# Climate-induced mortality of Siberian pine and fir in the Lake Baikal Watershed, Siberia

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Running title**: Conifer mortality within the Lake Baikal watershed**

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## ABSTRACT

Siberian pine (*Pinus sibirica*) and fir (*Abies sibirica*) (so called "dark needle conifers", DNC) showed decreased radial growth increment within the Lake Baikal watershed since the 1980s with increasing mortality recorded since the year 2000. Tree ring width was strongly correlated with vapor pressure deficit, aridity and root zone moisture. Water stress from droughts made trees more susceptible to insect attacks causing mortality in about 10% of DNC stands within the Lake Baikal watershed. Within Siberia DNC mortality increased in the southern part of the DNC range. Biogeographically, tree mortality was located within the DNC – forest-steppes transition. Tree mortality was significantly correlated with drought and soil moisture anomalies. Within the interior of the DNC range mortality occurred within relief features with high water stress risk (i.e., steep convex south facing slopes with shallow well-drained soils). In general, DNC mortality in Siberia was induced by increased aridity and severe drought (inciting factors) in synergy with biotic attacks (contributing factor). In future climate scenarios with predicted increase in aridity DNC could be eliminated from the southern part of its current range and will be replaced by drought-resistant conifers and broadleaf species (e.g., *Larix sibirica*, *Pinus silvestris*, and *Betula pubescence*).


Keywords: water stress, conifer mortality, Lake Baikal Region, drought, aridity increase, forest health

## 1. Introduction

Conifer decline (i.e., tree vigor decrease) and mortality was reported for a number of sites within the boreal zone (Lloyd and Bunn, 2007; Aitken et al., 2008; Millar and Stephenson, 2015). *Pinus ponderosa* decline has occurred in the North American forests (Logan et al., 2003; Fettig et al., 2013). Dieback or degradation of thousands of ha of spruce forests has been observed in Ukraine and in Baltic and European countries (Allen et al., 2009; Yousefpour et al., 2010; Martínez-Vilalta et al., 2012; Kharuk et al., 2015a). Large amounts of tree mortality were also reported in *Picea abies* stands in Belarus (Sarnatskii, 2012; Kharuk et al., 2016). Large-scale spruce mortality decline has been observed in the European part of Russia (Chuprov, 2008; Zamolodchikov, 2011). In the Russian Far East *Picea ajansis* and *Abies nephrolepis* die-off was documented (Man'ko et al., 1998). Siberian pine and fir stands mortality have been observed in the region of Lake Baikal and the southern Siberian Mountains (Kharuk et al., 2013a). Conifer mortality was attributed to bacterial diseases (Raffa et al., 2008; Review of forest heath…, 2010), root fungi and insects attacks (Logan et al., 2003; Pavlov et al., 2008; Chuprov, 2008; Kolb et al., 2016), and drought increase (Millar and Stephenson, 2015; Kharuk et al., 2013a,b; Kharuk et al., 2015a).

In recent decades, Lake Baikal watershed forests experienced decline and mortality. These forests are composed of Siberian pine (*Pinus sibirica*) and fir (*Abies sibirica*) with a mixture of spruce (*Picea obovata*) [so called "dark needle conifer" (DNC)] species. The main causes of DNC mortality were considered to be biotic and anthropogenic impacts (Review of forest heath…, 2010). These local watershed forests are a primary supplier of water for Lake Baikal, which is the largest (20% of the world's fresh water), deepest (1,642 m depth), and oldest (25 million years) lake in the world.

The main goal of this paper is to provide an analysis of causes of DNC mortality within (1) Lake Baikal watersheds and (2) within the DNC species range in Siberia. The hypothesis tested is DNC mortality was caused by increased aridity and severe drought (inciting factors) in synergy with bark and wood boring insects and fungi attacks (contributing factors).

## 2. Methods

The studies were based upon on-ground observations, dendrochronology, environmental variables (air temperature, precipitation, root zone wetness, vapor pressure deficit, drought index SPEI), remote sensing and GIS-technologies.

## *2.1. Study area*

The studied stands are located in the Lake Baikal watershed (Khamar-Daban Ridge, Fig. 1). The ridge is 60 km × 350 km in dimension with maximum height of about 2,370 m. Pine and fir stands are dominant at elevations up to 1,500–1,600 m. The treeline is formed by Siberian pine. The subalpine belt (up to 1,700 m) included meadows, shrubs and sparse trees (*Pinus sibirica* and *Abies sibirica*). Tundra communities are typical at higher elevations (i.e. >1,700 m).

## *2.2. Climate*

Environmental variables considered for this study included air temperature, precipitation, drought index SPEI (Standardized Precipitation-Evaporation Index) and root zone wetness. SPEI is a measure of drought intensity and duration (Vicente-Serrano et al., 2010), and is defined as the difference between precipitation and potential evapotranspiration:

$$D_i = P_i - PET_i ,$$

where *i* is the time period.

*PET* (mm) is calculated as:

$$PET = 16 \times K \times (10 \times T \times I^{-1})^m,$$

where *T* is the monthly mean temperature in °C; *I* is a heat index, *m* is a coefficient depending on *I*, and *K* is a correction coefficient. SPEI data (0.5° × 0.5° spatial resolution) was obtained from http://sac.csic.es/spei.

Mean air temperatures within the study area were 14–18 °C in July and -11…-25 °C in December-February. The mean annual air temperature in the mountains and on the shore of Lake Baikal are -3.4 °C and about 0° C, respectively. Maximum precipitation occurred in late July-August, and the minimum in spring and autumn. Maximum aridity was observed in June-July (Appendix Fig. A1d). Summer air temperature showed a positive trend in 1980–2002 (Appendix Fig. A1a). Drought increased since the 1980s (Appendix Fig. A1c). No trends in precipitation were found for the studied time period. Climate variables were obtained from “Kabansk” (52°05′N, 106°65′E; 466 m a.s.l.) and “Khamar-Daban” (51°53′N, 103°59′E; 1,442 m a.s.l.) weather stations located on the shore of Lake Baikal and in the nearby mountains, respectively.

