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**Effects of wind damage on the optimal management of
boreal forests under current and changing climatic
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Complete List of Authors:	Zubizarreta-Gerendiain, Ane; University of Eastern Finland, School of Forest Science; Basque Center for Climate Change, (BC3) Pukkala, Timo; University of Eastern Finland, Peltola, Heli; University of Eastern Finland, School of Forest Sciences
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1 **Effects of wind damage on the optimal management of boreal forests under current and**
2 **changing climatic conditions**

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4 **Ane Zubizarreta-Gerendiain,^{1,2*} Timo Pukkala,¹ Heli Peltola¹**

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7 ¹ School of Forest Sciences, Faculty of Science and Forestry, University of Eastern Finland,
8 PO Box 111 FI-80101 Joensuu, Finland

9 ² Basque Centre for Climate Change (BC3), 48008, Bilbao, Spain

10

11

12 * Corresponding author

13 Ane Zubizarreta-Gerendiain

14 ane.zubizarreta@uef.fi

15 Phone number: +358 449667503; Fax: +358 294 457 316

16

17 **Emails:** **Timo Pukkala,** timo.pukkala@uef.fi

18 **Heli Peltola,** heli.peltola@uef.fi

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Abstract

This study presented a new method for considering the risk of wind damage in forest planning and for predicting the amount of damage and its effects on timber production, economic profitability and carbon balance of forestry. The effects of wind damage on the optimal management of boreal forests under current and changing climatic conditions were analyzed by comparing four forest management plans. A reference plan maximized net present value (NPV) with even-flow harvesting constraints. The second plan minimized height differences between adjacent stands and the third minimized height differences while simultaneously maximizing NPV. The fourth plan maximized height differences between adjacent stands. To obtain damage-adjusted results, schedules that belonged to the optimal management plans were simulated with wind damage, taking into account the shelter provided by adjacent stands. Maximizing NPV and simultaneously minimizing height differences resulted in the highest damage-adjusted NPV. Increasing wind damage increased carbon balance of forest soil, but decreased the total carbon balance of forestry as it decreased the carbon balances of living forest biomass and wood-based products. Climate change slightly improved the total carbon balance of forestry. If wind damage was ignored in calculations, NPV, total carbon balance of forestry and timber production were overestimated.

Keywords: wind disturbance, risk management, carbon balance, spatial optimization, forest landscape structure

45 **Introduction**

46 Storms and strong winds have caused large economic losses in forestry in central and
47 northern Europe since the 1990s (e.g. Schelhaas et al. 2003). In Finland, strong winds have
48 damaged in total about 24.1 million m³ of timber in different winter and summer storms
49 between 2001 and 2014. The most timber was damaged in 2001 (7.3 million m³) and 2010
50 (8.1 million m³) (Gregow 2013). Finland also experienced strong storms in 2002, 2011, 2012,
51 2013, and 2014, with the annual damage ranging from 0.3 to 4 million m³.

52
53 The susceptibility of tree stands to wind damage (uprooting or breakage of trees) is affected
54 by stand and site characteristics (Peltola et al. 1999a; Gardiner et al. 2008; Pukkala et al.
55 2016). Most wind damage occurs in mature stands adjacent to newly clear-cut areas or in
56 recently heavily thinned mature stands, where trees have not acclimated to increasing wind
57 loading (e.g. Laiho 1987; Zubizarreta-Gerendiain et al. 2012). Norway spruce (*Picea abies*
58 Karst L.) with shallow rooting is more vulnerable to wind damage in Finnish conditions than
59 Scots pine (*Pinus sylvestris* L.) and birch (*Betula* spp.) (Laiho 1987; Peltola et al. 1999b). The
60 risk of wind damage may be decreased by avoiding new vulnerable edges, especially in
61 mature stands, and by cutting first the most vulnerable older stands (Tarp and Helles 1997;
62 Meilby et al. 2001; Zeng et al. 2007; Zubizarreta-Gerendiain et al. 2012). A smooth landscape
63 structure with small height differences between adjacent stands has also been found to
64 decrease the risk of wind damage (Zeng et al. 2007; Heinonen et al. 2009).

