SIBERIAN PINE DECLINE AND MORTALITY IN SOUTHERN SIBERIAN MOUNTAINS

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Abstract

The causes and resulting spatial patterns of Siberian pine mortality in eastern Kuznetzky Alatau Mountains, Siberia were analyzed based on satellite (Landsat, MODIS) and dendrochronology data. Climate variables studied included temperature, precipitation and Standardized Precipitation-Evapotranspiration Index (SPEI) drought index. Landsat data analysis showed that stand mortality was first detected in the year 2006 at an elevation of 650 m, and extended up to 900 m by the year 2012. Mortality was accompanied by a decrease in MODIS-derived vegetation index (EVI). The area of dead stands and the upper mortality line were correlated with increased drought. The uphill margin of mortality was limited by elevational precipitation gradients. Dead stands (i.e., >75% tree mortality) were located mainly on southern slopes. With respect to slope, mortality was observed within a 7°-20° range with greatest mortality occurring on convex terrain. Tree radial increment measurements correlate and were synchronous with SPEI ($r^2 = 0.37, r_s = 80$). Increasing synchrony between tree ring growth and SPEI indicates that drought has reduced the ecological niche of Siberian pine. The results also showed the primary role of drought stress on Siberian pine mortality. A secondary role may be played by bark beetles and root fungi attacks.

The observed Siberian pine mortality is part of a broader phenomenon of “dark needle conifers” (DNC, i.e., Siberian pine, fir and spruce) decline and mortality in European Russia, Siberia, and the Russian Far East. All locations of DNC decline coincided with areas of observed drought increase. The results obtained are one of the first observations of drought-induced decline and mortality of DNC at the southern border of boreal forests. Meanwhile if model projections of increased aridity are correct DNC, within the southern part of its range may be replaced by drought-resistant Pinus silvestris and Larix sibirica.

Keywords: climate-induced tree mortality, drought impact on forests, tree die-off, Siberian pine decline
1. Introduction

Forest decline and mortality caused by drought during the last decades has been documented on every continent (Allen et al., 2009). Elevated temperatures and water stress has caused forest mortality in Europe, including increased stand mortality in Spain (Penuelas et al., 2001), France (Breda et al., 2006; Landmann and Dreyer, 2006), Switzerland and Italy (Bigler et al., 2006; Dobbertin and Rigling, 2006). In North America *Populus tremuloides* mortality was observed across a million hectares (Hogg et al., 2008; Worrall et al., 2010; Anderegg et al., 2012). In the south-western part of USA drought-induced mortality of *Pinus edulis* was also documented for an area of over a million hectares (Breshears et al., 2005; Raffa et al., 2008; Van Mantgem et al., 2009). In Russia birch (*Betula pendula*) stands decline was recently described in the southeastern Siberia forest-steppe (Kharuk et al., 2013).

Scenarios of climate changes are likely to include further increases in drying, frequency and severity of droughts in some forested areas (Christensen et al., 2007; IPCC, 2007; Seager et al., 2007; Sterl et al., 2008; Aitken et al., 2008). This may lead to reduced forests growth and increases in stress and mortality caused by synergy of drought impact and climate-induced changes in the dynamics of dendrophyl insects and fungi (Lucht et al., 2006; Scholze et al., 2006; Lloyd and Bunn, 2007). Severe water stress is decreasing both growth and oleoresin production, making trees more susceptible to bark beetle attack. In addition to water stress affecting host tree susceptibility, insect population dynamics were directly affected by increasing temperature (Hansen et al., 2001; Breshears et al., 2005).