### *2.3. Field studies*

Field studies were conducted during July 2015 within an area known for major forest mortality (Fig. 1). Temporary test sites (TS, $N = 23$) were established along an elevational transect across the ridge. The transect began at the northern boundary of the declining stands and ended on the southern boundary. This transect included areas with high levels of tree mortality (>25% of trees), as well as stands without symptoms of decline. The following data were collected within each TS: tree inventory, soil, ground cover, and a description of topography (i.e., elevation, azimuth, slope steepness, terrain curvature (convex/concave)). A tree inventory (i.e., species composition, tree height, diameter at breast height (dbh), tree vigor) was conducted within circular plots of radius = 9.8 m. These data were also used for satellite data interpretation. Samples for dendrochronological analysis were taken by increment borer or chainsaw at breast height (1.3 m). Sampled trees were randomly chosen around the TS centerpoint within a 0.5 ha area and a ±10 m range of elevation.

Study stands were composed of Siberian pine and Siberian fir trees. Mean tree heights and (dbh) were 17 m (43 cm) and 13 m (18 cm) for Siberian pine and fir, respectively. Mean age was 130 years for pine and 90 years for fir. Shrubs were represented by *Juniperus sibirica*, *Duschekia fruticosa*, *Spiraea salicifolia*. Ground cover consisted of *Bergenia crassifolia, Vaccinium myrtillus, Cárex sp.*, and different species of mosses and lichens. Soils were well-drained sandy brown-mountain. Horizons $A_0$ and $C_0$ (bedrock level) were at 1–5 and 15–25 cm, respectively.

Within the DNC range in Siberia, Russian State Forest Service collected forest pathology data from 2008 to 2015. The dataset included tree's vigor status and causes of mortality (fires, insect attacks, climate impact, windfall, diseases, etc.). In this analysis we used data for insect attacks, climate impact, and diseases (total number of test plots was $N = 9681$, including 6046 of "insect attacks", 268 of "climate impact", and 3367 of "diseases"). That dataset was used in geospatial analysis of the relationships between tree mortality and drought index and root zone wetness.

### *2.4. Remote sensing data and GIS analysis*

DNC mortality was also analyzed based on data from multiple satellites. 1) Moderate resolution (30 m) Landsat data consisting of Landsat 8/OLI acquired 25.06.2015 and 18.06.2015; Landsat 5/TM acquired 30.09.1989 and 15.10.1992; and Landsat 4/MSS acquired 29.09.1989. (data source was http://glovis.usgs.gov), 2) High resolution imagery (0.41–0.5 m) from Worldview and GeoEye satellites was acquired 18.08.2010, 17.09.2010, 11.09.2010 and provided through NASA's NGA Commercial Archive Data (cad4nasa.gsfc.nasa.gov). 3) Topographic information was provided by NASA's Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) at 30 m resolution and available at (http://earthexplorer.usgs.gov). Soil water content/anomalies were analyzed based on NASA GRACE from (podaac.jpl.nasa.gov) and SMAP satellite data acquired from NASA's Snow and Ice Data Center (https://nsidc.org/data/smap/smap-data.html). We used the SRTM DEM for analysis of the relationship between DNC mortality with relief features (elevation, slope steepness, curvature, and exposure). Exposure or slope aspect was analyzed for eight directions (north (0°), northeast (45°), east (90°), etc.); slope steepness was analyzed with one-degree intervals. Curvature was presented in relative units (negative values for concave and positive for convex surface).

### *2.5. Stand mortality detection*

Declined stands were detected using Landsat data and maximum likelihood classification with a threshold procedure ($p$-value = 0.05). First a mask of dark-needle stands was generated for the period prior to tree mortality (1989). For this purpose 10 training areas (TA) of DNC stands were generated with average size of 699±117 pixels). Then, a mask of DNC was generated. Dead stands were detected on the Landsat (2015) scenes based on 30 TA (approx. 600 pixels each). TA were generated based on ground-truth data and high-resolution WorldView and GeoEye imagery. Spatial resolution of the scenes provided identication of individual trees. Furthermore, the following stand categories were identified: healthy and slightly damaged stands (mortality < 25%), moderately damaged stands (25–50%), heavily damaged stands (50–75%), and areas of tree mortality (> 75%). However, upon further analysis the first two categories were merged because of their low separability. Classification accuracies were estimated using KHAT ($\kappa$)-statistics (Congalton, 1991).

### *2.6. Data processing*

Remote sensing data were processed using Erdas Imagine software (http://geospatial.intergraph.com). GIS-analysis was carried out using ESRI ArcGIS software package (http://www.esri.com). Statistical analysis was realized using Microsoft Excel and Statsoft Statistica software (http://www.statsoft.ru). The C-correction algorithm for topographic correction of Riano et al., (2003) was applied to the Landsat scenes using the SRTM DEM.

## *2.7. Drought and soil moisture assessment*

### 2.7.1. Soil Moisture Active Passive (SMAP) product

The Soil Moisture Active Passive (SMAP) mission was launched in January 2015 with two sensors to provide information on surface soil moisture (http://smap.jpl.nasa.gov). The first sensor (passive) measures land surface microwave emission at 1.41 GHz and provides profile data with 36 km spatial resolution. The second one was an active sensor, which measured radar backscatter (at 1.26 GHz and 1.29 GHz) and provided scenes with on-ground resolution 3 km and swath width ~1,000 km. The active sensor (radar) was only in operation until July 2015, whereas the passive radiometer is still operating. We used the SPL4SMGP product (Reichle et al., 2015) with spatial resolution of 9 km for root zone soil moisture estimation (0–100 cm; wetness units, $m^3$ $m^{-3}$). This product utilizes SMAP's microwave brightness temperature at 36 km and GEOS-5 Forward Processing Model Data from the NASA Global Modeling and Assimilation Office at NASA's Goddard Space Flight Center. Data were downloaded from (https://n5eil01u.ecs.nsidc.org/SMAP).