65
66 The risk of wind damage for a certain stand may be evaluated based on the characteristics of
67 the stand itself and its immediate neighbor stands (e.g. Meilby et al. 2001; Zeng et al. 2007).
68 Mechanistic wind damage risk models offer means to predict the threshold wind speeds
69 needed to uproot or break trees in alternative management schedules, allowing calculation of

the probability of wind damage based on local wind characteristics (Peltola et al. 1999b, 2010; Gardiner et al. 2000, 2008; Ancelin et al. 2004; Byrne and Mitchell 2013; Seidl et al. 2014; Dupont et al. 2015). Zeng et al. (2007) employed a forest ecosystem model and a mechanistic risk model (HWIND) to calculate the risk of wind damage in an optimization study. They showed that the total length of edges vulnerable to wind damage could be decreased by aggregating clear-felling areas and by avoiding the creation of new clear-felling areas at the edges of older and high stands.

Heinonen et al. (2009, 2011) developed simple regression models based on HWIND model simulations (Peltola et al. 1999b) to predict the threshold wind speeds needed to uproot Scots pine, Norway spruce, and birch. The critical wind speed was predicted from the characteristics of the subject stand and the height of the adjacent upwind stand. Heinonen et al. (2009, 2011) also showed that the risk of wind damage clearly affects the optimal cuttings and the structure of forest landscapes. However, these previous studies did not actually simulate wind damage or evaluate its effect on timber production and its profitability. Meilby et al. (2001) were the firsts to analyze the influence of the risk of wind damage on the net present value (NPV) and optimal rotation length of single stands considering the effect of sheltering stands. In the presence of risk, the rotation length of unsheltered stands should be shortened, whereas the rotation of stands providing wind shelter for other stands should be lengthened (Meilby et al. 2001).

A warming climate may increase the risk of wind damage in Finland although the frequency and severity of storms may not increase (Gregow et al. 2011). This is partly because the frozen soil period, which currently improves tree anchorage from late autumn to early spring, will become shorter (Blennow et al. 2010; Kellomäki et al. 2010; Gregow et al. 2011).

95 Furthermore, forest growth and volume of growing stocks of Finnish forests are in general
 96 expected to increase under the projected climate change (see e.g. Kellomäki et al. 2008).
 97 Consequently, various abiotic and biotic risks to forests may increase, which should be taken
 98 into account in forest management as they may greatly affect forest productivity, carbon
 99 sequestration and stocks in forests (e.g. Lindner et al. 2010, 2014; Kolström et al. 2011; Seidl
 100 et al. 2011; Subramanian et al. 2016; Thom and Seidl 2016).

101

102 In this work, the aim was to introduce a new method for considering the risk of wind damage
 103 in forest planning and demonstrate the effect on wind- risk-related management objectives on
 104 forest landscape structure. The amount of wind damage was predicted and the effect of
 105 damage on timber production, economic profitability and carbon balance of forestry was
 106 calculated. The carbon balance of forestry included changes in the carbon pools of living
 107 forest biomass, dead organic matter (soil), and wood products. The carbon balance of wood
 108 products also included carbon releases from harvesting, transport, and manufacturing, as well
 109 as the substitution effects arising from reduced carbon emissions from fossil fuels due to the
 110 use of construction wood and forest biomass-based fuels (see e.g. Zubizarreta Gerendiain et
 111 al. 2015). The effects of wind damage on the optimal management of the boreal forest
 112 landscape were demonstrated by comparing results for four alternative forest management
 113 plans under the current and gradually changing climate. It was assumed that under the
 114 gradually changing climate, the mean annual temperature will increase by 4 °C, precipitation
 115 by 10%, and atmospheric CO₂ concentration by 272 ppm by 2070–2100 compared to the
 116 current climate (period 1960–2000), following the SRES A1B scenario of the CMIP3
 117 database (see IPCC 2013; Jylhä et al. 2009). A reference management plan maximized the
 118 economic profitability (NPV) with even-flow harvesting constraints. Other plans minimized
 119 height differences between adjacent stands as the only objective or aimed simultaneously at

maximal NPV, or maximized height differences between adjacent stands to derive the extent to which wind damage can be affected by forest management. Since the same treatment schedules were simulated without and with wind damage, it was possible to calculate the influence of wind damage on the timber production, NPV, and carbon balance of forestry. We hypothesized that by ignoring wind damage in calculations, the NPV, total carbon balance of forestry, and timber production are all overestimated.

