

Climate-induced mortality of spruce stands in Belarus

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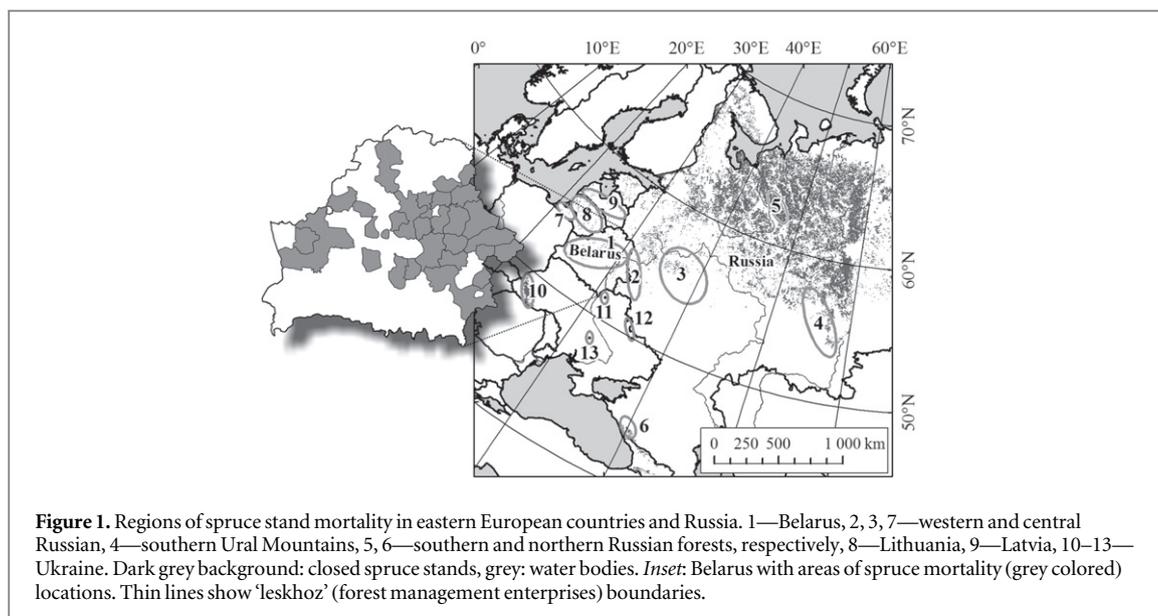
Abstract

The aim of this work is an analysis of the causes of spruce (*Picea abies* L.) decline and mortality in Belarus. The analysis was based on forest inventory and Landsat satellite (land cover classification, climate variables (air temperature, precipitation, evaporation, vapor pressure deficit, SPEI drought index)), and GRACE-derived soil moisture estimation (equivalent of water thickness anomalies, EWTA). We found a difference in spatial patterns between dead stands and all stands (i.e., before mortality). Dead stands were located preferentially on relief features with higher water stress risk (i.e., higher elevations, steeper slopes, south and southwestern exposure). Spruce mortality followed a series of repeated droughts between 1990 and 2010. Mortality was negatively correlated with air humidity ($r = -0.52$), and precipitation ($r = -0.57$), and positively correlated with the prior year vapor pressure deficit ($r = 0.47$), and drought increase ($r = 0.57$). Mortality increased with the increase in occurrence of spring frosts ($r = 0.5$), and decreased with an increase in winter cloud cover ($r = -0.37$). Spruce mortality was negatively correlated with snow water accumulation ($r = -0.81$) and previous year anomalies in water soil content ($r = -0.8$). Weakened by water stress, spruce stands were attacked by pests and phytopathogens. Overall, spruce mortality in Belarussian forests was caused by drought episodes and drought increase in synergy with pest and phytopathogen attacks. Vast *Picea abies* mortality in Belarus and adjacent areas of Russia and Eastern Europe is a result of low adaptation of that species to increased drought. This indicates the necessity of spruce replacement by drought-tolerant indigenous (e.g., *Pinus sylvestris*, *Quercus robur*) or introduced (e.g., *Larix sp.* or *Pseudotsuga menzieslii*) species to obtain sustainable forest growth management.

