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## RESEARCH ARTICLE

### Birch stands growth increase in Western Siberia

Viacheslav I. Kharuk<sup>a,b\*</sup>, Valeriy V. Kuzmichev<sup>a</sup>, Sergey T. Im<sup>a,b</sup> and Kenneth J. Ranson<sup>c</sup>

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Birch (*Betula pendula* Roth) growth within the Western Siberia forest-steppe was analyzed based on long-term (1897–2006) inventory data (height, diameter at breast height [dbh], and stand volume). Analysis of biometry parameters showed increased growth at the beginning of twenty-first century compared to similar stands (stands age = 40–60 years) at the end of nineteenth century. Mean height, dbh, and stem volume increased from 14 to 20 m, from 16 to 22 cm, and from ~63 to ~220 m<sup>3</sup>/ha, respectively. Significant correlations were found between the stands mean height, dbh, and volume on the one hand, and vegetation period length ( $r_s = 0.71$  to  $0.74$ ), atmospheric CO<sub>2</sub> concentration ( $r_s = 0.71$  to  $0.76$ ), and drought index (Standardized Precipitation-Evapotranspiration Index,  $r_s = -0.33$  to  $-0.51$ ) on the other hand. The results obtained have revealed apparent climate-induced impacts (e.g. increase of vegetation period length and birch habitat drying due to drought increase) on the stands growth. Along with this, a high correlation of birch biometric parameters and [CO<sub>2</sub>] in ambient air indicated an effect of CO<sub>2</sub> fertilization. Meanwhile, further drought increase may switch birch stand growth into decline and greater mortality as has already been observed within the Trans-Baikal forest-steppe ecotone.

**Keywords:** birch stands; CO<sub>2</sub> fertilization; climate-induced tree growth

#### Introduction

Climate-driven ecotones are most sensitive to changes in temperature and/or precipitation (e.g. Holtmeier 2009). This has been documented by the number of observations within alpine and northern forest-tundra ecotones (i.e. in zones of where temperature limits growth).

It has been shown that an increase of summer and winter temperatures along with the extension of vegetation period length caused within stand densification, an increase in tree growth increment and treeline advance into the tundra (e.g. Kullman 2007; Kharuk et al. 2010a, 2010b; Körner 2012; Rannow 2013). Meanwhile, in the forest-steppe ecotone (i.e. zone of precipitation limitation on growth), the air temperature increase may lead to dieback and mortality of stands. Thus, increasing frequency of drought increases mortality of aspen (*Populus tremuloides* Michx.) stands in Canada (Hogg et al. 2008) and birch stands (*Betula pendula* Roth) in the Trans-Baikal region of Russia (Kharuk et al. 2013b).

Along with the changes of climatic variables, significant increase in CO<sub>2</sub> concentration [CO<sub>2</sub>] in the atmosphere was observed during the last century. [CO<sub>2</sub>] has increased in ambient air from 296 to 400 ppm since 1900 (Etheridge et al. 2012; Tans & Keeling 2013). This increase should have resulted in an acceleration of tree growth due to the fertilizing effect of the CO<sub>2</sub>; however,

it has been reported that ambient [CO<sub>2</sub>] is still limiting tree growth (e.g. Norby et al. 2010). The effect of CO<sub>2</sub> fertilization has been found in a number of “in-chamber” experiments (e.g. Ainsworth & Long 2005). The woody species studied responded to the CO<sub>2</sub> increase by a consistent linear growth of plant biomass from preindustrial to ambient concentrations with saturation in the range of 450–550 ppm (Norby et al. 2010; Souza et al. 2010). A synergy of air temperature and [CO<sub>2</sub>] on loblolly pine (*Pinus taeda* L.) growth was shown by Wertin et al. (2012). Meanwhile, there were only a few in situ studies of the elevated [CO<sub>2</sub>r] impact on tree growth. Soule and Knapp (2006) reported that ponderosa pine's (*Pinus ponderosa* Laws.) radial growth increase was caused by elevated [CO<sub>2</sub>]. An observed significant increase of Scots pine's (*Pinus silvestris* L.) stand growth in Spain was attributed to CO<sub>2</sub> fertilization (Martínez-Vilalta et al. 2008). Radial growth of larch (*Larix sibirica* Ledeb.) within the alpine ecotones in the Altai-Sayan Mountains was correlated with rising [CO<sub>2</sub>] (Kharuk et al. 2011). However, the major limitation for this type of research is the lack of long-term in situ observations.

