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Ikonen V-P

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Regional risks of wind damage in boreal forests under changing management and climate projections

Ikonen V.-P.¹, Kilpeläinen A.¹, Zubizarreta-Gerendiain A.¹, Strandman H.¹, Asikainen A.², Venäläinen A.³, Kaurola J.³, Kangas, J.¹, Peltola H.¹

¹) University of Eastern Finland, Faculty of Science and Forestry, School of Forest Sciences, P.O. Box 111, FI-80101 Joensuu, Finland

²) Natural Resources Institute Finland, P.O. Box 68, FI-80101 Joensuu, Finland

³) Finnish Meteorological Institute, P.O. Box 503, FI-00101 Helsinki, Finland

Emails:

Veli-Pekka Ikonen veli-pekka.ikonen@uef.fi
Antti Kilpeläinen antti.kilpelainen@uef.fi
Ane Zubizarreta-Gerendiain ane.zubizarreta@uef.fi
Harri Strandman harri.strandman@uef.fi
Antti Asikainen antti.asikainen@luke.fi
Ari Venäläinen ari.venalainen@fmi.fi
Jussi Kaurola jussi.kaurola@fmi.fi
Jyrki Kangas jyrki.kangas@uef.fi
Heli Peltola heli.peltola@uef.fi

*) Corresponding author: Veli-Pekka Ikonen veli-pekka.ikonen@uef.fi +358-50-5921802
Abstract

We employed simulations by forest ecosystem (SIMA) and mechanistic wind damage (HWIND) models in upland boreal forests throughout Finland to study regional risks of wind damage under changing management preferences and climates (current, RCP4.5 and RCP8.5 scenarios) over 2010–2099. We used a critical wind speed for the uprooting of trees as a measure of vulnerability, which together with the probability of such wind speed defined a level of risk. Based on that, we also predicted the stem volume of growing stock at risk and the amount of damage. In this work, medium fertility sites were planted to one of Scots pine, Norway spruce or silver birch, or to the tree species that was dominant before the final clear-felling. The vulnerability to wind damage, the volume of growing stock at risk and the amount of damage all increased and the most in the south, when the proportion of Norway spruce (with shallow rooting) of the growing stock increased. Under a severe climate warming, the proportion of Norway spruce decreased the most in the south, opposite to that of birch. This decreased the risk of damage in autumn (while birch is leafless), unlike in summer. The low risk of damage in the north was due to the large proportion of Scots pine.

Keywords: CMIP5 multi-model climate projections, forest ecosystem modeling, mechanistic wind damage modeling, tree species, forest management.
1. Introduction

Since the 1990s, strong winds and storms have caused large economic losses in forestry in central and northern Europe (e.g. Schelhaas et al. 2003; Gregow 2013). In Finland, a total of 25 million m$^3$ of timber has been damaged in different storms since the year 2000 (e.g. Zubizarreta-Gerendiain et al. 2012; Gregow 2013). In 2003-2013, the wind damage compensations paid in Finland by insurance companies totaled 124 M€ (11.3 M€ a$^{-1}$) (Finnish Forest Research Institute 2014). Most wind damage has occurred in stands adjacent to newly clear-cut areas or in recently heavily thinned older stands (Laiho 1987; Zubizarreta-Gerendiain et al. 2012).

Under a warming climate, the risk of wind damage is expected to increase in Finland, despite no change in occurrence of extreme wind speeds in Northern Europe (Peltola et al. 1999a; Gregow et al. 2011a, b; Nikulin et al. 2011; Pryor et al. 2012; Outten and Esau 2013). This is because of the reduced period of frozen soil and tree anchorage during the windiest season of the year, i.e. from late autumn to early spring (Peltola et al. 1999a; Kellomäki et al. 2010; Blennow et al. 2010; Gregow et al. 2011a).

According to Peltola et al. (1999a), the duration of soil frost in 0-40 cm depth will decrease from 4-5 months to 2-3 months (mainly February – March) in southern Finland and from 5-6 months to 4-5 months (mainly January - April) in northern Finland, if a temperature elevation of 4 °C is assumed. As a result, 80% of 10 minutes mean wind speeds of >11 m s$^{-1}$ will occur at times of unfrozen soil conditions in southern Finland when at present the corresponding proportion is about 55% (Peltola et al. 1999a). The corresponding numbers in northern Finland are 40 and 50%, respectively. Also according to Gregow (2013), the soil is expected to hardly freeze at all in southern and central Finland by 2100 under the severe climate warming.

In Finland, about 45% of the volume of growing stock is currently Scots pine (Pinus sylvestris), 31% Norway spruce (Picea abies), and 24% silver and downy birches (Betula pendula and Betula pubescens) and other broadleaves. Norway spruce and silver birch are recommended to be
regenerated on upland forest sites of medium and high fertility and Scots pine on sites of medium and low fertility (Äijälä et al. 2014). Despite this, for example in 2009–2013, about 70% of the total planting area was planted by Norway spruce, and it has also been regenerated on sites typically occupied by Scots pine and silver birch due to moose browsing and other mammal damage in young Scots pine and birch stands (Finnish Forest Research Institute 2014). As a comparison, in the early 1990s, the share of Norway spruce was only 25–30%. The increasing proportion of Norway spruce of the growing stock volume could be expected to increase the risk of wind damage to forests in terms of uprooting. This is because Norway spruce with shallow rooting is more vulnerable to uprooting (lower critical wind speeds needed) than Scots pine and birches with the same tree and stand characteristics (Peltola et al. 1999b, 2010).