1. Introduction

Forest mortality is increasing in every continent (Martinez-Vilalta *et al* 2012, Andregg *et al* 2013, Kharuk *et al* 2013a, b, Bond-Lamberty *et al* 2014, O'Connor *et al* 2015), and this phenomenon has been attributed to increased drought episodes in synergy with biotic attacks (Breda *et al* 2006, Aitken *et al* 2008, Allen *et al* 2010, Lausch *et al* 2013, Hart *et al* 2014, Millar and Stephenson 2015). In the USA, Engelmann spruce mortality caused by bark-beetle outbreaks coupled with increasing summer temperatures and water stress has been among the largest and most severe in the documented record (Hart *et al* 2014, O'Connor *et al* 2015). In central and eastern Europe, where Norway spruce often grow in

monocultures, large-scale bark beetle outbreaks have had rapid and pronounced effects on a variety of landscapes (Raffa *et al* 2008, Sproull *et al* 2015). In eastern Europe, spruce (*Picea abies*, *P. obovata*) mortality has been documented in Belarus (Sazonov *et al* 2013), Lithuania and Latvia (Arkhipova 2013, Vasiljuskas 2013), and Ukraine (figure 1, sites 10–13; Usitsky 2013). Spruce monocultures are considered more vulnerable to drought and biotic disturbances (Yousefpour *et al* 2010, Sproull *et al* 2015). Simulation models suggest that by the end of this century climate-induced changes in temperature, precipitation, and the frequency and intensity of extreme disturbance events are likely to reduce the ecological suitability of spruce monocultures in Europe (Feltona *et al* 2010).



In Russia, the decline and mortality of dark-needle conifers (DNCs) have been reported from the Baltic Sea to the Pacific Ocean [DNC: Siberian pine (*Pinus sibirica* (Rupr.) Mayr.), spruce (*Picea obovata* L.), and fir (*Abies sibirica* L.)]. In the European part of Russia, spruce decline has been observed over an area of over 2 million hectares (sites 2, 3–7; figure 1). As potential causes of spruce mortality stands, overmaturity, drought impact, root fungi and insect attacks have been considered (Chuprov 2008, Zamolodchikov 2011). In the Asian part of Russia, fir mortality has been described in Baikal and in trans-Baikal regions; the mortality was attributed to bacterial attacks and climate impact (Roslesozashchita 2010, Stavnikov *et al* 2011). Siberian pine mortality has been observed in the Altai-Sayan region and was caused primarily by drought, with bark beetles and fungi attacks as a co-factor (Kharuk *et al* 2013a). Fir mortality in the Eastern Sayan Mountains over recent decades was attributed to drought episodes in synergy with biotic impact (Kharuk *et al* 2015). In the Russian far east, spruce (*Picea ajansis*) and fir (*Abies nephrolepis*) mortality were described by Man'ko *et al* (1998) and were attributed to unfavorable climatic factors, with fungi as a co-factor. In addition, a hardwood species (*Betula verrucosa*) was negatively impacted by severe drought in trans-Baikal forest–steppe ecotone (Kharuk *et al* 2013b), although in western Siberian forest–steppe ecotone, birch stands showed an increase in growth (Kharuk *et al* 2014).

Along with climate variables, topography may play a significant role in the spatial pattern of drought stress and tree mortality. Relief features (slope aspect and slope steepness) are known to strongly influence site moisture conditions (Whittaker 1967). Consequently, spatial variations in site moisture conditions may influence the spatial pattern and severity of drought-induced tree mortality (Guarin and Taylor 2005). The

potential mediating effects of topography on tree mortality were also evaluated in a few studies (e.g., Lausch *et al* 2013, Kharuk *et al* 2013a, Sproull *et al* 2015).

In this paper, the possible causes of spruce stand decline and mortality in Belarus were analyzed. Spruce mortality in Belarussian forests was documented for an area of about 300 thousand ha, which resulted in 29 million m³ of wood loss (Shatravko 2013, Forest protection 2014). As possible causes of spruce mortality, pollution, insect attacks, and unfavorable climate change were considered (Sarnatskii 2012, Sazonov 2013, Kharuk *et al* 2015). The latter hypothesis has been considered during recent years only, and to date has not been robustly tested.

We aimed to check the hypothesis of drought increase as a primary cause of spruce decline and mortality in Belarus, with biotic impact as a co-factor. We quantitatively analyzed spruce mortality dynamics with respect to (i) the main climate variables (temperature, precipitation, water vapor deficit, evapotranspiration, and drought index), (ii) anomalies in soil moisture, and (iii) relief features (elevation, aspect, slope steepness, and surface curvature).

