

Climate-induced larch growth response within the central Siberian permafrost zone

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PAPER

Climate-induced larch growth response within the central Siberian permafrost zone

OPEN ACCESS

RECEIVED

17 April 2015

REVISED

20 November 2015

ACCEPTED FOR PUBLICATION

24 November 2015

PUBLISHED

10 December 2015

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Viacheslav I Kharuk^{1,2}, Kenneth J Ranson⁴, Sergei T Im^{1,2,3} and Il'ya A Petrov¹¹ Sukachev Institute of Forest, Krasnoyarsk, Russia² Siberian Federal University, Krasnoyarsk, Russia³ Siberian State Aerospace University, Krasnoyarsk, Russia⁴ NASA's GSFC, Greenbelt, MD, USAE-mail: kharuk@ksc.krasn.ru**Keywords:** larch growth, permafrost thaw, tree ring growth, climate change, water stress**Abstract**

Aim: estimation of larch (*Larix gmelinii*) growth response to current climate changes. **Location:** permafrost area within the northern part of Central Siberia (~65.8°N, 98.5°E). **Method:** analysis of dendrochronological data, climate variables, drought index SPEI, GPP (gross primary production) and EVI vegetation index (both Aqua/MODIS satellite derived), and soil water content anomalies (GRACE satellite measurements of equivalent water thickness anomalies, EWTA). **Results:** larch tree ring width (TRW) correlated with previous year August precipitation ($r = 0.63$), snow accumulation ($r = 0.61$), soil water anomalies ($r = 0.79$), early summer temperatures and water vapor pressure ($r = 0.73$ and $r = 0.69$, respectively), May and June drought index ($r = 0.68$ – 0.82). There are significant positive trends of TRW since late 1980 s and GPP since the year 2000. Mean TRW increased by about 50%, which is similar to post-Little Ice Age warming. TRW correlated with GPP and EVI of larch stands ($r = 0.68$ – 0.69). **Main conclusions:** within the permafrost zone of central Siberia larch TRW growth is limited by early summer temperatures, available water from snowmelt, water accumulated within soil in the previous year, and permafrost thaw water. Water stress is one of the limiting factors of larch growth. Larch TRW growth and GPP increased during recent decades.

1. Introduction

In Siberia, about 70% of the permafrost areas are covered by larch. Larch (*Larix sibirica*, *L. gmelinii*, and *L. cajanderi*) are the widest-spread species in Russia and are found from the tundra zone in the north to the steppes in the south. The zone of larch dominance ranges from the Yenisei ridge in central Siberia west to the Pacific Ocean, and from Lake Baikal in the south to 73° north latitude. Within permafrost areas, larch competes effectively with other tree species because of its deciduous leaf habit and dense bark, which protects stems from winter desiccation and snow abrasion (Kharuk *et al* 2013). In eastern Siberia, the tree line is formed sequentially by *Larix sibirica*, *L. gmelinii*, and *L. cajanderi*. On its southern and western margins in central Siberia, larch is mixed with evergreen conifers (*Pinus sibirica*, *Pinus sylvestris*, *Picea obovata*, *Abies sibirica*) and hardwoods (*Betula pubescens*, *Populus tremula*). Larch forms high closure stands as well as

open forests, which are found mainly over permafrost, where other tree species barely survive.

Tree response to observed warming is expected to be significant at the northern latitudes where temperature is limiting tree growth. That response was predicted as expansion of forest into the tundra, an invasion of the relatively warmer adapted species into the traditional larch habitat zone, along with stands growth increase (Beniston 2003, Lloyd and Bunn 2007, Richardson and Friedland 2009). Observations on climate-driven invasion of 'southern' tree species (*Pinus sibirica*, *Picea obovata*) into larch dominated forested regions were reported by Kharuk *et al* (2005). In the polar Ural Mountains, Shiyatov *et al* (2007) documented an upward shift (about 35 m) of *Larix sibirica* stands between 1910 and 2000 in response to the observed increase in air temperature. Upslope shift of the tree-line position (approximately 30 to 50 m in altitude during the last century) was reported for the Putorana Mountains (71°N, 91°E),

and northern Siberia (Kirilyanov *et al* 2013). For the most northward 'forest island', Ary-Mas ($\sim 72^\circ\text{N}$), an increased stand densification and regeneration advance into the tundra was reported by Kharuk *et al* (2006). Similar observations were reported for a number of sites within European and North American mountains (e.g. Klasner and Fagre 2002, Munroe 2003, Kullman and Kjallgren 2006, Lenoir *et al* 2008, Harsch *et al* 2009). Meanwhile, for the sub-continental scale area between the Ural Mountains and the Pacific Ocean, climate impact on tree growth was studied within a few sites (Esper and Schweingruber 2004, Kharuk *et al* 2006, Shiyatov *et al* 2007, Devi *et al* 2008, Esper *et al* 2010). This area in north central Siberia is one of the 'hot spots' of observed warming (IPCC 2013).