Materials and methods

Overview

The analyzes of this study consisted of the following steps (Fig. 1):

1. Alternative treatments schedules were simulated for all stands of the study area without predicting the amount of wind damage.
2. The optimal combination of simulated management schedules was derived by using numerical optimization. Four alternative plans were compiled, referred to as the MaxNPV, MinRisk, MaxRisk, and MaxNPV-MinRisk plans. The optimal solutions together with the first-step simulations provided information about tree height development in every stand of the landscape.
3. The optimal schedules selected for the stands in Step 2 were simulated again including simulation of the wind damage at stand edges.

All steps were performed using the Monsu simulation-optimization system (Pukkala 2004).

All the models explained below were programmed in the Monsu software. The boreal forest landscape used as a study area in this work represented the conditions of the southern part of central Finland. It covered 360 ha, divided into 245 stands (Table 1).

Figure 1, Table 1

Simulation of treatment schedules

The simulation tool Monsu was used to simulate alternative 30-year management schedules for each stand. Based on a set of parameters (minimum basal area required for thinning treatment and minimum mean tree diameter required for final felling) the tool automatically simulated several treatment schedules for each stands and calculated the costs, removals, incomes, NPV, carbon balance and growing stock development for each schedule. The currently recommended site and species-specific thinning thresholds (stand basal area at which thinning is recommended) and average diameter at breast height required for final felling were applied (see Äijälä et al. 2014) to define the earliest possible time for thinning and final felling. In the other schedules, the thinning treatments or the final felling were postponed or were not done at all. Thinning from below was simulated so that half of the harvested basal area was removed by using the same thinning intensity in all diameter classes. Then, smallest diameter classes were removed until the post-thinning basal area reached the recommended target value. After the final felling, artificial regeneration by planting or sowing was used, except in Scots pine stands on sub-xeric and poorer sites where natural regeneration was used. This is advised in Finnish forest management recommendations (see Äijälä et al. 2014). Stand development was simulated for three consecutive 10-year periods. Thus, each stand had several alternative treatments schedules for the coming 30-year period.

The models of Pukkala et al. (2013) for diameter increment, tree survival and ingrowth were used to simulate stand development. Stem taper models (Laasasenaho 1982) were used to calculate assortment volumes of harvested trees (Table 2) and biomass models to calculate the biomasses of branches, foliage, stumps, and coarse roots. When calculating incomes from

timber sales, the assortment volumes of harvested trees were multiplied by the roadside prices of different timber assortments (Table 2). Harvesting costs, calculated with the functions of Rummukainen et al. (1995) were subtracted from the roadside value to obtain the net income from cutting.

Table 2

To calculate the NPV of a treatment schedule, all costs and incomes of the simulated 30-year period were discounted to the beginning of the period using a 6% discount rate. The NPV of the growing stock at the end of the simulation period was predicted with an algorithm of Pukkala (2005, 2015) and added to the NPV of the 30-year simulation period.

The effects of climate change were simulated using the species- and site-specific growth trend functions (multipliers of the diameter growth models) built by Pukkala and Kellomäki (2012) for Norway spruce, Scots pine, and silver birch (*Betula pendula*) for their typical growing conditions in central Finland (62° 40' N, 29° 38' E, 94 m a.s.l., 1050 d.d). Based on them, the increase in tree diameter increment ranges from 0.27 to 0.52% per year for Norway spruce, Scots pine, and silver birch, when the mean annual temperature increases by 4 °C, precipitation by 10%, and atmospheric CO₂ concentration by 272 ppm by 2070–2100 compared to the current climate (period 1960–2000). As a comparison, based on the climate data loaded from the latest CMIP5 database (IPCC 2013; van Vuuren et al. 2011) by the Finnish Meteorological Institute, the mean annual temperature in Finland is expected to increase by 3.3–5.5 °C, precipitation by 11–18%, and atmospheric CO₂ concentration by 172–447 ppm by 2070–2100 under greenhouse concentration pathways RCP4.5 and RCP8.5 (based on averages of 28 climate models).

