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Factors Affecting Wind and Snow Damage of Individual Trees in a Small Management Unit in Finland: Assessment Based on Inventoried Damage and Mechanistic Modelling

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In this work, we assessed the factors affecting wind and snow damage of individual trees in a small management unit in western Finland. This was done based on inventoried damage and observed wind speeds and snow loading in storms Pyry and Janika in 2001 and Mielikki in 2002 together with mechanistic model. First, we studied which factors explain the observed damage in individual trees. Secondly, we studied how well the mechanistic model (HWIND) could predict the wind speed needed to uproot individual trees at the margins of permanent upwind edges. We found that Pyry storm caused 70% and Janika and Mielikki 18 and 12% of observed damage. In Janika storm, all trees uprooted. In other storms, both uprooting and stem breakage occurred. Scots pine suffered the most damage. Recently thinned stands on the upwind edges of open areas suffered the most damage. But, damage occurred also on soils with relatively shallow anchorage. HWIND predicted correctly damage for 69% of all uprooted trees. No-uprooting was correctly predicted for 45 and 19% of standing trees (all Scots pines), which were measured within and at the immediate upwind edge of same stands. HWIND model needs further validation at the permanent edges and/or on soils with shallow rooting to improve its prediction accuracy in such conditions.

Keywords critical wind speed, snow loading, damage risk, *Pinus sylvestris*, *Picea abies*, *Betula* spp.

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1 Introduction

Storms and strong winds cause significant damage and consequent economic losses in forests and forestry in Central and Northern Europe. In Finland, a total of 7 million m^3 of timber was damaged in 2001 in two separate storms (named as Pyry and Janika) in late autumn. In 2010 a total of 8 million m^3 of timber was damaged in four summer storms, respectively. Again, in December 2011 approximately 3.5 million m^3 of timber was damaged in winter storms. The economic impact of such damages is large in managed forests due to the reduction in the yield of timber and the increased costs of unscheduled harvesting. Damaged trees left in the forest can also lead to detrimental insect attacks on the remaining trees because of an increase in the breeding material.

The susceptibility of individual trees and tree stands to wind damage is largely affected by tree and stand characteristics (e.g. tree species, tree height and diameter, crown and rooting characteristics and stand density) and soil conditions, in addition to the mean wind speed, and its duration and gustiness (Laiho 1987, Lohmander and Helles 1987, Valinger et al. 1994, Nykänen et al. 1997, Peltola et al. 1999). However, relatively low wind speeds can also cause detrimental damage especially if wet snow accumulates simultaneously on tree crowns, which usually happens with temperatures between +1 and –3 ºC (Solantie 1994, Pellikka and Järvenpää 2003). This was found in Pyry storm in 2001 in Finland. Another typical damage case with low wind speed is with freezing rain, which accumulates on the branches and crowns (Pellikka et al. 2000, King et al. 2005).

In Finnish conditions, wind damage is most likely to occur especially in older Norway spruce (*Picea abies*) stands, but also in Scots pine (*Pinus sylvestris*) stands grown at the edges of recently clear cut areas. Particularly stands that recently suffered heavy thinning have a high risk of wind damage due to the sudden increase in wind loading in such stands (Peltola 1996, Gardiner et al. 1997, Lohmander and Helles 1987). Snow damage is most evident in Scots pine and birch (*Betula* spp.), and especially after too late and heavy early thinning, i.e. related to the large height/DBH (diameter at breast height) ratio of trees in such stands (e.g. Persson 1972).

Typically, trees growing at permanent edges such as at the margins of agricultural fields and lakes are expected to be less susceptible to damage than trees at newly created stand edges or more inside the stand. This is because they have adapted to larger wind loading over their life-span, and have, thus, lower height/DBH-ratio of trees and larger soil-root plate (being possibly also wider on the windward site) compared to trees grown more inside the stand or at newly created edges (Mickovski and Ennos 2002, Cucchi et al. 2004, Nicoll et al. 2008). Thus, more severe damage may be observed in sheltered areas than in exposed ones by similar wind speeds. On the other hand, tree anchorage is also affected by tree species, soil conditions and rooting depth of trees (Nicoll and Ray 1996, Ray and Nicoll 1998, Nicoll et al. 2006).

In recent years, mechanistic models such as HWIND (Peltola et al. 1999) and GALES/Forest-GALES (Gardiner et al. 2000, 2008) have been developed for the assessment of risks of wind and snow induced damage related to forest management. These models can predict the threshold (critical) wind speeds and snow loading needed for the uprooting or stem breakage of trees based on the properties of the trees and stands. The HWIND model was originally designed to calculate the critical wind speed and snow loading at the upwind of newly created stand edges in Finnish conditions, whereas the GALES/Forest-Gales model was designed to calculate the critical wind speeds within and above the forest stands in British conditions. Despite this, a good agreement has been found between these models in model comparison (see Gardiner et al. 2000).

The HWIND model has previously predicted reasonably well the wind speeds needed to cause wind damage at stand level both in Finnish and Swedish conditions, i.e. compared to observed wind speeds causing such damage (Talkkari et al. 2000, Blennow and Sallnäs 2004). However, the prediction accuracy of the HWIND model has not yet been studied for trees grown at permanent upwind edges such as at the margins of agricultural fields. Recently, Cucchi et al. (2004) suggested that Maritime pine (*Pinus pinaster* Ait.) trees grown at permanent stand edges, and on soils with a hard pan would have 20% higher

Table 1. Average stands characteristics in Tanila farm in 2002 (after Pyry and Janika storms). The species in the stand were Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula* spp.).