2. Methods

2.1. Study area

Spruce species are among the dominant forest types in Belarussian forests, and occupy about 750 thousand ha, or 9.5% of forested territory with total stocks of 180 million m³ (Shatravko 2013). The first signs of spruce decline were observed in 1989, with widespread mortality occurring since 1993 (Fedorov and Sarnatskii 2001). The area with spruce mortality in Belarus is shown in figure 1. Spruce mortality dynamics for the period between 1996 and 2012 were described based on forest inventory data (Forest protection 2014). The yearly percentage of spruce mortality to the total area

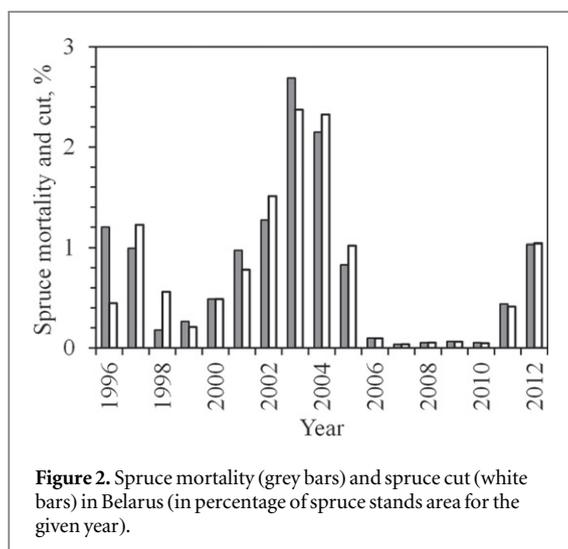


Figure 2. Spruce mortality (grey bars) and spruce cut (white bars) in Belarus (in percentage of spruce stands area for the given year).

of spruce stands derived from the inventory data is shown in figure 2.

2.2. Climate

The climate within the study area is temperate continental with frequent winter thaws. The mean winter, summer and annual temperatures are -5°C , $+18^{\circ}\text{C}$ and $+6^{\circ}\text{C}$, respectively. Mean annual precipitation varies from 500 mm yr^{-1} in the southern region to 800 mm yr^{-1} in the northwestern part. Maximum precipitation falls in the autumn and winter. The temporal dynamics of the climate variables are presented in figure 3. The climate variables analyzed included monthly, seasonal and annual air temperature, precipitation, atmospheric humidity, vapor pressure deficit, evapotranspiration, drought index (SPEI, the standardized precipitation–evapotranspiration Index), the number of spring frost days, and the average daily cloud coverage (in %). SPEI is the difference (D_i) between precipitation (P_i) and potential evapotranspiration (PET_i), where i = period (Vicente-Serrano *et al* 2010):

$$D_i = P_i - PET_i$$

Climate data were obtained from <http://badc.nerc.ac.uk> and <http://sac.csic.es/spei>; data were averaged for cells of $0.5^{\circ} \times 0.5^{\circ}$ ($\sim 33 \times 56\text{ km}$). We considered the following periods: winter, summer, the vegetation period (May–Sep), the hydrological year (Sept–Aug) and the calendar year (Jan–Dec). SPEI data were obtained and averaged for all territories where spruce mortality was observed (figure 1, inset; figure 3(d)).

2.3. Materials

Remotely sensed data (i.e., Landsat, GRACE (Gravity Recovery and Climate Experiment; <http://www.csr.utexas.edu/grace>)) and forest inventory data, forest maps, climate variables and GIS-tools were used in the analysis. Dead spruce stands were detected based on a joint analysis of (1) a map of spruce stands in Belarus

