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Communicating the amount of windstorm induced forest damage by the maximum wind gust speed in Finland

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Abstract. Windstorms are natural disturbance agents in forests playing a role in natural forest regeneration. In Finland, the most severe individual windstorms have commonly damaged 2–4 million m^3 of timber. In addition to financial losses caused to forest owners, windthrown trees have in many cases seriously disrupted the functionality of the national power grid. Communicating windstorm risks in duty forecasting is difficult. In this study, we aimed at developing windstorm impact estimates for forest damage in Finland to help the forecaster to improve communication of the risks of windstorms. We have compared the volume of forest damage caused by the most intense windstorms in Finland during the recent decade to the observed maximum inland wind gust speeds associated with the same windstorms. It was found out that the volume of forest damage follows approximately a power relation as a function of wind gust speed with a power of ~ 10. This is a tentative estimate because of a short time series and small number of inspected windstorms. Moreover, also wind direction, location of the affected area and soil properties among other factors have an impact to the amount of damage as illustrated in our inspection. Despite the shortness of the time series, we believe that our results demonstrating the steep increase in the impacts of windstorms with an increasing windstorm intensity are valuable. However, more detailed investigations with longer time series are needed in order to more specifically communicate the windstorm risks and their impacts in boreal forests.

1 Introduction

Windstorms are among the most hazardous abiotic disturbances affecting the northern European forests (Schelhaas et al., 2003; Kuuluvainen and Aakala, 2011; Mitchell, 2012; Gardiner et al., 2013; Gregow et al., 2017). Largest forest damage have been proven to occur when forests are impacted by wind gust speeds that exceed $35\,\mathrm{m\,s^{-1}}$ (e.g., Usbeck et al., 2010a; Gardiner et al., 2013). Recently, it was argued that year 1990 represents a change-point after which the windstorm induced large-scale forest damage have increased by a factor of three in Europe (Gregow et al., 2017).

In Finland, approximately 10–25 large scale windstorms occur every year but usually only a few of them are severe. The Finnish forests are especially affected by southerly, south-westerly and westerly winds, and in the central and eastern parts also north-westerly winds are common (e.g., Gregow et al., 2011). The most severe wind damage to forests have occurred during periods when there has not been soil frost inhibiting damage (e.g., Jokinen et al., 2015). Typical to the most severe large-scale storms in Finland is that the mean wind speeds over the marine and coastal stations have been above $25\,\mathrm{m\,s^{-1}}$ (Gregow et al., 2008).

The mechanistic impact models such as HWIND (Peltola et al., 1999) and GALES/Forest-GALES (Gardiner et al., 2000) have been used in assessing wind risk to forests in Finland. The model simulations indicate that trees approximately 20 m tall can be uprooted already if 10 min mean wind speeds are between 15–$25\,\mathrm{m\,s^{-1}}$ (e.g., Zubizarreta-Gerendiain et al., 2012). Thus, Finland is rather vulnerable to severe windstorms. In addition to financial losses caused to forest owners, windstorms and windthrown trees have disturbed seriously the functionality of the national power grid (Pilli-Sihvola et al., 2016, p. 12). Efficient adaptation to wind damage obligate adequate preparedness measures by the society (Nurmi et al., 2019).

Table 1. The most notable large-scale windstorms in Finland during the 2010s with their maximum observed wind gust speed at inland stations (excluding fell stations) operated by the FMI. The column for wind direction describes the directions of strongest winds associated with the storms.