Remote sensing is widely applied in studies of northern stands due to their remoteness and geographical range (e.g. Nelson *et al* 2009, Xu *et al* 2013). Larch growth within permafrost areas strongly depends on the soil thawing depth and drainage (Kharuk *et al* 2005, 2011). One of the promising tools for soil water anomalies studies is provided by GRACE (Gravity Recovery and Climate Experiment) mission. Since 2002, GRACE gravimetric measurements have made it possible to estimate the Earth's gravitational field anomalies resulted mainly from water mass transferring. GRACE data was used to study water mass changes in the Arctic and Antarctic (Chen *et al* 2006, Gardner *et al* 2011, Barletta *et al* 2013, Groh *et al* 2014). GRACE data was also used for analysis of permafrost thawing and landslide occurrence in Siberia and Alaska (Muskett and Romanovsky 2011a, 2011b, Steffen *et al* 2012, Velicogna *et al* 2012, Im and Kharuk 2015).

In this study our goal was to estimate *Larix gmelinii* growth response during the changes in temperature, precipitation and drought index (SPEI) over the last three decades. For this purpose we used dendrochronological and satellite (Aqua/MODIS, GRACE) data.

2. Materials and methods

2.1. Study area

The study area is located within the northern part of central Siberia and includes the watershed of the Embenchime River, a tributary of the Kochechum River; the watershed area is about $\sim 66\,300\text{ km}^2$ (figure 1). This is a hilly permafrost area with elevation range of 100–1100 m a.s.l. Forests are formed by larch (*Larix gmelinii* (Rupr.) with birch (*Betula pendula* Roth) admixture. Mean stands crown closure is about 0.2; mean height, diameter at breast height and age were 8.5 m, 12.5 cm and 250 years, respectively. Ground cover is composed by shrubs (*Betula nana*, *Salix* sp., *Ribes* sp., *Rosa* sp., *Juniperus* sp., *Vaccinium* sp),

lichen and moss. Soils are brown and cryogenic (Ershov 1998).

2.2. Climate

Climate within the study area is strongly continental with cold long winters and warm summers (figure 2). Maximum July temperatures reached $+39^\circ\text{C}$.

Analyzed climate variables, along with air temperature and precipitation, included 'drought index' SPEI. The SPEI (The Standardized Precipitation-Evapotranspiration Index) can measure drought severity according to its intensity and duration (Vicente-Serrano *et al* 2010). The SPEI uses the monthly difference (D_i) between precipitation and PET (potential evapotranspiration): $D_i = P_i - PET_i$. Positive June temperature and negative June SPEI trends have been observed since late 1980th ($p < 0.05$; figures 2(a), (c)). Because the study area was the uninhabited mountainous terrain without meteorological stations, climate variables (monthly air temperature, precipitation, and SPEI) data were obtained from British Atmospheric Data Centre (<http://badc.nerc.ac.uk>; <http://climexp.knmi.nl>). Data quality was at the $0.5^\circ \times 0.5^\circ$ grid ($\sim 33 \times 56\text{ km}^2$).

2.3. Field studies

'Ground truth' data was collected during the summer of 2012. Investigations were conducted within the watershed of the Embenchime River (figure 1). Tree samples were collected for dendrochronology analysis on test sites ($N = 8$) that were evenly spaced along the river route ($\sim 250\text{ km}$). Samples were disks cut just above the root collar, but out of the root tension zone. Live trees and snags were sampled within the area about 1.0 ha at distance about 50–200 m from the river. The total sample set was about one hundred, but only 18 trees were without burnmarks, either visible or hidden. It is known that *Larix gmelinii* can overheat burnmarks making them often invisible on the bark surface. A sample age distribution is presented on figure 3 (curve 2). Mean tree age was estimated to be 218 years.

2.4. Dendrochronological analysis

The surface of each disk was sanded and treated with contrast enhancing powder. The tree-ring widths (TRW) were measured with 0.01 mm precision using a linear table instrument (LINTAB-III). The TSAP and COFECHA computer programs were used in tree ring analysis (Holmes 1983, Rinn 1996). Dates of tree mortality were determined based on the master-chronology method described by Fritts (1991). A master chronology was constructed based on 18 trees without signs of fire impact. It should be noted that fire scarred trees can have growth irregularities that are non-climatic, and they can be of at least three different kinds. First, nutrient fluxes from fires can increase growth in surviving trees so long as climate is sufficient