### 2.7.2. MERRA-2 data

MERRA-2 used observation-based precipitation data as forcing for the land surface parameterization (Global Modeling…, 2015). Data (with spatial resolution 0.5° × 0.625°) are available since 1980. MERRA-2 monthly data were used for water content estimates within the "root zone" (0–100 cm). We used the MERRA2 M2TMNXLND product (http://disc.sci.gsfc.nasa.gov/uui/search/%22MERRA-2%22).

### 2.7.3. SPEI drought index analysis

We analyzed relationship between Siberian pine and fir mortality and SPEI values. For this purpose, a map of major droughts (SPEI three major minimums, $SPEI_{\min}$) was generated based on following equation:

$$SPEI_{\min,x,y} = \min{}_1(SPEI_{x,y}) + \min{}_2(SPEI_{x,y}) + \min{}_3(SPEI_{x,y}) \,, \qquad (1)$$

where $\min_1$, $\min_2$, $\min_3$ are SPEI minimums within the *i, j* grid cells; *x, y* – are cells coordinates. Then, within each grid cell regression analysis was performed (i.e., $SPEI_{\min}$ vs number of test sites with tree mortality). The range of $SPEI_{\min}$ values was divided into five classes (with ranges: -2 to -4; -4 to -6; -6 to -8; -8 to -10; -10 to -12). Then, for each of these classes the $SPEI_{\min}$ and number of test sites ($N_{ts,i}$) was determined. After that $N_{\mathrm{ts,i}}$ was normalized by the following procedure:

$$N_{norm,ts,i} = N_{ts,i} / N_{SPEI_{\min},i} \quad (2)$$

where $N_{norm,ts,i}$ – the normalized number of on-ground TS with tree mortality; $N_{SPEI_{\min},i}$ – a number of pixels in *i*-th class of $SPEI_{\min}$. Finally, regressions between $N_{norm,ts,i}$ and $SPEI_{\min}$ were conducted.

2.7.4. GRACE data

GRACE gravimetric data (available since 2003) were applied for detection of soil water anomalies. We used monthly EWTA (Equivalent of Water Thickness Anomalies). EWTA accuracy is 10–30 mm month$^{-1}$ with spatial resolution 1° × 1° (Landerer and Swenson, 2012; Long et al., 2014; http://www.grace.jpl.nasa.gov). Using analysis similar to SPEI above the relationship between Siberian pine and fir mortality and EWTA values was analyzed. Similarly, $EWTA_{\min}$ was generated based on equation (3):

$$EWTA_{\min,x,y} = \min{}_1(EWTA_{x,y}) + \min{}_2(EWTA_{x,y}) + \min{}_3(EWTA_{x,y}), \quad (3)$$

where $\min_1$, $\min_2$, $\min_3$ – are three major EWTA May-Jul minimums of EWTA for each (*x*, *y*) grid cell. TS normalization was similar to equation (2):

$$N_{norm,ts,i} = N_{ts,i} / N_{EWTA_{\min},i} \quad (4)$$

where – the normalized number of TS; $N_{SPEI_{\min},i}$ – a number of pixels in *i*-th class of $EWTA_{\min}$.

## *2.8. Dendrochronology analysis*

Dendrochronology dataset included 180 *Pinus sibirica* and 50 *Abies sibirica* cores and disks taken at breast height (1.3 m) by increment borer Tree ring width (TRW) was 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 and cross dating of chronology (Rinn, 2003). Dates of tree mortality were determined based on the master-chronology method (Fritts, 1991). For *Pinus sibirica* an initial master chronology was constructed based on 28 living trees from a control site (no signs of damage). The dataset was divided into "survivors" (*N* = 69) and "decliners" (*N* = 83) groups based on radial increment trends during 2000–2014. Trees with a positive tree ring increment trend formed a "survivors" cohort, whereas trees with a negative increment trend and dead trees formed "decliners" cohort. "Control" group included the above mentioned 28 trees. For both cohorts standard chronologies were constructed. Standard chronologies were indexed using ARSTAN software (i.e., detrending to remove long-term trends by negative exponential curve and a linear regression of negative slope or horizontal line; Cook and Holmes, 1986). The resulting chronologies were a unitless index of radial tree growth. For *Abies sibirica* chronologies were constructed for each (*N* = 3) site. In addition, chronologies with negative trends (*N* = 2) were combined. The dataset was then divided into "growth-release sites" (*N* = 16) and "growth-depressed sites" (*N* = 34).

## 3. Results

### *3.1. DNC growth: dendrochronology data*

Tree ring width (TRW) analysis showed that Siberian pine increment decreased since the middle of the 1980s. That decrease coincided with increases in VPD and drought, and root zone wetness decrease (Figs 2, 3). After a severe drought in 2003 trees were divided into "dead and decliners" and "survivors" cohorts (Fig. 2). Trees also decreased growth at the control site, although there were no visible signs of decline.

Fir trees response to ecological variables was more complicated. Within the "growth-depressed" site TRW decreased, whereas at the "growth-released" site TRW increased after the 2003 drought (Appendix Fig. A2). The latter site was composed of Siberian pine (upper canopy) and fir (lower canopy). After the 2003 drought nearly 100% Siberian pine trees were died.

### *3.2. DNC growth: relationship with climatic variables*

The Siberian pine "decliners" cohort showed strong sensitivity to climate variables (Fig. 3). That is, TRW had the highest correlation with SPEI ($r = 0.89$; $p < 0.001$). It is worth noting the significant correlation with prior year precipitation ($r = 0.46$; $p < 0.01$). For the "survivors" cohort a significant correlation was found only with VPD ($r = 0.58$; $p < 0.01$).

Similar to Siberian pine, fir trees from "growth depressed" site ("decliners") were sensitive to climate variables (the highest correlation was with SPEI, $r = 0.74$, $p < 0.001$; Appendix Fig. A3).

TRW was also significantly correlated with prior year precipitation ($r = 0.48$, $p < 0.005$).

### 3.3. DNC growth: dependence on soil moisture

The SMAP model derived root zone moisture map of Lake Baikal Region showed that within the Khamar-Daban Ridge, the greatest stand mortality was observed at locations where the lowest soil water content was observed (Fig. 4).