In Russia decline and mortality of “dark needle conifers” (DNC: spruce (*Picea obovata*), Siberian pine (*Pinus sibirica*), fir (*Abies sibirica*)) were reported from the western border (i.e., Kaliningrad region) to the Russian Far East. During the 21st century, climate-caused mortality was described in official Russian reports as the third-ranked factor (following fire and pest impacts) (Efremov et al., 2012). In Archangelsk in the European part of Russia spruce decline was observed over an area >1.6 million ha with mortality on the territory >390 thousands ha (Fig. 1 (site 1)). Other potential causes of forest mortality considered were over mature stands, drought, root fungi and insect attacks (Chuprovo, 2008; Sanitary, 2008). In the Russian Far East, mortality was reported over the vast area of mixed spruce (*Picea ajansis*) and fir (*Abies nephrolepis*) forests within the Sihote-Alin Ridge (Fig. 1 (site 7)). Mortality was observed mainly for the mature stands (Age =100-160 years), whereas regeneration was usually not damaged. Decline and die-off of spruce-fir stands were considered to be caused by “unfavorable climatic factors with fungi as a co-factor” (Man’ko et al., 1998). According to the Russian Forest Service,
Siberian pine and fir decline and mortality were observed in the southern Siberian Mountains (Kuznetzky Alatau and Sayan Mountains) and in the Baikal Mountains (mixed fir and Siberian pine stands) (Fig. 1 (Sites 2, 3, 4, 5)). In addition, birch mortality was documented in the Trans-Baikal area (Kharuk et al., 2013 (Fig. 1 (site 6)).

The goal of this paper was spatial and temporal analysis of Siberian pine mortality within the Kuznetzky Alatau Mountains, and analysis of potential causes of this phenomenon. We considered the following hypotheses. 1. Siberian pine decline and mortality were caused by drought. 2. Mortality pattern was dependent on relief features. The following questions were also addressed: When did the Siberian pine decline and mortality begin? What were the causes of stand mortality? What are the spatial and temporal patterns of mortality?

2. Material and methods

2.1. Study area

The study area (designated as the “Black Iyus” (BI) site) was located within the Kuznetzky Alatau Mountains (Fig. 1). These mountains are part of the Sayan-Altai Mountains in southern Siberia and composed of several northward oriented ridges with length and width about 300 km and 150 km, respectively, and maximal height about 2200 m. These mountains have relatively gentle slopes and are composed of limestone, quartzite, argillaceous and siliceous slates, with multiple intrusions of granites, diorite, gabbro and tuff.

2.2. Climate

Monthly climate data for the area were obtained from KNMI Climate Explorer (Climate Explorer, http://climexp.knmi.nl). Data were averaged for a cell size 0.5°×0.5°. Climate within the study area is continental with cold long winters and warm or hot summers. On western facing slopes annual precipitation is about 600-800 mm (with >1500 mm) within the central windward part of mountains). The western facing slopes actually create a "rain shadow" effect that results in a decrease in precipitation on the eastern slopes, where annual precipitation were in the range of 400-500 mm. Winter winds (predominately from the south-west) resulted in greatest accumulation of snow on northern and eastern slopes. Climate data for the BI site are presented in Table 1 and Fig. 2 (the beginning of the record is considered to be the year 1940 when reliable meteorological observations started). According to this record, mean January and July temperatures are -21.4°C and +16°C, respectively.
Fig. 1. Location of forest stands decline and mortality in Siberia. Background: evergreen conifer map (Bartalev et al., 2011). Color scale: SPEI (Standard Precipitation Evaporation Index) anomaly (2000-2009 vs 1902-2009 yr.). Sites: 1 – spruce stands in Archangelsk region; 2 – DNC of Kuznetzky Alatau Mountains; 3, 4 – DNC stands in southern Siberia; 5 – fir and Siberian pine site in southern Baikal area; 6 – birch stands within Trans-Baikal area (Kharuk et al, 2013); (7) – spruce stands in Russian Far East (Man’ko et al, 1998).

Table 1. Climate data for the “Black Iyus” site.

<table>
<thead>
<tr>
<th>Variable (1940-2009 yr)</th>
<th>Ann</th>
<th>Jun-Aug</th>
<th>Dec-Feb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean temperature, °C</td>
<td>-2.2</td>
<td>14.5</td>
<td>-20.0</td>
</tr>
<tr>
<td>Mean sum of precipitation, mm</td>
<td>562</td>
<td>234</td>
<td>71</td>
</tr>
</tbody>
</table>