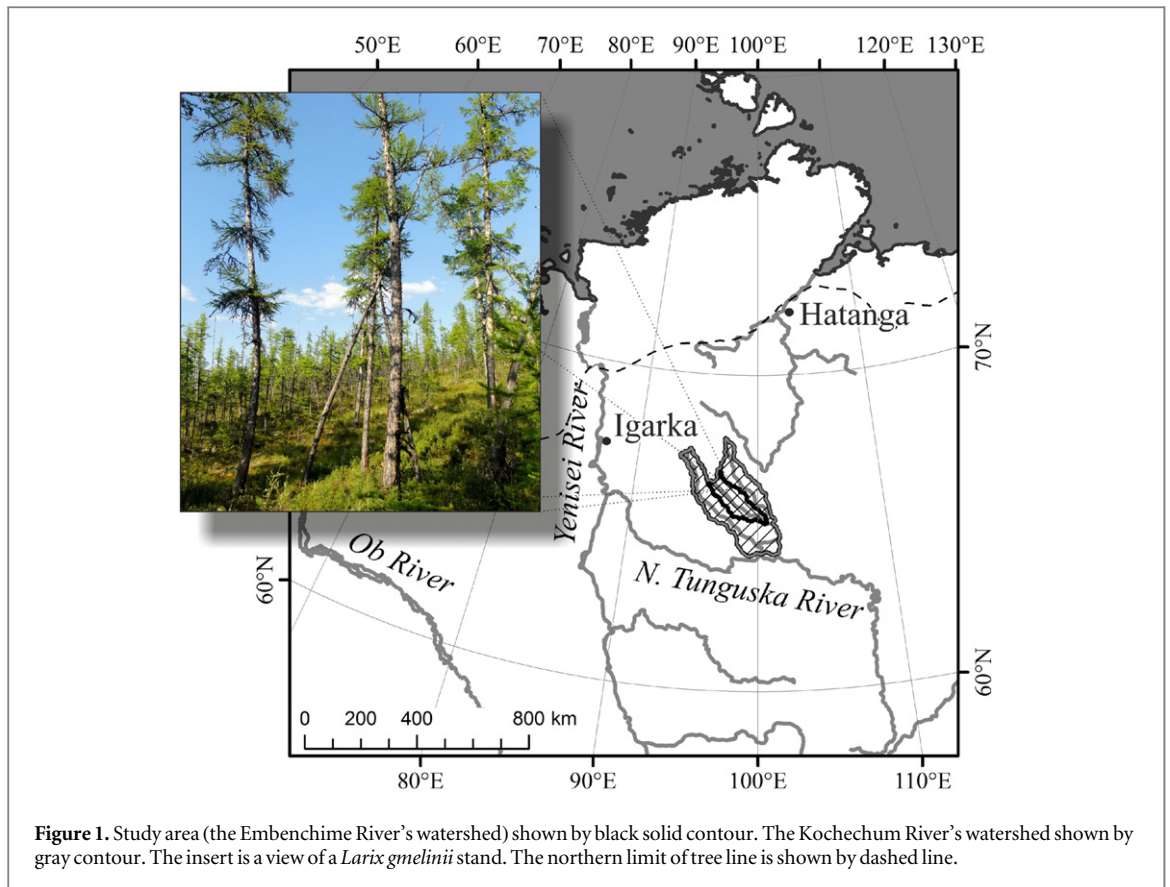


Figure 1. Study area (the Embenchime River’s watershed) shown by black solid contour. The Kochechum River’s watershed shown by gray contour. The insert is a view of a *Larix gmelinii* stand. The northern limit of tree line is shown by dashed line.

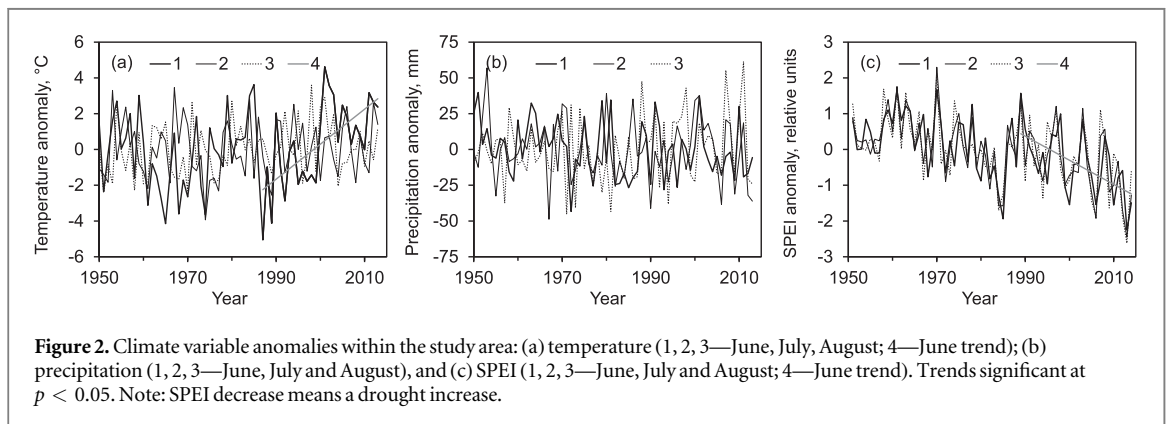


Figure 2. Climate variable anomalies within the study area: (a) temperature (1, 2, 3—June, July, August; 4—June trend); (b) precipitation (1, 2, 3—June, July and August), and (c) SPEI (1, 2, 3—June, July and August; 4—June trend). Trends significant at $p < 0.05$. Note: SPEI decrease means a drought increase.