Growth of the “decliners” Siberian pine cohort was found to be correlated with current year (July) root zone wetness ($r = 0.62–0.85$, $p < 0.05$; Fig. 5). A higher correlation was observed for growth and prior year (July) root zone wetness ($r = 0.76$, $p < 0.05$; Fig. 5). Fir showed similar sensitivity to the root zone wetness with correlations of $r = 0.62$ ($p < 0.001$) and $r = 0.67$ ($p < 0.001$) for current and prior year measurements, respectively (Appendix Fig. A4).

### 3.4. DNC mortality: relationship with relief features

The spatial patterns of dead stands and “all stands” (i.e., before mortality) were significantly different. Dead stands were found on steeper south-west convex slopes and at higher elevations (Fig. 6). The slope median of dead stands was 17°, whereas the median of all stands was at 12° (Fig. 6b).

It is interesting to note a predisposing “exposure effect” at the scale of individual trees. Since tree decline often begins on the sunlit side of the bole (Appendix Fig. A5) bark beetles primarily attack the “stressed” bole surface, whereas the bole’s northern side was still resistant to insect attacks (Appendix Figs A5b, A5c).

### 3.5. Biotic impact

We observed that within all test sites (with the exception of the control) Siberian pine and fir trees exhibited signs of bark and wood borer beetles attacks (i.e., *Pityogenes conjunctus* Rtt., *Monochamus urussovi* Fischer.). Along with that, survey data (Review of forest heath…, 2010) also indicated some bacterial diseases and root fungi attacks.

### 3.6. Area estimation of dead and declining DNC stands

Within the major dieback area (rectangle on Fig. 1) dead stands occupied about ~ 5.4 % of the total DNC area. Severely damaged (i.e., stands with 50–75 % of dead trees) occupied ~ 4.2 % of the

DNC area. Thus, the total fraction of dead and declining stands was about 10 %. Within the whole Khamar-Daban Ridge area about 9 % of DNC stands were severely damaged or dead.

### *3.7. Tree mortality within the DNC range*

Siberian pine and fir mortality was documented within the vast southern part of these species range in Siberia (Figs 7a, 8a). Significant correlations were found between DNC mortality and drought index and soil water anomalies ($r$ = -0.75, $p < 0.1$ and $r$ = 0.99, $p < 0.01$, respectively; Figs 7b, 8b).

## **4. Discussion**

Within the Lake Baikal watershed Siberian pine and fir growth was observed to decrease since the 1980s. This decrease coincided with increased aridity (i.e., observed long-term decrease in drought index). Water stress and severe drought split trees into “survivors” and “decliners” cohorts with an obvious “turning point” in the 2000s after severe drought (see Fig. 2). Root zone wetness, the major determinant of tree vigor, was also observed to decrease since the 1980s.

Spatial patterns of “survivors” and “decliners” were significantly different with decliners located mainly on south facing convex steep slopes. Survivors occurred on relief features with less water-stress (i.e., north facing concave slopes with less slope steepness).

Along the elevation gradient maximum tree mortality was observed within the elevation range of 1,000–1,500 m. At lower elevations along the shoreline, water stress was reduced by Lake Baikal's impact, whereas at higher elevations precipitation and relative humidity were increasing along the elevation gradient. Tree ring width of “decliners” was correlated with vapor pressure deficit, drought index SPEI, and root zone wetness. It is worth noting that TRW was also correlated with prior year precipitation and root wetness zone (Fig. 5). A similar effect has been reported in other studies. For example, Colenutt and Luckman (1991) showed that *Picea engelmannii*, *Abies lasiocarpa*, and *Larix lyallii* are strongly influenced by prior year precipitation and growing conditions. Soil water anomalies of the previous year also had a pronounced effect on *Larix gmelinii* growth and spruce *Picea abies* decline in Belarus (Kharuk et al., 2015a,b). In the case of Lake Baikal forests, significant correlations with prior year conditions indicate that trees are predisposed to biotic attacks. Signs of bark beetle and wood borer attacks were observed within all the test sites with the exception of the control. Similarly, extensive beetle outbreaks across the Engelmann spruce range in the United States were considered as a consequence of a trend of warmer and drier climatic conditions (O’Connor et al., 2015; Kolb et al., 2016). Synergy of drought and biotic impact was also reported for *Abies sibirica* stands in Southern

Siberian Mountains (Kharuk et al., 2016). On the other hand, intense drought itself may increase bark beetle activity and, consequently, increase tree mortality (Kolb et al., 2016).

Our results show Siberian pine experienced significant climate-induced growth decrease, which is attributed to the high precipitation sensitivity of this species (i.e., known in Russia as “the tree-of-fogs”). Observed fir growth decrease was less because fir forms the lower canopy and was partly protected from water stress by the shading effect of the upper canopy of Siberian pine. In addition, Siberian pine mortality facilitated fir growth release (Appendix Fig. A2) due to decreased competition for light and nutrients. Similarly, canopy protection facilitated regeneration survival of both species. Overgrowth of trees also caused stand mortality in some cases (e.g., Man’ko et al., 1998), but that is not the case for Baikal forests, where the mean age of Siberian pine and fir were 90 and 105 yrs., respectively. One of the reasons for high drought-sensitivity of Siberian pine and fir is high leaf area index (LAI), a major determinant of water balance. Mixed DNC stands had LAI up to 7–8, whereas LAI of drought tolerant *Pinus silvestris* stands are about 3–4 (Utkin, 1975, re-calculated data). Therefore, a high LAI of Siberian pine and fir leads to intolerance to low humidity. This agrees with our observed high correlations between TRW and VPD and SPEI (Figs 3, Appendix A3).

The geographical location of Lake Baikal forests are within the margins of the ranges of Siberian pine and fir and determines the high sensitivity to climate variables anomalies. Eastward and southward, these precipitation-sensitive stands have given way to more drought-resistant larch and Scots pine stands. Similarly, across the whole of Siberia DNC decline and mortality was observed within the southern portion of these species area (Figs 7, 8). Siberian pine and fir mortality was strongly correlated with soil moisture anomalies and SPEI drought index within the range of these species.

