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RESEARCH ARTICLE

Landscape configuration and storm characteristics drive spatial patterns of wind disturbance in boreal forest landscapes

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Abstract

Context Wind is an important disturbance in circumboreal forests, and its frequency and severity may change with climate change, highlighting the need to understand the drivers of wind disturbance. Currently, how landscape configuration drives wind disturbance is poorly understood.

Objectives We investigated whether and how landscape configuration is related to the extent and spatial pattern of wind disturbance, and how these relationships vary between windstorms and thunderstorms.

Methods We used salvage logging data after 16 storms that occurred in Finland between 2011 and 2021. We placed a total of 301 landscapes, each encompassing an area of 8024 ha, within the storm tracks and used regression models to test how wind disturbance extent, disturbance patch size, number of disturbance patches, and disturbance patch clustering were related to landscape configuration and storm characteristics.

Results Increasing mean gap size and edge density, including permanent openings (e.g., lakes) and recent harvest gaps, increased disturbance extent, disturbance patch size, and number of disturbance patches. Conversely, increasing mean harvest gap size decreased disturbance patch clustering. Increasing wind speed had the largest contribution to increasing disturbance extent and number of disturbance patches, and decreasing disturbance patch clustering, with the magnitude of the effect varying between windstorms and thunderstorms.

Conclusions The extent and spatial pattern of wind disturbances varied with landscape configuration and storm characteristics. Disturbance patches were larger in landscapes with large canopy gaps, resulting in a greater disturbance extent, exacerbated by increasing wind speed and thunderstorm development.

Keywords Wind disturbance · Landscape configuration · Windstorm · Thunderstorm · Boreal forest

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Introduction

Wind is one of the most important disturbance agents in the circumboreal forests (Kamimura and Shiraishi 2007; Shorohova et al. 2011; Ulanova 2000), and wind disturbances pose the greatest risk to the provision of forest ecosystem services across Europe (Lecina-Diaz et al. 2024). At the same time, wind disturbance is an integral part of natural forest dynamics (Kulha et al. 2020; Seidl et al. 2020), altering the structure and composition of forest landscapes (Allen et al. 2012; Kamimura et al. 2019) and benefiting biodiversity (Palm-Hellenurm et al. 2024; Staniaszek-Kik et al. 2023). However, an increase in wind-induced tree mortality has been reported in Europe (Patacca et al. 2022), and wind disturbances may become more frequent and/or severe with climate change (Ikonen et al. 2017; Seidl et al. 2017), highlighting the need to better understand their drivers.

The role of biotic (e.g., stem size, species, stand conditions) and abiotic (e.g., topography, soil properties) factors in predisposing trees to wind disturbance at different spatial scales is generally well understood (e.g., Fraser 1964; Gardiner 2021; Mitchell 2013). Similarly, the relationship between wind speed and disturbance severity has been reported (Everham and Brokaw 1996; Ikonen et al. 2017; Valta et al. 2019), and an understanding of the role of functional diversity in wind disturbance resistance and resilience is emerging (Barrere et al. 2024). However, empirical evidence on how the landscape configuration (i.e. spatial characteristics such as the distribution, size and shape of patch types within a forest landscape) affects the severity, extent and spatial arrangement of wind disturbances is still lacking, even though the influence of landscape pattern on disturbance occurrence has been (Turner 1989) and remains at the core of landscape ecology (Wu 2021). One of the reasons for this deficiency is the lack of broad-scale data on the occurrence of wind disturbances. For example, separating wind disturbances from harvests in remote sensing data remains a challenge, especially when the disturbance areas are rapidly salvage logged (Sebald et al. 2021; Tomppo et al. 2021).

Theoretically, the spatial arrangement of forest landscapes can influence the occurrence of forest disturbances by influencing how disturbances spread across the landscape and/or through the location of forest stands (i.e. landscape configuration), which influences the susceptibility of the landscape to a disturbance (Turner and Gardner 2016). Unlike fire and certain pathogens, the occurrence of wind disturbances is not spatially contagious, although wind disturbance patches may exhibit temporal autocorrelation through gap expansion within and between storm events (Dupont et al. 2015). Therefore, how landscape configuration influences disturbance susceptibility is particularly important for understanding the spatial patterns of wind disturbance. The location of a forest stand within a landscape can influence its susceptibility to wind disturbance because, for example, the susceptibility depends on the characteristics of the neighborhood in which the stand exists. For example, a stand located at the forest edge will have a higher susceptibility to wind than a stand located within a forest matrix (Díaz-Yáñez et al. 2016; Suvanto et al. 2019). An increase in average disturbance susceptibility at the stand level, e.g. due to increasing edge density between forest and non-forest, should therefore lead to an increase in disturbance severity and extent at the landscape level. However, it remains unclear whether the increased susceptibility leads to larger or more disturbance patches, or both. It is also unknown which aspects of landscape configuration best explain the spatial pattern of wind disturbances.

