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Spatial occurrence of drought-associated damages in Finnish boreal forests: results from forest condition monitoring and GIS analysis

Petteri Muukkonen[1], Seppo Nevalainen[2], Martti Lindgren[1] &
Mikko Peltoniemi[1]

[1] *Finnish Forest Research Institute, P.O. Box 18, FI-01301 Vantaa, Finland*
[2] *Finnish Forest Research Institute, P.O. Box 68, FI-80101 Joensuu, Finland*

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In boreal forests, some growing sites are more vulnerable to decreased soil moisture than others, which might result in stress symptoms in trees and thus affect their growth. We combined Finnish forest health data (ICP Level 1) with GIS data describing growing conditions, soil properties and soil water conditions to find out ways to identify the most vulnerable risk areas. The summer of 2006 was extremely dry, and the relative soil water index (SWI) in August relative to the 30-year average was only about 25%. This led to a higher percentage (24%) of sites (603 in total) where trees showed drought-damage symptoms. Our study shows that the risk of drought damages differs spatially depending on climatic conditions and soil properties. The most important variables to identify risk areas are the proportion of bare-rock areas, topographic wetness index (TWI), soil water indices (absolute and relative) and the spatial location on the north–south axis.

Introduction

Vitality of forest ecosystems is regularly affected by water availability, and drought (i.e. unusually dry and warm weather) may sometimes cause extensive tree damage. Even though drought is not the most frequent cause of forest damage in boreal taiga forests (Selikhovkin 2005, Lännenpää *et al*. 2008), it is of special interest because it may occur in nearly all forest ecosystems (Dale *et al*. 2001), and also because drought may sensitise trees to secondary stress factors (Bréda *et al*. 2006, Turtola *et al*. 2003). Drought takes place whenever growth and transpiration of trees are restricted by a low soil water content (Bréda *et al*. 2006). Although, the effects of drought in forests depend on several factors — such as soil texture and depth, exposure, species composition, and life stage — the frequency, duration and severity of drought have the most influence and are the most variable (Dale *et al*. 2001). Most of the time during an average year in the boreal zone, soil water content is sufficient for growth. Therefore, the actual evapotranspiration does not fall below the potential evapotranspiration (Lockwood 1979). However, substantial inter- and intra-annual changes in precipitation and evapotranspiration can alter conditions to which plants have adapted and acclimated. It is important to note that due to the process of

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acclimation to prevailing conditions, all trees of a single species may be nearly equally sensitive to drought, which we also adopt as an initial hypothesis for this study.

Drought occurring during a growing season may cause increased defoliation, discolouration of foliage or even tree mortality (Solberg 2004). Some symptoms of drought damage, such as defoliation, are delayed and become evident in late autumn (Solberg 2004, Bréda *et al*. 2006). Drought induces short-term physiological disorders, such as decreased carbon and nutrient assimilation, and sometimes even breakdown of the photosynthetic process itself. Trees must, however, allocate stored reserves according to the demand for repair, maintenance, growth and defence (Bréda *et al*. 2006). We assume that one of the major consequences of drought is the loss of transport capacity in the stem due to cavitation, which affects tree performance until growth gradually restores new balance, which in a water-limited environment may last longer. Due to an inherent delay in plant allocation processes, drought symptoms are typically seen during the next year's assessments (Solberg 2004). In numerous tree-decline studies, there are evident correlations between drought and tree mortality for different tree species and biomes (for example, Peñuelas *et al*. 2000, Solberg 2004).

The aim of this study was to examine the spatial and temporal occurrence of drought damage in boreal forests in Finland, and to identify the potentially drought-prone sites and their climatic conditions.

