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ORIGINAL ARTICLE

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Climatic responses of tree-ring widths of *Larix gmelinii* on contrasting north-facing and south-facing slopes in central Siberia

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Abstract An analysis was performed on the climatic responses of the radial growth of *Larix gmelinii* (Rupr.) Rupr. on contrasting north-facing and south-facing slopes in Tura, central Siberia. We developed chronologies of tree-ring width for four plots, designated as north-upper, north-lower, south-upper, and south-lower. Both residual and standard chronologies of tree-ring widths exhibited a significant positive correlation with temperature from the end of May until early June in all four plots. The chronologies of ring width did not reveal any major difference in the response to temperature among the four plots. The standard chronologies of ring widths on the north-facing slope were negatively correlated with precipitation during the winter (October–April) and in early and mid-May, whereas the residual chronologies did not reveal clear relationships with precipitation during the winter and May. The significant correlation between ring width and temperature from the end of May until early June indicates that temperatures in springtime play a significant role in the radial growth of *L. gmelinii*. The negative correlations between standard chronologies of tree-ring width and precipitation in the winter and in May on the north-facing slope indicate that low-frequency fluctuations in snowfall have negative effects on the radial growth. However, these effects vary and depend on the microscale topography.

Key words *Larix gmelinii* · Siberia · Permafrost · Climatic response · Tree-ring width

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Introduction

The Siberian boreal forest, which is the largest terrestrial carbon pool in the northern hemisphere, has the greatest potential affect the global storage of carbon.[1] For the most part, Siberian boreal forests are dominated by deciduous *Larix* species, which possess about 35% of the total carbon storage of the forests of Russia.[2,3] Thus, the responses of radial growth of larch trees to climatic change can significantly influence the carbon pool of the Eurasian boreal forest.

At the northern timberline in the continuous permafrost region in the Siberian subarctic, the ring widths of coniferous species are positively influenced by temperatures in June–July.[4] Similar results have been obtained for *Larix* species (*Larix sibirica, Larix gmelinii*, and *Larix cajanderi*) in the same region.[5,6] In addition, Kirdyanov et al.[6] postulated that the date of snowmelt is a significant factor in the control of the initiation of radial growth of larch trees. At present, published information on the responses of Siberian larch trees to climate remains limited and little research has been done on mechanisms responsible for the responses of tree-ring parameters to climate variables under varying growth conditions.

Topographical features of the landscape, such as slope exposure, create microclimatic differences. Kirchhefer[7] reported differences in the responses of tree-ring widths of *Pinus sylvestris* to temperature and precipitation between

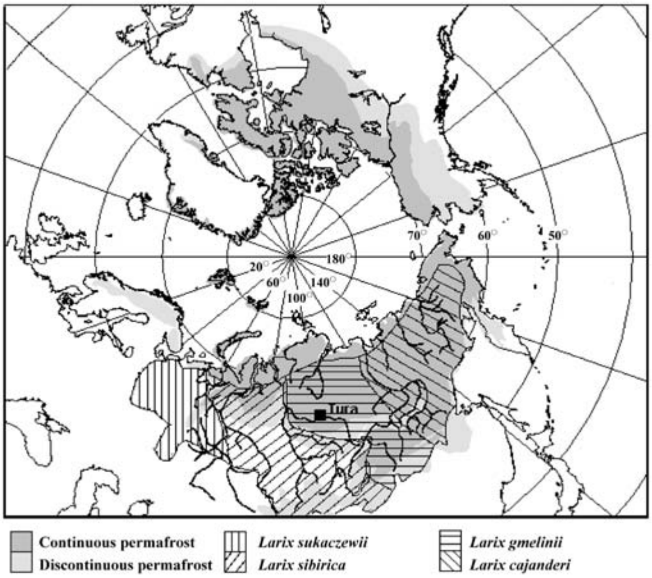

Fig. 1. Geographical location of the study site indicated by the *filled square*. The map shows the distribution of the permafrost in the Northern Hemisphere and the range of distribution of *Larix* species in Eurasia. Redrawn from Environmental Defense Fund[20] and Abaimov et al.[3]