2.3. Vegetation

In Kuznetzky Mountains, tundra communities are typical at high elevations (1350-1500 m.a.s.l.) with mountain-tundra soils. Within the subalpine belt (1100-1350 m) alpine meadows and sparse vegetation (Betula tortuosa, Larix sibirica, Pinus sibirica and Abies sibirica) grow on
mountain-subalpine soils. Top and middle parts of the forest belt (600-1100 m) are composed of Siberian pine dominated stands with an admixture of fir and spruce (*Picea obovata*). Soils are mountain light-grey rocky podzolized. Low elevations are occupied by larch and pine (*Pinus silvestris*) stands with admixture of Siberian pine and birch (*Betula pendula*). Here soils are mountain rocky podzolized. Steppes are found on steep south facing slopes at the lowest elevations (500-600 m.a.s.l.)

![Fig. 2](https://example.com/fig2.png)

**Fig. 2.** Climate variables within “Black Iyus” site. (a), (b) - mean air temperature and precipitation anomalies, correspondingly (1 – annual, 2 - May-August data); (c) – anomaly of SPEI drought index; (d) – annul (1) temperature and (2) precipitation. Trends for annual temperature (a) and SPIE (c) were significant at p<0.05.

2.4. **Field studies**

Forest mortality within the BI site was reported by local foresters in the year 2006. Field studies were executed in the summer of 2012 and included forest type description, trees height and diameter measurements, canopy closure estimation, and cutting of tree disks for
dendrochronology analysis. The BI site is located within an area with elevations of about 640-1040 m a.s.l. Stands are formed by Siberian pine (>95% of trees) with admixture of Abies sibirica and Picea obovata. Canopy closure was about 0.8-0.9. Average tree height was about 30 m, and DBH was 28 cm. Stands were mature (mean age of trees was about 160 years; the maximum Siberian pine lifetime is about 600-800 years). Ground cover was mesophytic (sedges dominant). Litter thickness was about 3-5 cm. Soils were light-gray forest type underlined by stony clay at 10-15 cm deepness. There were no signs of fires within study area, i.e., there were no carbon and burnmarks on the boles. During the year of ground measurements logging was carried out within areas of stands dieback and mortality. It is necessary to note that according to Russian forest rules logging of Siberian pine stands is strictly prohibited except in decline or dead stands. The area of logging within BI site is about 15 ha. Discs for dendrochronology analysis were collected at about breast height.

2.5. **Dendrochronology analysis**

The dendrochronology dataset included 56 disks (24 from living trees, 11 from declining and 21 from dead trees). The surface of each disk was sanded, planed with a scalpel and treated with a contrast enhancing powder. The widths of tree rings 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 and cross dating of chronology (Holmes, 1983; Rinn, 1996). Dates of tree mortality were determined based on the master-chronology method (Fritts, 1991). An initial master chronology was constructed based on 10 living trees. This master-chronology was used for cross dating of the remaining samples. As soon as a given sample was dated, it was included into the master chronology. This procedure provided increased reliability of further analysis. The final master chronology included 39 individual tree-ring series. The mean coefficient of correlation between individual tree-ring series and master-chronology was 0.43. The mean sensitivity of individual series included into master-chronology was 0.173. Discs with missing rings (n = 8) were not included into the master-chronology, but were involved in further analysys. Disks which were not possible to cross-date (n = 9) were removed from further analysis. Thus the final dataset (n = 47) was divided into “survivors” (n = 15) and “dead and declining” (n = 32) groups. This division was based on radial increment trends during the last decade (2000-2011) as described.

Trees with positive tree ring increments formed a “survivors group”, whereas a second group contained trees with negative increment trend and dead trees. For both groups standard and residual chronologies were constructed. Standard chronologies were indexed using ARSTAN
software (i.e., double detrending to remove long-term trends by negative exponential curve and a linear regression; Cook and Holmes, 1986). The resulting chronologies were a unitless index of radial tree growth. The residual chronologies were constructed based on standard chronologies by elimination of autocorrelation, i.e., increasing a climate signal (Cook and Holmes, 1986). Statistical analysis was carried out using Excel and StatSoft software; Student’s t-test was used to estimate result significance (StatSoft Inc, 2013). In addition to the correlation coefficient (r), the coefficient of synchronization (rs) was determined. The latter was calculated as the ratio of the number of annual segments with the same direction (i.e., increasing or decreasing growth increment) to the total segment number (Shiyatov, 1986).