Material and methods

Study area

The study area covers entire Finland (Fig. 1). Forests in this boreal region are dominated by conifers, typically Scots pine (*Pinus sylvestris*; 65% of the forested area) and Norway spruce (*Picea abies*; 24% of the forested area) (The Statistical Yearbook of Forestry 2012). The proportion of the forested area covered by broadleaved species — mainly birches (*Betula pendula* and *B. pubescens*) — is less than 10%. Approximately 75% of the total forested area in Finland is on mineral soils. The southwestern and western coasts of Finland are the warmest (annual mean temperature is about 5 °C), while the coldest places are in northern Lapland(annual mean temperatures between –2 and –4 °C). The annual precipitation in Finland is on average 500–700 mm. The areas with the lowest precipitation in Finland are on the coast of the Gulf of Bothnia and in the inner parts of northern Lapland. The highest annual rainfall in Finland, 1109 mm, was recorded in southern Finland, and the lowest, 121 mm, in Lapland (Solantie 1987). Snow cover may last for more than 200 days in Lapland but for less than 50 days on the southern coast (Tikkanen 2005). Consequently, snowmelt plays a different role in recharging soils for the summer in different parts of Finland.

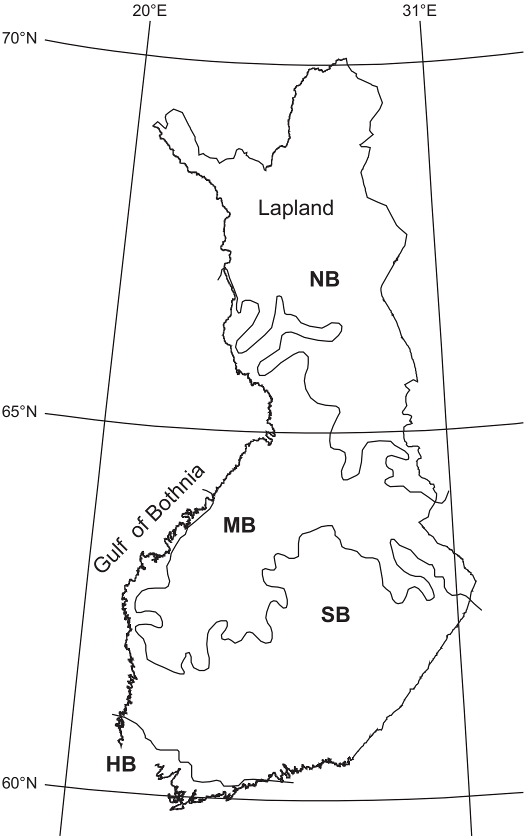

Fig. 1. The study area covered entire Finland. HB, SB, MB and NB are hemiboreal, southern boreal, middle boreal and northern boreal vegetation zones, respectively (Ahti *et al.* 1968).

Monitoring data

Our study is based on Level 1 annual tree-crown monitoring data of the pan-European monitoring program ICP Forests (International Co-operative Programme on the Assessment and Monitoring of Air Pollution Effects on Forests), initiated in 1985 and established under the UN/ECE Convention on Long-Range Transboundary Air Pollution (CLRTAP) (Derome *et al*. 2007). Extensive forest monitoring (Level 1) has been carried out on a network of approximately 6000 plots arranged in a systematic grid (16 × 16 km) covering entire Europe (Derome *et al*. 2007). Before 2009, the extensive (Level 1) forest health monitoring in Finland was carried out on a sub-sample of the permanent sample plot network of the eighth National Forest Inventory, established in 1985.

The data consisted of 620 (year 2005), 603 (year 2006), 606 (year 2007) and 488 (year 2008) study sites of the ICP-Level-1 grid. This grid is a dividend of a larger data set of the permanent sample plots provided by the Finnish National Forest Inventory (NFI). We defined a study site to be a drought-damaged site if there was at least a single tree with visible drought-related symptoms, such as defoliation and/or discoloration. These damages were assessed visually according to the internationally standardised methods (Eichhorn *et al*. 2010) and national field guidelines (*see* e.g., Lindgren *et al*. 2006). The ICP-Forests manual of damage causes was fully adopted in Finland in 2005. Thus, drought damage has been surveyed and identified separately since 2005. The survey is carried out annually between July and August by 10–12 trained observers. Even though observations of drought-related symptoms rely on the experience of field personnel, some errors related to the differences in personal interpretations are possible. We also excluded the field observations which were carried out before the dry period during the summer of 2006. In total, 544 study sites were analysed.