## 5. Conclusion

Lake Baikal is strongly dependent on the health of its watershed. Composed of Siberian pine and fir, the forests in these watersheds have experienced growth decrease and mortality since the 1980s that coincides with increased aridity and a decrease of root zone wetness. Dead stands were located mainly within relief features with highest water stress risk. Tree decline started from lower relief features, decreasing along with elevation because of the increased humidity and precipitation. Water stress predisposed trees to attacks by pathogens. The synergy of these impacts caused Siberian pine and fir mortality on about 10% of “dark needle conifer” of the Lake Baikal watershed stands.

Biogeographically Lake Baikal forests are located within the boundary between the “dark needle conifer” range and the southward forest-steppe ecotone populated with drought-resistant Scot pine and larch. Similar phenomena are observed for the whole range of DNC species in Siberia, where mortality has occurred primarily within ecotones of "DNC and drought-resistant species". Within the interior of DNC range mortality is located with relief features with maximum water stress risk (i.e., steep convex southward slopes with shallow well-drained soils).

DNC mortality in Siberia is strongly correlated with SPEI drought index and soil moisture anomalies ($r = -0.75$, $p < 0.1$ and $r = 0.99$, $p < 0.01$, respectively). Predicted aridity increase in southern Siberia (Climate Change, 2014), along with water-stress impact on trees, will also stimulate pest outbreaks. The synergy of water stress and insects attacks will lead to elimination of the precipitation sensitive "dark needle conifer" across the southern part of DNC range and its substitution by drought-resistant species (e.g., *Pinus silvestris, Larix sibirica, L. gmelinii*). DNC, in turn, are migrating now into northern larch-dominant communities (Kharuk et al., 2004).

The observed DNC decline within these species current range raises a question about reforestation within dead stands. In the light of observing and expected climate change, precipitation-sensitive Siberian pine and fir are not good for reforestation within observed areas of stands decline and mortality. This issue needs more study.

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**Figure legends**

**Fig. 1.** The study area location (Khamar-Daban Ridge). The right insert image expands this area and shows the location of major DNC mortality (rectangle) and field test sites (white discs). DNC stands are shown by dark tones on image. Left insert image is a photo of declining stands.

**Fig. 2.** Siberian pine tree ring chronologies vs SPEI, vapor pressure deficit (VPD), and root zone wetness. Drought dates: 2003, 2006, 2010 and 2015. Note: SPEI drought index increase means drought decrease, and vice versa. Trends are significant at $p < 0.01$.

**Fig. 3.** Relationship between Siberian pine TRW ("decliners" cohort; N = 83) and (a) air temperature (current year June), (b) precipitation (prior year July), (c) vapor pressure deficit (current year June), and (d) SPEI (current year May-August). Analyzed period: 1985–2013. Note: SPEI decrease means drought increase, and vice versa.

**Fig. 4.** SMAP-derived map of root zone wetness within Baikal Lake area (July 2015). Legend units are m3 m-3. Rectangle denotes an area of major Siberian and pine and fir mortality. Black dots indicate the locations of dead stands.

**Fig. 5.** Relationship between Siberian pine TRW and soil wetness. (a, b) – TRW ("decliners" cohort) vs root zone wetness in July of prior (a) and current (b) year. Analyzed period: 1985–2013. (c) – TRW ("decliners") vs soil water anomalies (EWTA in current year minimum). Analyzed period: 2003–2009. (d) – TRW ("survivors") vs soil water anomalies (1 – prior and 2 – current year, respectively). Analyzed period: 2003–2014.

**Fig. 6.** Spatial distributions of (1) "dead and declining" and (2) all stands (within rectangle on Fig. 1). (a-d): "dead and declining' stands vs (a) elevation, (b) slope steepness (medians shown as vertical dashed lines), (c) exposure, and (d) surface curvature (concave is negative, convex is positive).

**Fig. 7.** (a) Map of SPEI minimums ($SPEI_{min}$ for May-Aug, 2002–2015; 1, 2 – Siberian pine and fir ranges, respectively). Test sites with stand mortality are denoted as white disks. (b) The percentage of test sites with stand mortality (N = 9681 vs the drought index $SPEI_{min}$.

**Fig. 8.** (a) Map of soil water anomalies minimums ($EWTA_{min}$ for May-July, 2002–2015; 1, 2 – Siberian pine and fir ranges, respectively). Test sites with stand mortality are denoted as white disks. (b) The percentage of test sites with stand mortality (N = 9681) vs $EWTA_{min}$.