Wind-storm	Date	Area affected	WGmax $(m\,s^{-1})$	Wind direction	Forest damage $(10^6\,m^3)$	Other remarks
Rauli	27 August 2016	Central Finland	24.9	W	0.15	Summertime event
Valio	2–3 October 2015	Central Finland	27.6	W	0.8	
Lyyli	23 May 2015	Northern Finland	28.1	S...W	0.14	Summertime event
Seija	13 December 2013	Southwestern Finland	29.8	W...NW	1.0	Soil partly frozen
Oskari	1–2 December 2013	Southwestern Finland	26.4	NW	0.6	
Eino	17 November 2013	Central Finland	29.2	W...NW	1.5	
Antti	30 November 2012	Southern Finland	23.1	E	0.3	Rare wind direction
Hannu	27 December 2011	Eastern Finland	26.7	W...NW	0.5	
Tapani	26 December 2011	Western and Southwestern Finland	31.5	W	3.0	

Communicating windstorm risks and their impacts to the public and authorities by the weather forecasters is becoming increasingly important. Already Stern (2006) and Sills (2009) have foreseen the role of future forecasters to be focused on communicating effectively the predicted impacts of hazardous weather events. Traditionally, in operational safety weather services, warnings concerning windstorms and other weather hazards are issued based on the intensity of the forecasted phenomenon, e.g., based on wind speed. This is not sufficient, as an accurate and timely warning does not necessarily prevent major economic disruption or even guarantee safety of life (WMO, 2015). When the status of adaptation to climatic risks in Finland was recently mapped (Gregow et al., 2016), one of the key findings was that actionable impact-based predictions and warnings should be developed and be available. As well, the uncertainties and likelihood of the severe impacts should be communicated (Harjanne et al., 2017). Developing impact estimates to improve communication and as well, in order to concretize the windstorm risks to the society is thus considered extremely vital.

In this study, we developed windstorm impact estimates for forest damage in Finland. We first compare the amount of reported forest damage (in cubic meters of timber) to the observed maximum wind gust speeds associated with the most notable synoptic scale non-convective windstorms in Finland during the recent decade. We use the maximum wind gust speed as it is known that forest damage due to windstorms is best correlated with peak wind speed (Usbeck et al., 2010b). We also consider wind direction and soil conditions in our assessments. We believe that our findings can be valuable for the weather forecasters when they estimate and communicate the anticipated impacts of windstorms in Finland e.g. to power companies and forest authorities and owners.

2   Material and methods

In this study we use information from the Finnish Forest Centre, the Finnish Meteorological Institute (FMI) and the European Centre for Medium-Range Weather Forecasts (ECMWF). The number of damaged volume of timber in cubic meters (m^3) was obtained from the Finnish Forest Centre. The maximum 3 s wind gust speeds (WGmax) are from the weather stations operated by FMI. Each large-scale windstorm was analysed using the WGmax observed at any inland weather station. With an inland station we refer to all the stations neither located immediately adjacent to the sea nor on fell tops in Lapland. We visualized the storm tracks by employing the ERA5 reanalysis which has 1-hourly output with a horizontal resolution of 31 km (Hersbach and Dee, 2016). The positions of cyclone centres and thus tracks were plotted by using the latitude and longitude coordinates of the minimum mean sea level pressure associated with the cyclones. The tracks are plotted 12 h before and after the time step when the cyclone centre reached Finland.

The inspected windstorms are listed in Table 1. Those are the most severe non-convective synoptic scale windstorms impacted Finland during the 2010s. We did not include windstorms prior to 2010 into our analysis because the observation network for wind gust speeds was earlier sparser. Moreover, information regarding the forest damage was not readily available for all of the elder windstorms. As discussed in the next section, six of the nine inspected windstorms, named Valio, Oskari, Eino, Tapani, Hannu and Rauli had similar characteristics. These windstorms were thus selected to represent typical windstorms affecting Finland and they were used when forming the regression estimate between WGmax and forest damage.