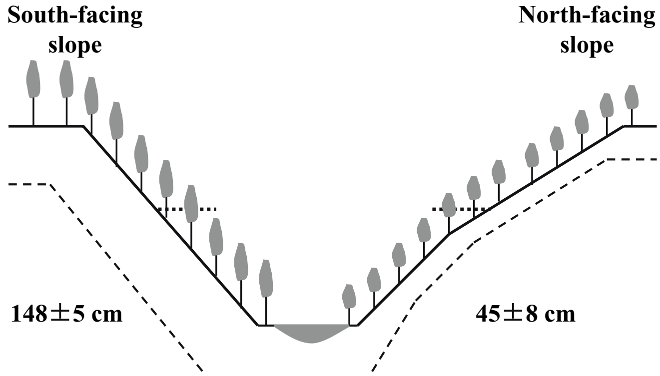

Fig. 2. Schematic representation of the study site. The depths of the active layers on the two slopes, as indicated by the *dotted line*, are taken from Koike et al.[8] *Horizontal dotted lines* indicate the borders of the upper and lower plots

the north-facing and south-facing slopes in an area north of the Arctic Circle in Norway. Koike et al.[8] reported differences in shoot morphology, rates of photosynthesis, and nutrient conditions of *L. gmelinii* in active soil layers of different depths on contrasting north-facing and south-facing slopes in central Siberia. Because of changes in the active layer that might be expected to occur as a result of possible future changes in climate, it is important to identify the responses of the radial growth of larch trees to climate variables under different microsite conditions with varying active layers of permafrost.

The purpose of the present study is to clarify the influence of temperature and precipitation on tree-ring widths of *Larix gmelinii* (Rupr.) Rupr. growing on contrasting north-facing and south-facing slopes in central Siberia. A comparison of the growth responses of tree-ring widths to climate variables between the two slopes should help to clarify the impact of temperature and precipitation on the radial growth of larch trees growing under specific conditions with microscale variations and to identify mechanisms that control radial growth.

Materials and methods

Study site and sample trees

The study site is located in the Tura Experiment Forest (64°19′N, 100°13′E; 200 m asl) of the Sukachev Institute of Forest (Siberian Branch, Russian Academy of Science, Russia), on the Central Siberian Plateau, close to the western edge of a region of continuous permafrost (Fig. 1). The climate of the region is continental, with very cold winters and relatively warm summers. The mean annual temperature is −7.6°C, as determined at the Tura Meteorological Station (Russian Research Institute of Hydrometeorological Information – World Data Center, RIHMI-WDC; http://www.meteo.ru/data/emdata.htm). The mean temperature in January is −36.5°C and that in July is 17.3°C. The mean annual precipitation is 380 mm.

We chose contrasting north-facing and south-facing slopes that are divided by a small stream (Fig. 2). The study site is located about 10 km northwest from Tura Meteorological Station. The difference of elevation between riverbed and hilltop is approximately 30 m, and the gradient of the slope is 18° on the south-facing slope and varies between 8° and 18° on the north-facing slope. The south-facing slope is almost entirely occupied by *Larix gmelinii*, whereas the north-facing slope is dominated by *L. gmelinii* with a small proportion of *Picea obovata*.[8] The forest stand became established after a forest fire that occurred in the early 1800s. The forest stand on the north-facing slope is unevenly aged, caused by survivors of the forest fire, whereas the south-facing slope seems to be evenly aged. The depth of the active soil layer differs markedly between the two slopes, being 148 ± 5 cm on the south-facing slope and only 45 ± 8 cm on the north-facing slope in the summer of 1997.[8] We divided the study site into four plots (approximately 40 × 20 m each) by dividing the north-facing and south-facing slopes into upper and lower parts (abbreviated as NU, NL, SU and SL), because we assumed that differences in soil moisture between the upper and lower parts of the slopes might arise. We chose to examine 30 dominant specimens of *L. gmelinii* per plot.