This study was based on forest inventory measurements within a forest-steppe ecotone in Western Siberia starting with the end of nineteenth century (Figure 1). The objective of this paper was to analyze long-term

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changes in the growth of birch stands and its possible relationships with the main climate variables (air temperature, precipitation, and drought) and CO<sub>2</sub> concentration in ambient air. We hypothesize that climate-driven changes in the vegetation growth period and elevated [CO<sub>2</sub>] in ambient air have positively affected birch stand growth (i.e. tree height, diameter, and stem volume).

### Materials and methods

The study area is a forest-steppe ecotone in Western Siberia (Figure 1). This is a plain at elevations about 100–120 m a.s.l. with the local topography variations reaching 2–10 m in height. The tree species recorded were birch (*B. pendula* Roth; about 85%), aspen (*Populus tremula* L.; about 10%), and pine (*P. silvestris* L.; about 5%). The birch stands within the test sites have a similar age (~50 years). The stands are a mosaic landscape with tree stands of areas less than 5 ha occupying about 90% of the study area. Soils are mainly soloth type. The water table level was about at 2.5 m. The climate is continental with cold long winters and warm or hot summers. Mean annual air temperature and precipitation are +0.9°C and 357 mm with mean summer and winter temperature and precipitation reaching +18°C, –17°C, and 158 mm and 52 mm, correspondingly.

Forest inventory data covering the period from 1897 to 2006 were available for the study. Measured parameters

were tree height ( $H$ ), diameter at breast height (dbh), and stands density (trees/ha). The applied inventory techniques did not change and were the same throughout the whole period of measurements. Temporary test plots were established within typical birch stands within the Western Siberia forest-steppe ecotone (Figure 1, Box 1). Test plots were established within stands without signs of natural or anthropogenic impact.

The initial data were composed of 212 test plots with sizes varying within the range of 0.2–0.4 ha. This data-set was equalized with respect to the stands density and tree age. That is, test plots with the following stand density were considered:  $N = N_m \pm \sigma$ , where  $N_m$  is a mean stem number for all test plots and  $\sigma$  is a standard deviation. Similarly, with respect to age, the cohort within the age range of 40–60 years was used. The final data-set included 83 test plots (see Table 1).

Tree stem volume was calculated based on the following equation:

$$V = 1.092g + 0.374gH \quad (1)$$

where  $g$  – tree cross-section at breast height,  $H$  – tree height (Igoshin & Kuzmichev 2008).

The following ecological variables were considered: air temperature and precipitation (summer, winter, and annual), vegetation period length, drought index, and [CO<sub>2</sub>]. The vegetation period length was approximated by the number of

