, bogs, and open woodland) also included areas with the presence of larch. According to the results of on-ground surveys, individual trees may occur at considerable distances (over 500 m) from the zone of open forests. In the zone of transition from sparse stands to the tundra, fructifying prostrate forms of larch prevail. Such plants may have up to 10–20 stems aged more than 100 years, with the root system being older than the above-ground plant parts. Under favorable conditions, prostrate larch plants can form large clusters, and this fact may account for the transition of some areas from the background class to larch stand classes.

Dynamics of the forest–tundra ecotone and orographic features of the area. Let us consider the dynamics of larch stands with respect to elements of relief (slope, elevation, and azimuth). The density of normal stands correlates with the slope of the area in which they grow, reaching the highest values on the steepest slopes (the peak of distribution corresponds to approximately ~13°). A similar distribution, with a peak at approximately ~12°, is characteristic of open stands. The distribution of sparse stands is leveled off, with the highest values corresponding to approximately 6° (Fig. 3a). The density of larch forests increases, and they expand along the altitudinal gradient (Fig. 3b). The distribution of sparse stands is shifted toward higher

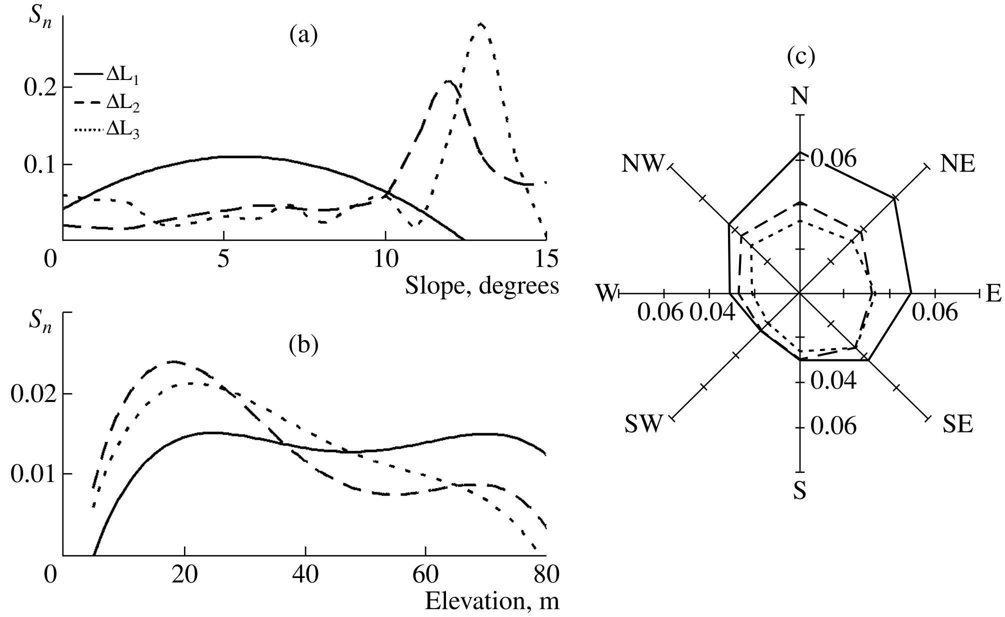

Fig. 3. Distribution of normalized increment in the areas of larch stands with respect to topographic features of terrain: (a) elevation above sea level, (b) slope, and (c) azimuth. ΔL_1, ΔL_2, and ΔL_3 are increments in the area of stands with densities L_1, L_2, and L_3; S_n is the normalized area of larch stands: $S_n = \sum_{i=1}^{N} x_i = 1$, where x_i are normalized discrete elements of the histogram, and N is the total number of elements.

elevations (70–80 m), whereas open and normal stands are better represented at elevations of about 20 m. The expansion of larch to the tundra is nonuniform with respect to azimuth, proceeding mainly in a south–north direction (Fig. 3c). The greatest distance of expansion is characteristic of sparse larch stands, then follow open and normal stands. The effect of slope on the distribution of larch is explained by the significance of topography for the survival of trees: larch stands concentrate in the areas protected from winds and the impact of snow they carry, which causes desiccation and damage of shoots. It is appropriate to remind that Ary-Mas is among the most windy areas in Russia, with wind velocity averaging approximately 5 m/s. The expansion of tree vegetation to the tundra zone is associated with its "departure" from protected sites and movement along the altitudinal gradient toward the areas open to severe winter winds.