Development of chronologies

We extracted two increment cores of 5 mm in diameter from each sample tree at breast height and parallel to the contour of the slope. This procedure provided 60 cores per plot, giving a total of 240 cores; these were smoothed with fine sandpaper and a razor blade. The tree-ring widths were measured to 0.01 mm precision under a stereomicroscope (MZ6; Leica, Solms, Germany) with a system for tree-ring measurement from Velmex (Bloomfield, NY, USA). The series of tree-ring widths were cross-dated visually by using skeleton plot procedures and confirmed by a statistical method to ensure that the correct date was assigned to each annual ring.[9] Statistical cross-dating was performed with the COFECHA program.[10] Some core samples in which there was evidence of the extensive formation of reaction wood were excluded because of cross-dating difficulties. The series of tree-ring measurements were standardized by fitting smoothing splines with a 50% frequency-response cutoff of 80 years to eliminate growth trends such as an age-related decline in growth rate and low-frequency variance due to natural disturbance.[11] A standardized series usually exhibits autocorrelation that negates the assumption of the independence that is necessary for most statistical analyses.[12,13] In order to remove the effects of autocorrelation, we transformed each of standardized series to a residual series through pooled autoregressive (AR) modeling.[14] Standardization and autoregressive modeling were performed with the ARSTAN program.[14] Standard and residual chronologies for the plots were developed by averaging the individual series by using a biweight robust mean. Expressed population signal (EPS) analysis[15,16] was used to assess the degree to which chronologies of each plot portrays the perfect hypothetical chronology.

Responses to climate variables

We analyzed the responses of ring widths to climate variables by calculating the simple correlations between both the residual and standard chronologies and climate variables. We used standard chronologies to analyze the effect of low-frequency fluctuations in climate because residual chronologies lost low-frequency fluctuation through AR modeling.

The climatic data used for calculations were obtained from the Tura Meteorological Station. Monthly mean temperatures and average daily mean temperatures for five consecutive days (pentads)[4] from May of the previous year to August of the current year were used in the analysis. We did not use the data after August of the current year because radial cell division finished until August (unpublished data). We chose to use pentads analysis because previous studies for coniferous species in Siberia reported strong relationships between tree-ring width and temperature in shorter time spans (5 days).[4–6] We used monthly precipitation data from the previous May to the current August. The precipitation during winter was calculated as the cumulative precipitation from November of the previous year to April of the current year because it falls as snow. In addition, the precipitation in May of the current growing season was divided into precipitation for the early, middle, and late part of the month for assessment of the short-term influence of precipitation of late winter and early spring. The analyses of ring widths and temperature covered the period from 1930 to 1995 ($n = 65$). The analyses of ring widths and precipitation covered the period from 1939 to 1995 ($n = 56$).

Observations on snowmelt and leaf development

For observations of the timing of the snowmelt on the contrasting slopes in the spring of 2004, we installed an automatic camera (KADEC21-EYE; Kona Systems, Sapporo, Japan) at the study site in the autumn of 2003. The snow cover on the ground on both slopes was visible in each photograph. One image was taken each day at noon.

Leaf initiation and expansion stages were observed visually in the spring of 2004, from 29 May to 14 June. Visual observations were made at four different observation sites located within 30 km of the study site during the fieldwork period.

Results and discussion

Snowmelt and leaf development

Snowmelt in the spring of 2004 occurred on 19 May on the south-facing slope and on 25 May on the north-facing slope. No major difference in stages of leaf development was found among the four observation sites. Leaf initiation at Tura town, 10 km from the study site, occurred on 25 May and leaf expansion continued until the middle of June. At the study site, no major difference was observed in the stages of leaf development between the two slopes observed on 9 June.

Chronology statistics

Cross-dating was successfully performed for all four plots. One core sample from SL and 14 core samples from NU were excluded from the analysis because of extensive formation of reaction wood. Absent rings were identified through cross-dating procedure (Table 1). They usually occurred in the years for which other cores exhibited very narrow rings. Both residual and standard chronologies of ring width were successfully constructed for all the plots from the early 1800s and satisfied the minimum EPS threshold of 0.85[16] (Table 1, Fig. 3).