Calculation of carbon balance

Our calculations of the carbon balance of forestry considered changes in the carbon pools of living forest biomass, dead organic matter (soil), and wood products (Fig. 2). The carbon balance of living forest biomass depended on the net biomass growth of living trees, regeneration, mortality and harvested amount of forest biomass. Inputs to the dead organic matter pool consisted of dead trees, residues of harvested trees, and above- and below-ground litter production of trees. Logging residues (tree tops and branches), stumps, and roots were left in the forest and included in the soil carbon balance. Wind-thrown trees were not harvested and were therefore added to the dead organic matter pool. Litter production was calculated from the biomass of branches, foliage, coarse roots and fine roots using the same species-specific turnover rates as in Pukkala (2014).

Figure 2

The soil and product carbon pools of each stand were initialized using the models of Pukkala (2014). This was done because omitting the decomposition of initial pools would have resulted in overestimated carbon balances. Inputs to the carbon pool of wood products consisted of harvested wood during the calculation period, and output consisted of the disposal of products based on defined product-specific lifetimes. The carbon balance of products also included carbon releases from harvesting, transport, and manufacturing, as well as the substitution effects arising from reduced carbon emissions from fossil fuels due to the use of construction wood and forest biomass-based fuels (Pukkala 2014; Zubizarreta-Gerendiain et al. 2016). Harvested stems were partitioned into saw log, pulpwood, and fuel feedstock. Harvesting emissions (tonnes of carbon released per tonne of carbon contained in

harvested biomass) decreased with increasing size (dbh) of harvested trees (see Pukkala 2011). Releases from transport were calculated from the fuel consumption of a truck for a return trip of 150 km for round wood and 100 km for biofuel. Manufacturing releases for production of sawn wood, chemical mass, mechanical mass and biofuel were adopted from literature (Liski 2001; Pukkala 2014).

The simulation tool of the Monsu software uses the Yasso07 model (Liski et al. 2009; Tuomi et al. 2011*a,b*) to simulate the decomposition of soil organic matter. In the Yasso 07 model, the decomposition rate depends on the mean annual temperature, annual precipitation, and temperature amplitude of the region (Liski et al. 2009; Tuomi et al. 2011*a,b*). All these decomposition drivers were assumed to change according to the trend functions presented in Zubizarreta-Gerendiain et al. (2016). These functions correspond to the SRES A1B climate change scenario.

The disposal of the products was simulated by using a decay curve:

$$Y_t = Y_0 e^{kt} \quad (1)$$

where Y_0 is the initial mass, Y_t is the remaining mass t years later, and k is the annual disposal rate. The annual disposal rate was 0.02 (2% per year) for sawn wood, plywood, and veneer, 0.1 for paper products, and 0.3 for biofuel. A part of the sawn wood, plywood, veneer, and paper products that was disposed of was assumed to be used as biofuel, having the same substitution effect (0.8) as other biofuels (Pukkala 2014). The remaining part decomposed, releasing CO₂ to the atmosphere.

Optimizations

Management was optimized by using the treatment schedules that were simulated without wind damage. The following four optimization problems were solved (Table 3): 1) maximizing NPV (MaxNPV); 2) minimizing the risk of wind damage (MinRisk) by minimizing height differences between adjacent stands; 3) maximizing the risk of wind damage (MaxRisk) by maximizing height differences between adjacent stands; and 4) maximizing NPV and simultaneously minimizing the risk of wind damage (MaxNPV–MinRisk). An even-flow cutting target of 25000 m³ was set for the three 10-year periods. This harvesting target is near the predicted 10-year volume increment of the forest.

Table 3

The optimization problems can be formulated as follows:

$$\max \text{ or } \min z = Z(\mathbf{x}) \tag{2}$$

subject to

$$q_i = Q_i(\mathbf{x}) = 25000, \quad i = 1, \dots, 3 \tag{3}$$

where z is the objective function (NPV or mean height difference between adjacent stands, or a combination of both), Z is the procedure that calculates the value of the objective function from the information of those treatment schedules that are included in the solution, q_i is the volume harvested during the 10-year period i , Q_i is the procedure that calculates the harvested volume of the solution, and $\mathbf{x}$ is a vector that indicates the ID numbers of those schedules that are included in the solution. Since all problems except one were spatial, a heuristic method (simulated annealing) was used to find the optimal combination of the simulated treatment schedules (Lockwood and Moore 1992).

270

271 *Wind damage calculation*

272 Optimization was used to find the optimal combination of the simulated treatment schedules.

273 Knowing the treatment schedule of every stand of the forest landscape provided information

274 on tree height development in the neighborhood of every stand. This information made it

275 possible to simulate wind damage.