Soil water simulations and soil water indices

We used the PRELES model (Peltoniemi *et al*. 2015a; for model equations *see* Peltoniemi *et al*. 2012) to predict the actual evapotranspiration and soil water content based on standard daily weather data spatially interpolated to a 10-km regular grid (Venäläinen *et al*. 2005). The water balance in the model is simplified. Evapotranspiration is predicted with an empirical model, and there are three water storages in the model. For intercepted rainfall, there is a small surficial water storage (mostly in canopy) which, above a certain storage maximum, leaks excess water into soil. A snow water storage melts according to temperature and radiation, approximating the recharge period of soil water storage after winter. The soil water storage is a one-layer pool which can hold water up to effective field capacity of the site, whereas excess water is drained away. In practice, drainage may occur during snowmelt and intense rainfall periods. A soil water storage estimate was used in our analyses.

The model was run with the stand and soil data from a model calibration site (Hyytiälä SMEAR II). This was done for practical reasons because soil data are frequently too unreliable, unless collected from intensively-measured sites. Due to these limitations, we consider that the model represents soil moisture indices which account for the temporal patterns of the ambient weather conditions.

In addition to the absolute soil water index (SWI) we also used a relative SWI (%) which is a ratio of an absolute SWI for a given period and location to a long-term (30 years; from 1978 to 2007) average of minimum modelled values for specified months or periods and locations multiplied by 100. Therefore, 100% equals the long-term average. We assumed that 30 years is a long-enough period to compensate for annual variation in SWI. SWIs of the closest weather grid point were used for each ICP-Level-1 plot.

GIS data and data analysis

We used vector-type, digital topographic maps provided by the National Land Survey of Finland (available freely from https://tiedostopalvelu.maanmittauslaitos.fi/tp/kartta?lang=en). We extracted all bare-rock areas, all marshes and wetlands, as well all waterbodies to produce the bare-rock polygon layer, the wetland mask and the waterbody mask, respectively. We calculated the proportion of bare-rock areas for each 100 × 100 m polygon grid.

We also used the digital elevation model (DEM) also provided by the National Land Survey of Finland. The spatial resolution of DEM was 25 × 25 m and the vertical resolution 1 m. We calculated two new output GIS raster layers based on DEM. First, we calculated the slope direction and, second, the topographic wetness index (TWI $= \ln(A_s/\tan\beta)$, where A_s is the specific upslope area (m^2), i.e. the accumulated flow area, and β is the surface slope) (Sørensen *et al*. 2005).

Since the data were non-normally distributed, the differences between sites with and without drought-damaged trees were analysed with a Mann-Whitney *U*-test for independent samples. In addition, we used a Wilcoxon signed-rank test to analyse the differences between the monthly soil water indices of the growing season in 2006 and the long-term (30-year) averages.

We also calculated a binary logistic regression and created a drought-vulnerability map for Finland. In this regression, the level of drought damage assumes values between 0 (no damage) and 1 (100% damage). Statistical analyses were carried out using the SPSS Statistics ver. 20 software. All GIS calculations were made in the ESRI ArcMap 10 environment.

Results

In 2005, 14 (2.6%) of the studied 530 sites were affected by drought. During 2006, the number of drought-damaged sites rose to 147 (25.2%) of the studied 544. In 2007 and 2008, the numbers of damaged sites decreased to 27 (of 538; 5.0%) and 16 (of 442; 3.6%), respectively (Fig. 2). In 2007, few drought-damage symptoms were observed, although the soil water content during the growing season in 2007 was above the 30-year average. The SWIs for August 2007 and 2006 were 125.2% and 23.6%, respectively, and in July of the same years they were 117.1% and 62.2%, respectively. This indicates that the slightly-elevated amount of drought-damage trees observed during the summer of 2007 was partly due to the dry summer in the previous year. In addition, the minimum SWI from June to August 2006 was statistically significantly lower than the 30-year average (Table 1). Especially, the end of the growing season was extremely dry.