Increasing storm intensity, i.e. increasing wind speed, increases disturbance severity (Everham and Brokaw 1996; Ikonen et al. 2017; Peltola et al. 1999). In general, forest disturbances begin to occur when wind gusts speeds exceed approximately 15 m/s (Gardiner 2021) and increase rapidly when gusts exceed 25 m/s (Valta et al. 2019). However, landscape configuration can alter the severity of wind disturbance by varying the exposure of trees to the wind. For example, in a fragmented landscape, large non-forested gaps increase wind loading on trees adjacent to the gaps (Panferov and Sogachev 2008). However, trees acclimate to their wind environment through, e.g., changes in root structure (Coutts et al. 2000), stem rigidity (Brüchert and Gardiner 2006), and crown architecture (Wade and Hewson 1979). As a result of acclimation, trees on the edge of a permanent gap, such as on a coast or adjacent to an open peatland, are more resistant to wind than trees within the forest matrix. Due to poor acclimation to high winds, trees adjacent to a newly created harvest gap are particularly susceptible to wind disturbance (Gardiner 2021; Peltola et al. 1999). For this reason, in managed forest landscapes wind-induced tree mortality should be concentrated at the edges of harvest gaps (Wohlgemuth et al. 2022). Increasing the size of harvest gaps further increases the susceptibility to high winds because increasing gap size increases the wind load on trees at gap edges (Panferov and Sogachev 2008).

In our study area, which covers most of Finland in northern Europe, two types of storms are typical: windstorms (i.e. extra-tropical cyclones) and thunderstorms. Both storm types often have southerly, southwesterly, or westerly winds, while northwesterly winds can also occur, especially in the central and eastern parts of the country (Gregow et al. 2011; Tuomi and Mäkelä, 2003). Thunderstorms typically occur during the warmest months, July–August (Tuomi and Mäkelä, 2003), while windstorms are the most frequent from September to April (Laurila et al. 2021). From a forest disturbance perspective, windstorms and thunderstorms have at least three major differences: they have different storm front sizes, different durations of strong winds, and different times of occurrence. Thunderstorms typically cause localized disturbances related to downbursts and associated gust fronts, are relatively short-lived, and occur when trees have leaves and the ground is not frozen (Gregow et al. 2011). In contrast, windstorms are widespread, last up to days, and are most common when trees have shed their leaves and the ground may be frozen. Therefore, the extent and spatial patterns of wind disturbance are likely to differ between the two storm types. However, the relative importance of storm type and landscape configuration on wind disturbance is unknown.

In this study, we examined landscape-scale spatial patterns of wind disturbance in a national-level analysis for two different storm types, windstorms and thunderstorms, with maximum wind gust speeds between 16 and 32 m/s. Specifically, we asked whether and how landscape configuration was related to (1) the proportion of disturbed forest, our measure of disturbance extent, and to the (2) size, (3) number, and (4) spatial pattern of wind disturbance patches.

Materials and methods

Response variables—wind disturbance data

We used forest use declarations (hereafter declarations) from four thunderstorms and 12 windstorms that occurred in Finland between 2011 and 2021 to quantify our dependent variables and certain covariates. In Finland, forest owners are required to submit a spatially explicit declaration for all planned forest management activities to the Finnish Forest Centre (FFC) at least ten days prior to any forest management activity. The declaration is valid for 3 years, and the specified management may be carried out the entire area covered by the declaration, only in parts of it, or in some rare occasions not at all. In a declaration, the submitter states the reason for the planned operation, such as commercial logging, thinning, or salvage logging. According to Section 6 of the Finnish Damage Prevention Act (1087/2013), salvage logging must be carried out if a stand that has passed the seedling stage has >10 m^3 per ha of damaged *Picea* spp with a butt diameter of more than 10 cm or >20 m^3 per ha of similarly damaged *Pinus* spp. Therefore, the declarations can be used to identify salvage logging operations in Finland. We used the declarations to identify storm-motivated salvage loggings. To do this, we separated declarations that were submitted with a "*forest damage qualifier*" record code of 1504 and/or a "*cutting realization practice*" record code of 20 or 21, indicating that the logging was motivated by wind disturbance. We downloaded the publicly available declarations for the years 2010–2021 from the e-service portal of the FFC (FFC 2019). The data are distributed as spatial polygons.

The information in the declarations is not attributed to a specific storm event. However, the number of storm-related declarations typically peaks within weeks of the storm, with the majority of the declarations typically submitted within 2 months of the storm (Laapas et al. 2023). In order to preserve all of the declarations associated with the 16 storm events examined here, we collected all storm-related declarations within 6 months of a storm's onset, examined their geographic locations, and subjectively delineated the primary impact area of a storm based on the locations of the declarations (Fig. S1). We selected the declarations within this area for further analysis.