The rate of larch expansion to the tundra. We estimated change in the area of larch stands (classes L_1, L_2, and L_3) and the rate of displacement of their boundaries (i.e., the velocity of expansion v) over the period between 1973 and 2000. Data on the average annual change in stand areas are shown in Table 1. The greatest and smallest changes were characteristic of denser (normal) and sparse stands (2.43 and 0.29%), with open stands occupying an intermediate position (0.6% per year). The average rate of larch expansion was estimated by approximating the area of each class (L_1–L_3) as a rectangle with one side oriented along the direction of expansion and the side perpendicular to it being equal to the size of the tundra ecotone (approximated by a straight line). This approximation is adequate, as the Ary-Mas range is an elevation with gentle slopes that is shaped like a truncated polyhedron.

Strong winds and a vertical temperature gradient provided for the formation of a relative uniform, linear boundary of larch growth across the slope. As noted above, larch expands up the altitudinal gradient. The length of altitudinal boundary (estimated from the Landsat image at approximately 93 km) was assumed to be equal for all three classes of stands, as they were similarly arranged on the slope after one another. The other (shorter) side of the rectangle was calculated from its area. The difference between these sides showed the displacement of the boundary of larch growth over the period from 1973 to 2000. The rates of this displacement (expansion) for sparse, open, and normal stands were estimated at 3, 9, and 11 m per year, respectively. In all cases, normal larch stands expanded at the highest rate, and sparse stands expanded at the lowest rate. As sparse stands (L_1) are at the forefront of advancement to the tundra, the rate for this class (approximately 3 m per year) should be regarded as the rate of larch expansion in general. It should be noted that the above rates reflect not only the expansion of trees to the tundra, but also an increase in the density of sparse and open stands.

Dynamics of radial increment and young growth density. The results of analysis of satellite remote-sensing data are indicative of an increase in the density of

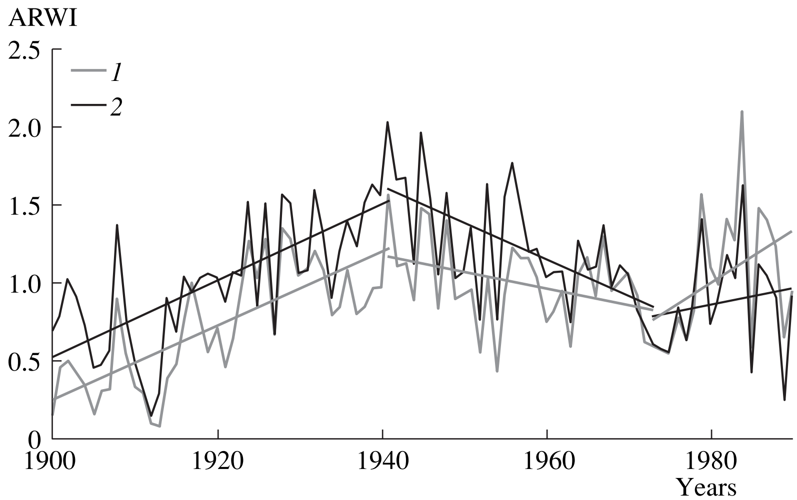

Fig. 4. Dynamics of the annual ring with index in (*1*) sparse and (*2*) open larch stands in the 20th century according to data from five test plots for each stand class.

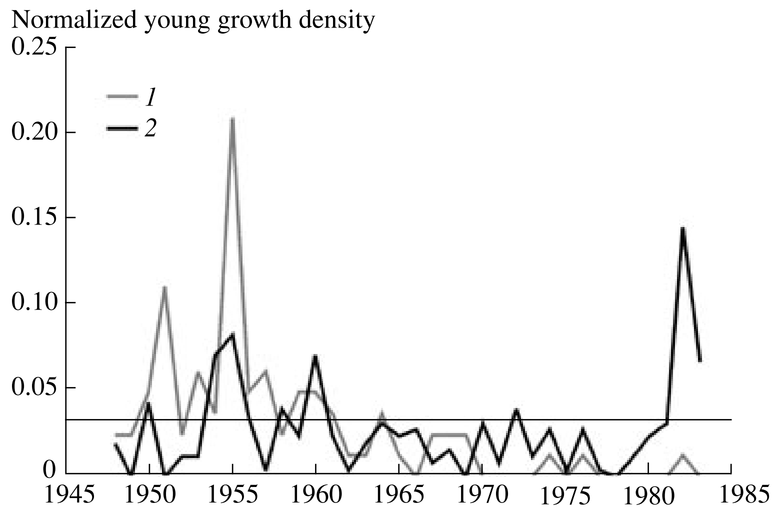

Fig. 5. Age structure of young growth in (*1*) sparse and (*2*) open larch stands according to data from five test plots for each stand class (254 and 81 model plants, respectively). The abundance of young growth is normalized by the formula $\Sigma N = 1$, where N is the number of plants.