In 2006, when the highest number of drought-damaged trees was observed, there were remarkable differences between the drought sites and the non-drought sites in some environment variables (Table 2). The annual effective temperature sum (the sum of the positive differences between diurnal mean temperature and +5 °C) was significantly higher at the drought-damaged sites than at sites without damages. Southern Finland was more vulnerable to drought-induced damage than northern Finland (Fig. 2 and Table 2). This was mainly due to the higher temperature sum. In addition, the proportion (%) of bare-rock areas in a 100-m pixel was significantly higher at the damaged sites. The TWI was slightly lower at the damaged sites (Table 2), indicating that a higher vertical topographic position increased the risk of drought.

In pine-dominated, spruce-dominated and broad-leaved forests, approximately 65.5%, 20.7% and 13.8% of the study sites, respectively, were found to be damaged by drought. In total, 24.4%, 19.4% and 39.2% of the pine-dominated, spruce-dominated and broad-leaved study sites suffered from drought in 2006. When comparing proportions of tree species (tree volume $m^3\ ha^{-1}$), only that of spruce was statistically significantly lower at the drought-damaged sites than at non-damaged ones (Table 2). Proportions of pine and broad-leaved trees did not differ significantly.

The relative SWIs for the damaged and non-damaged sites were statistically significantly different in all summer months (tested separately) but not in June (Table 2). It is worth noting that especially July and August 2006 were extremely dry (Table 1 and Fig. 3).

The relative SWIs varied from month to month. The SWI was at a normal level in the whole of Finland during the early stages of the growing season in 2006 (Fig. 3), but at the end of the growing season in the same year its value indicated that the conditions were much dryer than normally since the SWIs for July and August 2006 were only 62.2% and 23.6% of the 30-year average, respectively, while those