The basic statistics of the chronologies are shown in Table 1. The standard chronologies on the north-facing slope markedly yielded lower mean sensitivities, which is the average relative difference from one ring width to the next. They also revealed higher first-order autocorrelations and lower correlations between trees compared with those for the south-facing slope. The residual chronologies on the north-facing slope also yielded lower mean sensitivities and correlations between trees.

Responses to temperature

The June monthly mean temperature of the current year showed significant correlations with residual chronologies of ring widths in all four plots (Fig. 4). July temperatures of the previous growing seasons exhibited negative correlation

Table 1. Plots and chronology statistics for the study site

	Plot			
	NU	NL	SU	SL
Plot details				
DBH with standard deviation (cm)	16.8 ± 3.7	18.3 ± 4.0	20.1 ± 2.2	20.3 ± 1.9
DBH minimum–maximum (cm)	12.5–31.5	10.5–32	16–25	13–24.5
Starting year of chronology	1606	1590	1812	1818
Number of trees (radii) in chronology	28 (46)	30 (60)	30 (60)	30 (59)
Ring-width mean (mm)	0.32	0.33	0.43	0.42
Percentage of absent rings (%)	0.83	0.45	0.47	0.44
Standard chronology				
Mean sensitivity	0.18	0.18	0.24	0.24
Standard deviation	0.25	0.25	0.25	0.24
First-order autocorrelation	0.63	0.64	0.34	0.34
VARAR1 %[a]	41.4	43.1	11.4	11.7
Correlation between trees[b]	0.28	0.30	0.41	0.47
EPS	0.93	0.93	0.93	0.94
Minimum sample size for EPS 85%	13	13	13	12
SSS > 0.85[c]	1800	1812	1821	1821
Residual chronology				
AR model order	3	2	1	1
Mean sensitivity	0.20	0.18	0.26	0.26
Standard deviation	0.18	0.16	0.23	0.22
First-order autocorrelation	0.03	0.01	0.05	0.07
Correlation between trees[b]	0.33	0.34	0.51	0.52
EPS	0.93	0.94	0.94	0.94
Minimum sample size for EPS 85%	12	12	12	12
SSS > 0.85[c]	1800	1812	1820	1821

NU, Plot on north-facing upper slope; NL, plot on north-facing lower slope; SU, plot on south-facing upper slope; SL, plot on south-facing lower slope; DBH, diameter at breast height; EPS, expressed population signal; SSS, subsample signal strength; AR, autoregressive

[a] Variance due to first-order autocorrelation

[b] Calculated for the common interval from 1862 to 2002

[c] Earliest year for which SSS of the chronology is greater than 85% of the original EPS

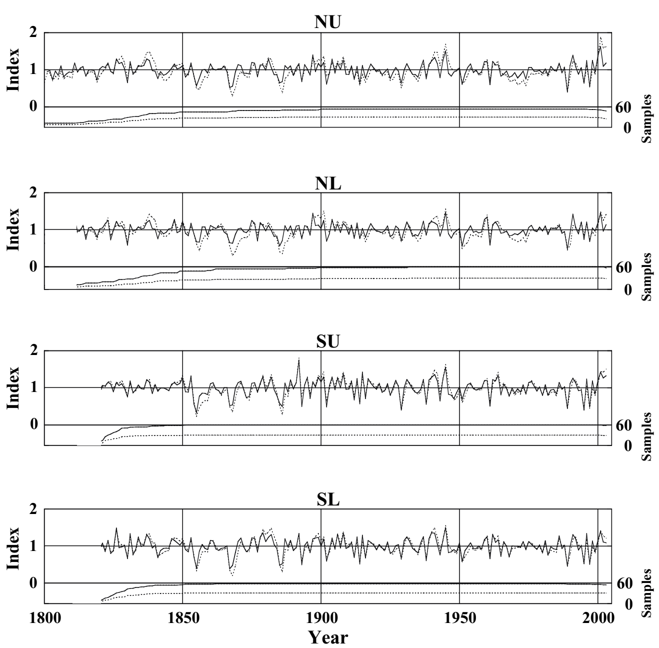

Fig. 3. Chronologies of tree-ring widths for *Larix gmelinii* on the north-facing (*NU* and *NL*) and south-facing (*SU* and *SL*) slopes of the site in Tura, central Siberia. *Solid lines* indicate residual chronologies and *dotted lines* indicate standard chronologies. The number of cores (*solid*) and trees (*dotted*) included per plot are indicated by the bottom lines in each graphic