The projected increases in mean annual temperature and precipitation (up to 6 C° and 18%), and atmospheric CO$_2$ concentration (approaching 1000 ppm) by 2100 (Ruosteenoja et al. 2016) are expected to increase the growth of Finnish forests (e.g. Briceño-Elizondo et al. 2006; Kellomäki et al. 2008; Alrahahleh et al. 2017). This is because the short growing seasons, relatively low summer temperatures and short supply of nitrogen limit the growth of boreal forests currently, and especially in the north (Hyvönen et al. 2007; Kellomäki et al. 2008). However, the responses of forests to the climate change may differ largely at the regional level due to the differences in the prevailing environmental conditions (climate, site) and current forest structure (age, species). Furthermore, they are also affected by the forest management applied, the degree of climate change and responses of different tree species to the changing environmental conditions (Bergh et al. 2003; Briceño-Elizondo et al. 2006; García-Gonzalo et al. 2007; Kellomäki et al. 2008; Lindner et al. 2010). There is also a pressure to increase wood harvesting in Finland and elsewhere in Europe to fulfill the increasing demand for wood biomass in the growing bioeconomy (The Finnish Bioeconomy Strategy 2014). This will increase the total area of forest harvesting, including thinnings and clear cuts, which may increase the risk of wind damages to forests (Zeng et al. 2007).
Climate warming and associate increase in drought may also make the growing conditions suboptimal for some tree species, like Norway spruce, and more optimal for others, affecting mortality and growth as well as tree species composition in forests (e.g. Kellomäki et al. 2001, 2008; Bergh et al. 2003; Briceño-Elizondo et al. 2006; Allen et al. 2010; Lindner et al. 2010; Hanewinkel et al. 2013; Torssonen et al. 2015; Bärring et al. 2016). Under the severe climate warming, the growth and success of Norway spruce is expected to decrease especially on southern upland Finnish forest sites due to reduced soil water availability (Kellomäki et al. 2001, 2008; Mäkinen et al. 2001; Briceño-Elizondo et al., 2006; Ge et al. 2010; Jyske et al. 2010; Torssonen et al. 2015; Ruosteenoja et al. 2017).

The effects of prevailing environmental conditions, current forest structure, forest management applied and the degree of climate change on the dynamics and growth of forests may be studied by applying forest ecosystem model simulations together with up-to-date information on current forest resources and alternative climate change projections, to consider uncertainties related to the projected climate change (Garcia-Gonzalo et al. 2007; Kellomäki et al. 2008; Seidl and Lexer 2013; Alrahahleh et al. 2017; Reyer et al. 2017). The use of simulation outputs of forest ecosystem models as inputs for mechanistic wind damage models offer also means to predict the threshold wind speeds needed for wind damage in forests, and consequently their probabilities based on prevailing wind climate and the volume of growing stock at risk and the amount of damage (Gardiner al. 2008; Peltola et al. 2010; Seidl et al. 2014).

In this work we aimed to study regional risks of wind damage under changing forest management preferences and climates (current, RCP4.5 and RCP8.5 scenarios) over 2010–2099 by employing forest ecosystem (SIMA) and mechanistic wind damage (HWIND) models in upland boreal forests throughout Finland (60–70° N). We used four different management scenarios. In a baseline management scenario, all site fertility types were, throughout Finland, planted to the tree species that was dominant before the final clear-felling. In alternative management scenarios, medium fertility sites were planted to one of Scots pine, Norway spruce or silver birch after the final clear-felling
throughout Finland. On other site fertility types, baseline management was always applied. We hypothesized that (i) by proper selection of tree species in forest regeneration the risk of wind damage can be decreased in long term regardless of climate and region applied, and (ii) depending on forest region the climate change impacts and proper adaption measures may be even contradictory. In this work, a critical wind speed for the uprooting of trees was used as a measure of vulnerability, which together with the probability of such wind speed defined a level of risk. Based on that, we also predicted the volume of growing stock at risk and the amount of damage.

The climate data used in this work for changing climate represented two future representative greenhouse gas concentration pathways (RCP4.5 and RCP8.5) of the new CMIP5 models (van Vuuren et al. 2011). Based on the severe climate change (RCP8.5) scenario, the mean annual temperature and precipitation may increase in Finland up to 6 °C and 18% with the increase of atmospheric CO₂ concentration up to 807 ppm until 2100 (Ruosteenoja et al. 2016). These new multi-model climate change projections simulate somewhat larger warming for summer, while the precipitation projections are nearly equal throughout the year, compared to the previous model generation (Ruosteenoja et al. 2016). As a comparison, in the previous assessment of critical wind speeds needed for the uprooting of trees in Finnish forests, Peltola et al. (2010) used only one climate change scenario of the previous model generation (SRESA2) and the baseline forest management.

2. Material and methods

2.1. Outlines for the ecosystem model SIMA

We used a gap type forest ecosystem model SIMA (Kellomäki et al. 2005, 2008; Torssonen et al. 2015) to simulate the regeneration, growth and mortality of boreal upland forests (on mineral soils) throughout Finland as affected by temperature sum, soil water and nitrogen availability, within-stand light and CO₂ concentration in the atmosphere, and competition of trees. This model was applied as
it is capable of simulating the development and dynamics of both single tree species stands and mixed stands of conifers and broadleaves. In simulations, management control included artificial regeneration (planting) with desired spacing and tree species, control of density in tending of a seedling stand and in thinning (incl. naturally born seedlings) and final cut (only timber harvested).