Stand ID	Area, ha	Stand density, stems ha^{-1}	Height, m	DBH, cm	Description
1	2.5	1500	10	18	Scots pine stand on partly open bedrock (stand edge facing north); not managed recently.
2a	0.8	625	25	27	Scots pine dominated stand (with mixture of Norway spruce) on sandy soil; heavy thinning in 2000 (stand edges facing north and east).
2b	0.8	600	23	21	Mixed stand of Norway spruce and Scots pine on slope; slight thinning in 2000 (stand edge facing north).
2c	0.7	714	18	14	Mixture of Norway spruce and Scots pine on wet soil; thinning in 2000 (stand edge facing east).
3	1	1766	14	12	Scots pine stand on drained peatland (drainage 30 years ago, stand edges in all directions); not managed recently.
4	1	570	16	18	Scots pine stand on moraine soil, close to a small hill. First thinning in 2000 (stand edges facing north and west).
5	0.2	2080	14	25	Scots pine stand (with deciduous mixture) on wet soil (stand edges facing north and west).
6	0.1	1480	10	15	Scots pine dominated stand on partly open bedrock (stand edges facing north and west).
10	1.7	30	19	19	Seed tree cutting in 1999, about 30 seed trees in Scots pine left (stand edges facing east and west).
11	0.7	2000	2	6	Old agricultural field, planted by Scots pine seedlings in 1994 (stand edges facing north).

resistance to uprooting (i.e. need 20% higher bending moment) than those growing more inside the stand.

In the above context, we aimed to assess the factors affecting wind and snow damage of individual trees in a small management unit in western Finland. This was done based on inventoried damage and observed wind speeds and snow loading in three separate storms (Pyry and Janika in 2001 and Mielikki in 2002) together with mechanistic modelling. First, we studied which factors could explain the observed wind and snow damage in individual trees. Secondly, we studied how well the HWIND model could predict the wind speed needed for uprooting of individual trees grown at the margins of permanent upwind edges such as agricultural fields.

2 Material and Methods

2.1 Study Layout and Inventoried Datasets

The study area of 9.5 hectares is a sub-compartment of Tanila farm (called later as management unit) and it consists of 11 stands. It is located in Jalasjärvi municipality (62º22'N and 22º50'E, 110–125 a.s.l.) in the South Ostrobothnia region, in western Finland. The area belongs to middle boreal vegetation zone characterised by coniferous forests, where the main species are Scots pine, Norway spruce and birch. A variety of soil types exists in a management unit: peat, sand clay, moraine and bedrock. Five of the 11 stands were thinned between 1999 and 2000 (2a, 2b, 2c, 4, 10) (Table 1). Most of the stands (1, 2a, 2b, 3, 4, 5, 6, 10, 11) were located at the edges of agricultural fields or recently regenerated (clear-felled) areas (Fig. 1).

The management unit was affected by Pyry storm on October 31st–November 1th 2001, by Janika storm on November 15th–16th 2001, and by Mielikki storm on September 23rd 2002. At the time of these storms, the soil was not frozen. The meteorological observations were based on synoptic 10-min wind speeds measured every three hours in Kauhajoki weather station (by Finnish Meteorological Institute), about 35 km northwest of the study area. Additionally, in the Pyry storm the average wind speed was 8–13 m s^{-1} with gusts of over 15 m s^{-1}. During the Janika

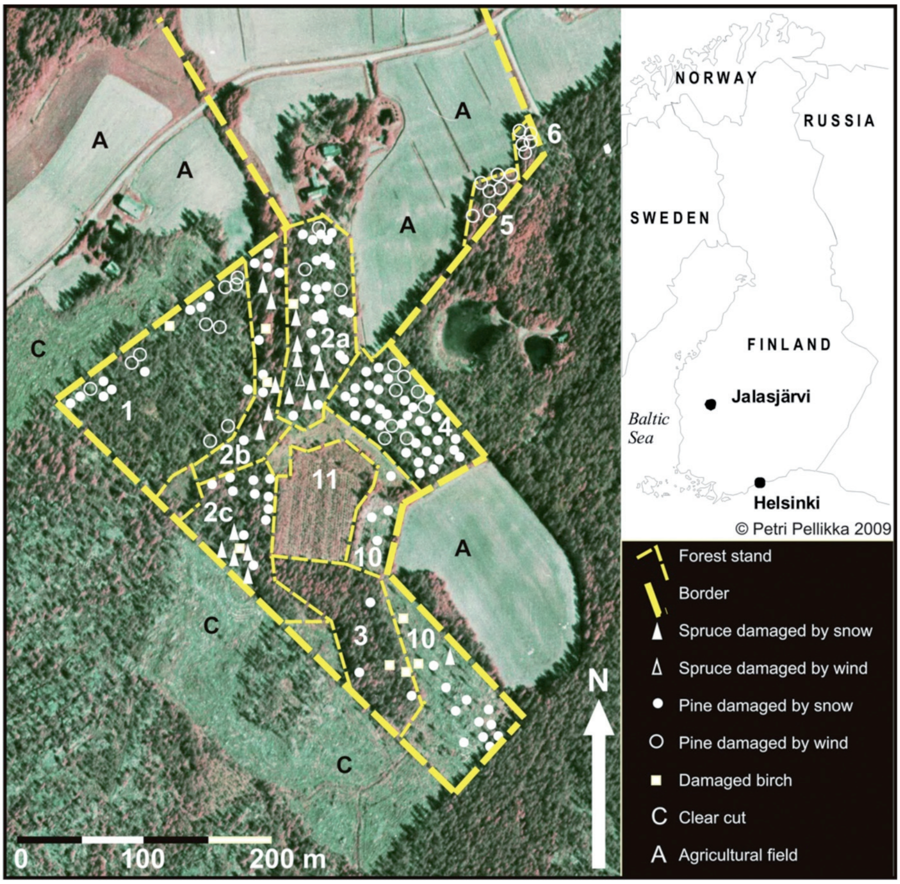

Fig. 1. The management unit with its eleven stands are shown on an aerial photograph acquired on June 2, 2002 after the Pyry (snow and wind) and Janika (wind) storms. In Mielikki storm in autumn 2002, some additional damage happened (in stands 1, 2a, 2b, 2c and 4) but this damage is not shown. Similarly, additional cross-validation dataset measured in winter 2010 (for stands 1, 2a, 2b, 2c, 3, 4 and 10) is also shown only in Tables 5 and 6.