tree stands and the advancement of larch to the tundra in the last decades of the 20th century. Let us consider to what extent they agree with data on the dynamics of tree increment, one of the main indices characterizing the ecological conditions of tree growth (Shiyatov et al., 2005). The diagram of ARWI as a function of time (Fig. 4) shows that this index increased between 1900 and 1941, decreased between 1942 and 1972, and increased again beginning from the early 1970s. The last period was crucial in the comparative growth dynamics of open and sparse stands, as ARWI values for the former became smaller than those for the latter. In the same period, the density of young growth increased as well, especially in sparse stands ($p > 0.95$) (Fig. 5).

The trend of radial tree increment γ) averaged for all test plots over the period from 1973 and 1990 negatively correlates with canopy density (r = –0.52, $p > 0.8$; τ = –0.48, p > 0.95): its values are higher in sparse stands and lower in open and normal stands (Fig. 5). This does not contradict the data presented in Table 1, because the 66% increment in the area of normal stands was accounted for by an increase in the density of sparse and open stands and their consequent transition to this class (Table 2).

Moreover, γ positively correlates with the depth of ground thawing ($r = 0.63, p > 0.9$; $\tau = 0.46, p > 0.9$) (Fig. 6).

This depth, in turn, increases with elevation above sea level ($r = 0.55$, $p > 0.9$; $\tau = 0.51$, $p > 0.95$), which is due to a decrease in the density ($r = –0.83$, $p > 0.95$; $\tau = –0.66$, $p > 0.95 > 0.95$) and thickness ($r = –0.88$; $p > 0.95$; $\tau = –0.75$, $p > 0.95$) of the moss–lichen layer. A negative correlation between γ and canopy density is unrelated to plant competition for light, because the maximum values of canopy density do not exceed 0.5, whereas the amount of incident solar radiation in summer is comparable to that in the tropics (15–16 kcal/cm^2 per month). However, competition for mineral nutrients is not excluded, but this issue needs further study.

The increasing depth of ground thawing and the decreasing coverage of the moss–lichen layer facilitate the advancement of larch up the altitudinal gradient (see Fig. 3b). The latter factor is favorable for germination of larch seeds, because a continuous ground vegetation layer "suspends" the seeds above the soil surface. On the other hand, climatic conditions on the corresponding elements of relief are most severe, and the establishment of larch in such sites is possible only in the periods of warming.

DISCUSSION

An analysis of the results of on-ground observations provides evidence for a relationship between the dynamics of subtundra tree stands and climatic changes in the last decades of the 20th century. Strong correlations are observed between the density of young larch growth, on the one hand, and summer air temperatures ($r = 0.91$, $p > 0.99$; $\tau > 0.68$, $p > 0.99$) and the number of days with temperatures above 15°C ($r = 0.98$, $p > 0.999$; $\tau = 0.9$, $p > 0.99$), on the other. A correlation between the density of young growth and winter temperatures ($\tau = 0.53$, $p > 0.8$) in the period between 1973 and 1983 is noteworthy, as no such correlation was revealed in the previous period (1948–1972). A probable explanation is that winter temperatures, which were relatively low between 1948 and 1972, increased by 1.3°C in the last decades of the 20th century ($p > 0.99$), and this increase had a favorable effect on the survival of young plants in winter. It should be noted that the increase of summer temperatures in this period (by 0.24°C) was statistically nonsignificant.