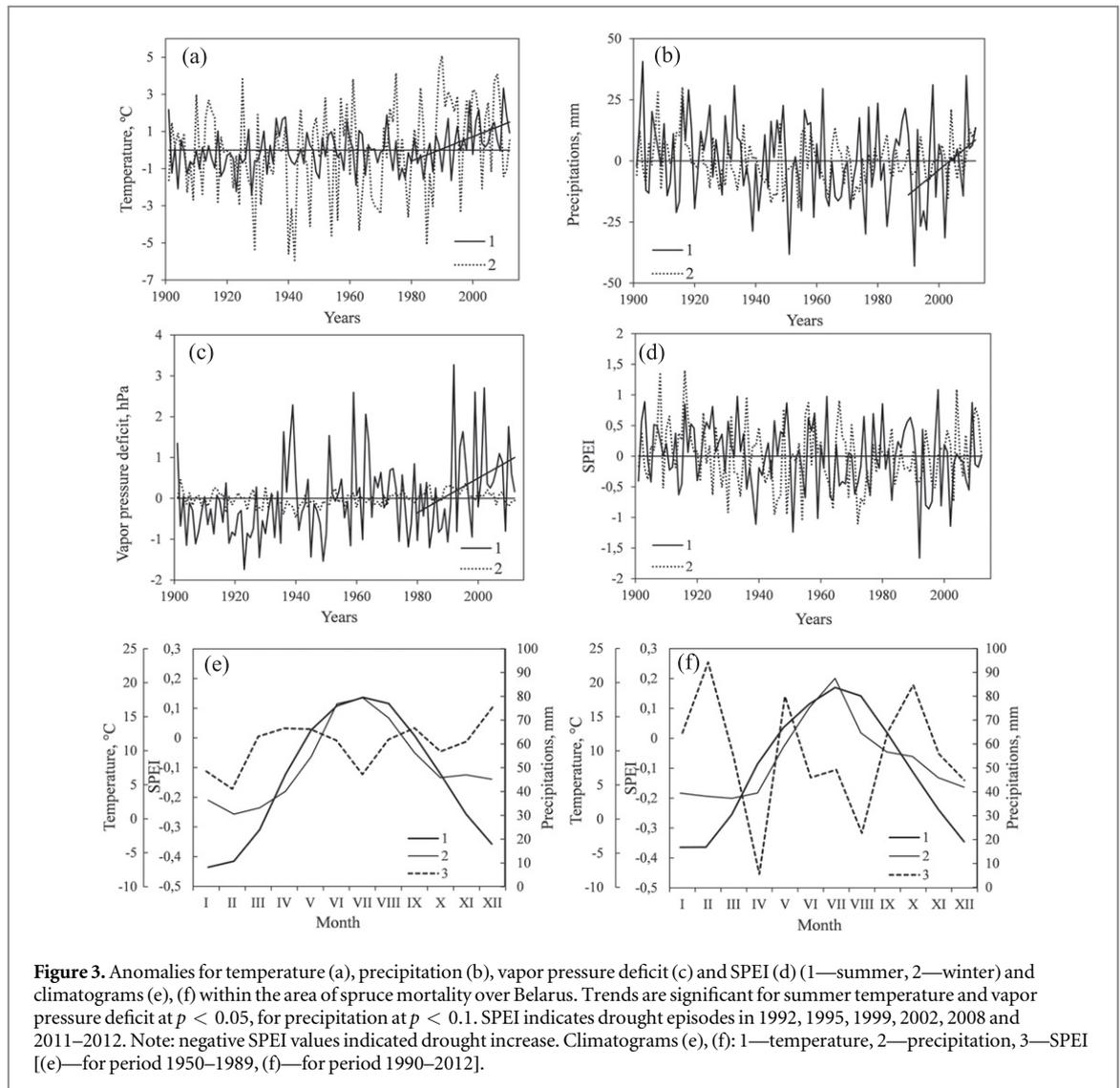
(Isaev 1990), (2) a sketch-map of the territories where spruce mortality was documented (Forest protection 2014; figure 1, inset), and (3) a Landsat-derived Forest Cover Change map for the period between 2000 and 2012 (Hansen *et al* 2013). The latter contains annual forest loss/gain global data with a spatial resolution of 30 m.

A sketch-map of spruce mortality was georeferenced, and then its vector mask was generated. That mask contained all Belarus ‘leskhoz’ (i.e., forest management enterprises) territories (area $S = 89\,502\text{ km}^2$) where spruce mortality was documented. That mask contained both dead and alive stands, as well as non-spruce stands. Then, the area of spruce and mixed stands within that mask was obtained. For that purpose the mask was overlain with the IGBP 2001 forest map, and the area of spruce and mixed stands was extracted ($S = 22\,805\text{ km}^2$). Thus, the total analyzed area was $89\,502\text{ km}^2$ (almost half of the Belarus territory) with $22\,805\text{ km}^2$ of affected stands within it.

The spatial distribution of spruce mortality was analyzed based on SRTM DEM with 90 m resolution (Jarvis *et al* 2008). Topographic aspects were divided into eight sectors (north, northeast, east, southeast, etc); slope steepness was discretized into one-degree intervals. In addition, spruce mortality was analyzed with respect to terrain curvature (i.e., convex or concave surfaces). GIS-analysis was realized using ESRI ArcGIS software (<http://www.esri.com/software/arcgis>). Statistical analysis of the data was carried out in Microsoft Excel and Statsoft Statistica (<http://statsoft.ru>) software. We used regression and Pearson correlation (r) analysis and Akaike information criterion (Akaike 1974) to determine significant relationships between spruce stand mortality, climate variables and soil water anomalies (EWTA, equivalent of water thickness anomalies).

2.4. GRACE data analysis

GRACE gravimetric data was applied for estimation of water anomalies in soil and snow. We used annual and monthly gravimetric values and EWTA for the analysis. EWTA were measured with an accuracy of 10–30 mm/month (Riegger *et al* 2012, Long *et al* 2014). GRACE spatial resolution was one by one degree ($\sim 66 \times 112\text{ km}^2$ at latitude 54°); data available since 2003 (<http://grace.jpl.nasa.gov>). Scale coefficients have been applied to recover signals reduced by filtration (Landerer and Swenson 2012). The satellite data were processed using Erdas Imagine software (<http://geospatial.intergraph.com>) and ESRI ArcGIS software (<http://www.esri.com>). StatSoft Statistica (StatSoft Inc 2013) was used in statistical analysis. GRACE data were analyzed for all ‘leskhoz’ areas where spruce mortality was documented ($S = 89\,502\text{ km}^2$; figure 1, inset, Forest Protection 2014).