storm, the corresponding average wind speed was 15–19 m s^{-1} with gusts of 30–50 m s^{-1}. The main wind direction in both storms was north-northwest. The average wind speed of Mielikki storm was 10–15 m s^{-1} with gusts of about 25 m s^{-1}. During the Pyry storm, a daily precipitation of 30 cm of wet and heavy snow occurred (corresponding wet snow of 30 kg m^{-2} crown area), which froze on the tree crowns (Fig. 2). The corresponding precipitation data was obtained from Hirvijärvi station, 15 km northeast of the study area. Mean daily temperatures at Jalasjärvi during the Pyry storm were 0.1, 0.3 and –0.1ºC for October 30th and 31st and November, 1st 2001 (Finnish Meteorological Institute, 2005). During the Janika storm, the mean daily temperature was –1.0 and –4.4ºC in November 15th and 16th 2001. After each storm, the number of broken and uprooted trees and their characteristics were inventoried in each stand (e.g. species, height and DBH) (see Table 2 and 3). The locations of individual trees damaged by the Pyry storm (up to about one tree height inside the stand) and the Janika storm (mainly at stand edge) are also shown in Fig. 1.

Fig. 2. Scots pine (*Pinus sylvestris*) stand (2a in Fig. 1) located in Tanila farm during Pyry storm November 1, 2001 (Photograph by Petri Pellikka).

2.2 Outlines for the HWIND Model and Model Computations

In this work, we used the mechanistic HWIND model, which was originally developed to predict the critical wind speeds (mean speed of 10 min at 10 m above ground level and top of the tree) and snow loading needed to uproot or break Scots pine, Norway spruce and birch trees at the newly created upwind stand edges, with varying gap sizes and distances from the stand edge (see Peltola et al. 1999). In the HWIND model, the forces acting upon a tree are divided into the horizontal force by wind and the vertical force by gravity, the latter one taking into account the effects of stem and crown weights and additional snow loading as well. The tree is assumed to deflect to a point of no return when acted upon by a wind of constant mean velocity and direction. In the model, a tree is also assumed to be uprooted if the maximum bending moment exceeds the resistance of the root-soil plate. The stem is assumed to be broken (calculated at 1.3 m height) if the breaking stress exceeds the critical value of the modulus of rupture.

The inputs needed for the HWIND model are tree species, tree height, diameter at breast height (DBH), stand density, distance from the stand edge, gap size (in this work fixed as 10 x stand height of downwind edge of open field) and possible snow loading on tree crowns (e.g. in Pyry storm: 30 kg/m^2 for the crown area, corresponding precipitation of 30 mm wet snow). The properties of the HWIND model with its parameters and inputs, and the validity of its outputs for Finnish and Swedish conditions have been reported in details by Peltola et al. (1999), Gardiner et al. (2000, 2008), Blennow and Sallnäs (2004) and Zeng et al. (2006). Previous studies have also shown that any inaccuracies in the input tree characteristics (e.g. DBH and height) and/or parameters that control the magnitude of the wind loading (e.g. gust factor, drag coefficient, crown streamlining) or the resistant bending moments of trees can have a large influence on the predicted critical wind speeds for uprooting and stem breakage (Peltola et al. 1999, Zeng et al. 2006).

In this work, HWIND was first used to calculate the critical wind speeds (10-min average at 10 m high above ground) needed for uprooting the trees, that actually uprooted in Janika, Mielikki and Pyry storms at the margins of permanent upwind edges, i.e. from the immediate edge in Janika, Mielikki and Pyry up to about one tree height from upwind edge in Pyry. Because the inventory data for damaged trees did not include tree height measurements for all broken trees, we were not able to calculate the corresponding critical wind speeds needed for stem breakage. Furthermore, the trees with height or DBH less than 10 m and 10 cm, respectively, could not be used in HWIND simulations (i.e. model was not validated for such small trees).

We also used 18 Scots pine trees, which uprooted later in the Janika storm in the same stands 1, 2a and 4 as in the Pyry storm (see Table 4) as a cross-validation data for the Pyry storm and calculated critical wind speeds with additional snow loading for uprooting of those trees. The number of observations for birch and Norway spruce were very limited regardless of the storm, as was the case for Scots pine in the Mielikki storm, and therefore, they could not be used as a corresponding cross-validation data (see Table 4). For this reason, in winter 2010 we measured an additional cross-validation dataset for this work (see Table 6 for average tree characteristics for this dataset). It consisted of randomly selected 63 standing Scots pine trees in the same stands in which these three storms previously caused damage, i.e. a total of 20 trees at the immediate stand edge and 43 trees within distance of one tree height from edge.

2.3 Statistical Data Analyses and Validation of HWIND Predictions

In the statistical data analyses, we studied if average height, DBH and height/DBH ratio of damaged trees differ statistically significantly (one-way ANOVA used, $p < 0.05$, SPSS 16.0) in different storms, between tree species and damage type (i.e. uprooted and broken) for each species. However, this was done only for those damaged trees for which both height and DBH were available (for most of the broken trees height measurements were not available, see Table 3). We also calculated the right predicted % for uprooting and for no-uprooting of standing trees. Moreover, differences in average tree (and soil) characteristics between correctly and incorrectly predicted cases at various conditions were also studied.

3 Results

3.1 Observed Damage

Pyry, Janika and Mielikki storms uprooted or broke a total of 189 Scots pine, Norway spruce and birch trees during 2001 and 2002 in our study area. Pyry caused 69.8%, Janika 18% and Mielikki 12.2% of all damage (Table 2). Scots pine suffered 78.8% of all damage as main tree species of the study area. The corresponding percentages for Norway spruce and birch were 14.8 and 6.3%. In Janika storm, all trees uprooted, while in Pyry and Mielikki storms 53 and 52% damaged trees uprooted. Furthermore, in Pyry and Mielikki storms 58 and 44% of the damaged Scots pines uprooted, while the corresponding numbers for Norway spruce were 33 and 60% and for birch 40 and 100% (Table 2).