The date of the onset of the growing period (on which the sum of above-zero temperatures exceeds 300°C) has a significant effect on the density of young larch growth ($r = –0.60$, $p > 0.99$; $\tau = –0.4$, $p > 0.99$). This applies to the entire period considered in this study. Such an effect is slightly weaker in the case of the radial tree increment ($r = –0.41$, $p > 0.99$, $\tau = –0.24$, $p > 0.95$). Variation in the radial increment by years (1973–1990) in sparse and open larch stands positively correlates with summer temperatures ($r = 0.65$, $\tau = 0.39$) and negatively correlates with the amounts of precipitation in summer ($r = –0.51$, $\tau = –0.41$) and winter ($r = –0.70$, $\tau = –0.48$). The density of young larch

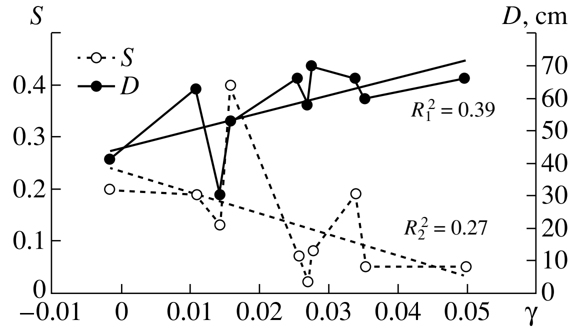

Fig. 6. Relationships between the trend of ARWI (γ) and canopy density (S) and the depth of ground thawing (D).

growth also shows a negative correlation with the amount of precipitation in summer ($r = –0.56$, $p > 0.99$; $\tau = –0.38$, $p > 0.99$), which is probably due to a decrease in the amount of sunlight and air temperature on rainy days. The amount of precipitation in winter decreased in the end of the 20th century, whereas air temperatures in the winter season (including May) increased. This entailed a change in the date on which the ground becomes free of snow. As the snow cover disappears first on elevations where sparse larch stands prevail, the growing period of larch in such stands is longer than in open and normal stands. However, the temperature of needles (a factor limiting photosynthesis) is different in larch trees growing in wind-protected sites and in sparse stands open to strong winds. When the sun shines, the temperature of needles is markedly higher than that of ambient air (Saeki, 1966), and this apparently has a favorable effect on the rate of photosynthesis at low air temperatures. When wind blows, however, this difference is leveled off. Moreover, larch at the beginning of the summer phenophase is capable of vegetative development even in the presence of snow cover. Therefore, additional ecophysiological studies are necessary for correctly determining the length of the growing period in larch stands located in different elements of relief.

As follows from the results of deciphering the Landsat images, this is the density of stands, rather than the position of the forest boundary, that most rapidly responds to climatic changes. A similar result was obtained for the upper forest boundary in the Polar Urals (Shiyatov et al., 2005). The expansion of trees to the tundra is a more inertial process. Under favorable conditions, seedlings take root within the range of natural seed dispersal from the maternal stand (50–60 m). Seed transfer by snowmelt in the Ary-Mas range can be ignored, because larch expands up the altitudinal gradient. The next round of dispersal may be observed after approximately 30 years, when young trees reach the age of fruiting. As a peak of young growth density was observed in the late 1970s–early 1980s (Fig. 5), larch could expand for the aforementioned 50–60 m by the year 2000, when the last satellite image considered in this study was made. Assuming that the rate of expansion of sparse larch stands is 3 m per year (see above), we found that they could expand for about 90 m during the same period. The result of this comparative estimation may be regarded as satisfactory, especially with regard to the second component of larch expansion to the tundra and, namely, seed dispersal from individual trees and prostrate forms of larch, which may grow at large distances (1–3 km) from the maternal stand. As lower branches of prostrate larch plants are capable of taking root, these plants are often multistemmed and, under favorable conditions, can form large clusters. This fact may account for the transition of some areas from the background class to larch stand classes (see Table 2). The second component may markedly accelerate the expansion of tree vegetation to the tundra. In fact, the real forest boundary does not coincide with its theoretically possible position: its regression upon cooling is delayed, as mature trees are more hardy than young trees, and its advancement upon warming is retarded because of ecological limitations on seed production, dispersal, germination, and seedling survival.

CONCLUSIONS

(1) The radial increment of larch in the Ary-Mas range depends on summer temperatures ($r = 0.65$, $\tau = 0.39$) and the amounts of precipitation in summer ($r = -0.51$, $\tau = -0.41$) and winter ($r = -0.70$, $\tau = -0.48$). The trend of radial tree increment depends on canopy density ($r = -0.52$, $p > 0.8$; $\tau = -0.48$, $p > 0.95$) and the depth of ground thawing ($r = 0.63$, $p > 0.9$; $\tau = 0.46$, $p > 0.9$).