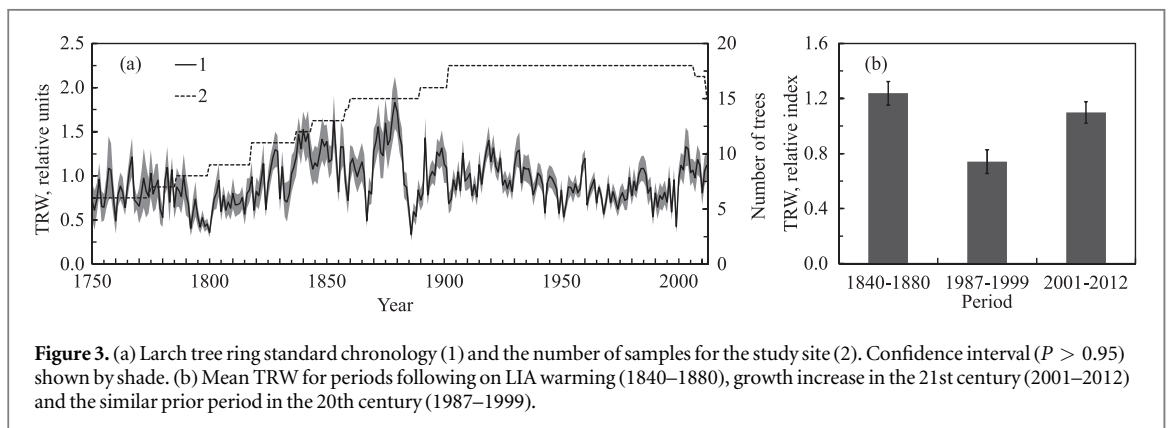


Figure 3. (a) Larch tree ring standard chronology (1) and the number of samples for the study site (2). Confidence interval ($P > 0.95$) shown by shade. (b) Mean TRW for periods following on LIA warming (1840–1880), growth increase in the 21st century (2001–2012) and the similar prior period in the 20th century (1987–1999).

to support normal growth. Second, trees that survive can have positive growth anomalies associated with a decrease in competition with neighbors for nutrients, light, or water. Third, trees that survive can have negative growth anomalies associated with crown scorch that subsequently decreases leaf area for production for the same amount of sapwood maintained. Larix is somewhat unique in that it is well adapted to the third influence because of its deciduous habit, but the first two might bias the growth climate relationships. However, climate-driven growth release would take more time, whereas fire-related growth surges are rapid and not sustained. In addition, we did analysis of the fire chronosequence within the study sites. The latest fires within the sites occurred 36–165 yr before our sampling. Therefore, any possible effect of fire melioration on tree growth increase during recent decades (see Results) should be minor. The mean coefficient of correlation between individual tree-ring series and master-chronology was 0.57. The mean sensitivity of individual series included into master-chronology was satisfactory (0.321). Standard chronologies were indexed using ARSTAN software (i.e., double detrending to remove long-term trends; Cook and Holmes 1986). Detrending by a negative exponential curve and linear function of zero or negative slope was used in this study as a more suitable for fitting trends in individual tree-ring series in open-canopy forests and remain low-frequency variations in final chronology (Cook and Kairiukstis 1990). Every single chronology was detrended separately to remove growth trends. Final chronology was developed with biweight robust mean. The resulting chronologies were a unitless index of radial tree growth. In addition, the residual chronologies were constructed based on standard chronologies (Cook and Holmes 1986). In all climatic analysis a standard chronology were used with exception to the analysis with GRACE data. The latter covered a rather short (11 yr.) period, thus it was not possible to fix low-frequency variations. Because of that, GRACE data were analyzed versus residual chronologies. Statistical analysis was carried out using Microsoft Excel and StatSoft software (StatSoft Inc. 2013).