**Figure 1**

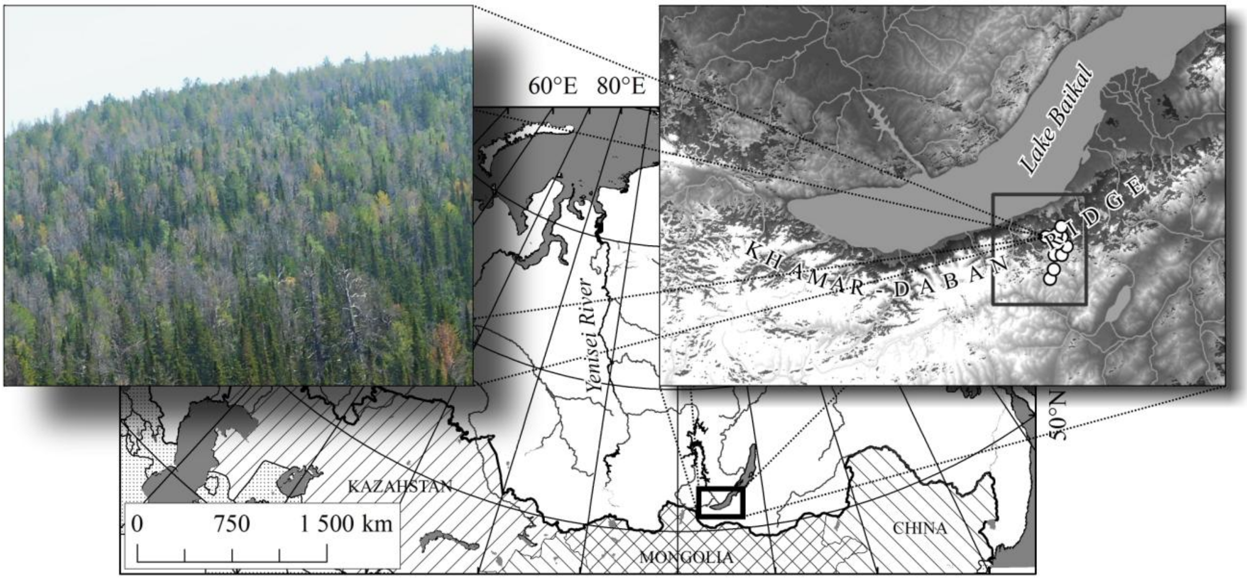



**Figure 2**

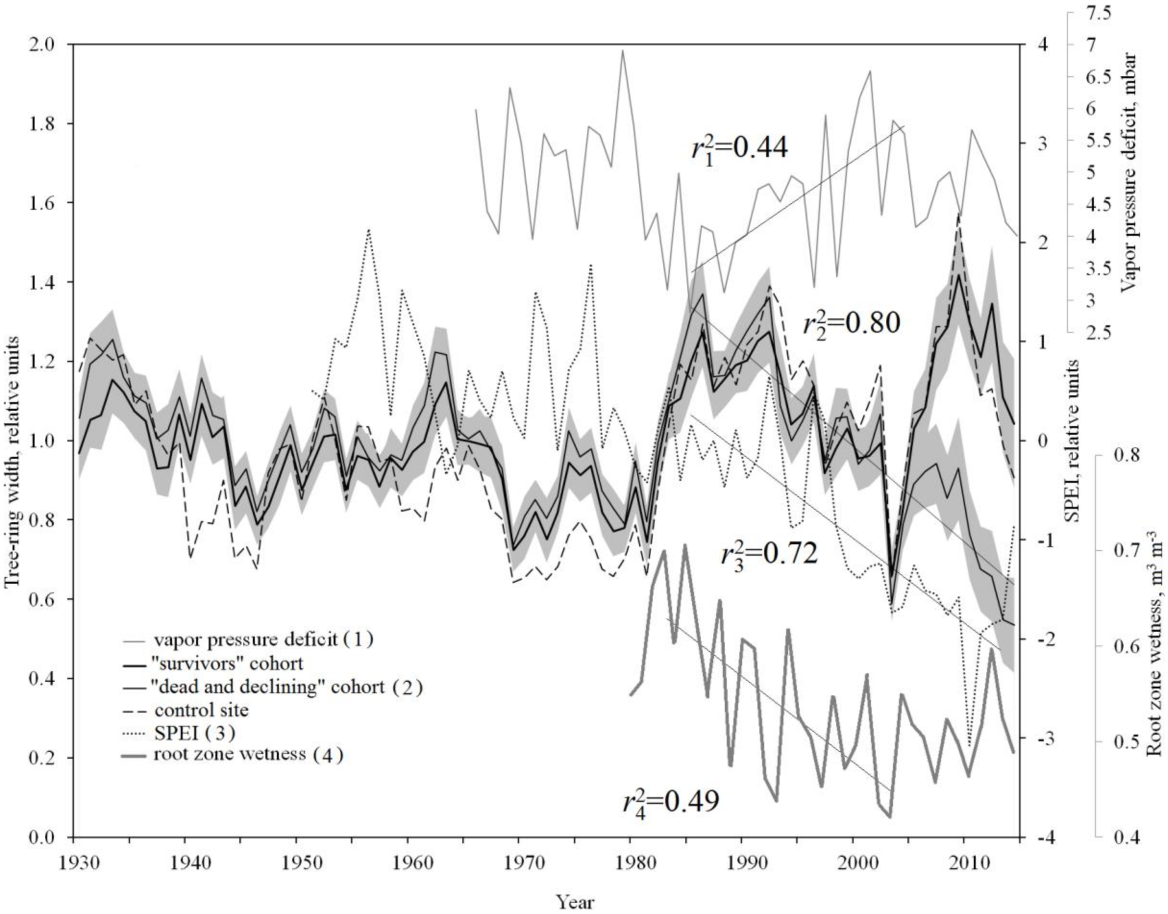


**Figure 3**

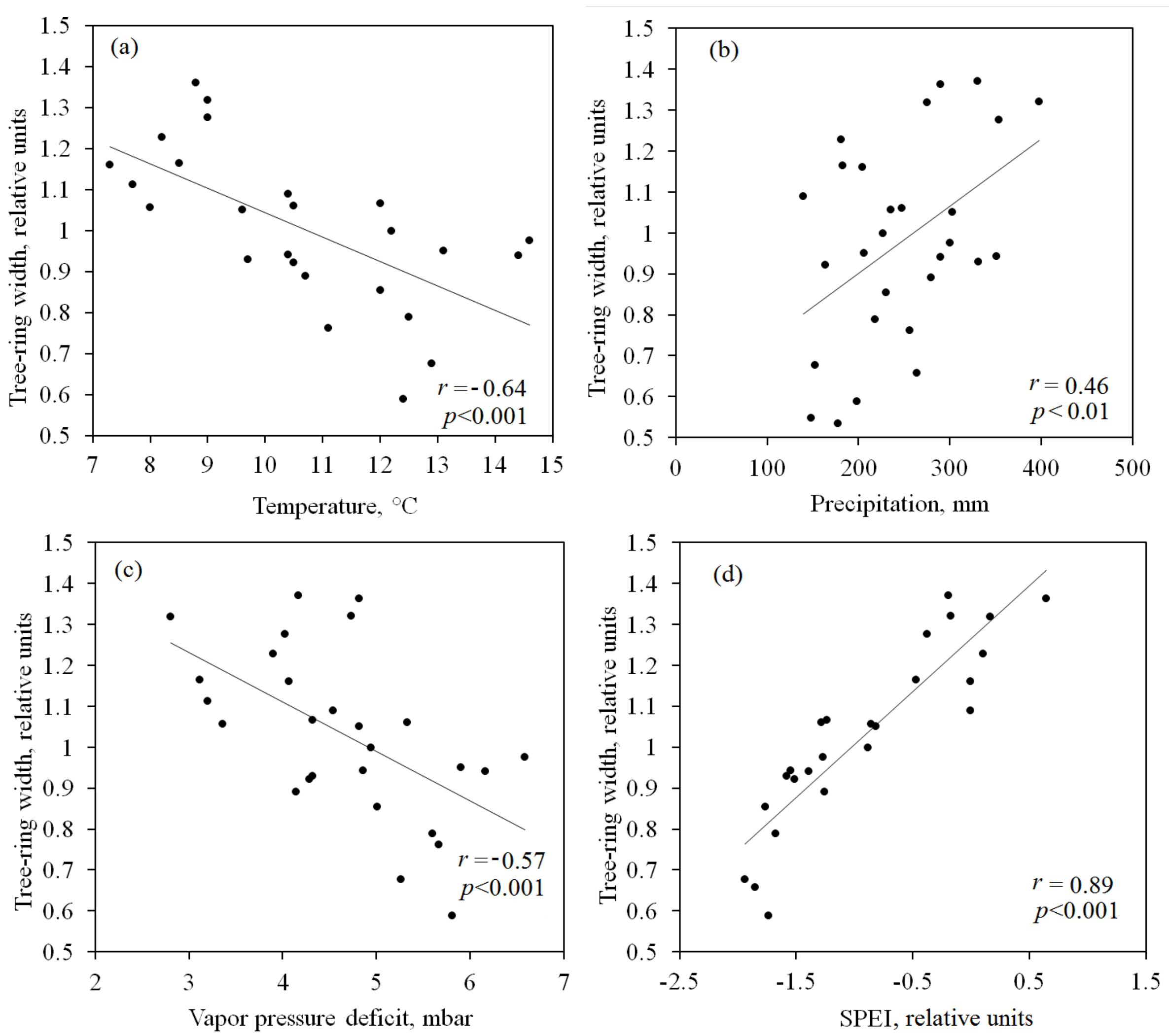

(a)
Tree-ring width, relative units
Temperature, °C
r = - 0.64