The spatial patterns of wind disturbance cannot be directly examined using the declaration polygons because their boundaries follow forest stand boundaries. Therefore, to remove the effect of stand boundaries, we gridded the declaration polygons. In practice, we randomly placed as many 5 km-radius circular study landscapes consisting of 1 ha rectangular cells

(8024 cells per landscape) as possible within the primary impact area of each storm and used the landscapes as the basic units in the analyses (Fig. 1). We chose to use circular landscapes because we expected the circular shape to be neutral with respect to the wind direction during the storm and the storm track. In placing the landscapes, we used rasterized information from wall-to-wall Multi-Source National Forest Inventory (MS-NFI) records, downloaded from Natural Resources Finland e-service (Luke 2024), to assign a forest/non-forest (1/0) status to each grid cell before the storm occurred. To do this, we quantified the proportion of forest cover in a grid cell and classified cells with ≥ 50% forest cover as forested (1) and other cells as non-forest (0). We also used this classification to quantify the proportion of forested cells in the total landscape area and included it in the analyses as a covariate called *forest proportion*. We then quantified the disturbance status of each forest cell. If ≥ 50% of a forest cell was covered by a storm-related declaration, we considered the cell to be disturbed (1). We retained the landscape for further analysis if ≥ 1% of its forest area was disturbed by the storm and the landscape did not overlap with the already placed landscapes. If the 1000th attempt did not result in a successful landscape placement, we did not attempt to place any more landscapes within the primary impact area of that storm event. In total, we placed 301 landscapes within the primary impact area of 16 different storm events, with the number of study landscapes varying from two to 26 between the storms (Table 1).

Next, we searched for openly available aerial imagery taken shortly after any of the storms we studied to examine how well the declarations represented actual disturbance patterns. We chose to use high-resolution aerial imagery because we wanted to be able to identify both stand-replacing and partial disturbances. To separate wind disturbance from subsequent salvage logging, the images had to be taken shortly after the storm occurred (Laapas et al. 2023). We found aerial imagery covering parts of the primary impact area of the storm Paula, taken seven days after the storm's onset. We visually inspected the wind disturbance declarations overlapping these images to assess whether wind disturbance signs (similarly oriented downed woody debris) were present throughout the stand indicated in the declaration, in one or several parts of the stand, or no wind disturbance signs could be detected in the photograph. We examined a total of stands that had not yet been salvage logged. Of these, 39.4% (n = 480) showed signs of wind disturbance throughout the stand and 46.3% (n = 564) showed signs of wind disturbance in one or several parts of the stand (Fig. S2). The remaining stands showed no signs of wind disturbance on aerial photographs. This validation procedure suggested that the declarations captured the actual disturbance pattern relatively well.

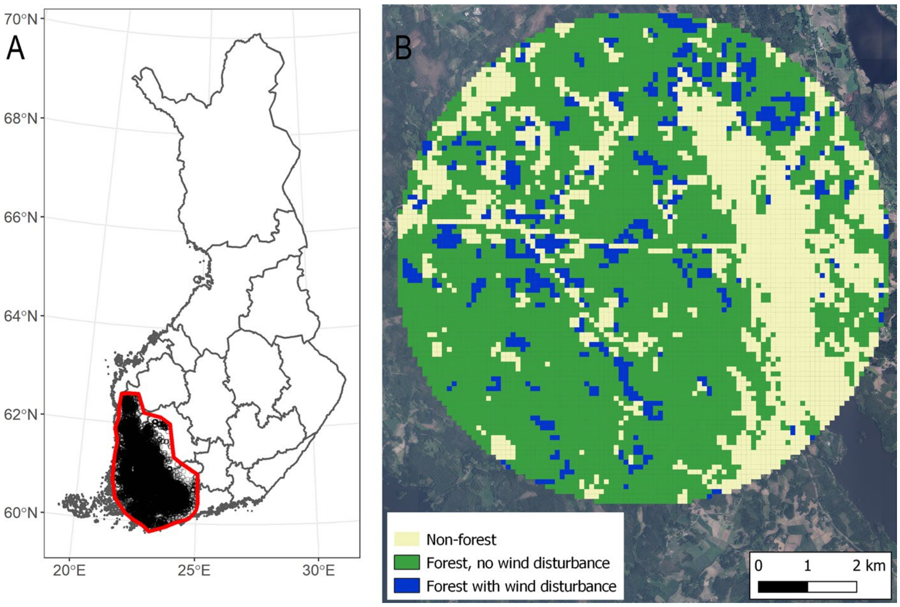

Fig. 1 The primary impact area for the storm Tapani, shown as a red polygon (**A**). The black dots are the centers of the declaration polygons indicating salvage logging due to the particular storm. **B** Shows one of the study landscapes for the same storm on an aerial photograph obtained from the National Land Survey of Finland (MML 2024)