In the model, the species-specific response to the temperature sum is modeled based on the downwards-opening symmetric parabola. The minimum (TS\textsubscript{min}, 370, 390, 390 d.d.), maximum (TS\textsubscript{max}, 2060, 2500, 4330 d.d.) and optimum temperature sum for growth (TS\textsubscript{opt}, 1215, 1445, 2360 d.d.) were smallest in Norway spruce, followed by Scots pine and birch (Kellomäki et al. 2008; Torssonen et al. 2015; see also Kienast 1987 and Nikolov and Helmsaari 1992). The effects of temperature increase on forest growth were calculated by considering the changes of monthly temperature sums only from April to September (i.e. the potential growing season, considering prevailing light conditions), following the previous study of Torssonen et al. (2015). The soil texture together with field capacity and wilting point define the soil moisture available for growth (as a function of precipitation and evaporation). Site fertility type and regional temperature sum affect the amount of soil organic matter (and carbon) and the nitrogen available for growth, which are also affected by the inputs of litter and deadwood (stem wood, branches, needles and leaves, stumps and coarse to fine roots) on the soil layer and their decay. The observed long-term mean in Finland for atmospheric nitrogen deposition (10 kg N ha\textsuperscript{-1}) is used in simulations (Järvinen and Vänni 1994; Kellomäki et al. 2005).

The model simulations with a time step of one year are carried out on an area of 100 m\textsuperscript{2}, based on the Monte Carlo technique (i.e. certain events, such as the birth and death of trees, are stochastic events). The mean values of 20 iterations of each output variable are used in the data analyses, following the work by Alrahahleh et al. (2017). This was undertaken as 10–20 iterations will be sufficient to stabilize the mean values based on our analysis (the coefficient of variation was 1.6% for 20 iterations over a 90-year period in total stem volume at plot level).
Previous results of model simulations have shown good agreement with the measured average annual volume growth (1996-2003) of main Finnish tree species on the permanent upland National Forest Inventory plots for different regions of Finland (see e.g. Kellomäki et al. 2008). Also simulated mean annual volume growth of managed Scots pine and Norway spruce stands over an 80-year rotation period on medium fertility sites, for 13 different locations from southern to northern Finland, has shown good agreement between the SIMA model and the empirical growth and yield model Motti (Hynynen et al. 2002; Routa et al. 2011).

2.2. Forest management used in SIMA model simulations

In this work, we simulated the development of upland Finnish boreal forests on 10th National Forest Inventory plots (in total 2642 plots throughout Finland) under changing climatic and management conditions over 2010-2099. After a regeneration cutting (clear-cut), medium fertility upland forest sites (*Myrtillus* type, MT) were planted to one of Scots pine, Norway spruce or silver birch, or to the same tree species that dominated the site before the final clear-felling (initial average breast height diameter of seedlings was 2.5 cm). The later one was named as a baseline management scenario. Other sites were regenerated following the baseline management scenario. In planting, a density of 2000 seedlings ha⁻¹ was used for Norway spruce and Scots pine and 1600 seedlings ha⁻¹ for silver birch, respectively. In addition to planting, Scots pine, Norway spruce, and birch seedlings were expected to regenerate on all sites naturally (see Kellomäki and Väisänen 1995; Kellomäki et al. 1997). Tending of the seedling stand was also always carried out before the first commercial thinning (mostly smaller or suppressed trees were removed).

We used in all simulations the region, site and tree species specific Finnish thinning rules, where the thinning (from below) is done whenever the basal area threshold for thinning at given dominant height is reached, and the basal area is reduced to the recommended threshold value after thinning (Äijälä et
In addition, clear-cut was done following the corresponding recommendations for basal area weighted diameter (range 22-30 cm) at breast height. We also used in cuttings a mean delay of 13 years compared with the management recommendations, because in current forest management practice in Finland large variation exists in timing and intensity of thinning and final cut (Finnish Forest Research Institute 2014). Furthermore, we left 10-30% of forest inventory plots from central to northern Finland outside management, unlike in southern Finland where current forest conservation area is very low around 2% (Finnish Forest Research Institute 2014). By doing so, the predicted volume growth, volume of growing stock and harvested amount of timber were in the first period 2010-2039 under the current climate in good agreement with the forest statistics for the period of 2004–2010 (Finnish Forest Research Institute 2014).

2.3. Climate data used in SIMA model simulations

The current climate data used in simulations are based on measurements by the Finnish Meteorological Institute (FMI) for temperature and precipitation during the reference period 1981–2010. The observational data were interpolated onto a 10 km x 10 km grid throughout Finland (Venäläinen et al. 2005; Aalto et al. 2013). We used for changing climatic conditions climate data representing two future representative greenhouse gas concentration pathways, scenarios RCP4.5 and the RCP8.5 (van Vuuren et al. 2011). This climate scenario data downloaded from the Coupled Model Intercomparison Project Phase 5 (CMIP5) database represent a mean of 28 different climate models (Ruosteenoja et al. 2016). These datasets comprise the projected change of monthly mean temperatures and precipitation for future periods (2010-2039, 2040-2069, and 2070-2099). The climate change data were interpolated by the FMI onto the 10 km x 10 km grid as the observational data. Based on these RCP4.5 and RCP8.5 climate change projections, the mean temperature is expected to increase in Finland on average by 3-5 C° and precipitation by 7-11%, during the potential growing season (April to September) by 2100 (Table 1). Meanwhile, temperature is expected to increase by 3-6 C° and precipitation by 10-20%, during the dormancy season (October to March) by
The atmospheric CO\textsubscript{2} concentration is expected to increase from the current climate (360 ppm) to 532 ppm and 807 ppm under the RCP4.5 and the RCP8.5 scenarios by 2100 (Ruosteenoja et al. 2016).