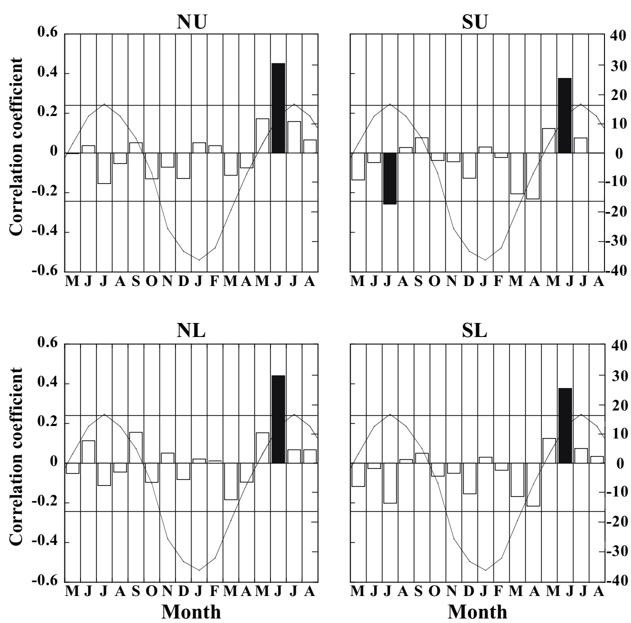

Fig. 4. Correlations between residual chronologies of tree-ring width and monthly temperature for *Larix gmelinii* on the north-facing and south-facing slopes of the site in Tura, central Siberia. The meteorological data used were from May of the previous year to August of the current year. *Solid horizontal lines* indicate the level at which the correlation is significant (P = 0.05). *Black bars* indicate significant correlations ($P < 0.05$). *Sinusoidal curves* show mean values of monthly average temperatures calculated for the period from 1930 to 1995

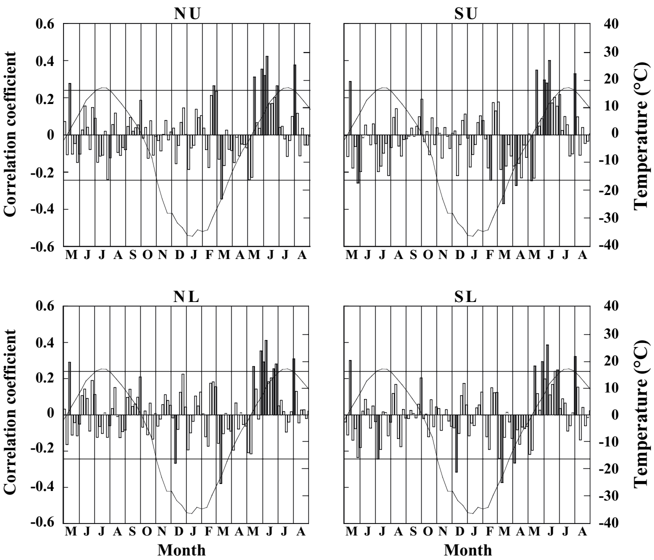

Fig. 5. Correlations between residual chronologies of tree-ring width and 5-day average temperature for *Larix gmelinii* on the north-facing and south-facing slopes of the site in Tura, central Siberia. *Sinusoidal curves* show mean values of 5-day average temperatures calculated for the period from 1930 to 1995