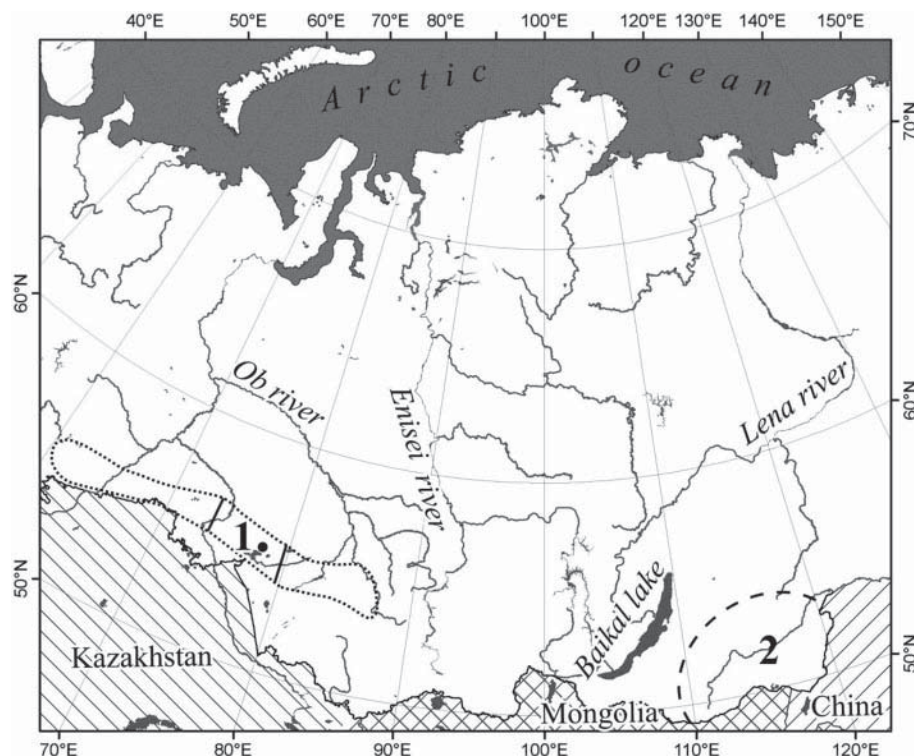


Figure 1. Sketch map of study area location. (1) Filled circle shows Barabinsk Meteorological Station location. Dotted line is the approximated forest-steppe ecotone in Western Siberia. (2) Former study site in Trans-Baikal forest-steppe ecotone (Kharuk et al. 2011).

Table 1. Test plots data ( $N = 83$ ).

Year	Number of test plots	Test plot size (ha)	Number of trees per ha (N/ha)	Age (years)	Height (m)	Dbh (cm)	Stem volume (m <sup>3</sup> /ha)	Basal area (m <sup>2</sup> /ha)
1897	19	0.27	668 ± 200	47 ± 3	13.8 ± 0.4	15.6 ± 1.7	63 ± 18	12.4 ± 2.7
1925	2	0.21 ± 0.15	817 ± 25	50 ± 7	18.4 ± 1.2	17.6 ± 1.7	134 ± 23	19.9 ± 3.3
1960	11	0.31 ± 0.1	778 ± 226	50 ± 8	18.9 ± 1.2	18.7 ± 2.6	170 ± 45	20.4 ± 4.1
1965	5	0.43 ± 0.13	606 ± 206	51 ± 9	18.6 ± 2.3	19.6 ± 3.3	143 ± 30	17.3 ± 2.9
1969	11	0.22 ± 0.06	872 ± 165	48 ± 5	18.0 ± 1.6	17.2 ± 1.8	165 ± 48	20.2 ± 4.8
1974	3	0.42 ± 0.07	635 ± 143	43 ± 3	18.1 ± 0.8	20.1 ± 1.9	155 ± 36	20.0 ± 4.7
1978	7	0.41 ± 0.12	614 ± 146	52 ± 6	19.2 ± 1.5	19.4 ± 2.9	164 ± 74	17.8 ± 5.4
2005	6	–	579 ± 182	56 ± 8	21.9 ± 0.9	23.2 ± 1.6	231 ± 33	23.8 ± 4.0
2006	19	0.27 ± 0.2	629 ± 143	48 ± 7	20.5 ± 1.6	22.2 ± 2.5	211 ± 38	23.9 ± 4.0
Δ (2006–1897)	–	–	–	–	6.7 ± 2.0	6.6 ± 4.2	148 ± 56	11.5 ± 6.7

days with positive air temperatures ( $N_{t>0}$ ). Drought index Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano et al. 2010) was used for water balance estimation. Like the Palmer Drought Severity Index (Palmer 1965), the SPEI can measure drought severity according to its intensity and duration and can identify the onset and the end of drought episodes. The SPEI uses monthly difference ( $D_i$ ) data between precipitation ( $P_i$ ) and potential evapotranspiration (PET). The SPEI uses the  $D_i$  between  $P_i$  and PET:

$$D_i = P_i - \text{PET} \quad (2)$$

PET (mm) is obtained by:

$$\text{PET} = 16 \times K \times (10 \times T \times I^{-1})^m \quad (3)$$

where  $T$  is the monthly mean temperature in C;  $I$  is a heat index [ $I = (T/5)^{1.514}$ ], which is calculated as the sum of 12-month 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 (Vicente-Serrano et al. 2010). SPIE data for the study area were calculated for the period of May–August. May was added to the summer period because spring droughts were typical for the study area. Spatial resolution for the SPEI data was  $0.5^\circ \times 0.5^\circ$  ( $\sim 33 \times 56 \text{ km}^2$ ).