By employing WGmax and the known volume of forest damage (FD) (m^3) caused by each of the six windstorms in Finland, a power relation was formed:

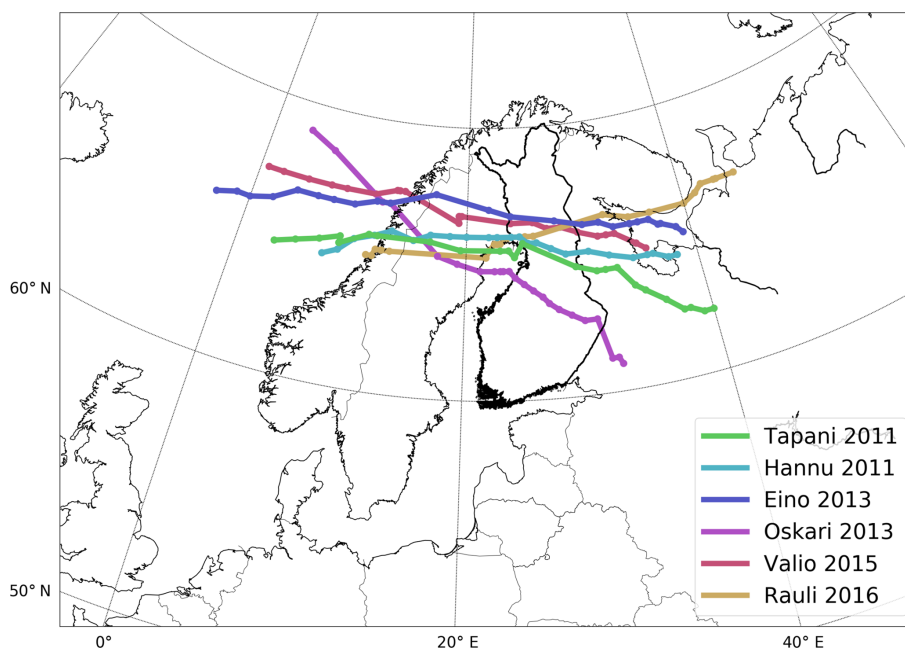$$FD = a \cdot WGmax^b, \tag{1}$$

Figure 1. Storm tracks for the six typical windstorms affected Finland during the 2010s.

Table 2. Volume of forest damage as a function of maximum wind gust speed (WGmax) according to Eq. (1).