2.6. Satellite data

2.6.1. Aqua/MODIS and Terra/MODIS data analysis

Aqua/MODIS and Terra/MODIS satellite data were used for temporal analysis of stands vigor based on Enhanced Vegetation Index (EVI). EVI is responsive to canopy structural variations, including leaf area index, stands vigor, canopy type, plant physiognomy, and canopy architecture (Huete et al., 1999). Technically EVI data are available as a ready to use MODIS product MOD13Q1 from NASA’s site (EOSDIS, http://reverb.echo.nasa.gov). For this purpose a temporal series of satellite data from MODIS products were compiled.

EVI is defined as:

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

where \( \rho_{NIR} \), \( \rho_{red} \) and \( \rho_{blue} \) 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 (Huete et al., 1999).

In this study the MODIS EVI values covered the period from 2000 to 2012 with ground resolution of 250×250 m. Earlier it was reported that Terra/MODIS sensor degradation impacted NDVI trend analysis (Wang et al., 2012). Here Terra/MODIS data were used for the 2000-2001 period only, when there was no significant sensor degradation. The time interval 2002-2012 was analyzed based on Aqua/MODIS data which were already corrected (Wang et al., 2012).

A mask of evergreen conifers for the whole of Siberia and the study area in particular was generated based on the Terra Norte forest vegetation map (Bartalev et al., 2011). This mask was used to track changes within evergreen conifer stands only.
2.6.2. Landsat data and GIS analysis

Landsat scenes (MSS/TM/ETM+, 15-60 m spatial resolution, acquired during the years 1976-2012) were obtained from USGS GloVis (http://glovis.usgs.gov). The selected scenes were georeferenced to topographic maps (scale 1:100000). Dead stands (i.e., those exhibiting >75% tree mortality) were visually detectable on the images. The total area of the analyzed territory was 382 ha. An analysis of the scenes showed that stand mortality could be detected as early as the year 2006. Also available were digitized maps of dead stands produced by a forestry expert for each year from 2006 to 2012. Image interpretation was facilitated by data acquired from our field studies. Polygons were delineated on an image display and recorded by ArcGIS software (http://www.esri.com).

Topography analysis of stand mortality was based on the DLR SRTM-X DEM product (http://eoweb.dlr.de:8080/index.html). DEM horizontal accuracy was ±20 m (absolute) and ±15 m (relative). The vertical accuracy was ±16 m (absolute) and ±6 m (relative). The minimum interval (contour) of elevation of 50 m was used. The following parameters were considered: elevation, aspect, slope steepness, and curvature (i.e., convex/concave slope parameters). Aspect, slope steepness and curvature data were calculated from SRTM-X DEM using ArcGIS tools. The aspect data were quantized into eight directions (i.e., by 45 degrees corresponding to north, northeast, east etc.). The distribution of landscape elements with given altitude, azimuth and slope steepness was uneven within the analyzed area and thus could lead to biased analysis. To avoid this, the data were normalized by the following procedure. The analyzed study area (about 400 ha) with given azimuth, slope steepness and elevation was related to the larger (“reference”) territory (ca 3000 ha) with similar parameters:

\[
\kappa_{c(i)} = \frac{A_{c(i)-f}}{A_{c(i)-I}}
\]  

where the \(c(i)\) subscript represents the \(i^{th}\) category of landscape feature \(c\), \(A_{c(i)-f}\) is the area of the given on-ground class within the \(i^{th}\) category of the topography feature \(c\), and \(A_{c(i)-I}\) is the area of the \(i^{th}\) category of topography feature \(c\) over the “reference” territory. ERDAS Imagine software (http://geospatial.intergraph.com) was used in the analysis.