2.5. Satellite data

Aqua/MODIS and GRACE satellite data was analyzed. Aqua/MODIS products MYD13Q1 and MYD17A2 (https://lpdaac.usgs.gov/products/modis_products) were used for EVI (enhanced vegetation index) and GPP (gross primary production) dynamics analyses. EVI is defined as:

$$\text{EVI} = G \times (\rho_{\text{NIR}} - \rho_{\text{red}}) \times (\rho_{\text{NIR}} - C_1 \times \rho_{\text{red}} + C_2 \times \rho_{\text{blue}} + L)^{-1} \quad (1)$$

where ρ_{NIR} , ρ_{red} and ρ_{blue} are atmospherically-corrected surface reflectance in MODIS bands #1

(620–670 nm), #2 (841–876 nm) and #3 (459–479 nm); L is the canopy background adjustment; C_1 and C_2 are the coefficients of the aerosol correction; G —gain factor. EVI data (on-ground resolution 250×250 m) has been available since 2002 and taken from <http://reverb.echo.nasa.gov>. Gross primary production (GPP, kg C m^{-2}) was analyzed based on the Aqua/MODIS product MYD17A2 version 5 (<http://reverb.echo.nasa.gov>; available since 2002). MYD17A2 is 8-days composite scenes with $1 \times 1 \text{ km}^2$ spatial resolution. In total 318 summer scenes were analyzed for 2002–2014. GPP monthly and maximal values were extracted from GPP time series and averaged within the analyzed territory. The latter included larch-dominated communities only within the Embenchime River watershed ($\sim 14\,536 \text{ km}^2$). For detection of larch-dominated communities, a mask was obtained from Russian Land Cover map (Bartalev *et al* 2011; <http://terranorte.iki.rssi.ru/>). The data was processed using GIS-tools realized in ArcGIS software (www.esri.com). The watersheds of Kochechum and Embenchime Rivers were determined based on the SRTM digital elevation model (<http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1>) using the ESRI ArcGIS Hydrology toolset.

GRACE gravimetric data has been available since 2002 (<http://grace.jpl.nasa.gov>). We used the analysis annual and monthly gravimetric values, and EWTA (equivalent of water thickness anomalies). EWTA data was averaged within the Kochechum River's watershed (right-sided tributaries, including Embenchime River; total watershed area $\sim 66\,300 \text{ km}^2$). EWTA were measured with accuracy of $10\text{--}30 \text{ mm month}^{-1}$ (Riegger *et al* 2012, Long *et al* 2014). GRACE spatial resolution was one by one degree ($\sim 112 \times 44 \text{ km}^2$ at latitude 66°). A 300 km Gaussian filter was applied to the data. A glacial isostatic adjustment correction was also applied. Scale coefficients have been applied to recover signals reduced by filtration (Landerer and Swenson 2012). The satellite data was processed using Erdas Imagine software (<http://geospatial.intergraph.com>) and ESRI ArcGIS software (<http://www.esri.com>). StatSoft Statistica (www.statsoft.com) was used in the statistical analysis.