3. Results

3.1. Spruce mortality and relief features

Dead spruce stands over Belarus (for the study period of 1996–2012) were unevenly distributed with respect to relief features; the distributions of dead spruce stands and all spruce stands (i.e., before mortality) differ significantly (figure 4). With respect to elevation, maximum mortality was observed at higher elevations (220–240 m), whereas the maximum of the elevation distribution of all spruce stands before mortality occurred at 180–220 m (figure 4(a)). Mortality occurred on relatively steeper slopes (figure 4(b)). With respect to terrain curvature, mortality was mainly on convex surfaces (figure 4(c)). With respect to aspect, mortality was observed mainly on western and southwestern facing slopes (whereas the distribution of stands before mortality was approximately uniform with respect to slope; figure 4(d)).

3.2. Spruce mortality and climate variables

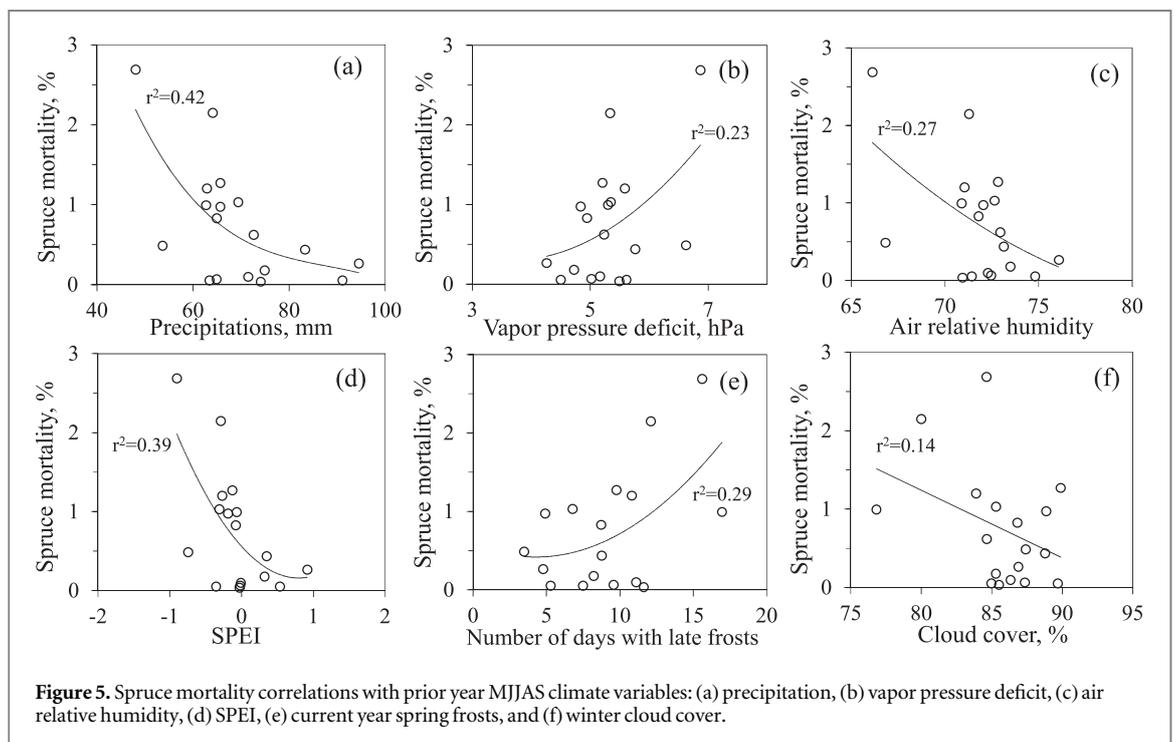
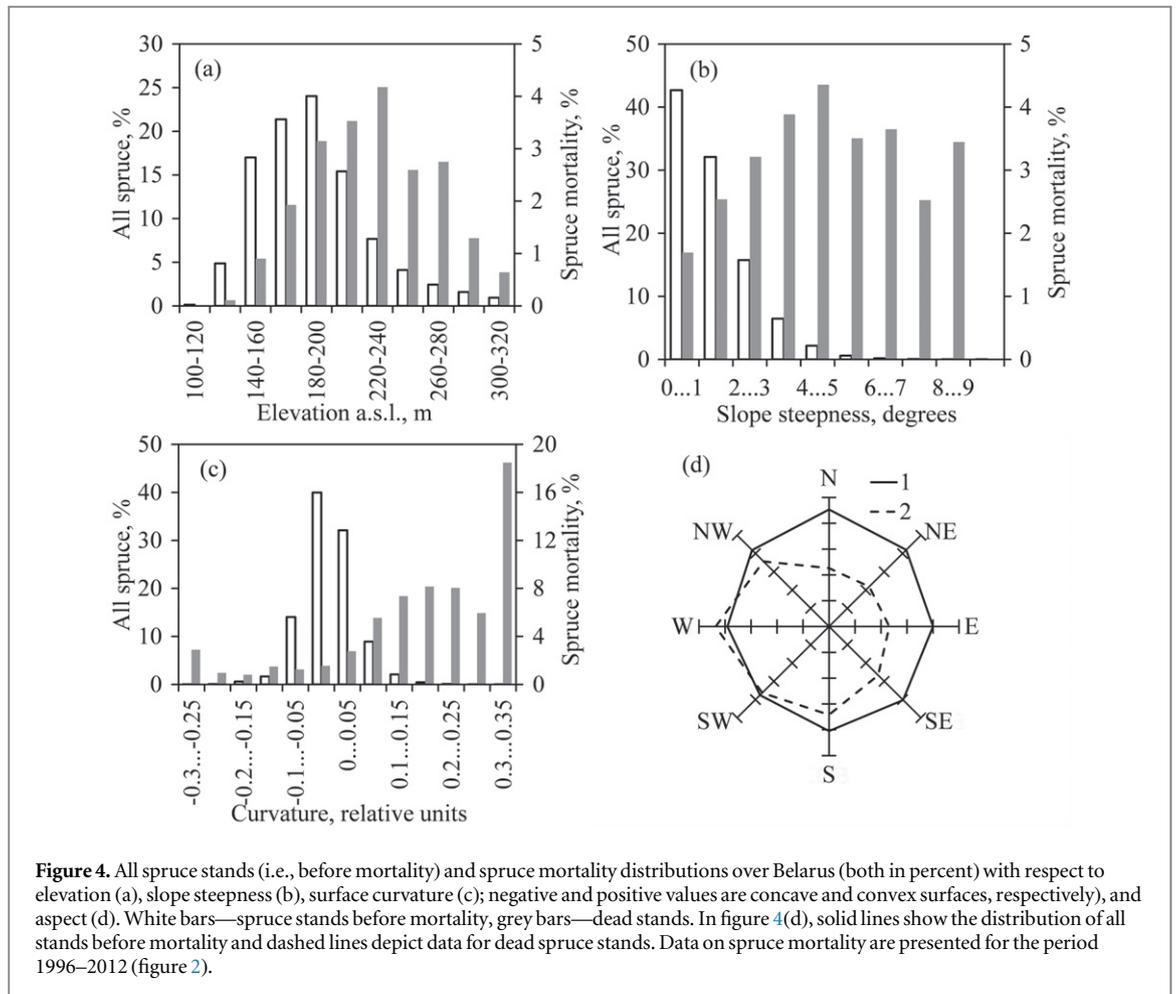
Spruce mortality increased followed consecutive droughts in 1992, 1995, 1999, 2002, 2008 and