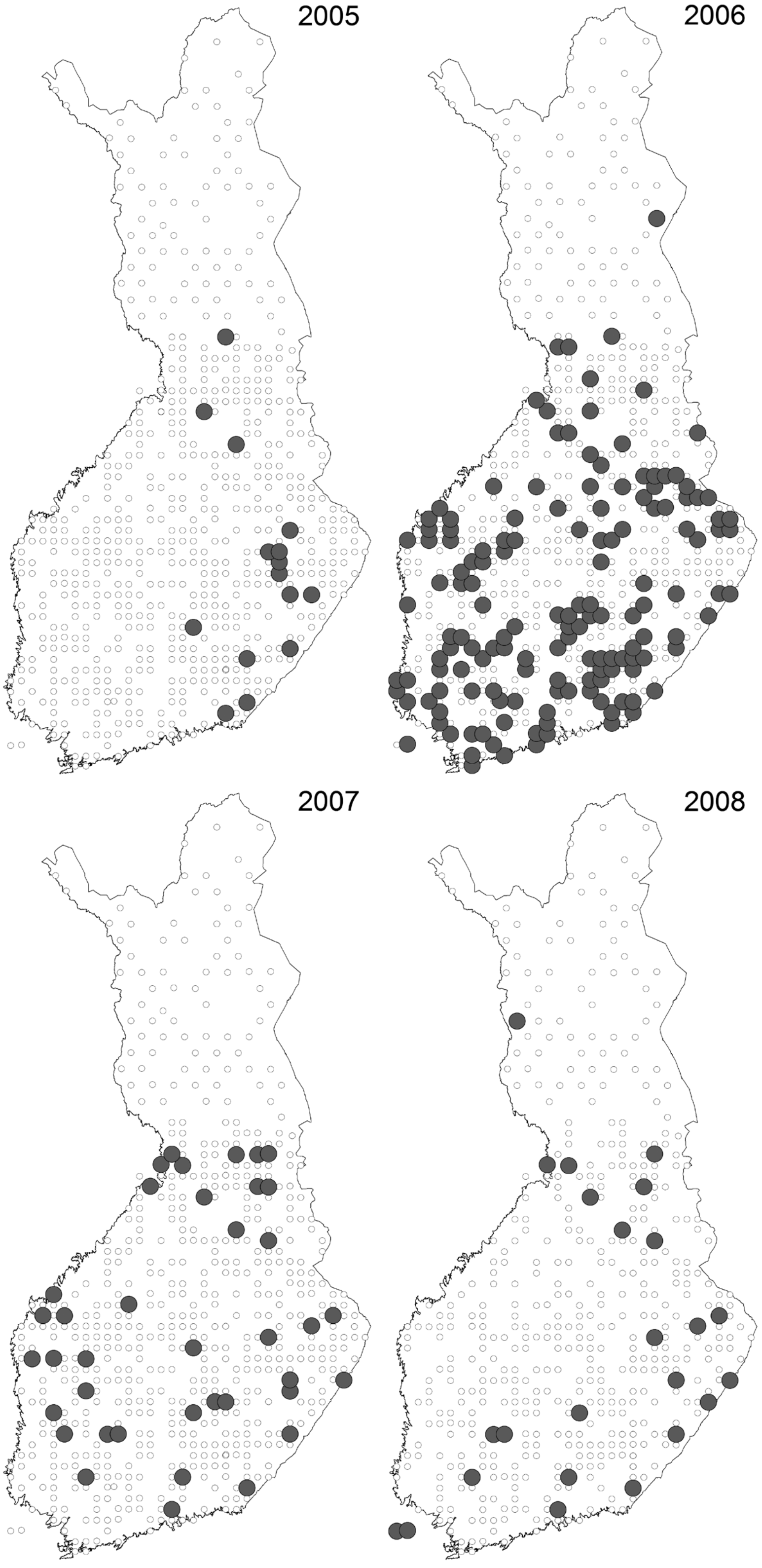

Fig. 2. Locations of forest drought damages during 2005–2008. Large dots and small circles indicate drought damage sites and non-damage sites, respectively.

for May and June 2006 were 100% and 97%, respectively.

A binary logistic regression indicated that drought vulnerability can be predicted using variables such as temperature sum, proportion of spruce, proportion of bare rock areas and the TWI (Table 3). Vulnerability is the probability (between 0 and 1) of observing drought symp-

Table 1. Soil water indices and significance of differences between thir monthly minima and 30-year averages for May, June, July and August 2006 evaluated using a Wilcoxon signed-rank test. The number of the study sites is 544.

Soil water index (SWI)	SWI value	Rank test	*p*
Minimum during May 2006	169.7	–2.71	0.007
30-year long-term average for May	169.5		
Minimum during June 2006	138.1	11.51	< 0.001
30-year long-term average for June	143.1		
Minimum during July 2006	76.4	21.01	< 0.001
30-year long-term average for July	120.1		
Minimum during August 2006	28.8	21.28	< 0.001
30-year long-term average for August	114.6		

Table 2. Significance of differences between sites with (1) and without (0) drought damage (137 and 407 sites, respectively) evaluated using a Mann-Whitney *U*-test for the observations in 2006. TWI = topographic wetness index, relative SWI = ratio of an absolute SWI for a given period and location to a 30-year average of minimum modelled values for specified months or periods and locations multiplied by 100 (%).

Variable	Drought damage	Average	*U*-test	*p*
Y coordinate (degrees)	1	62.29	–6.88	0.001
	0	63.69		
X coordinate (degrees)	1	25.93	–1.92	0.055
	0	26.36		
Temperature sum	1	1142	6.83	0.001
	0	1019		
Stand age (years)	1	57.9	–1.25	0.213
	0	66.7		
Basal area (m^2 ha^{-1})	1	18.0	1.31	0.189
	0	16.7		
Pine share (%)	1	55.3	0.46	0.649
	0	54.1		
Spruce share (%)	1	19.8	–0.75	0.451
	0	26.0		
Broadleaved share (%)	1	20.9	1.26	0.206
	0	16.7		
TWI	1	8.5	–2.10	0.036
	0	9.9		
Bare rock proportion (%)	1	5.7	5.66	0.001
	0	1.3		
Relative SWI (%)				
May 2006	1	99.1	–4.10	0.001
	0	100.4		
June 2006	1	95.4	–1.32	0.187
	0	96.7		
July 2006	1	58.4	–3.01	0.003
	0	63.5		
August 2006	1	20.2	–2.60	0.009
	0	24.8		