In these three storms, stands 2a and 4 suffered the most damage, but damage was also notable in stands 1, 2b, 2c and 10 (Table 2). However, the severity of damage in different stands varied depending on the storm. Pyry storm damaged mostly the recently thinned stands 2a, 2b, 2c and 4. It also damaged stand 10 in which seed tree cutting was recently done. In addition, unmanaged stands 1 and 5 also suffered damage to some degree. Pyry storm also damaged trees from the immediate upwind edge of the stand up to about one tree height inside the stand. The other storms mainly damaged trees at the immediate upwind edge of the stand. In Janika storm, unmanaged stands 1, 5 and 6 suffered the most damage. But, stands 2a and 4 (the latter on a small hill with north sloping aspect) also suffered damage. Mielikki storm caused the most severe damage in managed stand 2c, but some damage occurred

Table 2. Total number of damaged trees N and uprooted %, in each stand, for Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula* spp.) in Pyry, Janika and Mielikki storms. Uprooted trees % in each species shown in parenthesis.

Stand ID	Storm	Scots pine	Norway spruce	*Betula* spp.	N	Uprooted %
Stand 1	Pyry	11	0	1	12	100
	Janika	10	0	0	10	100
	Mielikki	2	0	0	2	100
Stand 2a	Pyry	22	9	1	32	28
	Janika	3	1	0	4	100
	Mielikki	4	1	0	5	0
Stand 2b	Pyry	9	6	1	16	38
	Mielikki	1	1	0	2	0
Stand 2c	Pyry	11	5	2	18	61
	Mielikki	5	3	2	10	90
Stand 3	Pyry	2	0	3	5	20
Stand 4	Pyry	32	0	0	32	69
	Janika	8	0	0	8	100
	Mielikki	4	0	0	4	25
Stand 5	Janika	7	0	0	7	100
Stand 6	Janika	4	1	0	5	100
Stand 10	Pyry	14	1	2	17	53
Total number (uprooted, %)						
	Pyry	101(58)	21(33)	10(40)	132	53
	Janika	32(100)	2(100)	0(0)	34	100
	Mielikki	16 (44)	5(60)	2(100)	23	52

also in stands 1, 2a, 2b and 4.

Regardless of the storm, the size of uprooted Scots pine trees (i.e. height, DBH and height/DBH ratio) in general, did not differ from uprooted Norway spruce and birch trees ($p > 0.05$, excluding height/DBH ratio in Pyry storm) (Table 3). However, the number of observations in Norway spruce and birch was very limited. In Pyry and Mielikki storms, the average height/DBH ratio of uprooted Scots pines was also lower than that for broken ones (in Mielikki storm DBH was also smaller). For birch and Norway spruce, the corresponding comparison was not done because of very limited data. Regardless of tree species and damage type, in the Mielikki storm the damaged trees were on average taller than in the other storms ($p < 0.05$) (Table 3).

3.2 Predicted Critical Wind Speeds for Uprooted Trees in Each Storm

The HWIND model predicted uprooting correctly for 69% of the damaged trees in Pyry, Janika and Mielikki storms (see Table 4). In Janika storm, the correctly predicted percentage was 83%, while in Pyry and Mielikki storms it was 71 and 22%. In Scots pine, the correctly predicted percentage of damage was on average 71% for different storms, while in Norway spruce and birch with very limited data it was 75 and 33%, respectively (Table 5). The height/DBH ratio of uprooted Scots pines was also significantly higher for correctly predicted trees than for incorrectly predicted ones regardless of the storm, as was also the case for tree height in Pyry storm ($p < 0.05$) (Table 5). Moreover, slender trees had on average lower predicted critical wind speeds for uprooting. In Scots pine the predicted critical wind speed was on average 40% lower in Pyry and Janika storms for correctly predicted uprooting cases than for incorrectly predicted ones, whereas it was 26% lower in Mielikki storm. Predicted critical wind speeds (CWS) for uprooted Scots pines for each storm are shown in Fig. 3. Similar comparisons were not possible for Norway spruce and birch due to limited data. Regardless of the storm, the CWS needed for uprooting decreased along with

Table 3. Average height (H, m), DBH (cm) and H/DBH ratio for each damage type and storm for Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula* spp.) trees in which H and DBH information was available. In parenthesis is shown the total number of damaged trees in each case. Statistically significant differences are shown in bold ($p < 0.05$) ^{1} between tree species and ^{2} between broken/uprooted trees within a storm, and ^{3} between different storms.

Storm	Damaged trees			Uprooted trees			Broken trees		
	Uprooted	Broken	Total	DBH	Height	H/DBH	DBH	Height	H/DBH
Pyry:									
Scots pine	58 (59)	19 (42)	77 (101)	20.4±7.0	15.1±4.2	**77.6±17.5**^{1,2}	18.2±7.2	14.9±5.1	**88.5±27.1**^{2}
Norway spruce	7 (7)	0 (14)	21 (21)	15.4±5.2	13.1±4.8	**84.1±9.0**^{1}	–	–	–
Birch	4 (4)	2 (6)	6 (10)	13.8±2.2	13.8±1.3	**101.8±17.8**^{1}	8.0±1.4	7.5±2.1	92.9±10.1
Total	69 (70)	21 (62)	104 (132)	19.5±7.0	**14.8±4.1**^{3}	79.7±17.7	17.2±7.6	14.2±5.3	89.0±25.8
Janika:									
Scots pine	26 (32)	0(0)	26 (32)	20.7±6.8	15.2±4.4	77.2±22.2	–	–	–
Norway spruce	2 (2)	0(0)	2 (2)	18.5±16.3	14.0±11.3	79.5±8.7	–	–	–
Total	28 (34)	0(0)	28 (34)	20.5±7.3	**15.1±4.8**^{3}	77.5±21.4	–	–	–
Mielikki:									
Scots pine	7 (7)	9 (9)	16 (16)	**19.9±7.2**^{2}	16.0±4.9	**83.7±14.7**^{2}	**20.8±2.5**^{2}	20.6±2.2	**99.4±7.6**^{2}
Norway spruce	3 (3)	2 (2)	5 (5)	25.7±14	17.7±8.4	71.8±9.0	23.0±0	22.8±1.1	98.9±4.6
Birch	2 (2)	0(0)	2 (2)	17.7±3.5	15.5±6.4	86.7±18.9	–	–	–
Total	12 (12)	11 (11)	23 (23)	20.9±8.6	**16.3±5.5**^{3}	81.2±14.1	21.2±2.4	21.0±2.2	99.3±6.9