p<0.001
(b)
Precipitation, mm
r = 0.46
p < 0.01
(c)
Vapor pressure deficit, mbar
r = - 0.57
p<0.001
(d)
SPEI, relative units
r = 0.89
p<0.001

**Figure 4**

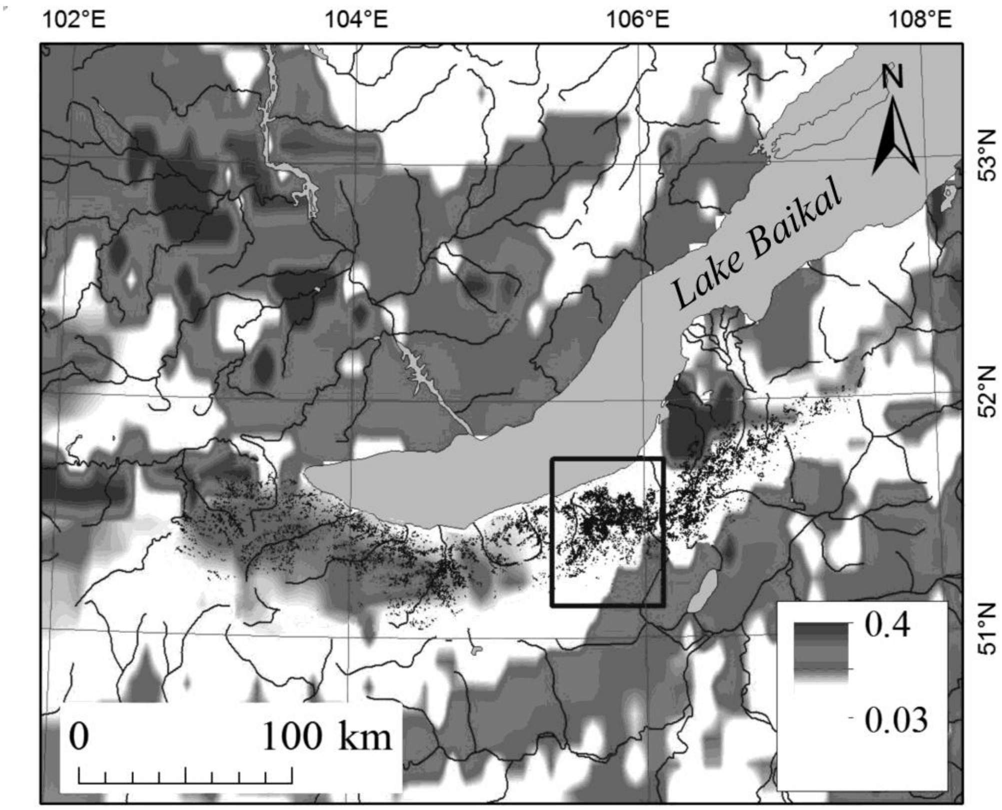
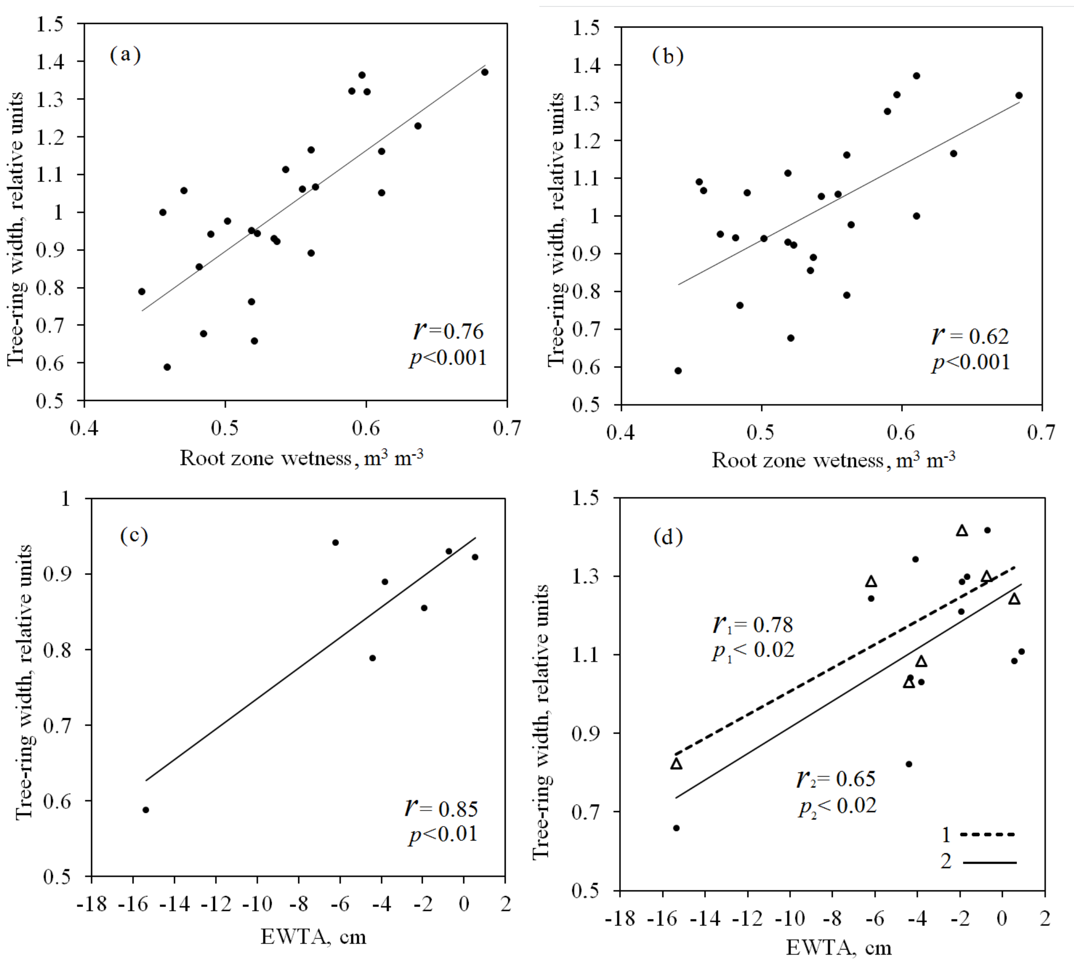