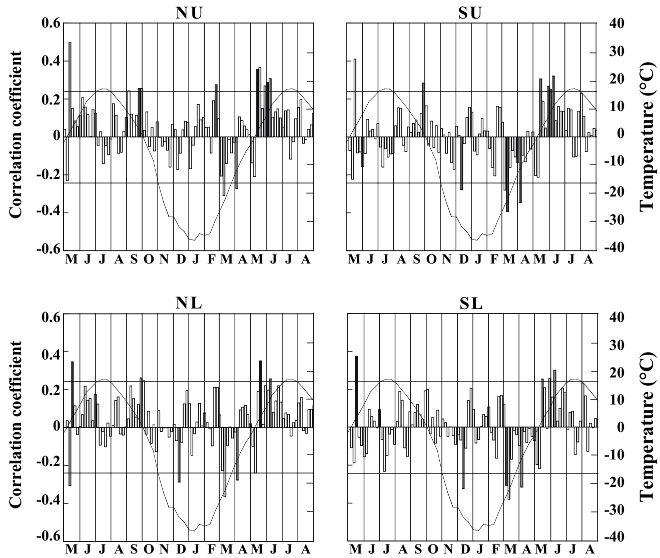

Fig. 6. Correlations between standard chronologies of tree-ring width and 5-day average temperature for *Larix gmelinii* on the north-facing and south-facing slopes of the site in Tura, central Siberia

with ring widths in SU. In analysis over shorter time spans, the residual chronologies of tree-ring width were significantly and positively correlated with temperature from the end of May until early June in all four plots (Fig. 5). Temperatures in late June and from the end of July to the beginning of August of the current growing season also showed significant positive correlations with ring widths in all four plots. The temperature from 10 May to 14 May of the previous growing season was correlated with ring width in all four plots. The temperatures of early December, early March, and early April that preceded growth showed negative correlations with tree-ring widths in some of the plots.

The standard chronologies also revealed significant and positive correlations with temperature from the end of May until early June in all four plots (Fig. 6). The temperature of mid-May of the previous growing season revealed the highest correlation in all four plots.

Both analyses on residual and standard chronologies indicated that temperatures from the end of May to early June played the most significant role in the radial growth of *Larix gmelinii*. There was no major difference in the responses of ring widths on the north-facing and south-facing slopes to temperature. In addition, no major difference in the responses of ring widths was present on the upper and lower parts of both slopes. On both slopes, the period of significant correlation also coincided with the observed leaf flushing (25 May) and subsequent stages of leaf development until early June in the spring of 2004. This observation indicates that differences in site-specific conditions (e.g., the depth of the active layer of permafrost) do not influence the responses of tree-ring widths to temperature. The spring temperatures might directly affect stages of leaf development and the related radial growth of stems. Our present results confirm the results of earlier studies in Siberia revealing the temperature in June is one of the most important factors that define radial growth.[4,6]

Responses to precipitation

The residual chronology of tree ring width in NU was negatively correlated with precipitation during early May prior to growth (Fig. 7). Ring width in SL was positively correlated with precipitation in August of the previous growing season. On the other hand, the standard chronology of tree ring width in NU was negatively correlated with precipitation during the winter and from early to mid-May prior to growth (Fig. 8). Ring widths in NL were also negatively correlated with precipitation in early May of the current year. Both standard chronologies on the north-facing slope were negatively correlated with precipitation in May of the previous year. By contrast, standard chronologies of tree-ring widths in SU and SL were not significantly correlated with precipitation of winter and May of the current year. However, the standard chronology of tree-ring width in SL was positively correlated with precipitation in August of the previous year.

On the south-facing slope, both residual and standard chronologies did not reveal significant correlations with the precipitation of winter or May. By contrast, on the north-facing slope, differences in responses to precipitation of winter and May existed between residual and standard chronologies. The weak correlations with residual chronologies indicate that the precipitation of winter and May do not affect year-to-year (high-frequency) variations in ring widths. On the other hand, the negative correlations between standard chronologies and the precipitation of winter and May indicate a possibility that low-frequency fluctuations in precipitation influence the radial growth.