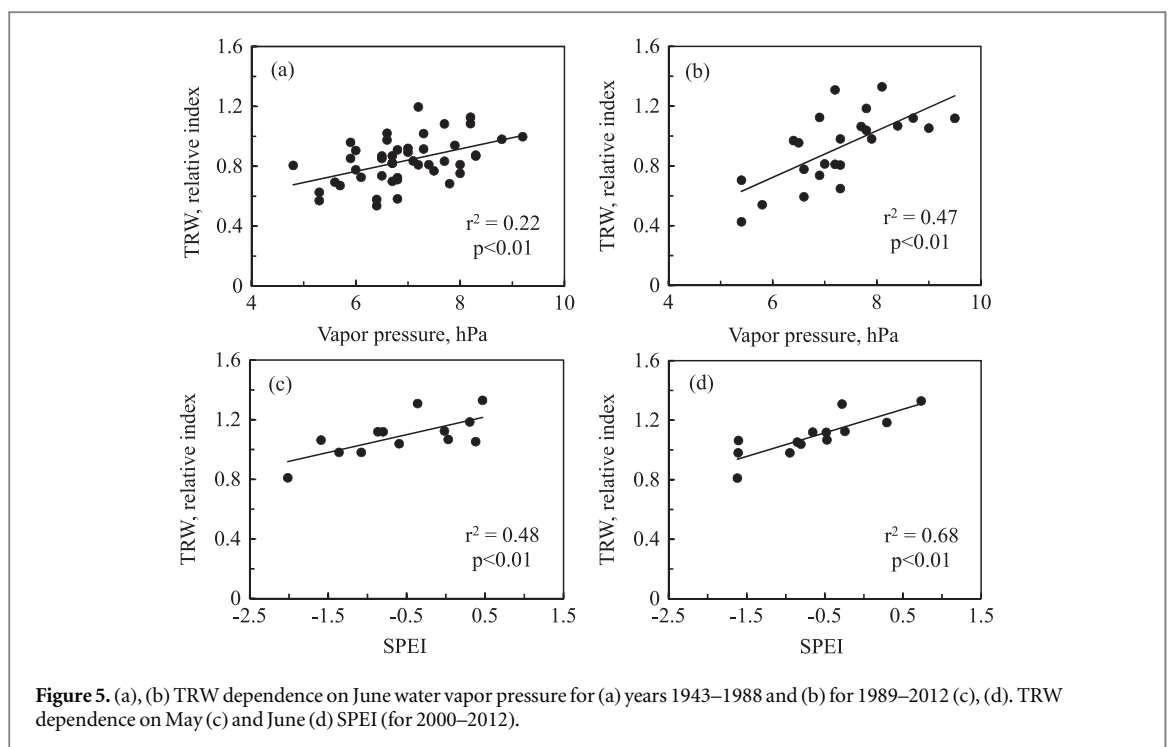
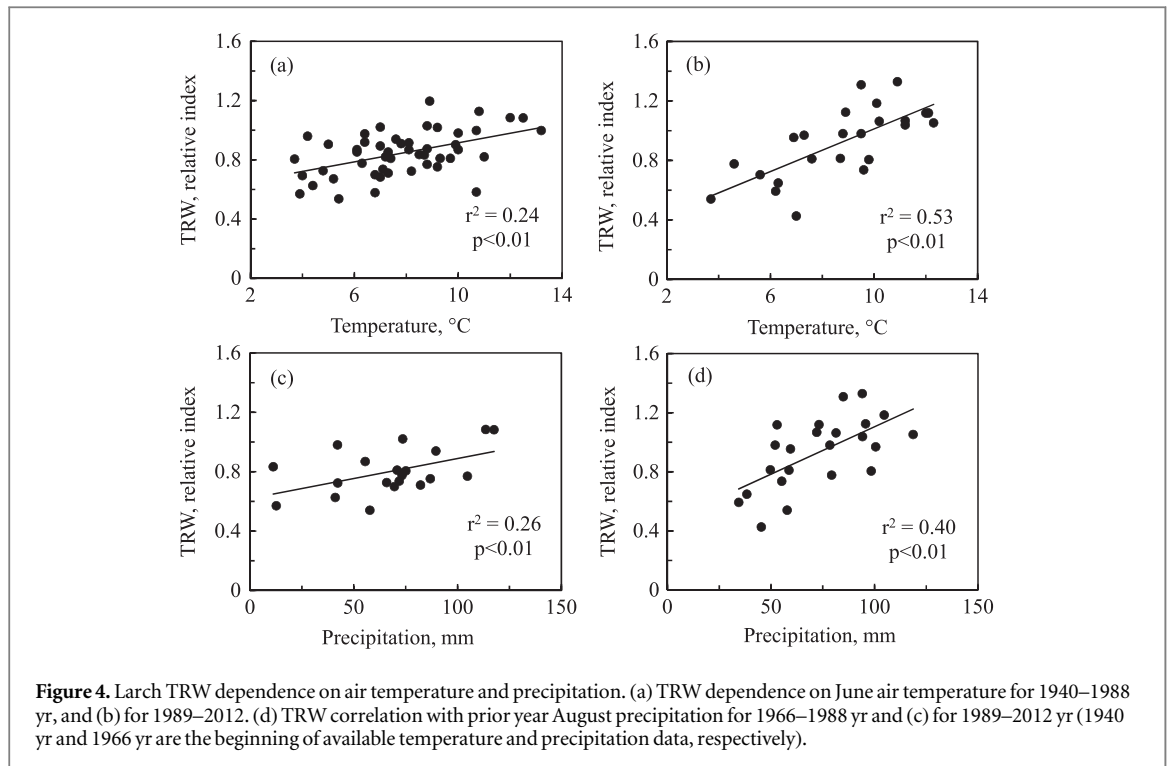
3. Results

3.1. Trends in larch TRW

Larch standard chronology is presented in figure 3. TRW increase was observed at the beginning of the 21st century that is about 50% higher in comparison with the similar period of the 20th century and that is similar to maximal tree ring growth during post-Little Ice Age warming (ca. 1840–1880 figure 4(b)).