| WGmax (m s^{-1}) at inland stations	Volume of forest damage (m^3)	Volume of forest damage (m^3) per 100 ha	Verbal description of impacts
15	1800	<0.04	Individual fallen trees
16	3400	<0.07	
17	6200	0.12	
18	11 000	0.22	Local power outages possible
19	19 000	0.38	
20	32 000	0.64	A few hundreds customers without electricity
21	52 000	1.0	
22	83 000	1.7	
23	130 000	2.6	A few thousands customers without electricity
24	200 000	4.0	
25	300 000	6.0	
26	440 000	8.8	Tens of thousands customers without electricity
27	640 000	13	
28	930 000	19	
29	1 300 000	26	Substantial forest damage in localized areas
30	1 900 000	38	
31	2 600 000	52	
32	3 500 000	70	
33	4 800 000	96	Hundreds of thousands customers without electricity
34	6 500 000	130	
35	8 700 000	170	
36	11 500 000	230	
37	15 000 000	300	Substantial forest damage in wide areas
38	20 000 000	400	
39	26 000 000	520	
40	33 000 000	660	Widespread havoc in forests
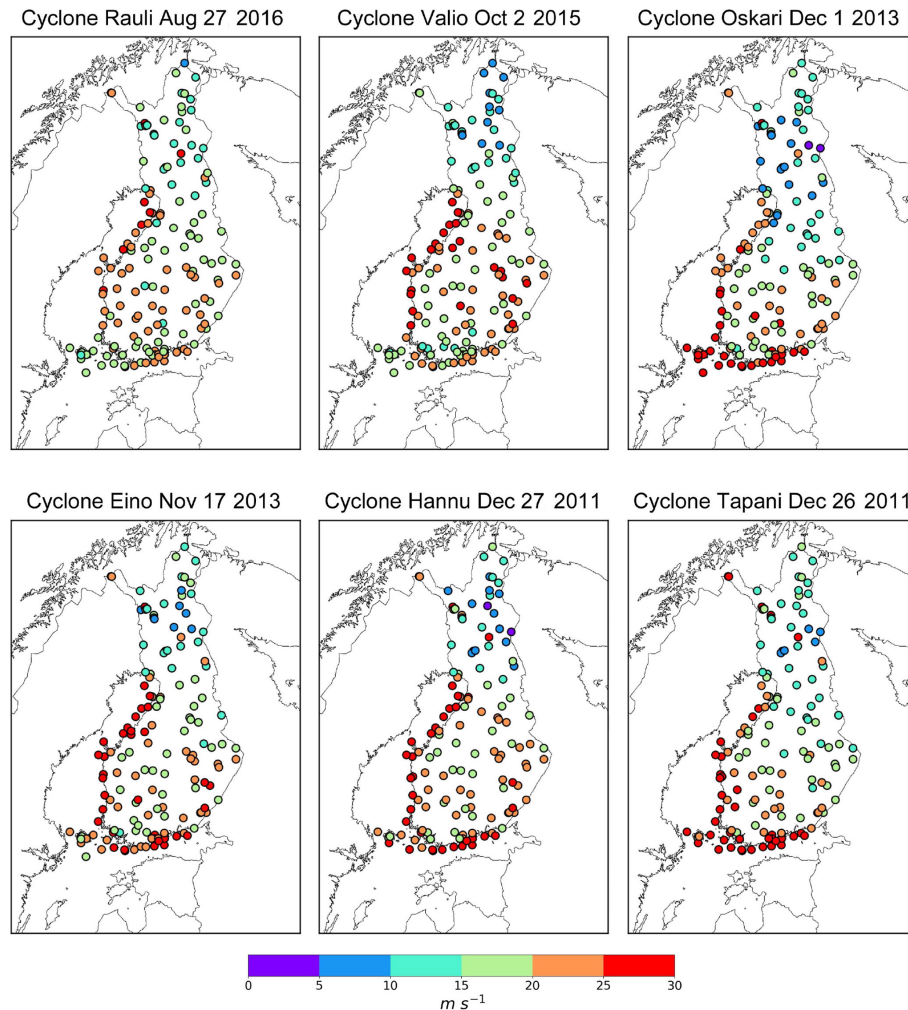
Figure 2. The maximum wind gust speed (m s^{-1}) observed at the stations operated by the FMI (coastal and fell stations included) associated with the six large-scale windstorms during the 2010s.

Here WGmax is in m s^{-1}, $a = (2.858 \pm 14.58) \times 10^{-15}$ and $b = 10.03 \pm 1.49$. The parameters a and b with their 95 % confidence intervals were estimated by using the R package nlstools (Baty et al., 2015). We moreover estimated the volume of forest damage per 100 hectares by assuming that the damaged area has a spatial extent of approximately 50 000 km^2.

3   Results

When considering the nine windstorms presented in Table 1, it can be noted that six of them (Valio, Oskari, Eino, Tapani, Hannu and Rauli) had similar characteristics. Firstly, these storms developed over the North Atlantic and their low-pressure centres propagated across central parts (63–65° N) of Finland to Russia (Fig. 1). Hence, the storms impacted southern and central parts of country (Fig. 2) and the strongest winds associated with these storms blew from

west or northwest. Moreover, they occurred when soil was not frozen. Windstorm Rauli (27 August 2016) occurred in late summer when deciduous trees had their leaves and it impacted a slightly different region with strongest winds concentrated on the coast of Bothnian Bay. Rest of these six windstorms occurred between October and December. Storm Antti (30 November 2012) was different from the six storms having easterly blowing winds. Storm Lyyli on the other hand (23 May 2015) only impacted Northern Finland. Lastly, during storm Seija (13 December 2013) soil was already partly frozen and thus there was already some anchorage to the trees and they were locally less easily uprooted.