Long-term daily climate data (1900–2007) were obtained from the meteorological station located within the study area (Figure 1). For the whole study area monthly climate data were obtained from KNMI Climate Explorer (Climate Explorer 2012). The data were presented for a cell size  $0.5^\circ \times 0.5^\circ$  or ( $\sim 70 \times 70 \text{ km}$ ); the total averaged area was  $74^\circ\text{E}–80^\circ\text{E}$ ,  $54^\circ\text{N}–56^\circ\text{N}$  (Figure 1). The  $[\text{CO}_2]$  data were obtained from Tans and Keeling (2013) and Etheridge et al. (2012). The statistical analysis (nonparametric Spearman's statistics and

multiple regressions) was based on the Excel and Statsoft software (StatSoft Inc. 2013).

## Results

Since 1897, an increase of stands mean height (+6.7 m), dbh (+6.6 cm), stem volume (+148 m<sup>3</sup>/ha), and basal area (+11.5 m<sup>2</sup>/ha) has been observed (Table 1, Figure 2).

Dynamics of ecological variables during that period were shown in Figure 3.

An increase of annual and summer air temperatures and vegetation period length, as well as  $[\text{CO}_2]$  in ambient air were observed since 1900 (Figure 3a and 3c). Summer precipitation and SPEI actually decreased since 1948 (Figure 3b and 3d).

All stands growth parameters ( $H$ , dbh,  $S$ , and  $V$ ) were positively correlated with the vegetation period length ( $N_{t>0}$ ), summer temperatures ( $T_s$ ), and  $[\text{CO}_2]$ . Negative correlations were observed with SPEI and summer precipitation (Table 2).

An impact of winter temperature was not considered because birch winter damage was not observed within the study area. Winter desiccation and snow abrasion were significant at higher latitudes or within alpine forest-tundra ecotone (e.g. Kharuk et al. 2010a). Some climate variables in Table 2 were correlated. Namely, SPEI drought index was calculated based on the summer temperature and precipitation (Equations 2 and 3). Thus, the latter variables were excluded from the following analysis. Relative input of ecological variables was estimated based on the multiple regression analysis. Equations describing relationships between stands growth parameters (dbh, height, and stem volume) and ecological variables ( $N_{t>0}$ ,  $\text{CO}_2$ , and SPEI) are presented in Table 3.

## Discussion

Long-term observations within the Western Siberia forest-steppe zone have revealed a steady increase of birch stands



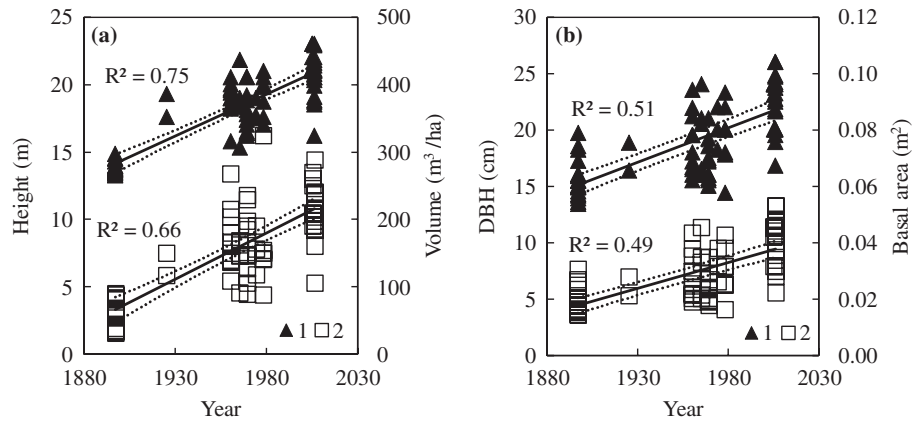


Figure 2. Temporal changes of birch stands biometrics: (a) stem volume (1) and height (2); (b) dbh (1) and cross-section area (2). Trends are shown by solid lines. Confidence intervals ( $p < 0.05$ ) are shown by dotted lines.