2.7. Water balance estimation

For water balance estimation, the Standardized Precipitation-Evapotranspiration index (SPEI; Vicente-Serrano et al., 2010) was used. Like the PDSI (The Palmer Drought Severity Index;
Palmer, 1965), the SPEI measures drought severity according to intensity and duration, and can be used to identify the onset and end of drought episodes. The SPEI uses the monthly difference ($D_i$) between precipitation and PET (potential evapotranspiration):

$$D_i = P_i - PET_i$$

PET (mm) is obtained by:

$$PET = 16 \times K \times (10 \times T \times I)^m,$$

where $T$ is the monthly mean temperature in °C; $I$ is a heat index, which is calculated as the sum of 12 monthly index values, $m$ is a coefficient depending on $I$, and $K$ is a correction coefficient computed as a function of the latitude and month which takes into account number of sun hours in a day. SPEI data for the study area were calculated for the May-August period. May was added to summer period because May droughts were typical for the study area. Spatial resolution for the SPEI data was 0.5°×0.5° (~33×56 km²).

3. Results

3.1. Remotely sensed data

An overall decrease in Vegetation index (EVI) for “dark needle conifers” stands was observed within the Kuznetzky Alatau Mountains. This decrease in "greenness" was correlated with drought during the first decade of the 21st century (Fig. 3a, b). Within the BI site EVI decreased about ~4% (p<0.05) between 2006 and 2012, and was accompanied with a drought increase (Fig. 3c). The dynamics of forest mortality are presented on Fig. 4, 5. With an increase in drought (i.e., SPEI decrease) the dead stands area increased ($r_1^2 = -0.98$) and stand mortality was propagated along the elevation gradient ($r_2^2 = -0.92$) (Fig. 5).

3.2. Relief features

Maximum mortality was observed on the slopes of southern and southeastern exposures (Fig. 6b). The location of dead stands was relatively higher within convex terrain elements (Fig. 5c). With respect to slope, mortality was maximal within the range of slopes between 7° and 20° (>75% mortality; Fig. 6c). With respect to elevation, mortality was observed mainly within the lower elevation belt (starting from Black Iyus river level: 650 m a.s.l.) and decreasing upwards. No mortality was detected above 900 m (Fig. 6d). The elevational limit of tree mortality was negatively correlated with SPEI (Fig. 5).
3. Dendrochronology data

The statistics of master-chronologies (both standard and residual) for “surviving” and “dead and decline” groups are shown in Table 2. The mean tree ages of “survivors” and “dead and decline” groups were 154 and 173 years, respectively. All groups have relatively high correlations between individual series and master-chronology ($r^2=0.39-0.41$). Mean sensitivity values which signify the relative change in ring-width from one year to the next, were low for all
Fig. 5. Dynamics of forest mortality with respect to relief features. (a) - mortality dependence on aspect, (b) - mortality distribution with respect to slope steepness (dashed line: a median, thin lines: boundaries of 75% of dead stands area), (c) – mortality distribution on concave/convex relief features, (d) - mortality dependence on elevation. Groups (0.180-0.183; i.e., the climate signal was low), which is indicative for trees with a favorable growth pattern (Shiyatov, 1986). Correlations for “survived” and “dead and decline” chronologies with master-chronology (0.92-0.97) were very high, i.e., trees growth pattern was homogeneous (Fritts, 1991).

<table>
<thead>
<tr>
<th></th>
<th>Tree group</th>
<th></th>
<th>Master Chronology</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>&quot;Survivors&quot;</td>
<td>&quot;Dead &amp; decline&quot;</td>
<td></td>
</tr>
<tr>
<td>Mean ring width (mm)</td>
<td>0.94</td>
<td>0.84</td>
<td>0.95</td>
</tr>
<tr>
<td>Maximum ring width (mm)</td>
<td>3.88</td>
<td>5.12</td>
<td>4.86</td>
</tr>
<tr>
<td>Mean sensitivity</td>
<td>0.180</td>
<td>0.183</td>
<td>0.173</td>
</tr>
<tr>
<td>Interseries correlation</td>
<td>0.39</td>
<td>0.41</td>
<td>0.43</td>
</tr>
<tr>
<td>Autocorrelation</td>
<td>0.69</td>
<td>0.63</td>
<td>0.60</td>
</tr>
</tbody>
</table>
No significant correlations were found between radial tree growth and temperature and precipitation. The relationship between tree radial growth and SPEI index was developed from correlations over the period from 1940 to 2009 yrs (with window sizes of 3, 5, 7, 9, 11 and 15 yrs). To do this, a correlation was established between the first selected years of the climate record and the corresponding years for the tree-ring record. The same process was repeated with a 1-year lag through the end of the SPEI record. Similarly, a coefficient of synchronization was calculated. Tree radial increment was significantly correlated and synchronized with SPEI drought index ($r^2 = 0.37$, $rs = 80$; Fig. 7). Trajectories of “dead” and “survivors” diverged at the beginning of the 21st century. Tree mortality was observed after the 1998 drought (Fig. 8).