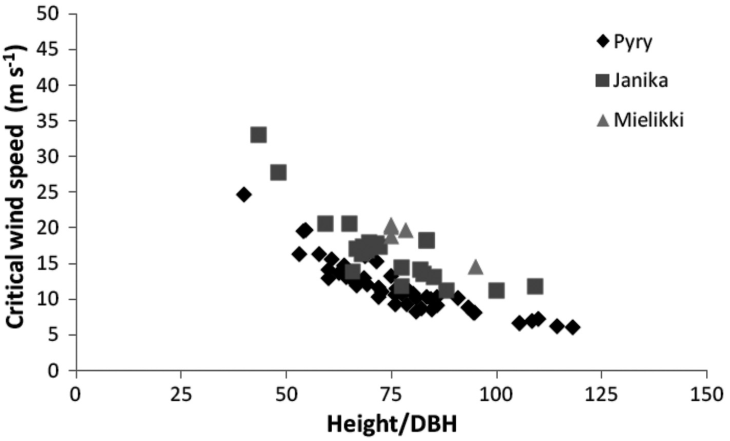

Fig. 3. Predicted critical wind speeds (HWIND) needed to uproot damaged Scots pine (*Pinus sylvestris*) trees with various height/DBH ratios for various storm conditions.

increase in the height/DBH-ratio, i.e. indicating that slender trees (with same tree height) needed lower wind speed for uprooting (Fig. 3).

At individual stand level, the correctly predicted percentage of uprooted Scots pines varied in Pyry storm from 0 to 100%, and in Janika and Mielikki storms between 63–100% and 0–50%, respectively (Table 4). The best agreement was observed for Scots pine in stands thinned in 2000 (i.e. 2a, 2c and 4). In Norway spruce and birch, uprooted trees were very often predicted correctly (up to 100%) in Pyry and Janika storms, as opposite to Mielikki storm (Table 4). Some of the stands with large discrepancy between observed and predicted damage were located on soils with a relatively shallow anchorage (partly open bed-

Table 4. Average characteristics of uprooted Scots pine (*Pinus sylvestris*) (SP), Norway spruce (*Picea abies*) (NS) and birch (*Betula* spp.) trees for each stand and storm used in the calculations, and corresponding critical wind speeds (CWS) predicted by the HWIND model. Number (N.R.) and percentage (%) of correctly predicted uprooted trees are shown. In Janika storm, in parenthesis it is also shown CWS and correctly predicted number and % for those uprooted Scots pine trees in stands 1, 2a and 4, which were used as additional cross validation dataset for Pyry storm.

Stand	Species	N[1]	H (m) Mean±sd	DBH (cm) Mean±sd	H/DBH Mean±sd	CWS[2] Range (m s^{-1})	Correctly predicted N.R.	%
Pyry[3]:								
1	SP	6	12±1	21±8	61±13	13–25	0	0
2a	SP	7	21±2	25±6	85±16	7–13	7	100
2b	SP	4	17±1	28±3	61±8	12–16	1	25
2c	SP	5	16±3	19±6	82±11	8–13	5	100
4	SP	20	15±2	19±5	84±18	6–16	16	80
10	SP	7	17±3	23±2	71±6	8–14	6	86
2a	NS	1	19	24	79	10	1	100
2b	NS	1	11	13	85	12	1	100
2c	NS	3	16±0	17±1	92±3	9–10	3	100
1	Birch	1	14	16	88	23	0	0
2c	Birch	1	14	11	127	13	1	100
3	Birch	1	12	13	92	23	0	0
10	Birch	1	15	15	100	16	0	0
Total		58	–	–	–	–	41	71
Janika[4]:								
1	SP	8	15±3	22±5	68±13	13–33 (11–28)	5 (6)	63 (75)
2a	SP	3	23±1	30±5	77±11	11–14 (10–12)	3 (0)	100 (0)
4	SP	7	15±2	19±4	83±16	11–17 (7–14)	7 (3)	100 (43)
5	SP	3	16±4	26±2	62±12	16–28	2	67
6	SP	2	14±6	17±7	83±1	14–18	2	100
2a	NS	1	22	30	73	13	1	100
Total		24	–	–	–	–	20	83
Mielikki[5]:								
2c	SP	4	19±1	24±3	81±10	15–20	1	25
4	SP	1	18	24	75	20	0	0
2c	NS	2	23±1	34±5	68±8	17–21	0	0
2c	Birch	2	16±6	18±4	87± 19	12–25	1	50
Total		9	–	–	–	–	2	22

[1] Number of uprooted trees used for HWIND calculations.
[2] Observed 10min average wind speeds were 13, 19 and 15 m/s in Pyry, Janika and Mielikki storms.
[3] Pyry: in HWIND simulations additional snow load of 30 kg m^{-2} expected, no crown streamlining. Birch without leaves.
[4] Janika: in HWIND simulations used fixed 20% streamlining of crown.
[5] Mielikki: in HWIND simulations crown streamlining expected as function of wind speed. Birch in leaf.

rock, e.g. stand 1 and 6) and/or poor drainage (e.g. stand 2c, 3 and 5, see Table 1). In such soil conditions, the HWIND model overestimated clearly the wind speeds needed for uprooting the trees, which was evident especially in Scots pine in the Pyry storm ($p < 0.05$), but also in the Janika storm ($p = 0.057$).