276

277 The treatment schedules selected for the optimal plans were simulated again including

278 simulation of wind damage. The shelter provided by adjacent stands was taken into account in

279 the calculation of wind damage at a certain stand edge, based on mean height differences of

280 neighboring stands. The results from these repeated simulations were used to calculate wind-

281 damage-adjusted results for timber production, NPV, and the carbon balance of forestry.

282

283 To calculate the amount of wind damage, we first calculated the critical wind speeds (*CWS*)

284 needed to uproot trees at stand edges by employing the regression models of Heinonen et al.

285 (2009). These models use the characteristics of the subject stand (tree species, mean stand

286 height, and diameter/height ratio) and the adjacent (stand height and surface area) as

287 predictors for the *CWS* (for more details, see Heinonen et al. 2009). The gap diameter (mean

288 gap diameter for winds blowing from the adjacent stand) was assumed to be equal to the

289 diameter of a circle whose area is equal to the surface area of the stand.

290

291 Based on the predicted *CWS* for each edge, the probability of the wind speed exceeding the

292 threshold speed for uprooting a tree at a stand edge was calculated. The model for the

293 probabilities of different maximum wind speeds was based on the daily maxima of 10-minute

294 average wind speeds measured at the Helsinki-Vantaa airport weather station (see more

details in Peltola et al. 2010). These data were used to calculate the annual maxima, and from long-term statistics it was possible to calculate probabilities for different maximum annual wind speeds. The obtained empirical probabilities were used to fit the following logit model for the probability of having wind speeds higher than x m/s at least once per year:

$$y = 21.79 - 1.058x \tag{4}$$

$$P[\text{max wind speed} \geq x] = \exp(y)/(1 + \exp(y)) \tag{5}$$

where y is the logit transformation of the observed probability of having wind speeds of at least x m/s. Since the time step of growth simulation was five years, the annual probability obtained from Equation 5 was converted into a five-year probability as follows:

$$P[\text{max 5-year wind speed} \geq x] = 1 - (1 - P[\text{max 1-year wind speed} \geq x])^5 \tag{6}$$

Damage was simulated on the basis of the *CWS* calculated for a stand edge and the probability of having such a wind speed during a five-year period. The directional distribution of strong winds was not considered in this work to simplify the approach (see Heinonen et al. 2011). It was assumed that wind throws occurred within an edge zone whose width was equal to the mean tree height of the subject stand (Fig. 3). This was assumed because the predicted wind speed for uprooting increases sharply within one to two tree heights from the edge, depending on stand density (Peltola et al. 1999b). Most wind damage occurs in the immediate proximity of the newly created stand edge (see Peltola et al. 1999b; Zubizarreta-Gerendiain et al. 2012). The proportion of trees expected to be uprooted in a wind damage event was 0.03 (3% of trees uprooted or broken), calculated from the wind damage measurements done after the Pyry,

Janika, and Mielikki storms (Zubizarreta-Gerendiain et al. 2012). As a result, the proportion of trees damaged in an edge area was:

$$P[\text{damaged within the edge zone}] = 0.03 \times P[\text{max 5-year wind speed} > CWS] \quad (7)$$

where CWS is the critical wind speed calculated for the edge. The proportion of damaged trees among all trees in the stand was equal to

$$P[\text{damaged}] = P[\text{damaged within the edge zone}] \times \text{Area of edge zone} / \text{Area of stand} \quad (8)$$

The proportion of trees that escaped damage at edge i was

$$s_i = 1 - P[\text{damaged}]_i \quad (9)$$

and the proportion of trees that escaped all damage occurring at any of the n borders of the stand was

$$S = \prod_{i=1}^n s_i \quad (10)$$

The survival probability of each tree of the stand, as predicted by the survival model of Pukkala et al. (2013), was multiplied by S to obtain the wind-risk-adjusted survival probability.

Figure 3

The strongest winds in Finland occur from late autumn to early spring (Peltola et al. 1999a). Frozen soils provide a strong anchorage for trees against uprooting during the windiest season of the year. It was assumed that climate change lengthens the period of non-frozen soil by 0.17% per year (Kellomäki et al. 2010). Consequently, the amount of wind damage was assumed to increase by 0.17% per year when climate change was assumed.