![Graph showing correlations between SPEI and tree mortality and elevation](image)

Fig. 6. Dead stands area ($1, r_1^2$) and mortality elevation limit correlations with SPIE ($2, r_2^2$). $r_1^2$ and $r_2^2$ are significant at $p < 0.02$ and $p < 0.08$, correspondingly.
Fig. 7. Running 15-year coefficients of synchronization (1) and correlation (2) between tree ring radial growth SPIE and. 3 – level on medium (>69%) synchronization, 4 – significance level (p>0.05) for correlation coefficients. Note: synchronization coefficient values $0.69 > r > 0.50$ were considered as a low, $r > 0.69$ were considered as a satisfactory (Shiyatov, 1986).

Fig. 8. Tree ring chronology of (1) “survivors” and (2) “dead and decline” trees. Confidence interval (p< 0.05) shown by grey background. 3 - SPEI dynamics, 4 – percentage of sampled dead trees (n=21) which dying in the given year.
4. Discussion

Siberian pine mortality was tracked since 2006, when mortality was first detectable (Fig. 4a, b). The spatial pattern of dead forest stands was uneven with respect to topographic relief features. Dead stands were mainly located on slopes with southern aspect (Fig. 6b). This pattern is typical for drought-induced mortality (e.g., aspen mortality in the western US (Huang and Anderegg, 2012), or birch mortality in Trans-Baikal area, Russia (Kharuk et al., 2013). The area of dead stands was correlated with a drought increase ($r^2 = 0.98$; Fig. 5).

The majority of dead stands were located on relatively steep slopes with the median at about 13° (Fig. 5c). The slope and aspect of those stands are approximately normal to peak direct solar radiation during the middle of June to the beginning of July (when sun elevation angles reach about 60°). Mortality was relatively higher within convex terrain elements (Fig. 5c), whereas within areas of higher soil moisture (e.g., toeslopes and river alluvium terraces) mortality was lower. These facts suggest moisture stress as a factor of forest mortality. The other evidence of moisture stress impact is a strong correlation between mortality and drought index (Fig. 8).

Mortality was maximal within the lower elevation belt (starting from the footslope) and decreased with elevation with no signs of mortality above 900 m (Fig. 4b). This elevational pattern could be attributed to increased precipitation at higher elevations. Within the study area precipitation increased with elevation by about 1.8 mm m$^{-1}$, which translates into 460 mm more precipitation at 900 m in comparison with 650 m (i.e., where mortality was first observed; Fig. 4). As drought increased, mortality extended uphill and reached elevations of 900 m by the year 2012 (Fig. 6). The upward shift of mortality was correlated with SPEI values (Fig. 5). It is important to note that Siberian pine (which is also known as "tree-of-fog") is a precipitation-sensitive species with optimal precipitation values $>1000$ mm year$^{-1}$. At higher elevations (in addition to precipitation increase) frequency of fogs (clouds) also increased. A drought impact on Siberian pine was amplified by shallow well-drained soils especially at convex relief features.

Notably, less drought-sensitive birch and aspen trees, which make up about 1-3% of Siberian pine stands, did not exhibit signs of drought impact.

Dendrochronology analysis also supported the hypothesis of the primary role of drought stress in Siberian pine stands decline and mortality. Drought increase (Fig. 3b, c) was accompanied by a decrease in radial increment (Fig. 7). Similar observations were reported for aspen growth during drought years (Hogg et al., 2008). Starting at the end of the 20th century trees increment trajectories diverged. The "decline and dead" group showed negative increment trends, whereas "survivors" temporarily increased their growth increment (Fig. 7). The growth release in the surviving and declining trees was likely caused by a decrease in competition with the dying trees since the surviving and declining trees were interspersed within the same stand. With drought
increase in the following years (2008-2009) radial increment of “survivors” also decreased (Fig. 7).