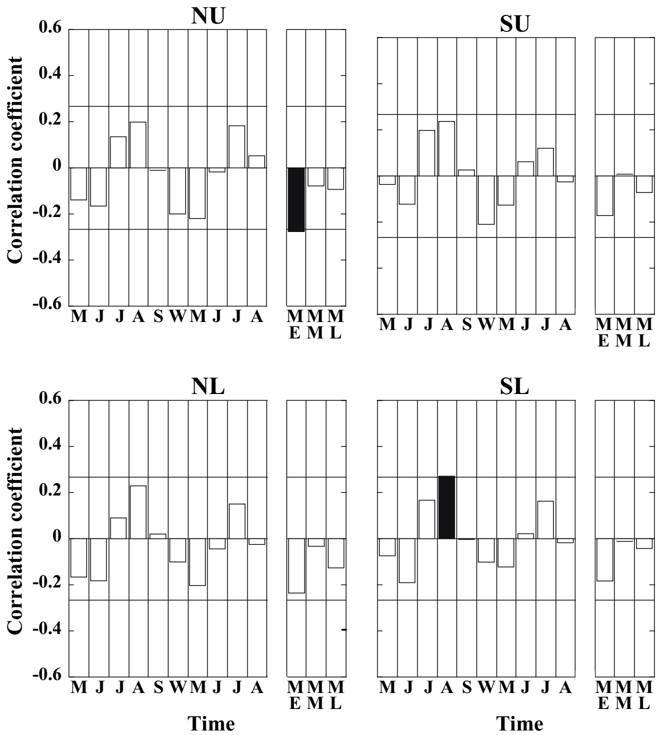

Fig. 7. Correlations between residual chronologies of tree-ring width and precipitation for *Larix gmelinii* on the north-facing and south-facing slopes at the site in Tura, central Siberia. *W*, Winter (November to April) accumulation; *ME*, early May; *MM*, middle May; *ML*, late May; *letters of the alphabet* indicate months

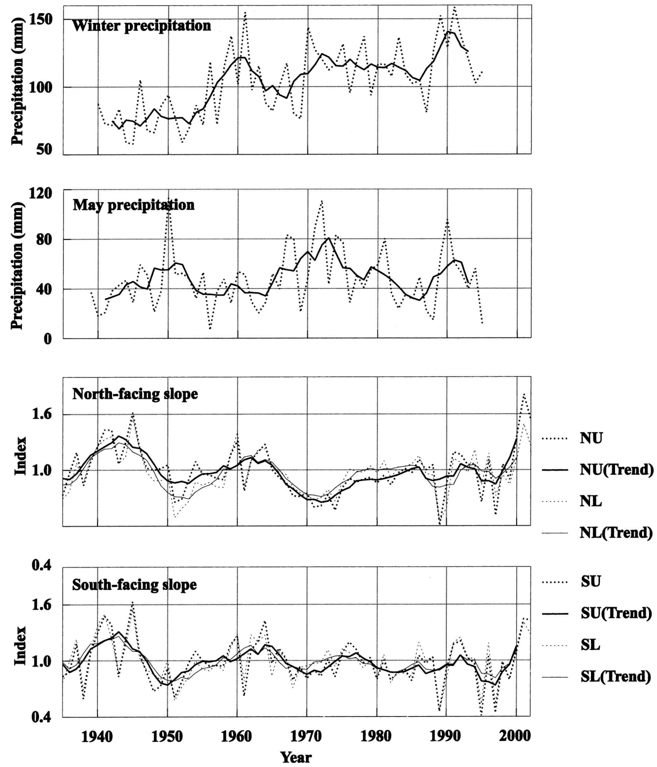

Fig. 9. Variations in precipitation of winter (November to April) and May observed at Tura Meteorological Station, and standard chronologies of tree-ring width for four plots in Tura, central Siberia. *Dotted lines* indicate standard chronologies and *solid lines* indicate trend curves calculated by 5-year moving average