Table 1.

2.4. Outlines for the mechanistic wind damage model HWIND and its simulations

The mechanistic wind damage model HWIND (Peltola et al. 1999b) was used to calculate the 10 min averages for critical wind speeds (CWS) for different simulation cases by the SIMA model. HWIND predicts the CWS needed to uproot or break Scots pine, Norway spruce and birch trees (Peltola et al. 1999b). This CWS is computed at 10 m height above an open lawn surface or at the top of the edge trees at risk. A tree uproots if its maximum bending moment at the ground level exceeds the resistance of the root-soil plate, and a tree stem breaks if its maximum bending moment at 1.3 m high exceeds the threshold value of modulus of rupture (Peltola et al. 1999b).

Based on previous HWIND simulations (see e.g. Peltola et al. 1999b, Dupont et al. 2015), Norway spruce has the lowest CWS and Scots pine the largest, with the same tree and stand characteristics, when uprooting is considered. Birch has rather small CWS while in leaf (in summer), i.e. being between Scots pine and Norway spruce with the same tree and stand characteristics, opposite to in autumn without leaves. The outputs of the HWIND model (i.e. CWS needed to uproot or break the trees at stand edge) have been in reasonable agreement with other mechanistic wind damage models such as GALES and FOREOLE (see Ancelin et al. 2004). The properties of the HWIND model, its parameters, inputs and the validity of its outputs as well as performance for upland forests in Finland...
and Sweden, have also been discussed in detail by, for example, Peltola et al. (1999b), Gardiner et al. (2008), Blennow and Sallnäs (2004) and Zeng et al. (2006).

In this work, outputs of the SIMA model on different sample plots (i.e. tree species, tree height and diameter at breast height (DBH) for each sample tree and stand density) were used as inputs for HWIND model. The calculations of CWS for uprooting were done assuming unfrozen soil conditions throughout the year and that all trees at risk are located within one dominant stand height distance from the new upwind stand edge (with an upwind gap of $10 \times$ dominant height of stand edge), where they have the highest risk of damage in Finnish conditions (see Peltola et al. 1999b; Zubizarreta-Gerendiain et al. 2012). Thus, the calculated CWS represent maximum vulnerability of trees to uprooting. In calculating the CWS, the mean stand conditions (stand density and dominant stand height) were first used to calculate the mean wind profile for the sample plot, which was further on applied for calculating the wind loading for sample trees.

The calculated minimum CWS values (at canopy top) of sample trees in each plot of a given year were further on converted into an equivalent velocity that would be measured by a virtual or real meteorological station at 10 m above the ground, located above a homogeneous surface (see Dupont et al. 2015). This conversion was performed by assuming (i) identical mean wind speeds at 200 m height at the forest edge and at the meteorological site, and (ii) a logarithmic velocity profile above the meteorological station. This 200 m height is supposed to be high enough for the airflow to be in equilibrium over the landscape (Dupont et al. 2015).

2.5. Data analyses

In this work, we studied first how increasing use of certain tree species in forest regeneration affects the average proportions of different tree species (of total stem volume) under changing climatic conditions from southern to central and northern Finland in three 30-years simulation periods (2010-2039; 2040-2069 and 2070-2099). Thereafter, we studied how the changes in the proportions of tree
species affect the shares of CWSs <17 ms⁻¹ in southern, central and northern Finland, which differed in terms of growing conditions (e.g. average prevailing temperature sum, growing degree-days, gdd, with a +5°C threshold). The temperature sum in southern Finland (Forest center sub-regions 1–6) was >1100 gdd, in central Finland (sub-regions 7–10) 1000–1100 gdd and in northern Finland (sub-regions 11–13) <1000 gdd.

In this work, the proportions of different CWSs classes (<14 ms⁻¹, 14–17 ms⁻¹, 17–20 ms⁻¹, >20 ms⁻¹ and no risk; and CWS <17 ms⁻¹) for each plot and period were calculated based on the annual CWSs of the individual sample trees. We focused in this work especially on CWSs <17 ms⁻¹, because the CWSs of 14–17 ms⁻¹ occur approximately once in ten years in different regions of Finland, causing wind damage (e.g. Zubizarreta-Gerendiain et al. 2012; Gregow 2013). In contrast, CWS >17 ms⁻¹ very seldom occur in Finnish conditions (Peltola et al. 2010; Gregow 2013).

The calculation of the maximum average annual vulnerability (i.e. average minimum CWS) of forest plots to wind damage over each 30-year period was based on the minimum CWS for each plot (i.e. the most vulnerable tree cohort, regardless of tree species). These plot level results were averaged for each sub-region (old forest center units) and further for southern, central and northern Finland by weighting the results by the forest area of each sub-region. Results were also analyzed separately expecting birch in leaf (hereon named as summer) and birch without leaves (autumn, birch having no risk). Trees with a height <10 m and birches without leaves were considered to have a very low risk (i.e. very high critical wind speeds and very low probability of such wind speeds).