Synchronization between tree radial growth and SPEI increased after 1960 and became significant by the middle of the 1970s with highest values observed during the last decade (Fig. 7). Similarly, correlation between tree radial growth and SPEI was significant in the mid 1990s and beginning of the 21st century and were increased by repeated extreme droughts during the last decades (1998, 2003 and 2012 yrs; Fig. 7). This coincided with observations of other authors of increased growth sensitivity to climate in the years preceding mortality (McDowell et al., 2008). Increased synchrony between tree ring growth and SPEI also suggest that past droughts narrowed the Siberian pine ecological niche. Thus, Siberian pine mortality occurred after exposure to prior droughts (years 1998, 2002) that initiated tree ring growth decline (Fig. 8).

Similarly, aspen stands (Populus tremuloides) experienced severe stress in the beginning of the 21st century, which caused mortality of stands (Worrall et al., 2010; Anderegg, 2012). The progressive decrease of tree increments (Fig. 8) indicated, along with water stress, the presence of other effects (including possibly carbon starvation). Although in recent studies of aspen die-off in western North America no evidence was found that drought stress led to depletion of carbohydrate reserves (Anderegg et al., 2012). A potential (also secondary) role in Siberian pine decline may be bark beetles attack. Thus, insect and larvae galleries were observed within the bark and xylem of severely weakened and dead trees. It is known that bark beetles attacked weak and old growth trees (e.g., Kharuk et al., 2004). However, this was not the case within the study area where stands were not over mature (mean tree age was 160 years) and Siberian pine stands become overmature at Age >300 yr. Evergreen conifer decline and mortality in some Russian forests were also attributed to root fungi impacts, which were facilitated by a drought-caused decrease in stand vigor (Chuprov, 2008; Pavlov et al., 2008). Fungi and insect attacks should be considered as drought co-factors in the DNC decline phenomenon, which agrees with conception of multiple mechanisms of drought-induced mortality (water stress, carbohydrate depletion, and insect, fungi and bacterial attack) (McDowell et al., 2008; McDowell, 2011; Anderegg et al., 2012; Choat et al., 2012; Fettig et al., 2013).

The problem of Siberian pine decline has a special significance for forest management, because Siberian pine stands logging is strongly prohibited with the exception of declined stands. In the last case, selective cutting is allowed. Thus legitimate forest harvesting is dependent on timely management decisions based on forest monitoring data. Increasing climate impacted Siberian pine mortality during recent decades and expected increase of precipitation-sensitive species mortality point to the need for changes in forest management policy.
The studied site is within the marginal area between the forest-steppe and black taiga area, and further increases in drought impacts may turn this area into forest-steppe. This will lead to, in particular, introducing drought-resistant species (*Pinus silvestris, Larix sibirica*) via natural succession. Meanwhile an expected decrease of the Siberian pine population in this area will not require its assisted migration (as in the case of *Pinus albicaulis*; McLane and Aitken, 2012). This species is not highly threatened by climate change because its area is (1) broad (from ca 49°N to 67°N) (2) there is evidence of climate-driven increase of Siberian pine area by its invasion into larch habitat and into the alpine tundra zone (Kharuk et al., 2005, 2009).

Along the BI site, DNC within the Kuznetzky Alatau Mountains region experienced increased drought (and vegetation index, EVI, decrease) during the end of the 20th - beginning of the 21st centuries (Fig. 3c). Several sites of tree decline and mortality were reported by local foresters within these mountains and its vicinities (Fig. 1, sites 4).