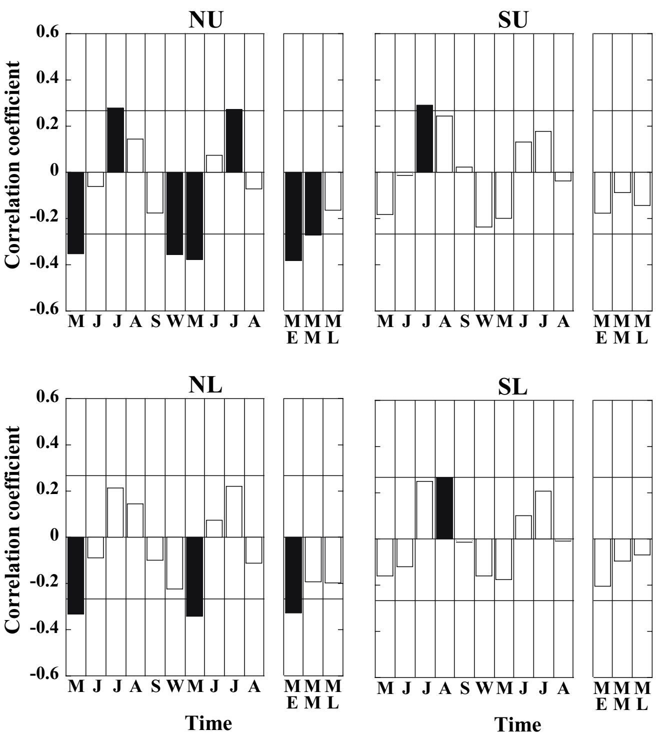

Fig. 8. Correlations between standard chronologies of tree-ring width and precipitation for *Larix gmelinii* on the north-facing and south-facing slopes at the site in Tura, central Siberia

The low-frequency variations in standard chronologies revealed a trend opposite to that in the precipitation of winter and May (Fig. 9). The decreasing trend from the late 1960s to the early 1970s in standard chronologies on the north-facing slope coincided with increasing trend in both winter and May precipitation. The increasing trend from the mid-1970s to the mid-1980s in standard chronologies coincided with decreasing trend in winter and May precipitation. The above-mentioned trends were not clearly seen in residual chronologies for the north-facing slope and in both standard and residual chronologies for the south-facing slope (Figs. 3, 9). These results suggest that the precipitation of winter and May influence the low-frequency variations in ring width of larch trees growing on the north-facing slope.

The changes in the precipitation of winter and early to middle May might result in changes in snow accumulation in spring, because the average temperature of early May remains below freezing. Delayed soil thawing caused by accumulated snow in spring might lead to a decreased depth of the active soil layer and to limited duration of root activity. The role of roots of larch trees growing in nutrient-poor permafrost soils is thought to be important with a high allocation rate of biomass to roots.[17] It can be hypothesized that cumulative inhibition of root activity by snowfall that shows low-frequency fluctuations may results in decline in radial growth of larch trees on the north-facing slope where the active soil layer is shallow.

The lower mean sensitivities on the north-facing slope (Table 1) may be due to the predominant effect of precipitation with low-frequency fluctuation compared with the south-facing slope. The higher first-order autocorrelations for the north-facing slope (Table 1) can also be attributed to predominance of low-frequency fluctuation. It can also be associated to slow rate of carbon turnover. Kagawa et al.[18,19] reported that assimilated carbon was carried over and used for xylem development in following years and the carbon turnover rate of *L. gmelinii* in Siberian permafrost was slower than that of temperate trees. There is the possibility that higher first-order autocorrelation is due to higher rate of carryover of photo-assimilate to following years on the north facing slope.

Vaganov et al.[4] and Kirdyanov et al.[6] proposed that the date of snowmelt, which was estimated from temperature and winter precipitation, has a significant effect on ring width. They stated that the trend toward increasing precipitation in winter and a delay in snowmelt might have a significant effect on the radial growth of larch trees in Siberia. The present study revealed similar results for the north-facing slope; however, no significant response to snow cover was identified on the south-facing slope. Thus, the negative effect of snow cover seems to vary and to depend on microscale topography. The present study suggests that changes in spring temperatures and accumulated snow are important in assessing the effect of future changes in climate on radial growth of *L. gmelinii* in central Siberia. The study also suggests the importance of microscale topography in assessing the effects of snow accumulation.

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