Based on the average minimum CWS for each plot, and wind climate, we calculated the probabilities of such CWS, as well as the volume of growing stock at risk and the amount of damage, by assuming birch to be in leaf. The annual probability of a certain CWS (P_{cws}) to occur was calculated based on predicted average minimum CWS and wind climate of Helsinki airport (weather station), i.e. P_{cws} = e^y / (1 + e^y), where y = 21.79 - 1.058 * CWS (see Peltola et al. 2010; Zubizarreta-Gerendiain et al.
We assumed unfrozen soil conditions, because we did not have available wind climate alone for unfrozen soil conditions (soil layer of 0-40 cm) for different climate projections. In calculating the volume of growing stock at risk and the amount of damage, we also assumed that the trees at risk are located within one dominant stand height distance from the new vulnerable upwind stand edge (vulnerable edge length expected to be 100 m). Furthermore, we expected that only 3% of the volume at risk will be actually damaged, based on wind damage measurements in Finland in 2001 after the Pyry (associated with additional snow loading on tree crowns), Mielikki and Janika storms, with mean 10 minutes wind speeds of 8-13, 10-15 and 15-19 m s\(^{-1}\), respectively (see Zubizarreta-Gerendiain et al. 2012). This assumption was done, because the calculated probability of damage was based on the average minimum CWS. Simulation of the amount of wind damage annually at the tree scale for all simulation cases (i.e. changing management preferences and climates for different regions and periods) would also have been too challenging due to large number of sample plots (in total 2642 plots) and sample trees in each plot.

3. Results

3.1. Tree species proportions

Under the current climate with baseline management, the proportion of Scots pine increased slightly (from 42 to 48 %) from first 30-year period to the last 30-year period in southern Finland (Appendix 1. Table A1., Figure 1). In central and northern Finland, it remained quite similar (51-52 % and 62-65%). The proportion of Norway spruce increased also slightly in central and northern Finland (from 31 to 39 % and from 22 to 29 %), but remained quite same in southern Finland (40-43 %). Also, the proportion of birch decreased slightly in southern and central Finland (from 18 to 8-9 %), and in northern Finland (from 13 to 9 %). Under the current climate, the proportion of Scots pine increased
in the last 30-year period largely (up to 72-75 %) regardless of the region when its planting increased.

Similarly, the proportion of Norway spruce and birch increased largely in southern and central Finland (up to 62-67 and up to 32-35 %), and in northern Finland (up to 47 and 27%) when their planting increased.

Also under the scenario of climate change with baseline management, the proportion of Scots pine increased largely in southern and central Finland (up to 61-64 %) and in northern Finland (up to 70 %) in the last 30-year period. In contrast, the proportion of Norway spruce decreased in southern Finland (to 18 %) and in central and northern Finland (to 23-27 %). The proportion of birch increased slightly (up to 21 %) in southern Finland, but remained quite the same than that under the current climate in northern and central Finland (6 and 9%). When the planting of Scots pine increased, its proportion increased largely (being in a range of 75-81 %) regardless of the region. Similarly, the proportions of birch (ranging from 48-63 % in the south to 21-22 % in the north) and Norway spruce (ranging from 38-61 % in the south to 43-44 % in the north) increased largely when their planting increased. In general, the increase of certain tree species planting area affected their proportions more than the climate applied did.

Figure 1.

3.2. Shares of CWSs <17 ms⁻¹

In the first 30-year period, in southern Finland the shares of CWSs <17 ms⁻¹ were 60 and 48% of all predicted CWSs in summer (birch in leaf) and in autumn (birch without leaves) under the current climate with baseline management (Figures 2 and 3). In central Finland, corresponding percentages were clearly lower (36 and 32%), mainly due to the larger proportion of Scots pine, opposite to that
of Norway spruce (Appendix 1. Table A1., Figure 1). The increasing use of certain tree species or
the climate applied did not affect the shares of CWSs <17 ms\(^{-1}\) in the first period. In northern Finland,
shares of CWSs <17 ms\(^{-1}\) were also marginal, regardless of the period, the climate and management
applied or the season considered.

In the second 30-year period, the shares of CWSs <17 ms\(^{-1}\) were in southern Finland under the current
climate with baseline management slightly lower than in the first 30-year period (54 and 37 % in
summer and autumn). This result was related to the increased proportion of Scots pine, opposite to
that of Norway spruce. The increase of Scots pine planting area decreased the shares of CWSs <17
ms\(^{-1}\) 9–13 %-units compared to baseline management, opposite to the increase of Norway spruce
planting area (the increase of 8–11 %-units). The increase of the proportion of birch increased this
share slightly (by 4%-units) in summer but decreased it (by 9 %-units) in autumn. Also in central
Finland, the shares of CWSs <17 ms\(^{-1}\) were lower in the second 30-year period under the current
climate, regardless of management preferences. Changing climate affected them only slightly in the
second 30-year period, regardless of region. Observed changes in CWSs were partly affected by the
harvesting of a large amount of timber (including so called cutting savings) in the first period when
following the management recommendations strictly, which does not happen in current forest
management practice. As a result, also the volume of growing stock was smaller in the second period
than in the first period.

In the third 30-year period, the shares of CWSs <17 ms\(^{-1}\) were in southern Finland under the current
climate with baseline management the same magnitude as in the first 30-year period (59 and 53% in
summer and autumn), due to increased proportion of Scots pine, opposite to that of Norway spruce.
The increase of Scots pine planting area (and thus increase its proportion) decreased the shares of
CWSs <17 ms\(^{-1}\) by 22–24 %-units regardless of the season compared with baseline management. On
the other hand, the increase of Norway spruce planting area increased them by 14–17 %-units. The
increase of birch planting area increased them also by 11 %-units in summer opposite to autumn
Also in central Finland, the shares of CWSs <17 ms$^{-1}$ were under the current climate with baseline management almost the same as in the first period, regardless of season (35 and 33% in summer and autumn). The increase of Scots pine planting area decreased them by 11 % - units opposite to the increase of Norway spruce planting area (the increase of 10 % - units). The increase of birch planting area either increased or decreased them by 4 % - units, depending the season. Under the changing climate, the shares of CWSs <17 ms$^{-1}$ were lower in southern Finland compared to the current climate with the same management scenario, whereas in central Finland, changing climate affected them only slightly.