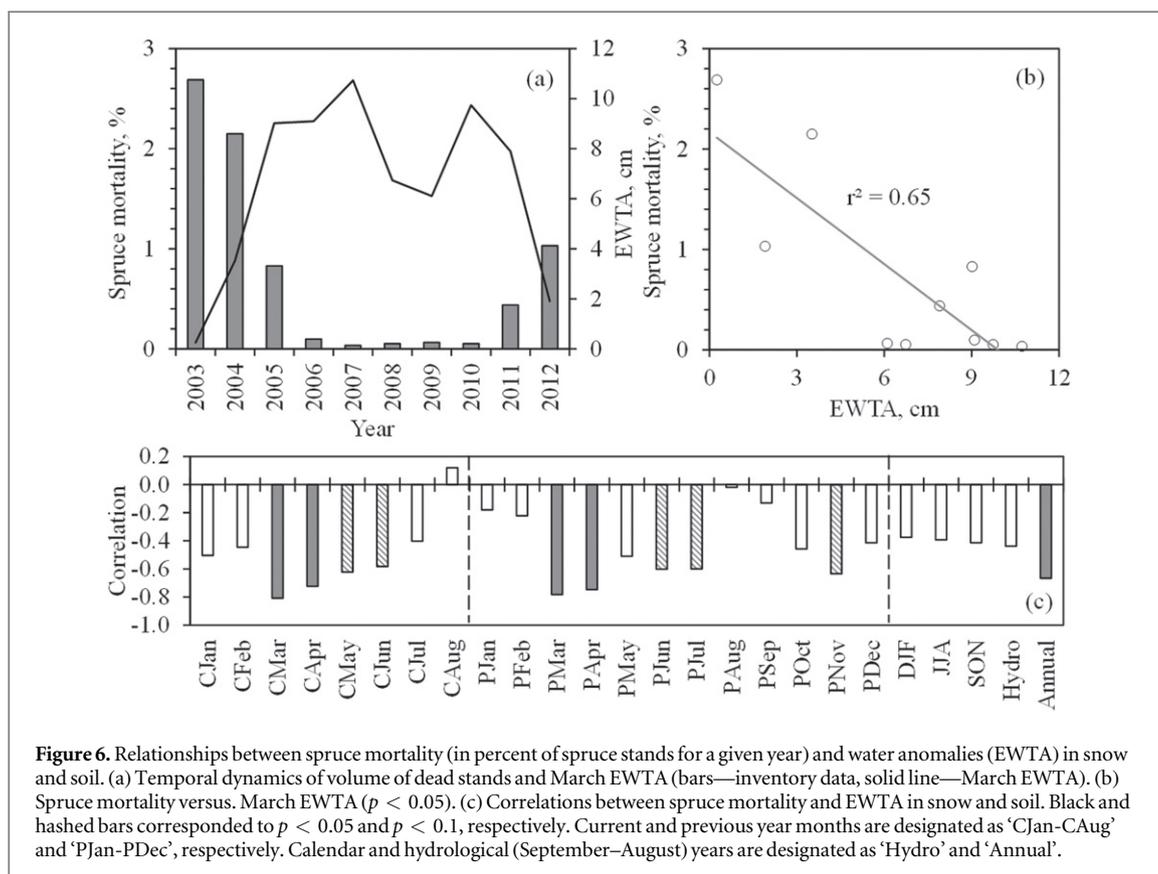
2010–2011 (figure 3(d)). Mortality was correlated with the prior year climate variables and decreased with atmospheric humidity and precipitation increases (figures 5(a), (c)), and increased with vapor pressure deficit and drought increases (figures 5(b), (d)). Notably, the mean drought index SPEI distributions changed significantly since 1989 (i.e., since the first signs of spruce mortality were noticed; figures 3(e), (f)). That is, the drought intensity increased, with the driest conditions experienced in the spring (figure 3(f)). Mortality was also correlated with an increase in late spring frosts (figure 5(e)), whereas a negative correlation between winter cloud coverage and mortality was observed (figure 5(f)). Correlations with air temperatures and evapotranspiration were insignificant.