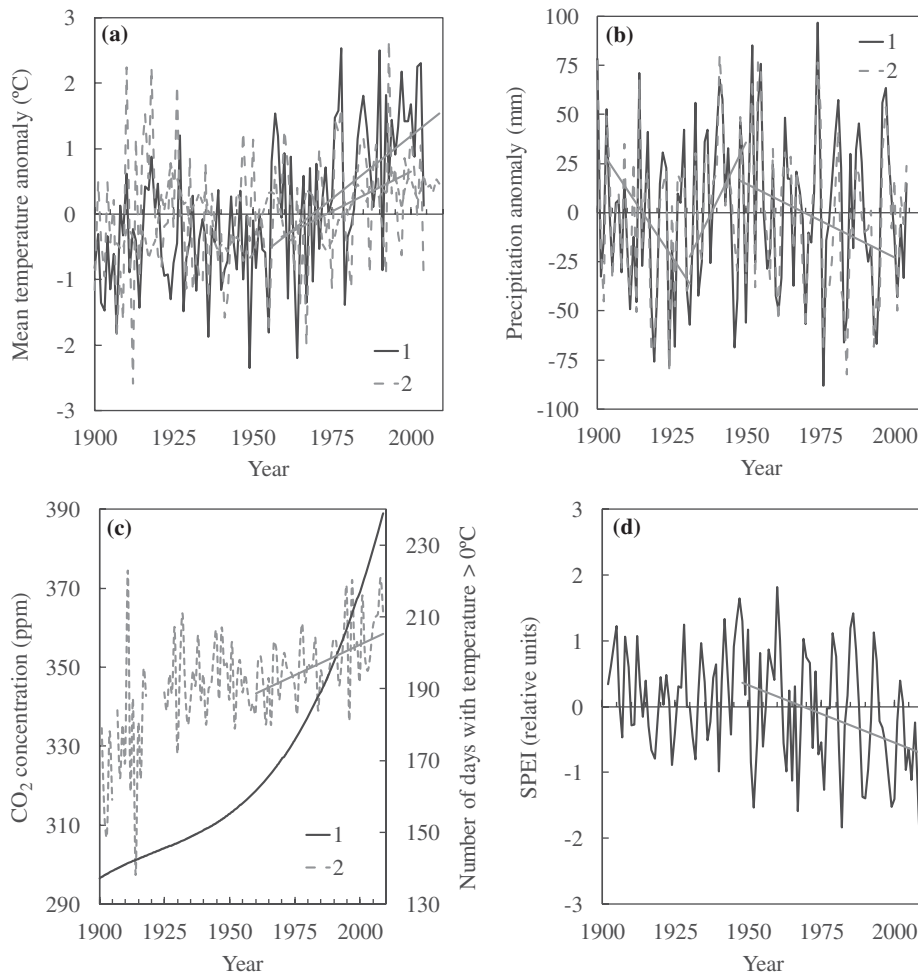


Figure 3. Mean air temperature (a) and precipitation anomalies (b) within the study area; 1 and 2 – annual and summer anomalies, respectively. (c) Vegetation period length,  $N_{t>0}$  (1) and  $[CO_2]$  in air (2) (Etheridge et al. 2012; Tans & Keeling 2013). (d) Drought index. Trends are significant at  $p < 0.05$ .

height, dbh, and stem volume during the last century indicating increased growth. The growth increase was correlated with the vegetation period length ( $r_s = 0.71$  to 0.74), drought index (i.e. SPEI decrease:  $r_s = (-0.33)$  to

$(-0.51)$ ), and  $[CO_2]$  concentration in ambient air ( $r_s = 0.71$  to 0.76). The approximate relative importance of ecological variables was estimated based on multiple regression equations. Coefficients of multiple correlations in

Table 2. Spearman's correlations ( $r_s$ ) between birch stands parameters and ecological variables.

Variable	$H$ (m)	dbh (cm)	$S$ (m <sup>2</sup> /ha)	$V$ (m <sup>3</sup> /ha)
CO <sub>2</sub>	0.75	0.71	0.71	0.76
$N_{t>0}$	0.74	0.71	0.71	0.72
SPEI	-0.39	-0.51	-0.51	-0.33
$T_s$	0.52	0.53	0.53	0.51
$P_s$	-	-0.29	-0.29	-

Note: All correlations are significant at  $p < 0.05$ .

Table 3. Multiple correlations of stands' biometric parameters with CO<sub>2</sub> and vegetation period length ( $N_{t>0}$ ) and SPEI.