3.3 Predicted Critical Wind Speeds for Standing Trees

In the wind and snow loading conditions of the Pyry storm, HWIND predicted no-uprooting correctly for 50% of those Scots pine trees, which survived Pyry storm but not later Janika storm in stands 1, 2a and 4 (see Table 2). In stand 1, uprooting was predicted correctly for 75% of Scots pine

Table 5. Average Height (H, m), diameter at breast height (DBH, cm) and H/DBH ratio for uprooted trees, in which damage was predicted correctly (N.R.) and incorrectly (N.W.) for each storm (Pyry, Janika, Mielikki) and tree species. N: total number of trees used in computations. Significant differences ($p < 0.05$) for tree characteristics between correctly/incorrectly predicted trees are given in bold.

Tree species / Storm	N	N.R.	Correctly predicted Height Mean±sd	DBH Mean±sd	H/DBH Mean±sd	N.W.	Incorrectly predicted Height Mean±sd	DBH Mean±sd	H/DBH Mean±sd
Scots pine (*Pinus sylvestris*)									
Pyry	49	35	**17±3**	21±6	**84±15**	14	**14±2**	24±6	**61±9**
Janika	23	19	17±4	22±6	**78±12**	4	13±3	24±3	**54±10**
Mielikki	5	1	19	20	**95**	4	19±2	25±2	**76±2**
Norway spruce (*Picea abies*)									
Pyry	5	5	16±3	18±4	88±6	–	–	–	–
Janika	1	1	22	30	73	–	–	–	–
Mielikki	2	–	–	–	–	2	23±1	34±5	68±8
Birch (*Betula* spp.)									
Pyry	4	1	14	11	127	3	14±2	15±2	93±6
Mielikki	2	1	20	20	100	1	11	15	73

Table 6. Average characteristics of standing Scots pine (*Pinus sylvestris*) trees for each stand at the immediate upwind stand edge and one tree height from the edge, for each storm, with corresponding range of critical wind speeds (CWS, m s^{-1}) predicted by HWIND model. Number of right (N.R.) and percentage (%) of correctly predicted no-uprooted trees are also shown.

Stand	N^1	Height (m) Mean±sd	DBH (cm) Mean±sd	H/DBH Mean±sd	Correctly predicted no-uprooting. CWS^2	N.R.	%	CWS^2	N.R.	%	CWS^2	N.R.	%
Scots pine at the upwind edge					Pyry^3			Janika^4			Mielikki^5		
1	6	15±1	22±4	69±7	12–16	4	67	16–20	3	50	23–27	6	100
2a	5	20±2	29±3	70±9	10–14	1	20	13–18	0	0	18–24	5	100
2b	3	21±3	31±3	68±3	10–12	0	0	–	–	–	17–21	3	100
3	4	19±1	26±5	75±11	9–13	0	0	–	–	–	–	–	–
4	2	20±0	26±2	78±3	10–10	0	0	13	0	0	18–18	2	100
Scots pine, 1 tree height from upwind edge					Pyry^3			Janika^4			Mielikki^5		
1	9	13±2	21±4	63±9	16–27	9	100	23–33	9	100	31–45	9	100
2a	9	23±2	25±4	91±13	8–17	1	11	12–21	1	11	17–29	9	100
2b	1	17	29	57	19	1	100	–	–	–	32–32	1	100
2c	4	19±1	23±3	83±14	10–17	2	50	–	–	–	20–29	4	100
3	9	17±3	20±5	88±13	11–20	6	67	–	–	–	–	–	–
4	8	18±1	21±4	86±18	7–17	1	13	11–22	1	13	14–30	7	88
10	3	18±1	29±1	64±3	11–13	1	33	–	–	–	–	–	–

[1] Number of standing trees used for HWIND calculations (for uprooting) in each storm.
[2] Average wind speeds in Pyry, Janika and Mielikki storms were 13, 19 and 15 m/s, respectively.
[3] Pyry: Snow load was 30 kg m^{-2}, no streamlining, birch without leaves.
[4] Janika: In calculation constant 20% streamlining was used.
[5] Mielikki: streamlining as a function of wind speed.

trees, but in other stands the percentage ranged from 0 to 43% (see Table 4).

HWIND predicted no-uprooting correctly for the Pyry storm conditions for 41% of the 63 standing Scots pines in the same stands in which Pyry actually caused damage. More specifically, it predicted correctly no-uprooting for 25% of edge trees and for 49% of trees more inside the stand for same storm (Tables 6 and 7). HWIND also predicted correctly no uprooting for storm conditions like Janika for 36% of 39 Scots pine trees grown in same stands in which Janika storm

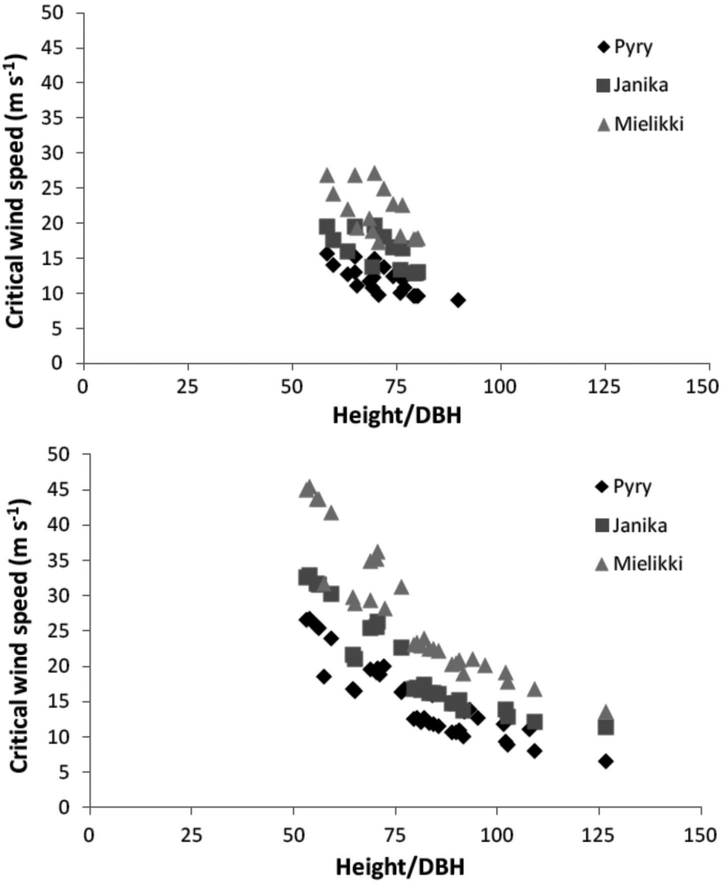

Fig. 4. Predicted critical wind speed (HWIND) needed to uproot standing, undamaged, Scots pine (*Pinus sylvestris*) trees with various height/DBH ratio at immediate stand edge (above) and within one tree height from upwind edge (below).