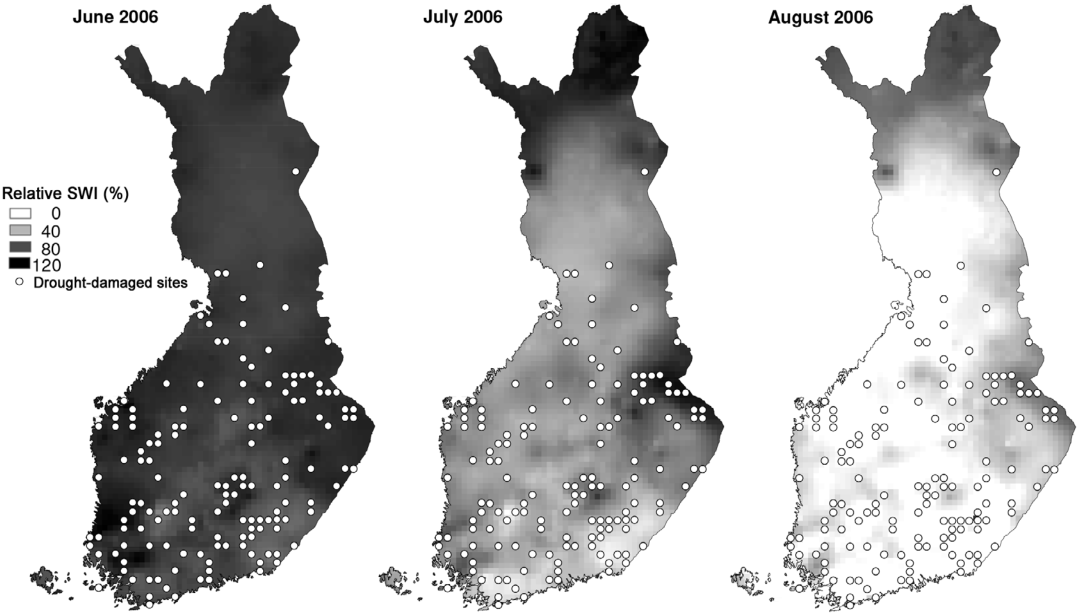

Fig. 3. Relative soil water index (SWI, %) in the growing season of 2006.

toms in trees during an extreme drought event. The predicted drought vulnerability is highest in southern Finland (Fig. 4).

Discussion

Our results indicate that dry and warm summers may cause an increase in drought-related symptoms in trees. It is well recognized that drought is an important stress agent in boreal forests (Helama and Lindholm 2003). However, our data showed that the occurrences of drought damage differed spatially, with more drought damage observed in the southern part of the country. The main factor behind this is the higher temperature sum in the south. Additionally, bare rock formations with shallow soil profiles slightly increase the vulnerability to drought. These shallow soil profiles can efficiently narrow down trees' possibilities to acclimate their root distribution to water acquisition. The TWI confirmed that hill summits are more vulnerable than lower lands in catchment areas. It must kept in mind that our study was carried out at a national level, hence it does not detect processes, such as microclimate and microtopography (< 25 m resolution), which are important factors in local ecological processes (Chen *et al*. 1999). Further investigations are required to study their effects.

Soil characteristics were not included in the soil water model (*see* Peltoniemi *et al*. 2015a). This simplification may have eliminated the potential spatial correlation of soil moisture predictions and drought-damage events. We, however, adopted the simplest way of running the model and related the model estimates to 30-year averages. Methods, which extend the simplicity even more, have been presented by e.g., Palmer (1965), McKee *et al*. (1995) and Vicente-Serrano

Table 3. Binary logistic regression of drought vulnerability. The regression equation is Logit(P) = $a + bT + cS + dB + e$TWI, where T is the temperature sum, S is the share of spruce trees, B is the proportion of bare rock areas and TWI is the topographic wetness index. The r^2 value and the overall percentage of correct predictions are 0.147 and 77.2%, respectively.