Multiple regression analysis showed that spruce mortality (M) was related mainly with drought and, to a lesser extent, spring frost impact:

$$M = -0.9*S + 0.1*F - 0.1 \quad (R^2 = 0.48),$$

where S is the SPEI value, and F is the number of days with frosts. The equation is significant at $p < 0.05$; the





coefficients of S and F are significant at $p < 0.05$ and $p < 0.1$, respectively.

3.3. Spruce mortality, snow and soil water anomalies

Considering figure 6(c), spruce mortality is negatively correlated with water accumulation in snow (March–April) and in soil (November of the prior year). Good correlation was observed between the maximum March EWTA (i.e., maximal snow accumulation) and spruce mortality. That is, the higher the snow accumulation, the lower the mortality (figures 6(a), (b)). Similar correlations were observed with annual soil water anomalies and June and July soil water content (figure 6(c)).

4. Discussion

The results obtained indicate that spruce mortality in Belarus is related to water stress. More dead stands were located on the relief features with a maximum water stress risk. In comparison with the stand distribution before mortality, mortality was observed in terrain with relatively higher elevation, steeper slopes, southwestern exposure, and convex relief surfaces (figure 4). The topographic effect on tree mortality (drought- and biotic-induced) has been described in other papers (e.g. Allen and Bre-shears 1998, Lausch *et al* 2013). However, the mortality responses were not temporally resolved.

Spruce mortality in Belarus followed repeated drought episodes during recent decades (figure 3(d)). Significant negative correlations were observed between mortality and prior year atmospheric humidity and precipitation, whereas an increase in vapor pressure deficit and drought caused an increase in mortality (figures 5(a)–(d)). Since the first signs of spruce mortality were observed (in 1989; Fedorov and Sarnatskii 2001), significant changes in the annual pattern of the SPEI drought index occurred. Drought intensity increased, with maximum drought conditions occurring in April (figure 3(f)). Thus, spruce stands experienced spring droughts during recent decades. A persistent spring water stress was one of the factors in Engelmann spruce decline in the western USA (O'Connor *et al* 2015).