On a broader scale, the Siberian pine stand mortality observed within the Kuznetzky Alatau Mountains is part of the phenomenon of DNC decline and mortality in Siberia, European Russia and Russian Far East. Forest mortality locations based on literature data and the authors’ observations are presented in Fig. 1. Notably all reported areas of DNC decline coincided with the zones of negative SPEI values (i.e., drought increase; Fig. 1). Thus, monitoring of drought severity (SPEI) is likely to be useful as an early warning indicator of climate-related mortality across forests in other areas and regions, especially those composed of drought-sensitive species (*Pinus sibirica, Abies sibirica and Picea obovata*). The data obtained are one of the first observations of drought-induced decline and mortality of DNC at southern border of boreal forests, and supported deforestation scenario within this zone with increasing aridity. Meanwhile with an increase in aridity drought-resistant conifers (i.e., *Pinus silvestris* and *Larix sibirica*) may replace DNC within its habitat. Drought increase may also slowdown Siberian pine seedlings recruitment within the alpine forest-tundra ecotone at southern border of Siberian forests (Kharuk et al., 2010a, 2010b).

This described phenomenon, along with published data on birch stands die-off in the Trans Baikal zone (Kharuk et al., 2013), coincided with world-wide observations of increased episodes of climate-induced forest decline and mortality (Aitken et al., 2008; Worrall et al., 2010; Anderegg et al., 2012), and supports the hypothesis of wholesale redistribution of trees in the next century (Aitken et al., 2008) . Thus, the extent, dynamics and causes of decline and mortality in Siberian "dark needle conifer" forests warrants further investigation.

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Figure captions

Fig. 1. Location of known forest stands decline and mortality in Siberia. Background: evergreen conifer map (Bartalev et al., 2011). Color scale: SPEI (Standard Precipitation Evaporation Index) anomaly (2000-2009 vs 1902-2009). Sites: 1 – spruce stands in Archangelsk region; 2 – DNC of Kuznetzy Alatau Mountains (location of this study designated by the red box); 3, 4 – DNC stands in southern Siberia; 5 – fir and Siberian pine site in southern Baikal area; 6 – birch stands within Trans-Baikal area (Kharuk et al., 2013); 7 – spruce and fir stands in Russian Far East (Man’ko et al., 1998).

Fig. 2. Climate variables within “Black Iyus” site. (a), (b) – mean air temperature and precipitation anomalies, correspondingly (1 – annual; 2 – May-August data); (c) – anomaly of SPEI drought index; (d) – annual (1) temperature and (2) precipitation. Trends for annual temperature (a) and SPEI (c) were significant at p<0.05. Data were averaged for a cell size 0.5°×0.5°.

Fig. 3. EVI and SPEI anomaly for the Kuznetzy Alatau Mountains and BI site. Box indicates location of the BI study area. (a) – EVI anomaly (2012 vs 2000-2012 mean); (b) – SPEI anomaly (2000-2009 mean vs 1902-2009 mean); c) – EVI (1) and SPEI (2) dynamics for the BI site. Bars showed 0.95 confidence level. Trends are significant at p<0.007 (EVI) and at p<0.023 (SPEI).

Fig. 4. (a) Forest mortality map (background: topographic map) and (b) trend of forest mortality from 2006 to 2012 (1 – dead stands area; 2 – elevation limit of dead stands at given year).

Fig. 5. Dead stands area (1, r1²) and mortality elevation limit correlations with SPEI (2, r²). 3, 4 – linear regressions of the dead stands area and mortality elevation limit, correspondingly. r1² and r² are significant at p<0.02 and p<0.08, respectively.
Fig. 6. Characteristics of forest mortality with respect to relief features. (a) – Mortality dependence on aspect; (b) – mortality distribution with respect to slope steepness (dashed line: a median, thin lines: boundaries of 75% of dead stands area); (c) – mortality distribution on concave/convex relief features; (d) – mortality dependence on elevation.

Fig. 7. Running 15-year coefficients of synchronization (1) and correlation (2) between tree ring radial growth and SPEI; (3) – level of medium (>69%) synchronization; 4 – significance level (p>0.05) of correlation coefficients. Note: synchronization coefficient values 69>r>50 were considered as a low, r>69 were considered as a satisfactory (Shiyatov, 1986).

Fig. 8. Tree ring chronology of (1) “survivors” and (2) “dead and declining” trees. Confidence interval (p<0.05) shown by gray background; 3 – SPEI dynamics; 4 – percentage of sampled dead trees (n=21) which died in the given year.