Variable		Wald statistics	p
Constant	–4.485	29.21	< 0.001
Temperature sum	0.003	22.02	< 0.001
Spruce share (%)	–0.010	7.98	0.005
Bare rock proportion (%)	0.028	7.18	0.007
TWI	–0.025	2.53	0.050

(2010). Further investigations of the drought damage prediction could benefit from elaborate soil water models, which in principle, should be able to more accurately reproduce the temporal patterns related to soil drying and wetting. However, there are rarely required input data available for such models.

Our study proposes some very simple ways of improving the large-scale predictions of drought (and excess moisture) events, based on recorded drought events and selected factors. Firstly, the effect of the proportion of open-rock areas on damage susceptibility should be associated with soil depth, so as to limit the soil water available to a plant. Of course, not all forest sites in such an area are equally vulnerable, but a landscape of this type will have some higher-risk forest sites. Soils with excess water should be simply associated with the TWI (or a map-based identification of peatlands). Recent studies by Murphy *et al.* (2008, 2009) offer an alternative to the TWI-based identification. Peltoniemi *et al.* (2015b) classified sites into drought-prone, normal and water-logged based on the identification of open-rock areas and peatlands on the map, as well as on assumptions of water-holding capacities of such sites, while generating national level predictions of forest GPP at a high resolution.

It has been noted in a recent study that the weather of the whole summer, rather than that of any single month is of utmost importance (Solberg 2004). We noticed a totally different pattern: the first phase of the growing season in 2006 (May and June) was characterised by average moisture conditions, whereas in July and August their relative SWIs for entire Finland were as low as 62.2% and 23.6%, respectively. This means that in July and August 2006, the forests were subjected to an extraordinary drought during the growing period. In total 25.2% of the 544 ICP Level 1 study sites showed some kind of drought symptoms — i.e., at least one tree per study site was visibly drought-damaged — when typically, the share of drought damaged study sites is around 2%–4%.

We conclude that a very simple soil water index (SWI) is useful for analysing potential climate-induced drought events and their consequences. We further conclude that simple topographic map based indices are useful for identifying regions with a higher susceptibility to drought. Although drought events alone may not cause large decreases in tree growth in places under forest management, they may make trees more sensitive to secondary stress factors (Bréda *et al.* 2006) such as insect attacks and disease. When damages caused by drought and other factors appear simultaneously, it may difficult to isolate the role of drought. This is an important point for further studies.

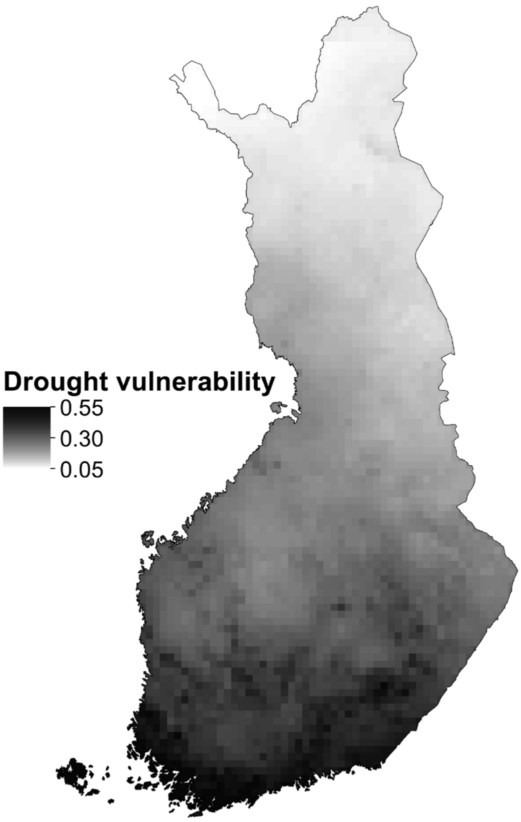

Fig. 4. Predicted drought vulnerability in Finland. Vulnerability is the probability (0.0–1.0) of detecting drought symptoms in a forest during a dry growing season.

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