(2) The density of young larch growth depends on air temperatures in winter ($\tau = 0.53$, $p > 0.8$) and summer ($r = 0.98$, $p > 0.99$; $\tau = 0.9$, $p > 0.99$) and the date of the onset of the growing period ($r = -0.60$, $p > 0.99$; $\tau = -0.4$, $p > 0.99$). In addition, this parameter negatively correlates with the amount of precipitation in summer ($r = -0.56$, $p > 0.99$; $\tau = -0.38$, $p > 0.99$).

(3) In Ary-Mas, the world's northernmost forest range, an increase in the density of larch stands (by approximately 65%) and the expansion of larch to the tundra (for 3–10 m per year) were recorded in the late 20th century. This effect, being induced by climatic trends, depends on orographic features of the study area. Larch is now expanding to areas poorly protected from winds due to their topographic features (elevation, azimuth, and slope). According to the present-day scenarios of climate change (*IPCC*…, 2001), this process will result in the expansion of larch to the Arctic coast, the phenomenon that took place in the Holocene. On the other hand, the zone dominated by larch is invaded by dark coniferous species (Siberian stone pine, spruce, and fir) entering from the south and west (Kharuk, 2005).

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REFERENCES

Ary-Mas (Ary-Mas), Leningrad: Nauka, 1978.

Gordon, C., Cooper, C., Senior, C., et al., The Simulation of SST, Sea-Ice Extents, and Ocean Heat Transport in a Version of the Hadley Centre Coupled Model without Flux Adjustments, *Clim. Dyn.*, 2000, vol. 16, pp. 147–168.

Hustich, I., The Boreal Limits of Conifers, *Arctic*, 1953, vol. 6, pp. 149–162.

IPCC Third Assessment Report, vol. 1: *Climate Change 2001, The Scientific Basis,* Cambridge: Cambridge Univ. Press, 2001.

Kharuk, V.I. and Fedotova, E.V., Forest-Tundra Ecotone Dynamics, in *Arctic Environment Variability in the Context of Global Change*, Bobylev, L.P., Kondratyev, K.Y., and Johannessen, O.M., Eds., Heidelberg: Springer-Praxis, 2003, pp. 281–299.

Kharuk, V.I., Dvinskaya, M.L., Ranson, K.J., and Im, S.T., Expansion of Evergreen Conifers to the Larch-Dominated Zone and Climatic Trends, *Ekologiya*, 2005, no. 3, pp. 186–193.

Lloyd, A. and Fastie, C., Spatial and Temporal Variability in the Growth and Climate Response of Treeline Trees in Alaska, *Climate Change*, 2002, vol. 52, pp. 481–509.

Myneni, R.B., Keeling, C.D., Tucker, C.J., et al., Increase in Plant Growth in the Northern High Latitudes from 1981–1991, *Nature*, 1997, vol. 386, pp. 698–702.

Nonparametric Statistics. StatSoft, Inc., 2003. http://www.statsoft.com/textbook/stnonpar.html.

Rosenfield, G.H., Fitzpatric-Lins, K., A Coefficient of Agreement As a Measure of Thematic Classification Accuracy, *PE & RS*, 1986, vol. 52, no. 2, pp. 223–227.

Saeki, A., Temperature Fluctuations in Wintering Trees, *Physiol. Plant.*, 1966, vol. 19, no. 1, pp. 105–114.

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

Shiyatov, S.G., Terent'ev, M.M., and Fomin, V.V., Spatiotemporal Dynamics of Forest-Tundra Communities in the Polar Urals, *Ekologiya*, 2005, no. 2, pp. 1–8.

Skre, O., Baxter, R., Crawford, R.M.M., Callaghan, T.V., and Fedorkov, A., How Will the Tundra–Taiga Interface Respond to Climate Change?, *AMBIO Special Report 12, Tundra–Taiga Treeline Research*, 2002, pp. 37–46.

Suarez, F., Binkley, D., and Kaye, M.W., Expansion of Forest Stands into Tundra in the Noatak National Preserve, Northwest Alaska, *Ecoscience,* 1999, vol. 6, pp. 465–470.

Tyulina, L.N., Forest Vegetation near Its Northern Limit in the Khatanga Region, in *Trudy Arkticheskogo instituta* (Proceedings of the Arctic Institute), Leningrad, 1937, vol. 63 (Geobotanika), pp. 83–180.

Vaganov, E.A., Hughes, M.K., Kirdyanov, A.V., et al., Influence of Snowfall and Melt Timing on Tree Growth in Subarctic Eurasia. *Nature*, 1999, vol. 400, pp. 149–151.