Results

Forest landscape structure

Consideration of the risk of wind damage had a strong influence on the forest landscape structure (Fig. 4), regardless of the climatic conditions applied. When the risk of wind damage was minimized by minimizing the height difference between adjacent stands (MinRisk), the optimization resulted in a smooth forest landscape structure, whereas the MaxRisk plan resulted in a rough one. At the beginning of the simulation period, the mean height difference between adjacent stands was around 4 m. At the end of the 30-year period, it was around 5 m in the MinRisk and MaxNPV-MinRisk plans, 13 m in the MaxRisk plan, and 7 m in the MaxNPV plan (Fig. 5).

Figures 4 and 5

When the risk of wind damage was minimized (MinRisk), the thinned area was larger than the clear-felled area (Fig. 6). The opposite was true for the MaxRisk plan. Climate change did not substantially affect the thinned and clear cut areas, since the periodical cutting target was equal in all optimizations.

Figure 6

Net present value, timber production, and carbon balance of forestry

Wind damage affected the NPV and 30-year carbon balance of forestry. Under the current climate, the MaxNPV and MaxNPV-MinRisk plans had the highest damage-adjusted NPV. They also resulted in the highest timber production. The MinRisk and MaxRisk plans had 7 to 13% lower NPV and 4 to 19% lower timber production (Table 4). Climate change increased NPV by 1–2% and timber production by 4–10% compared to the corresponding plan under the current climate.

Table 4

Under the current climate, the MaxNPV and MaxNPV-MinRisk plans had the highest total carbon balance of forestry during the 30-year calculation period (Fig. 7). The MinRisk and MaxRisk plans had 18 and 44% lower carbon balances, respectively, compared to the MaxNPV plan (Table 4). The carbon balance of living forest biomass was negative in all optimization problems (ranging from -0.71 to -1.07 tonnes $\text{ha}^{-1} \text{y}^{-1}$) because of wind damage and the fact that the harvesting target was slightly higher than the damage-adjusted volume increment of the forest. The MaxRisk plan had up to 50% lower carbon balance of living forest biomass than the MaxNPV and MaxNPV-MinRisk plans, mainly due to the high amount of wind damage in the MaxRisk plan. The carbon balances of forest soil and wood products were positive (Fig. 7). The carbon balance of wood products was almost equal in all plans because the target for the harvested volume was constant. Climate change improved the total carbon balance slightly.

Figure 7

Bias caused by omitting wind damage in calculations

Simulation of the optimal management both with and without wind damage made it possible to calculate the bias caused by omitting wind damage in the calculations (Fig. 8). In this study, positive bias means that omitting wind damage leads to an overestimated value of the variable in question.

Figure 8

Figure 8 shows that the NPV, timber production, and carbon balance of forestry were all overestimated, regardless of the plan and climatic conditions, when wind damage was not taken into account. The MaxRisk plan resulted in the largest overestimation because it had more simulated wind damage than the other plans. Under both climatic conditions, timber production and the carbon balance of forestry were overestimated by 10–12% and the NPV by around 3%. The bias was smallest in plans that minimized the risk of wind damage.

When the bias in carbon balance was calculated separately for the three carbon pools, it turned out that the carbon balance of forest soil was underestimated if wind damage was not simulated (Fig. 8). This was because wind-thrown trees were treated as coarse woody debris, which was treated as input to the soil carbon pool. Ignoring wind damage led to overestimated carbon balances of living biomass and wood products since wind damage decreased the carbon inputs to these two pools (Fig. 9).

Figure 9

Discussion and conclusions

This study introduced and demonstrated the use of a new method of considering the risk of wind damage in forest planning and predicting the amount of damage and their effects on timber production, economic profitability and carbon balance of forestry. This methodology could be easily applied to other forest regions where sufficient input data are available. The method used for simulating wind damage could also be used to further analyze the effect of wind damage on the amount and type of deadwood in the forests. This would provide valuable information on the forest as habitat for many endangered species that depend on deadwood (see, e.g., Tikkanen et al. 2007).

In our case study forest, wind damage decreased timber production in all management plans regardless of climatic conditions, since it reduced both growth and harvested amount of timber when damaged trees were left in the forest. The MaxNPV and MaxNPV-MinRisk plans had the highest damage-adjusted timber production and MinRisk and MaxRisk plans had the lowest. Consideration of the risk of wind damage in management planning did not decrease the economic profitability of forestry when the NPV was maximized simultaneously with the minimization of vulnerable stand edges (MaxNPV-MinRisk plan).