In Fig. 3 we show the volume of forest damage as a function of observed WGmax for the inspected windstorms. The volume of forest damage estimated by the Eq. (1) is also shown. The expected volumes of forest damage caused by typical windstorms according to Eq. (1) are also given in Table 2 with short verbal description of impacts. Accord-
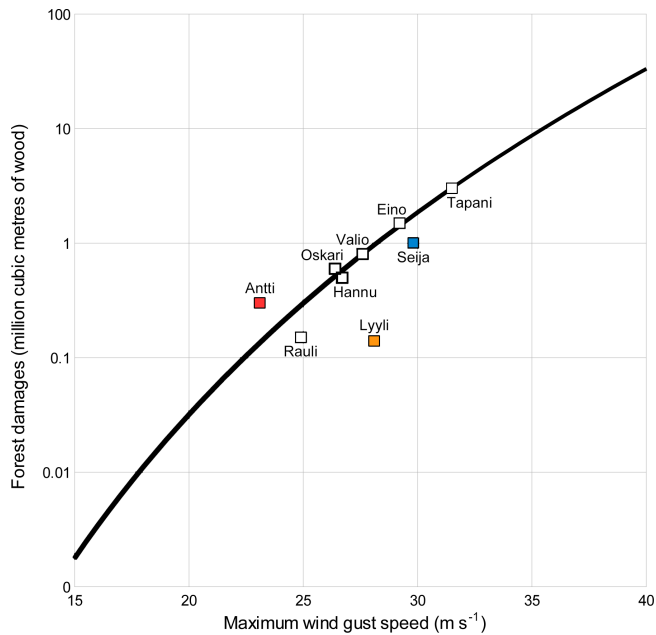
Figure 3. The volume of forest damage as a function of maximum observed wind gust speed for the windstorms during the 2010s in Table 1 and including also the windstorms Janika and Pyry. The black curve depicts the best estimate for the power relation between the maximum wind gust speed and forest damage for typical windstorms (open squares). Windstorm Antti with rare wind direction (easterly) is shown with a red square, windstorm Seija with partly frozen ground with a blue square and windstorm Lyyli that raged in Northern Finland with an orange square.

ing to Eq. (1), a 10 % increase in the WGmax leads to almost three times larger forest damage. Local power outages due to windthrown trees are expected when the highest wind gust speeds approach $20\,\mathrm{m\,s^{-1}}$. When the WGmax exceeds $25\,\mathrm{m\,s^{-1}}$, already tens of thousands of customers are likely to be left without electricity. Substantial damage is expected with WGmax above $30\,\mathrm{m\,s^{-1}}$.

The power relation was obtained by employing the forest damage and WGmax of the six large-scale windstorms in Finland. The power relation explains the damage caused by the typical windstorms when the WGmax varies approximately between 25 and $32\,\mathrm{m\,s^{-1}}$. A post analysis indicates that the weakest windstorm Rauli is poorly estimated by the power relation. The true value of forest damage caused by Rauli was only $0.15\,\mathrm{Mm^3}$ but the power relation gave an estimate of $0.5\,\mathrm{Mm^3}$. In case of the three storms that were not considered as typical windstorms and were thus not included in fitting the power relation, the forest damage could not be estimated based on the power relation. In the case of Seija storm, the observed damage (Table 1) were only half of those given by Eq. (1) (Fig. 3). This was assumedly because soil was already partly frozen in the affected area. Windstorm Lyyli that raged in northern Finland damaged only $0.14\,\mathrm{Mm^3}$ of timber but the estimate based on Eq. (1) would have been

almost one million $\mathrm{m^3}$. Windstorm Antti having a rare easterly wind direction, on the other hand, caused three times larger damage than estimated based on Eq. (1).