3.3. Average minimum CWS, probabilities and amount of wind damage

The average minimum CWS over a 30-year period was under the current climate with baseline management quite the same in the first and the last 30-year period, regardless of region. They were also clearly lower in southern and central Finland (16-18 and 19-21 m s$^{-1}$) than in northern Finland (26-28 m s$^{-1}$) (Figures 4 and 5). The increase of Scots pine planting area increased the average minimum CWS at the regional level. In the last 30-year period, the average minimum CWS ranged under the current climate with the increase of Scots pine planting area from 21 to 29 m s$^{-1}$ from southern to northern Finland, respectively. Climate change affected them mainly indirectly through changes in forest growth and dynamics.

The average predicted probabilities for the CWSs to occur were in the first 30-year period in southern, central and northern Finland 0.8, 0.6 and 0.1, regardless of climate or management scenario applied (Figures 4 and 6). In the second and third 30-year period they were quite the same and in a range of
0.4-0.8, 0.3-0.7 and 0.0-0.1, respectively. The increase of Scots pine planting area resulted in lowest probabilities opposite to those of Norway spruce and birch in both the second and third 30-year period.

The average predicted amount of damage was in the first 30-year period in southern and central Finland in a range of 0.5-0.7 m³ ha⁻¹ a⁻¹ (0.4-0.5 % a⁻¹), regardless of climate or management scenario applied (Table 2, Figures 4 and 6). In the second and third 30-year period, the corresponding ranges were quite the same but larger than in the first 30-year period, i.e. 0.2-0.9 m³ ha⁻¹ a⁻¹ (0.2-0.6 % a⁻¹).

The predicted amount of damage was the largest under the current climate with the increase of Norway spruce planting area and under the changing climate with the increase of birch planting area, opposite to that of Scots pine. In northern Finland, the predicted amount of damage was about 0.1 m³ ha⁻¹ a⁻¹ (0-0.1 % a⁻¹), regardless of the period considered. Climate change affected the amount of damage mainly through changes in forest growth and dynamics, and CWSs.

4. Discussion and conclusions

We employed simulations by forest ecosystem (SIMA) and mechanistic wind damage (HWIND) models to study regional risks of wind damage in Finnish forests under changing forest management preferences and climates (current, RCP4.5 and RCP8.5 scenarios) over 2010–2099. A critical wind speed for the uprooting of trees was used as a measure of vulnerability, which together with the probability of such wind speed defined a level of wind damage risk to forests. As a comparison, in
the previous assessment of critical wind speeds needed for the uprooting of trees in Finnish conditions, Peltola et al. (2010) used only one climate change scenario of the previous model generation (SRESA2) and the baseline forest management. The new multi-model climate change projections (especially RCP8.5) used in this work simulate somewhat larger warming for summer, while the precipitation projections are nearly equal throughout the year, compared to the previous model generation (see Ruosteenoja et al. 2016).

In general, the vulnerability to wind damage, the volume of growing stock at risk and the amount of damage all increased and the most under the current climate in the south, when the proportion of Norway spruce (with shallow rooting) of the growing stock increased, opposite to that of Scots pine. However, under a climate change, the proportion of Norway spruce decreased and especially in the south, opposite to that of birch. The increase of birch proportion decreased the risk of wind damage in autumn (while birch is leafless), unlike in summer. The vulnerability of forests to wind damage were higher (i.e. lower critical wind speeds) in southern than northern Finland, regardless of the period, climate or management applied.

The increase of planting area for different tree species affected in the long term more tree species proportions, wind speeds needed for the uprooting of trees and the predicted amount of damage than climate change did. Climate change affected them mainly through changes in forest growth and dynamics. The effects of management preferences were largest in the last 30-year period due to the gradual change of forest structure (age, species) over time. In southern Finland, the predicted amount of damage was the largest under the current climate when planting of Norway spruce was increased. This was not the case under severe climate warming (RCP8.5), which decreased the share of Norway spruce (opposite to birch) in southern Finland compared to the current climate because growing conditions became sub-optimal for Norway spruce (see Ruosteenoja et al. 2017). Under a severe climate warming, the predicted amount of damage was largest in southern Finland when the planting of birch increased. This was also partly due to increased volume of the total growing stock compared
to other management scenarios. In northern Finland, forests are nowadays largely dominated by Scots pine, which is, in general, less vulnerable to wind damage than Norway spruce and birch (in leaf) with the same tree and stand characteristics (see e.g. Laiho et al. 1987; Peltola et al. 1999b; Zubizarreta-Gerendiain et al. 2012). Furthermore, in northern Finland, trees have on average lower height to breast height diameter ratios for same tree height than in southern Finland, which also explains their lower vulnerability to wind damage (Peltola et al. 2010).