actually caused damage. The corresponding percentage for the Mielikki storm conditions was 98% of 47 trees (Table 6). For the Janika and Mielikki storms, HWIND predicted correctly no uprooting for 23 and 100% of edge trees, and for 42 and 97% of trees more inside the stand Table 7). In general, lower critical wind speeds are predicted to uproot trees of similar size at the immediate upwind edge of stand compared to inside the stand.

The corresponding percentage of standing Scots pine trees predicted to survive equally all storms was on average 36%, i.e. 19% for edge trees and 45% for trees inside the stand (not shown in details in Table 7). The result was, thus, clearly poorer at the immediate upwind edge of stand, which represented mainly permanent edges of agricultural fields, than more inside the stand. At the immediate stand edge conditions the trees had also on average lower height/DBH ratio than more inside the stand (see Table 6), which also increased the predicted critical wind speed for damage (see Fig. 4). The result also varied largely between different stands as can be seen in Table 6. Furthermore, in Pyry and Janika storms, the average height and height/DBH ratio of Scots pine were significantly smaller in correctly predicted trees than in the incorrectly predicted ones, both at the immediate edge and inside the stand ($p < 0.05$, see Table 7).

Table 7. Average characteristics for height (m), diameter at breast height (DBH, cm) and H/DBH for standing Scots pine (*Pinus sylvestris*) trees in which no-uprooting was predicted correctly/incorrectly for each storm for stand edge and inside the stand. N: Number of trees in computations; N.R.: number of correctly (and %) and N.W.: number of incorrectly predicted cases. Statistically significant differences in bold ($p < 0.05$).

Storm	N	Correctly predicted no-uprooting N.R. (%)	Height Mean±sd	DBH Mean±sd	H/DBH Mean±sd	Incorrectly predicted no-uprooting N.W.	Height Mean±sd	DBH Mean±sd	H/DBH Mean±sd
Scots pine, at the upwind edge:									
Pyry	20	5 (25)	**15±2** ^{1}	24±5	**65±6** ^{1}	15	**20±2**^{1}	**27±5** ^{2}	**74±7** ^{1,2}
Janika	13	3 (23)	**15±2** ^{1}	24±5	**64±6** ^{1}	10	**19±3**^{1}	26±5	**73±7** ^{1,2}
Mielikki	16	16 (100)	18±3	**26±5** ^{2}	70±7	0	–	–	–
Scots pine, 1 tree height from the upwind edge:									
Pyry	43	21 (49)	**15±3** ^{1}	23±5	**69±12** ^{1}	22	**20±3** ^{1}	**22±4** ^{2}	**91±14** ^{1,2}
Janika	26	11 (42)	**14±3** ^{1}	22±5	**63±8** ^{1}	15	**20±3** ^{1}	23±4	**92±13** ^{1,2}
Mielikki	31	30 (97)	18±4	**23±4** ^{2}	78±16	1	16	13	127

[1] differences between correctly/incorrectly predicted trees
[2] differences between stand edge and 1 height from the edge

In correctly predicted Scots pines (suffering no damage), the average tree characteristics did not differ between edge trees and trees located further inside the stand, in conditions like Pyry and Janika storms. But, in Mielikki storm conditions, DBH differed (Table 7). In Pyry storm conditions, the height/DBH ratio and DBH differed for incorrectly predicted Scots pines (suffering damage) between the immediate stand edge and within stand condition ($p < 0.05$, see Table 7). In the Janika storm, the case was same for height/DBH ratio. In Mielikki storm conditions, there were no incorrectly predicted cases at the upwind edge.

4 Discussion and Conclusions

4.1 Evaluation of Factors Affecting the Damage by Wind and Snow

In this work, we analysed the factors affecting wind and snow damage of individual trees in a small forest management unit by employing inventoried tree characteristics of damaged trees, observed wind speeds and snow loading during Pyry, Janika and Mielikki storms and the mechanistic model HWIND. For the first time, we could study the performance of HWIND model at the margins of permanent upwind edges such as agricultural fields, using characteristics of individual damaged trees as inputs for HWIND simulations. It would have been ideal, if the wind and snow observations used to characterise the storm conditions were measured in the actual study area. But, unfortunately such information was not available. Therefore, we used for this purpose the observations (i.e. maximum of 10-min mean wind speeds measured once for every three hour) obtained from the nearest weather station, located about 35 km northwest of the study area. Most probably damaging wind speeds could have been to some degree higher in our study area, which causes some uncertainties in the evaluation of real storm conditions.

The Pyry, Janika and Mielikki storms uprooted or broke altogether 189 Scots pine, Norway spruce and birch trees. Scots pine was the main tree species in the study area, and suffered about 79% of all damage. In the Janika storm all damaged trees uprooted, whereas in Pyry and Mielikki storms about 50% of the trees uprooted. The uprooting percentage varied between species depending on the storm. The Pyry storm had the lowest 10-min average wind speed and gust speed, but it caused most of the damage (i.e. 69% of all damage). This was, because it was accompanied by wet and heavy snow load frozen on tree crowns (i.e. snow load of 30 kg m^{-2} crown area). Similarly, in previous studies, relatively low wind speeds together with snow loading of 20 to 40 kg m^{-2} have increased the risk of stem breakage of trees, as well as uprooting of trees during unfrozen soil conditions in boreal conditions (Solantie 1994, Päätalo 2002).