Equation	$R^2$	$p$ level
$V$ (m <sup>3</sup> /ha) = <b>0.43</b> ·CO <sub>2</sub> + <b>0.56</b> · $N_{t>0}$ + <b>0.3</b> ·SPEI	0.67	0.01
$H$ (m) = 0.19·CO <sub>2</sub> + <b>0.82</b> · $N_{t>0}$ + <b>0.26</b> ·SPEI	0.77	0.01
dbh (cm) = <b>0.49</b> ·CO <sub>2</sub> + 0.26· $N_{t>0}$ + 0.02·SPEI	0.55	0.01
$S$ (m <sup>2</sup> /ha) = <b>0.54</b> ·CO <sub>2</sub> + 0.19· $N_{t>0}$ + 0.03·SPEI	0.55	0.01

Note: Bold values are significant at  $p$  level  $< 0.01$ .

normalized regression equations can be interpreted as an approximation of the variables importance (StatSoft Inc. 2013). Thus, the main factors influencing a stand's height, dbh, basal area, and stem volume are the vegetation period and [CO<sub>2</sub>] increases during the last century. The positive impact of the vegetation period length on the tree growth was not unexpected because the significance of length of the growth period for tree growth is well-known (e.g. Fritts 1991). The satellite data record has also showed the vegetation period increase within the study area (Xu et al. 2013).

A good correlation between birch growth and [CO<sub>2</sub>] does not mean, of course, a "cause-effect" relationship; thus, CO<sub>2</sub> fertilization effect should be carefully checked. There were no independent observations of the elevated [CO<sub>2</sub>] impacts on tree growth within the study area. Meanwhile, for the other regions, there are some relevant reports. For example, Martínez-Vilalta et al. (2008) attributed Scots pine basal area index increase (about 84%) during the twentieth century to the elevated atmospheric [CO<sub>2</sub>]. The evidences of CO<sub>2</sub> fertilization were also described for *L. sibirica* growth within an alpine forest-tundra ecotone in the Altai Mountains (Kharuk et al. 2011).

Along with the CO<sub>2</sub> fertilization there are other possible impacts on birch stands growth. Namely, "natural melioration" (i.e. birch habitat natural drainage), and potential anthropogenic nitrogen fertilization. We found significant correlations between birch growth and drought index increase ( $r_s = (-0.33)$  to  $(-0.51)$ ). This effect was due to a higher water table within the study area in the

beginning of the twentieth century. Later, increased drought caused reduction in soil moisture content of the birch stands. Negative growth correlation with summer precipitation (Table 2) also supported this conclusion; however, there are no direct data on the soil drainage impact on the stands growth. Again, indirect data (Kurepin 1961) showed an increase of birch growth with reduction of the water table. Thus, birch stands within moist boggy areas had heights between 7–13 m, 14–15 m within wet sites, and 15–20 m within well-drained sites. For Scotch pine decreased soil moisture caused a one-third increase in stem volume (Konstantinov 1999). Additional evidence of climate-driven drought was the decrease of the number of lakes within the study area (and adjacent northward territories; Shiklomanov et al. 2012). Thus, increased drainage was one of the causes of birch stand growth increase. On the other hand, the model has predicted the increase of tree growth following the combined effect of CO<sub>2</sub> and air temperature increases (Matala et al. 2005). Thus, Soule and Knapp (2006) found a significant increase of *P. ponderosa* growth rates especially during the drought year periods. A similar effect was equally probable within the Western Siberia forest-steppe, where drought increase has been observed since 1950s (Figure 2d).

Potential anthropogenic fertilization within the study area did not exceed 3–10 kg ha<sup>-1</sup> yr<sup>-1</sup>, which is far below growth-stimulating rates (Environmental and health atlas of Russia, edited by Feshbach (1995)). Finally, it is important to note that test sites in this study were selected (according to inventory rules) within stands without any signs of anthropogenic impact (e.g. selective cut, pasture, or wildfires).

Thus, the potential causes of the birch stand growth increase in the Western Siberian forest-steppe were the synergy of vegetation period increase, CO<sub>2</sub> fertilization, and reduced soil moisture within birch stands due to increased drought. However, further drought increase in the Western Siberia forest-steppe can switch birch growth into decline and mortality. Indeed, severe drought resulted in the birch mortality within Trans-Baikal forest-steppe ecotone (Figure 1, Site 2; Kharuk et al. 2013b). Similarly, there are evidences of Siberian pine (*Pinus sibirica* (Rupr.) Mayr.), fir (*Abies sibirica* Ledeb.), and spruce (*Picea obovata* Ledeb.) decline following increased growth period within the Southern Siberian Mountains. The likely causes of that phenomenon were drought increase (with severe droughts episodes) in synergy with bark beetles and pathogens (Kharuk et al. 2013a).

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