3.2. TRW and climate variables

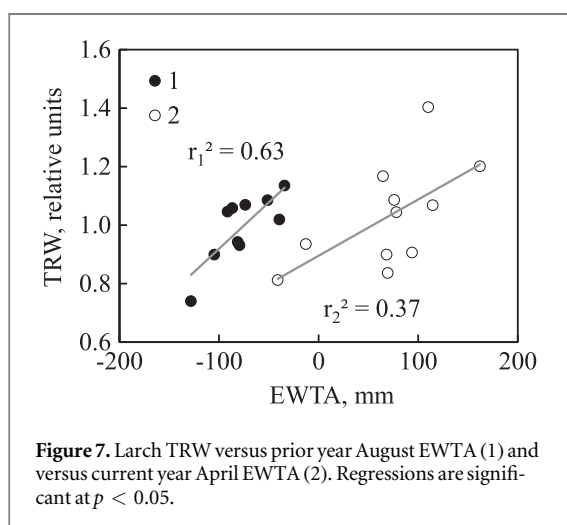
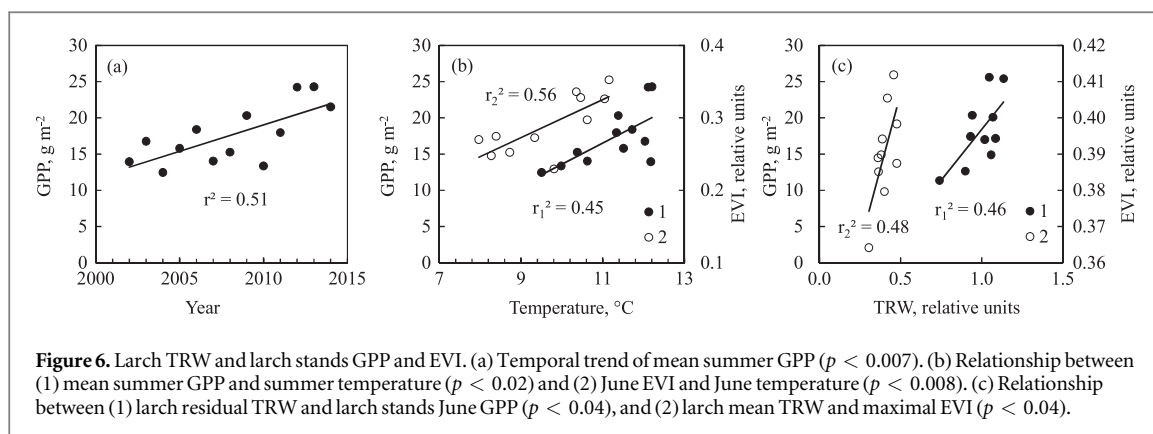
In TRW versus climate variables analysis standard chronologies were used. Correlations were calculated



for the period from 1989 (i.e. since the beginning of accelerated temperature increase within the study area) and for the previous period since the beginning of reliable meteorological observations (year 1940 for temperature, 1966 for precipitation, and 1943 for VPD). TRW correlation with June temperatures since 1989 were higher than for the previous period ($r = 0.73$ versus $r = 0.49$; figures 4(a), (b)). Correlations with May, July and August temperatures were not significant. No significant correlations were found

for current year monthly or annual precipitation. Meanwhile, a good correlation was observed with prior year August precipitation ($r = 0.63$; figure 4(d)). The prior year July precipitation correlation was less ($r = 0.5$). Correlations with precipitation before 1989 were also lower ($r = 0.5$).

TRW is also correlated with water vapor pressure in June (figures 5(a), (b)). Correlation values increased during recent decades ($r = 0.69$, versus 0.47). A good correlation was observed between TRW and May and



June drought index SPEI (figures 5(c), (d)). SPEI trends for previous period (1940–1999 yr) were insignificant.

3.3. Larch TRW and larch stands EVI and GPP

Larch stands GPP had a positive trend since the beginning of the 21st century (for the period for which we have vegetation response data; $r^2 = 0.51$; figure 6(a)). GPP correlated with summer temperatures (figure 6(b)). There is a significant correlation between larch TRW and satellite-derived larch stands GPP ($r = 0.68$; figure 6(c)). Larch stands EVI values correlated with temperature and TRW (figures 6(b), (c)).

3.4. Soil water anomalies and TRW

There is strong correlation between larch TRW and prior year water anomalies in August EWTA ($r = 0.79$, figure 7). TRW also correlated with maximum snow accumulation (occurred in April; $r = 0.61$).

4. Discussion

Within the permafrost zone of Central Siberia, positive trends in tree ring growth and larch stands

productivity were observed at the beginning of the 21st century. Mean TRW increased by about 50%, which is similar to maximal TRW growth during post-Little Ice Age warming (ca 1840–1880). TRW growth correlated with larch stands GPP and EVI ($r = 0.68$ – 0.69). Notably, according to Bunn and Goetz (2006) our study area is within the area of increased productivity of stands.