Spruce is known to have the highest sensitivity to water stress among conifer species. In contrast to *Pinus sylvestris*, spruce greatly depends on water availability and is vulnerable to both soils and atmospheric droughts. The latter is related to a high leaf area index (LAI), which is the main factor that regulates water balance in trees. Thus, the LAI of Norway spruce stands is about 3.1–4.3 (Pokorný and Stojnič 2012), whereas the LAI of drought-tolerant Scotch pine is about 2.1 (Soudani *et al* 2002). Due to the high LAI, spruce does not tolerate low air humidity, especially in spring, which became a common occurrence in 1990–2000. Positive spring air temperature provoked spruce photosynthesis on the background of low

precipitation and limited melted soil water. That may induce chlorophyll degradation and needle mortality.

Snow water accumulation has a positive effect on spruce vigor (figure 6(b)). Soil water accumulation during the previous year's fall season also leads to a decrease in spruce mortality (figure 6(c)). Prior year precipitation, vapor pressure deficit and drought, as mentioned above, also affected spruce mortality. It is known that prior year climate conditions have a significant impact on current year growth. Thus, tree ring width depends 20–43% on prior year growth conditions (Kagawa *et al* 2006, Skomarkova *et al* 2006). Previous year water accumulation in soil has a positive effect on larch (*Larix gmelinii*) growth (Kharuk *et al* 2015). Previously, Colenutt and Luckman (1991) showed that Engelmann spruce (*Picea engelmannii* Parry), alpine fir (*Abies lasiocarpa* (Hook.) Nutt.), and larch (*Larix lyallii* Parl.) are strongly influenced by the precipitation and growing conditions of the previous year. Bond-Lamberty *et al* (2014) found that both current- and previous-year higher minimum and maximum air temperatures exerted a negative influence on tree growth, while precipitation and climate moisture index had a positive effect.

Along with climate variables, spruce mortality is also correlated with late spring frosts ($r = 0.5$; figure 4(e)). Spruce is known for its sensitivity to late frosts that kill 'flushed' apical shoots (Lesnaya Encyclopedia 1985). In contrast, winter cloud cover is negatively correlated ($r = -0.37$) with spruce mortality. That should be attributed to reduced winter desiccation supported by the observed negative correlation of spruce mortality air humidity during winter months ($r = -0.55$). Climatograms also showed an increase in atmospheric drought in December over recent decades (figures 3(e), (f)).

It is known that drought-weakened trees are targets for insect and fungal attacks (e.g., Fettig *et al* 2013, O'Connor *et al* 2015). Thus, prior year water stress weakens trees, which become susceptible to phytopathogen attacks. Indeed, the spruce mortality in Belarus was followed by bark beetle outbreaks and increased root fungi growth (e.g., Sarnatskii 2012, Sazonov 2013, Sazonov *et al* 2013). Similar synergetic drought and biotic impacts were reported for *Abies sibirica* stands in the East Sayan Mountains, Siberia (Kharuk *et al* 2015). This supports the finding that water stress was the primary cause of spruce mortality in Belarus, whereas insect and fungi attacks are co-factors. Similarly, in studies of Engelmann spruce mortality in Colorado, USA, Hart *et al* (2014) also considered drought stress (i.e., a decrease in host tree defenses) as a trigger for spruce beetle outbreaks. Extensive beetle outbreaks across the Engelmann spruce range are expected in the western United States as a consequence of the climatic trend toward warmer and drier conditions (O'Connor *et al* 2015). The latter agrees with the concept of multiple mechanisms of drought-induced mortality (hydraulic failure, xylem

embolism, and biotic attack; McDowell *et al* 2008, Andregg *et al* 2013, Fettig *et al* 2013, Millar and Stephenson 2015). Other animal induced impacts (e.g. bark peeling by moose and elk) on spruce mortality in Belarus have been documented for young trees within plantations, but not for mature trees (Shatravko 2013).

5. Conclusion

Widespread spruce stand mortality in Belarus was triggered by repeated drought episodes in synergy with pest and phytopathogen attacks, and that is a part of the broader phenomenon of spruce mortality in Lithuania, Latvia, Ukraine and European Russia (figure 1). This phenomenon indicates spruce vulnerability to increase in drought, which raises the question of spruce replacement by drought-tolerant species. One possible adaptation is the introduction of drought-tolerant species (for example, *Larix sp.* or *Pseudotsuga menziesii*) to Belarus forests. According to climate models (Climate Change 2014), a future increase in negative effects is highly probable. Increasing ambient temperature and drought, besides weakening trees, will stimulate pest outbreaks, which in synergy with negative climate impacts may result in the mortality of dark needle forest stands across a significant part of their range (Raffa *et al* 2008, Gauthier *et al* 2015, Millar and Stephenson 2015).

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