4 Discussion and conclusions

Our results show that the volume of wind-induced forest damage in Finland can conditionally be estimated based on a simple power relation as a function of WGmax. The power relation is applicable for large-scale windstorms that affect southern, western and eastern parts of Finland when: (1) the wind direction is between west and northwest, (2) the WGmax ranges between $25–32\,\mathrm{m\,s^{-1}}$, (3) the soil is not frozen, and (4) the deciduous trees are without leaves. Additionally, the centres of the large-scale storms usually travel across northern or central parts of Finland approximately between 63–65° N. With these conditions, the power relation gives reasonable estimates for the likely volume of forest damage in southern or central parts of Finland. On the other hand, it is likely that rare wind direction, i.e., easterly or northerly, substantially increases the forest damage. This is presumably because south to north-westerly winds are most common in Finland and the root systems of the trees have adapted to this typical wind direction (e.g., Nicoll and Ray, 1996). Northerly and easterly winds on the other hand uproot the trees more easily as the root systems on the easterly to northerly sides of the trees are weaker.

The power relation of this paper was derived for Finnish conditions. Using this power relation and historical windstorms of the neighbouring countries, the potential damage of similar storms in Finland can be estimated. For instance, in Sweden the most devastating windstorm Gudrun (9 January 2005), damaged approximately 70 million $\mathrm{m^3}$ of wood (Holmberg, 2005; Bengtsson and Nilsson, 2007; Gregow, 2013). The measured WGmax during Gudrun was 36–$42\,\mathrm{m\,s^{-1}}$ in coastal regions of southern Sweden and slightly above $35\,\mathrm{m\,s^{-1}}$ in some inland locations (Holmberg, 2005). If a storm like Gudrun would arrive to Finland, the damage would thus be very high. With the range of wind gust speeds 36–$42\,\mathrm{m\,s^{-1}}$ the damage would correspond to 10–$55\,\mathrm{Mm^3}$ based on the power relation. Thus, if a storm is forecasted with probabilities for this range of wind gust speeds, we can also give an estimate of the danger it would imply to our forests. And if the highest wind speeds ($42\,\mathrm{m\,s^{-1}}$) are only occurring over the sea, we can pick the highest wind gust speeds that most probably occur over the land, and give a corresponding estimate for the most likely windstorm induced forest damage risk. This kind of communication would also prepare the society to facing the risks and the uncertainty range in a more concrete manner as was desired by the Finnish authorities in support of adaptation planning (Harjanne et al., 2017).

It is unclear whether the power relation of Eq. (1) can be extrapolated to more intense windstorms with the maxi-

mum wind gust speeds above $32 \, \mathrm{m \, s^{-1}}$, like for the storms comparable to intensities of storm Gudrun. Probably over a certain limit, the volume of forest damage approaches some saturation level and thus a sigmoid function could better describe the relationship between maximum wind gust speed and damage to forests. Moreover, other additional factors are likely to contribute to the amount of forest damage. For instance, soil moisture is known to affect to the damage (e.g., Kamimura et al., 2012). Forests are most prone to wind damage when soil is wet and unfrozen (Usbeck et al., 2010a). This is the situation typically in Finland in late autumn and early winter when most of severe windstorms occur. Notwithstanding, our results indicate that a 10 % increase in wind gust speed leads to almost three times larger forest damage if other conditions remain similar. Moreover, it seems that in northern Finland the volume of forest damage remain much smaller than in southern Finland. We expect this to be depended on the lower tree height and smaller volume of growing stock in the northern forests. Rare wind direction, on the other hand, is likely to substantially increase the amount of forest damage. This was demonstrated by the unexpectedly large amount of damage caused by storm Antti.

To conclude, we believe that the data as well as the approach presented in this study will be valuable for the duty weather forecasters who need to communicate the risks and impacts of windstorms on forests in Finland. More analyses about seasonal, soil and forest related aspects resulting in windstorm induced forest damage in the Finnish conditions remain as future work.

Author contributions. HV prepared the prestudy about the storms based on extensive forecasting experience. IL and HG wrote the paper. TKL prepared the wind gust speed map and storm track figures. AV participated in writing and supervising the work. He leads the FORBIO and WINDSURFER WPs at FMI. ML fitted the power relation to the data and cross-checked the wind gust speed data. All have read and accepted the manuscript for submission.

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