The severity of the damage in different stands varied depending on the storm. But, in general, very recently managed stands (thinning or seed tree cutting) which were located on the upwind edges of open areas (and/or on small hills with increased wind flow) suffered the most damage regardless of the storm. Also previously it has been suggested that the risk of such damage is most likely to occur where there are sudden changes in wind loading to which the trees are not acclimated, as in recently thinned stands or stands adjacent to recently clear-felled areas (Laiho 1987, Lohmander and Helles 1987, Valinger and Lunqvist 1992 and Valinger et al. 1994). However, the risk of damage has been found to decrease within a few years after thinning, along with increase in stem growth near the stem base and enhanced root anchorage, which together will increase tree stability (Nykänen et al. 1997). In this study, the stands suffering damage in different storms had also relatively long upwind edges at risk and their shapes were quite narrow. Thus, in practice, a relatively large proportion of damaged trees were located at the immediate upwind edge (Janika, Mielikki and Pyry) or at short distance from it (Pyry).

The stands located on soils with relatively shallow rooting (e.g. due to open bedrock or high soil moisture conditions) also suffered substantial damage in our study area, regardless of the storm. In these conditions, trees with a relatively low height/DBH ratio suffered also the most damage. This result could be explained by the fact that the development of rooting depth (and anchorage) is districted in such conditions (Nicoll and Ray 1996, Ray and Nicoll 1998, Cucchi et al. 2004, Nicoll et al. 2006, 2008, Achim and Nicoll 2009).

In general, the vulnerability of trees to damage will increase with tree height, and especially tall and slender trees are the most vulnerable to increased wind loading (Persson 1972, Valinger and Lunqvist 1992, Peltola et al. 1999). According to Peltola et al. (1999, 2000), trees with large height/DBH ratio need smaller bending moments and critical wind speeds for uprooting than trees with lower height/DBH ratio, but with same height. On the other hand, relatively short trees, with high height/DBH-ratio may also suffer especially the snow induced damage, as was found in Pyry storm. This result is in line with previous studies in which trees with height/DBH-ratio of less than 1:90 to 1:100 have been found to be particularly susceptible to such damage (Petty and Worrel 1981, Petty and Swain 1985, Peltola et al. 1999, Päätalo 2002).

4.2 Evaluation of Performance of HWIND at the Margins of Permanent Upwind Edges

The HWIND model predicted uprooting correctly for 69% of the trees over three storms. In Scots pine, the correctly predicted percentage was 71%, and in Norway spruce and birch 75 and 33%, respectively. The average height/DBH ratio of the trees was also significantly higher for correctly predicted Scots pines. The predicted critical wind speed was, on average, 26–40% lower for correctly predicted uprooting cases in Scots pine, regardless of storm. Similarly, Cucchi et al. (2004) previously found, that Maritime pine (*Pinus pinaster* Ait.) trees grown on soils with a hard pan would be 20% more resistant to uprooting (i.e. need 20% higher bending moment) at the upwind stand edge than more inside the stand.

In this work, the highest agreement between observed and predicted damage was found in recently thinned stands located on soils with normal drainage conditions and not districted tree anchorage. On the soils with a relatively shallow anchorage (partly open bedrock, e.g. stand 1 and 6) and/or poor drainage (e.g. stand 2c, 3 and 5), the HWIND model clearly overestimated tree anchorage, as such soils were not present in the Finnish tree pulling database which was used for model validation (see Peltola et al. 1999, 2000). The discrepancy was most obvious for trees having very low height/DBH-ratio. In the HWIND model, root anchorage (rooting depth and width) is also dependent on DBH, which explains this result.

The HWIND model also most probably underestimated the anchorage of trees grown at the immediate upwind edges of agricultural fields, where trees are acclimated to higher wind loading than that expected on more sheltered areas, and thus, develop stronger root anchorage, too. Especially at such stand edges many uprooted trees (regardless of soil conditions) had very low height/DBH ratio. Such trees are also rare in the Finnish tree pulling database (e.g. in Scots pine height/DBH ratio of 102±19), which has been used previously for validation of HWIND model (Peltola et al. 2000). This explains also some discrepancies observed in the HWIND predictions.

The HWIND model predicted correctly no-uprooting for 45% of standing Scots pines trees inside the stand while the corresponding percentage was 19% at the immediate upwind edge in the stands in which all three storms caused some damage. Thus, the percentage of correctly predicted cases for standing trees was clearly lower at the immediate upwind edge of the stand. On average, it was 36% regardless of tree position in a stand, ranging from 36% in Janika to 98% in Mielikki. Moreover, HWIND predicted correctly no-uprooting in Pyry storm conditions for 50% of Scots pine, which uprooted in same stands later in Janika storm. Also for standing trees, the correctly predicted percentage differed considerably, depending on the storm and individual stands. The height/DBH ratio was clearly lower for those Scots pine trees for which no-uprooting was correctly predicted.

5 Conclusions

This work identified the factors affecting the risk of wind and snow induced damage on individual Scots pine, Norway spruce and birch trees in Finnish conditions based on a ground-true inventory dataset. In this work, for the first time we were able to study, the performance of the HWIND model at the margins of permanent upwind edges such as agricultural fields and on the soils with a relatively shallow anchorage and/or poor drainage. As a result, we observed that the trees growing at the immediate upwind edges of open fields such as agricultural fields seem to be, in general, more stable than trees at the newly created upwind stand edges. This can be explained by lower height to diameter ratio of trees at same tree height and stronger anchorage of trees (and windward roots) in such conditions with larger prevailing wind loading.

Our model validation work had also some limitations due to 1) the omission of measurements that would have allowed calculation of critical wind speed for stem breakage, 2) the large distance between wind speed and snow loading measurements and the examined site, and 3) the limited data restricting the exercise to one species: Scots pine. Thus, further work is still needed to validate the HWIND model predictions for permanent edges as well as for soils with districted anchorage, and considering also other tree species than Scots pine. In the future, it would also be ideal for model validation if wind and snow loading measurements would be available in a location where actual damage occurred, instead of using measurements from meteorological station with some distance from the damaged area.

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