In Finnish conditions, relatively low wind speeds (i.e. the CWSs $< 19$ ms$^{-1}$) are needed to cause wind damage (Laiho 1987; Gregow et al. 2011a, b; Zubizarreta-Gerendiain et al. 2012). Since 2000, about 1.6 million m$^3$ a$^{-1}$ of timber has damaged due to wind storms in Finland and the most in southern and central Finland, and at the edges of new clear cut areas or in recently thinned stands (Laiho et al. 1987; Gregow et al. 2011a; Zubizarreta-Gerendiain et al. 2012). Currently, the annual regeneration area is about 1 to 2% in Finland, depending on region (Finnish Forest Research Institute 2014). However, the expected increase of wood harvesting in Finland due to the increasing demand for wood biomass in the growing bioeconomy will increase the total area of forest harvesting, including thinnings and clear cuts, which may increase the risk of wind damages to forests. Fortunately, the vulnerability of downwind stand edge of clear cut decreases along with the height increase of seedling stand, which increases the shelter for the downwind stand (Dupont et al. 2015). However, this could take up to 20 years in Finnish conditions depending on growing conditions. If assuming 1 to 2 % annual share of forest regeneration area, based on our calculations on average 1.1-2.1 and 1.3-2.6 million m$^3$ a$^{-1}$ of timber could be damaged in Finland with the increased planting areas of Scots pine and baseline management during the 90 years study period (over all climates). In contrast, with the increasing planting areas of Norway spruce or birch, the corresponding range would be higher, on average 1.5-3.0 million m$^3$ a$^{-1}$.

Under the changing climate, many abiotic and biotic risks to forests (Peltola et al. 2010; Subramanian et al. 2016; Thom and Seidl 2016; Lehtonen et al. 2016; Reyer et al. 2017; Ruosteenoja et al. 2017)
are expected to increase and counteract at least partly the increasing forest productivity (see e.g. Zubizarreta-Gerendiain et al. 2017; Reyer et al. 2017). In this sense, they should be taken into account in forest management to adapt properly to the projected climate change (Kellomäki et al. 2005; Peltola et al. 2010, Seidl et al. 2011; Hanewinkel et al. 2013; Subramanian et al. 2016; Reyer et al. 2017).

Especially Norway spruce may have a large risk of many biotic (e.g. *Heterobasidion* spp. and bark beetles such as *Ips typographus*) and abiotic damages (e.g. wind damages, drought) (Kellomäki et al. 2008, Peltola et al. 2010; Subramanian et al. 2016; Thom and Seidl 2016; Honkaniemi et al. 2017).

The period of frozen soil will also largely shorten and nearly disappear under moderate and severe climate warming, especially in southern Finland (Peltola et al. 1999a; Kellomäki et al. 2010; Gregow et al. 2011a; Gregow 2013). This may increase wind damage risks to forests due to the decrease of tree anchorage during winter (Peltola et al. 1999a; Kellomäki et al. 2010; Gregow et al. 2011a). This will be the case, despite any change in storms or strong winds (see e.g. Gregow et al. 2011a, b; Nikulin et al. 2011; Pryor et al. 2012; Outten and Esau 2013).

In this work, we calculated the annual probability and amount of wind damage for each plot based on the CWS of the most vulnerable trees per plot. We also expected that only 3% of the volume at risk will be actually damaged based on previous wind damage measurements (see Zubizarreta-Gerendiain et al. 2012). This was done because simulating the amount of wind damage annually at the tree scale for all simulation cases (i.e. changing management preferences and climates for different regions and periods) would have been too challenging due to a large number of sample plots (in total 2642 plots) and sample trees in each plot. However, this kind of approach would be suitable to study the differences in the vulnerability of different stand types across a range of wind speeds as was done recently by Anyomi et al. (2017), for example. We also assumed that the wind damage will occur mainly within one dominant stand height distance from the upwind stand edge (of 100 m in length), which is typical to Finnish conditions (see e.g. Zubizarreta-Gerendiain et al. 2012). This was also done because, within the stand, clearly larger wind speeds are in general needed for wind damage in
Finnish conditions than at the newly cut upwind edge, especially if the stand is not very sparse (Peltola et al. 1999b). Neighboring trees also provide shelter and support for each other and therefore, wind damage is seldom complete without severe wind storm (see e.g. Schelhaas et al. 2007; Anyomi et al. 2017).

We may overestimate the risk of wind damage, especially under the current climate and mild climate change regardless of the region. This is because we did not have available wind climate alone for unfrozen soil conditions (soil layer of 0-40 cm) for different climate projections. These uncertainties should be taken into account in the generalization of findings. Recently, Saad et al. (2017) evaluated the effects of climate change (RCP4.5 and RCP8.5) on windthrow risk of Canadian forests by considering the wind speed prevailing only during the period of the year when soils are unfrozen. They found that under the changing climate an increased risk of windthrow was mainly due to an increased duration of unfrozen soil conditions (up to 2 to 3 months).

The impacts of climate change on extreme wind speeds are also largely still an unresolved question (see e.g. Gregow et al. 2011a, b; Nikulin et al. 2011; Outten and Esau 2013). Considering past wind climate in Finland, Laapas and Venäläinen (2017) found a mainly negative trend in both mean and maximum wind speed time series. Some climate model simulations indicate an increase and others a decrease of extreme wind speeds. Knowledge of any possible increase or decrease of the frequency of wind speeds causing damage to forests and infrastructure is urgently needed. Hopefully, new research activities such as EURO-CORDEX (Jacob et al. 2013) will widen our understanding on this issue and would more robustly take into account the possible change of wind storm frequency.

To conclude, climate warming is expected to make in Finnish conditions the growing conditions more suboptimal for Norway spruce than for other main boreal tree species, affecting mortality and growth as well as tree species composition in forests. Norway spruce with shallow rooting is more vulnerable to uprooting (the lowest CWS) compared to birch and Scots pine, with the same tree and stand conditions...
characteristics. In this sense, an increase of planting of more wind-firm (e.g. Scots pine) and better adapted (to climate warming) tree species would be a good adaptive measure. Growing forests with suitable tree species mixture could also be an option to reduce the negative effects of climate change on forests (see e.g. Anyomi et al. 2017). Wind damage risks to forests could also be decreased by avoiding the creation of large height differences for adjacent older stands (Zeng et al. 2007; Heinonen et al. 2009; Zubizarreta-Gerendiain et al. 2012).