Our results also showed that if the risk of wind damage is minimized in the management planning of even-aged forestry, the forest landscape structure becomes smoother than without wind risk minimization. This was found also by Heinonen et al. (2009). Most probably the effect would be much smaller in continuous cover forestry because it does not use clear-fellings, which are the cause of vulnerable new stand edges (Pukkala et al. 2016). We also demonstrated that without considering wind damage in calculations, the predicted NPV, timber production, and total carbon balance of forestry are all overestimated. However, the

soil carbon balance is underestimated if wind damage is ignored in calculations, because damaged trees will increase the soil carbon balance if not harvested.

The MaxNPV and MaxNPV-MinRisk plans had the highest NPV and carbon balance of forestry, regardless of the climatic conditions. When wind damage was not simulated, the MaxNPV plan had a higher NPV than the MaxNPV-MinRisk plan. However, the MaxNPV plan had more wind damage, which decreased its damage-adjusted NPV. As a result, when wind damage was taken into account, the plan in which NPV was maximized and the risk of wind damage simultaneously minimized eventually gave a slightly higher NPV than was obtained under the MaxNPV plan. A similar conclusion was drawn earlier by Forsell et al. (2011).

For all planning problems and climatic conditions, the harvested timber volume was set to 25000 m³ per 10-year period. However, the management actions needed to obtain the same volume varied depending on the planning problem. Minimization of the risk of wind damage increased the thinned area and decreased the clear-felled area when the same total timber harvest target was applied since, opposite to clear-felling, thinning treatments did not increase the length of vulnerable stand edges. Minimization of the risk of wind damage resulted in a smoother landscape due to the decreased height differences between adjacent stands.

Similar to our study, Zeng et al. (2007) showed that the risk of wind damage could be decreased by aggregating clear-felled areas due to the decrease in the length of vulnerable edges. Heinonen et al. (2009, 2011) also demonstrated that the risk of wind damage could be decreased significantly by minimizing the height differences between adjacent stands. Other authors have also suggested that the shelter provided by a neighboring stand reduces the

vulnerability to wind damage (Meilby et al. 2001; Schelhaas et al. 2007; Seidl et al. 2014; Pukkala et al. 2016). Meilby et al. (2001) also suggested that increased rotation lengths should be used for those stands that provide shelter to other stands.

Climate change is expected to increase forest growth, growing stock volume and timber production potential in Finnish forests, although the growth of Norway spruce with shallow rooting is expected to suffer drought on soils with low water holding capacity in the southern part of the country (Kellomäki et al. 2008). The increasing growing stock volume may increase the risks of various abiotic and biotic damages, which may change the carbon stocks of forests (Schelhaas et al. 2003; Thom and Seidl 2016). Similarly, climate change is expected to intensify natural disturbance regimes in forests (e.g. by wind storms, forest fires, bark beetle and root rot damages), of which biodiversity will generally benefit while a sustainable provisioning of other ecosystem services like timber might suffer (Jönsson et al. 2009; Subramanian et al. 2016; Thom and Seidl 2016). In this study, we did not consider these issues, but they should be taken into account in future studies.

Consideration of various risks to forests is becoming increasingly important under the changing climate due to the increase of associated risks to forests. However, risk management may be challenging if the forest holdings are very small like currently in Finland (20–30 ha on average). Co-operation between neighboring forest holdings is needed when planning forest management actions because the risk of wind damage within a single forest holding depends on the management of adjacent holdings.

To conclude, our work demonstrated well that by using a simple approach, namely minimizing height differences between adjacent stands, it is possible to decrease wind

damage without reducing the economic profitability of forestry. It also showed that consideration of wind damage in forest management planning clearly affects the development of the forest landscape structure due to the effects of risk management objectives on the type, location, and timing of cuttings. Minimization of the risk of wind damage increases the thinned area, whereas it decreases the clear-felled area. But results may vary depending on the initial forest structure and wind climate of the region (i.e. directional distribution of strong winds and their probability).

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654

Draft

Table 1. Characteristics of the study area.