According to the majority of studies, larch growth within permafrost areas is limited by summer air temperatures (e.g., Sidorova *et al* 2007, Vaganov and Kir-dyanov 2010). Here we showed that TRW growth correlated with early summer (June) temperatures ($r = 0.73$). More importantly, TRW growth indicated sensitivity to water stress, and correlated with water vapor pressure deficit ($r = 0.69$) and May and June drought index ($r = 0.68$ – 0.82). Snow accumulation (and, consequently, snowmelt water) also has a positive impact on tree ring growth ($r = 0.61$). In addition, TRW significantly correlated with water accumulated within soil in the previous year ($r = 0.79$). Correlation of TRW with previous year August precipitation was less ($r = 0.63$). August and September precipitation formed the ‘conserved’ water storage in the soil. The September contribution to storage is less because it is mainly in the form of snow. In addition, soil thawing depth is maximal in August, i.e., possess a maximal water accumulation ability. Thus, current larch growth depends on the prior year water accumulation in the permafrost active layer, as well as on the snowmelt water. Permafrost water use by larch was also shown in experiments with oxygen isotopes and it was found that larch used permafrost melt water mainly during a summer drought (Sugimoto *et al* 2002). In other studies, influence of droughts of previous year was also observed. Engelmann spruce and alpine fir growing at the same site were influenced by precipitation and growing conditions of the previous year in Canada’s Banff National Park (Colenutt and Luckman 1991). Also, growth of Engelmann spruce in the US’s North Cascade Mountains is negatively influenced by warm July–August temperatures of previous year (Peterson and Peterson 1994). In our work, all correlations between TRW and climate

variables increased during the last decades (in comparison with similar previous period; figures 4, 5). Although correlations with summer temperature were less at the end of 20th century, they are significant. The latter indicated that no ‘divergence phenomenon’ (i.e., lack of positive response of growth to temperature) was observed within our study. Earlier the divergence was reported for some sites within the boreal zone (e.g. D’Arrigo et al 2005, Andreu-Hayles et al 2011).

One of explanation for this phenomenon was increased moisture stress caused by increased evapotranspiration. That is, forests where ‘divergence’ is detected may have reached a threshold beyond which tree growth is no longer positively influenced by summer temperature which could, in turn, be linked to the rapid warming in the area (Beck et al 2011). Indeed, in this study no correlation was found with July temperature, whereas a good relationship was observed between TRW and June temperature (figure 4). Meanwhile TRW growth correlated with a drought index SPEI and water from permafrost thaw, which indicated water stress and water limitation within the study area. Definitely, increased drought was observed since the last decades of the 20th century (figure 2(c)). It should be noted that SPEI is an imperfect characterization of drought in permafrost systems as it relies only on the monthly difference between precipitation and PET, whereas the water available can be from prior months’ precipitation or active layer thaw. Under drought increase, significance of permafrost melt water for tree growth should also increase. The latter depends on the previous year rainwater accumulation, which is termed by August rainfalls mainly, while in September soil was already frozen. Indeed, TRW strongly correlated with prior year August soil water anomalies (EWTA; $r = 0.79$). The higher correlation results because the prior year August EWTA best represents the available water when the active layer thaws. Surprisingly no correlation was found with the current year summer precipitation. Possibly, it was caused by the fact that only a minor portion of rainwater is trapped by the active layer, especially in June and July, when active layer depth is still shallow. Poor correlation with current August precipitation is likely the result of low photosynthesis rate since larch senescence begins in August at the study site latitude. Meanwhile, active layer melting in synergy with precipitation caused solifluction within the study territory. Within the solifluction sites, trees deviate from the vertical direction and form fascinating so-called ‘drunk forest’.

The warming-induced permafrost thawing considered will cause strong negative effect on the larch growth due to possible water stress increase (e.g., Sugimoto et al 2002). However, the total precipitation within the study area (ca 400 mm) is sufficient for maintaining normal larch growth since larch is known as a drought-tolerant and high-efficiency water use species

(Kloppel et al 1998). Meanwhile, seasonal availability and interannual and interdecadal variability have more to do with its effect on vegetation than its mean precipitation. As shown above, larch experienced water stress at the beginning of vegetation period (figure 7).

In the current climate snowmelt and rain waters runs off mainly to the rivers due to, as mentioned above, low water infiltration and storage by the shallow active layer. With warming, the increased active layer will capture a larger proportion of water flow. The other consequence of permafrost thawing will be the loss, by larch, of its role as the predominant species in the area due to invasion of less cold-tolerant species (*Pinus sibirica*, *Abies sibirica*, *Picea obovata* and *Pinus sylvestris*; Kharuk et al 2005).

5. Conclusion

At the beginning of the 21st century, an increase of larch stand productivity and tree ring growth within a permafrost area of Central Siberia were observed. Tree ring growth shown to correlate with early summer air temperature, water vapor pressure deficit, drought index, water accumulated within soil in the previous year, snowmelt and permafrost melt water. Water stress along with early summer temperature is a limiting factor of larch growth within the northern Siberia permafrost zone.

Acknowledgments

Authors thanks two anonymous reviewers for helpful comments on a previous version of the manuscript. Russian Science Foundation (grant #14-24-00112) supported this research. Additional support for field measurements by NASA’s Terrestrial Ecology program.

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