Acknowledgements

This work was supported especially by the FORBIO project (no. 14970), funded by the Strategic Research Council of the Academy of Finland, and led by Prof. Heli Peltola at University of Eastern Finland. It was also supported by the ADAPT project (no. 14907, 2012–2016), which was led by Prof. Heli Peltola and funded by the Academy of Finland. The National Forest Inventory data obtained from the Natural Resources Institute Finland and climatic data (for the current climate and changing climate scenarios) obtained from the Finnish Meteorological Institute (Kimmo Ruosteenoja), are acknowledged.
References


Hanewinkel, M. 2017. Are forest disturbances amplifying or cancelling out climate change-induced productivity changes in European forests? Environmental Research Letters 12(3), 034027.


Figure legends

Figure 1. Proportions of tree species (different colors) under the current climate and climate change scenarios RCP4.5 and RCP8.5 (different stacked bars from left to right in each region) for each management scenario in the last period (2070-2099) and different regions of Finland (south, central and north, represented by different bar groups). Medium fertility sites were planted to one of Scots pine, Norway spruce or silver birch (i.e. preferring Scots pine, Norway spruce or birch) throughout Finland, or to the tree species that was dominant before the final clear-felling (baseline management).

Figure 2. Shares of minimum CWSs of each wind speed class (different wind speed classes with different colors, ms$^{-1}$) in summer (birch in leaf) and in autumn (birch without leaves) under each climate scenario (different stacked bars, from left to right the current climate and RCP4.5 and RCP8.5 scenarios) for different regions of Finland (different bar groups) under each management scenario. Medium fertility sites were planted to one of Scots pine, Norway spruce or silver birch (i.e. preferring Scots pine, Norway spruce or birch), or to the tree species that was dominant before the final clear-felling (baseline management). Trees shorter than 10 m or birches without leaves were considered to have no risk.

Figure 3. The shares of CWSs <17 ms$^{-1}$ versus the proportions of each tree species, and Norway spruce and birch together, in southern Finland (A) and central Finland (B) in the final period of 2070–2099. Medium fertility sites were planted to one of Scots pine (Pref. SP), Norway spruce (Pref. NS) or silver birch (Pref. B), or to the tree species that was dominant before the final clear-felling (baseline management).

Figure 4. Volume of growing stock (m$^3$ ha$^{-1}$), average minimum CWS (m s$^{-1}$), predicted probabilities (0..1) based on average minimum CWSs, amount of damage (m$^3$ ha$^{-1}$ a$^{-1}$) and damaged percentage (% a$^{-1}$) in summer for each period and each management scenario under the current climate and climate change scenarios RCP4.5 and RCP8.5 in southern, central and northern Finland. Medium
fertility sites were planted to one of Scots pine (Pref. SP), Norway spruce (Pref. NS) or silver birch (Pref. B), or to the tree species that was dominant before the final clear-felling (baseline management).

**Figure 5.** Average minimum CWSs under baseline management for 2010–2039, 2040–2069 and 2070–2099 and for other management scenario for 2070-2099 in summer and autumn under the current climate, and climate change scenario RCP8.5. Medium fertility sites were planted to one of Scots pine (Pref. SP), Norway spruce (Pref. NS) or silver birch (Pref. B), or to the tree species that was dominant before the final clear-felling (baseline management).

**Figure 6.** Predicted probabilities (0..1) based on average minimum CWSs and amount of damage ($m^3 \text{ ha}^{-1} \text{ a}^{-1}$) in summer in the period of 2070–2099 for each management scenario under the current climate and climate change scenarios RCP4.5 and RCP8.5. Medium fertility sites were planted to one of Scots pine, Norway spruce or silver birch (i.e. preferring Scots pine, Norway spruce or birch), or to the tree species that was dominant before the final clear-felling (baseline management).

Figures 5 and 6 will be printed in color.
Figures

Baseline management  Preferring Scots pine  Preferring Norway spruce  Preferring birch

Figure 1.
Figure 2.
Figure 3.
Figure 4.
Figure 5.
Figure 6.
Tables

Table 1. Projected average temperature change (°C) and average precipitation change (%) compared with the current climate (1981-2010) over the potential growing season (April-September) in northern, central and southern Finland.

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Note: The changes are relative to the baseline climate. Both RCP4.5 and RCP8.5 are averages of 28 individual climate models.
Table 2. Average volume of growing stock (m$^3$ ha$^{-1}$) and predicted amount of damage (m$^3$ ha$^{-1}$ a$^{-1}$) in each 30-year period and management scenarios for different regions under the current and changing climates. Medium fertile sites were planted to one of Scots pine (Pref. SP), Norway spruce (Pref. NS) or silver birch (Pref. B), or to the tree species that was dominant before the final clear-felling, as was done on other fertile site types (baseline management).

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* No remarkable differences between management scenarios in the first period.
Appendix 1. Table A1. The proportion of tree species (stem volume, %) in each 30-year period and management scenarios for different regions under the current and changing climates. Medium fertile sites were planted to one of Scots pine (Pref. SP), Norway spruce (Pref. NS) or silver birch (Pref. B), or to the tree species that was dominant before the final clear-felling, as was done on other fertile site types (baseline management).

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* No remarkable differences between management scenarios in the first period.