Total forest area, ha	360
Forest biomass, (above and below ground), tonnes ha ⁻¹	165
• Scots pine (<i>Pinus sylvestris</i>) (%)	10.4
• Norway spruce (<i>Picea abies</i>) (%)	46.1
• <i>Betula</i> spp.	43.4
Total carbon stock, tonnes ha ⁻¹	256
• Trees	72
• Mineral soils	184

655 Table 2. Minimum top diameters and roadside prices of different timber assortments of the
 656 main species.

	Scots pine	Norway spruce	Birch
Minimum top diameter, cm			
- Saw log	15	16	18
- Pulpwood	7	8	7
Minimum piece length, m			
- Saw log	4.3	4.3	3.4
- Pulpwood	3	3	3
Roadside price, € m ⁻³			
- Saw log	58	58	44
- Pulpwood	30	31	30

657

658 Table 3. Optimization problems.

Short name	Description
MaxNPV	NPV was maximized. Wind risk management was not an objective.
MinRisk	Risk of wind damage was minimized by minimizing height differences between adjacent stands. NPV was not an objective.
MaxRisk	Risk of wind damage was maximized by maximizing height differences between adjacent stands. The purpose was to calculate the maximum possible wind damage. NPV was not an objective.
MaxNPV- MinRisk	NPV was maximized and height differences between adjacent stands were minimized to find equilibrium between the economic profit and the losses due to wind damage.

659

Table 4. Damage-adjusted net present value (NPV, 6%), 30-year timber production and 30-year carbon balance of forestry under the current climate (CU) and gradually changing climate (CC) in four management plans (see Table 3 for more detailed explanations of the management plans).

Management plan	NPV		Timber production		Carbon balance of forestry	
	(€ ha ⁻¹)		(m ³ ha ⁻¹ y ⁻¹)		(tonnes ha ⁻¹ y ⁻¹)	
	CU	CC	CU	CC	CU	CC
MaxNPV	4647	4721	4.25	4.72	0.88	0.98
MinRisk	4331	4392	4.09	4.46	0.72	0.82
MaxRisk	4042	4077	3.43	4.17	0.50	0.58
MaxNPV-MinRisk	4649	4724	4.19	4.83	0.87	1.01

FIGURES

Figure 1. Flow chart of the method developed for analyzing the effects of wind damage.

Numbers correspond to the numbering of the main steps explained in the text

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676

677 Figure 2. Carbon pools and their inputs and outputs. Recycling, substitution effects, and
 678 releases from harvesting, transport, and manufacturing were included in the carbon balance of
 679 wood products.

680

681 Figure 3. The principle of simulating wind damage. The critical wind speed (CWS) is
682 calculated for each edge of the subject stand using the characteristics of both the subject and
683 the adjacent stand. Then, the probability of having wind speeds higher than CWS (P) is
684 calculated. Damage occurs within the border zone (gray areas). The width of the border zone
685 is equal to the average tree height of the subject stand. The proportion of damaged trees
686 within the border zone is equal to $0.03 \times P$, where P is the probability of wind speed higher
687 than CWS and 0.03 is an empirical parameter. H is the mean tree height of the stand.

688

689

690 Figure 4. Forest landscape structure (stand height) after 30 years in management plans that
691 maximize NPV (MaxNPV), minimize the risk of wind damage (MinRisk), maximize the risk
692 of wind damage (MaxRisk), and simultaneously maximize NPV and minimize the risk of
693 wind damage (MaxNPV-MinRisk) under the current climate.

Figure 5. Mean stand height difference between adjacent stands under four management plans from 2015 to 2045 (see Table 3 for more detailed explanations of the management plans) under the current and gradually changing climate.

Figure 6. Thinned and clear cut areas under the current climate for the three 10-year periods in four management plans (see Table 3 for more detailed explanations of the management plans).

Figure 7. Carbon balance of forest biomass, forest soil, and wood products and total carbon balance of forestry under the current and gradually changing climate in four management plans (see Table 3 for descriptions of the management plans).

711

712

713 Figure 8. Bias (%) in the NPV, timber production, and total carbon balance of forestry caused
 714 by the omission of wind damage from calculations (positive bias means overestimation) under
 715 the current and gradually changing climate in four management plans (see Table 3 for
 716 descriptions of the management plans).

717

Figure 9. Bias (%) in the components of the total carbon balance of forestry (living biomass, forest soil, and wood products) caused by the omission of wind damage from calculations (positive bias means overestimation) under the current and gradually changing climate in four management plans.