**Figure 5**

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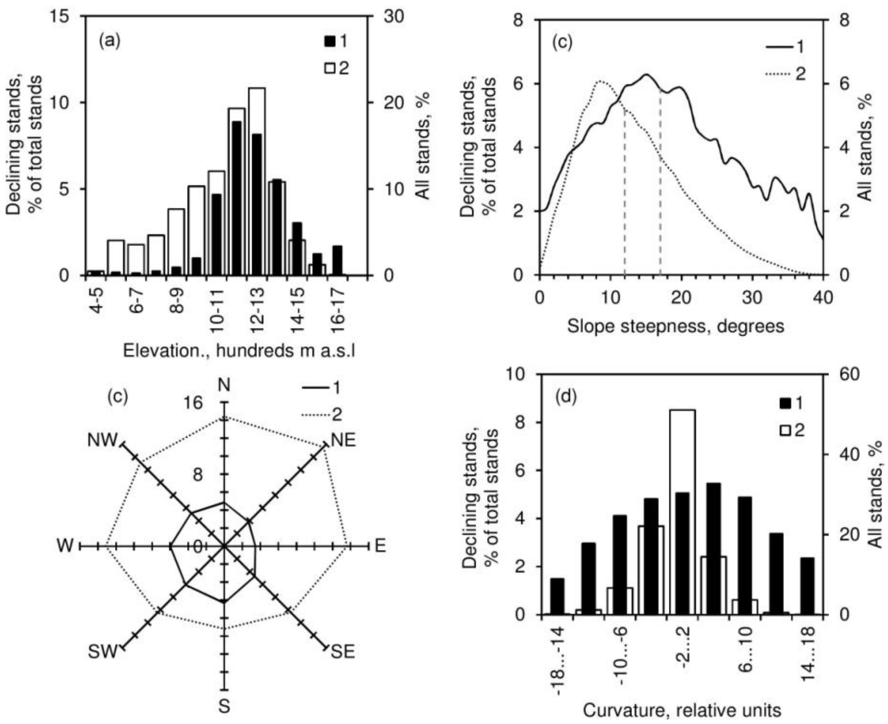

**Figure 7**

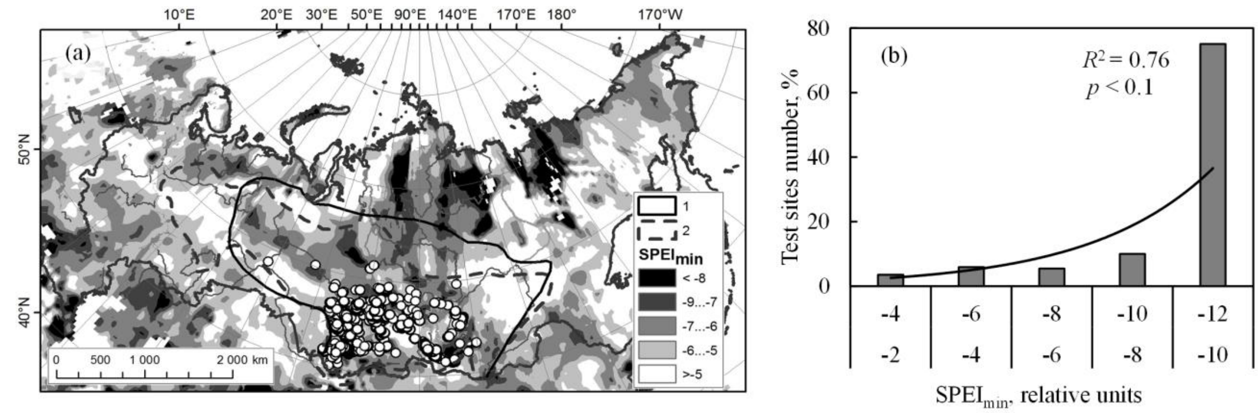


**Figure 8**