Table 1 Examined storm events ordered from oldest to newest

Storm name	Storm date	Primary impact area in Finland	Storm type	Wind gust speed (m/s)	Size of the primary impact area (km^2)	Number of study landscapes	Year of MS-NFI data
Tapani	26.12.2011	Southwestern	Windstorm	19.6–25.1	41,021	26	2011
Hannu	27.12.2011	Central to eastern	Windstorm	18.0–21.3	80,037	12	2011
Eino	17.11.2013	Western to southeastern	Windstorm	17.6–23.0	72,673	26	2013
Oskari	1.12.2013	Southwestern	Windstorm	16.3–21.1	37,812	26	2013
Seija	13.12.2013	Southeastern to central	Windstorm	15.5–25.7	67,283	26	2013
Helena	31.7.2014	Central to eastern	Thunderstorm	10.0–17.2	103,392	26	2013
Lyyli	23.5.2015	Central to eastern	Windstorm	16.4–21.4	89,777	10	2013
Valio	2.10.2015	Central to eastern	Windstorm	18.2–19.8	102,120	10	2013
Rauli	27.8.2016	Central to eastern	Windstorm	18.9–19.0	64,255	2	2015
Kiira	12.8.2017	Southern	Thunderstorm	12.3–16.2	5276	12	2015
Aapeli	1.1.2019	Central	Windstorm	11.8–31.7	124,792	10	2017
Tuuli	22.2.2020	Eastern	Windstorm	13.8–16.4	39,000	20	2019
Päivö	30.6.2020	Central	Windstorm	12.8–24.2	52,689	26	2019
Aila	17.9.2020	Western	Windstorm	17.5–27.0	30,632	17	2019
Paula	22.6.2021	Northern	Thunderstorm	17.3–23.6	9113	26	2019
Aatu	23.6.2021	Western to central	Thunderstorm	8.4–21.5	108,943	26	2019

The wind gust speed column shows the range of highest daily wind gust speeds during the storms in the study landscapes. The size of the storm's primary impact area refers to the size of the area manually delineated based on the declarations used in this study. See also Fig. S1 for a map of the primary impact areas

To answer the first research question, we used the proportion of the forest landscape disturbed by wind as the dependent variable in the analysis, with disturbed proportions ranging from 0.1 to 9.9%. For research questions 2–3, we formed the dependent variables by transforming the disturbed/nondisturbed grid cells into raster format using the Rook's case criterion and calculating the average disturbance patch size and number of disturbance patches in each landscape using the *landscapemetrics* package (Hesselbarth et al. 2019) in R version 4.3.1. The average disturbance patch size varied between 1.0 and 106.9 ha, and the number of disturbance patches varied between 1 and 73, depending on the landscape. To answer the fourth research question, we used the center points of the rasterized wind disturbance patches to quantify the F- and G-functions for each study landscape. The F-function (i.e. the empty space function) denotes the probability that an area of radius *r* around a randomly selected location contains at least one disturbance patch center point, whereas the G-function describes the spatial arrangement of the center points through a cumulative distribution function of the nearest neighbor distances (Baddeley and Turner 2005). For each landscape, we subtracted the F-function from the G-function and used the most extreme value of this subtraction (either negative or positive) as our dependent variable. The subtraction of the F- and G-functions can range from -1 to 1, with a value of 1 indicating maximum clustering between the disturbance patches and vice versa. The advantage of this approach is that the clustering of disturbance patches can manifest itself at any distance, rather than limiting the analysis to certain predefined distances. For analytical purposes, we scaled the difference between the G- and F-functions between 0 and 1. After scaling, the response variable varied between 0.44 and 0.98 across the landscapes, with increasing values indicating increasing disturbance patch clustering. We quantified the G- and F-functions using the *spatstat* package (Baddeley and Turner 2005) in R.

Landscape configuration covariates

Our primary objective was to examine how landscape configuration influences the spatial patterns of wind disturbance at the landscape scale during different storms. To quantify landscape configuration, we calculated the edge density as meters of edge per the study landscape size in hectares between forests and harvest gaps created by clearcutting no more than five years prior to the storm. We also quantified edge density between forested and non-forested areas (e.g., water bodies, arable land), including harvest gaps, as well as the sizes of harvest gaps and non-forested areas to be used as covariates in the analyses. We assumed that increasing edge density and harvest and non-forest gap sizes would increase susceptibility to wind disturbance, the harvest gaps increasing susceptibility more than the non-forest gaps. We chose the 5-year time limit for harvest events based on the existing literature, which shows the greatest increase in susceptibility to wind disturbance in stands adjacent to clearcuts that were harvested no more than 5 years before a storm event (Suvanto et al. 2016).

We used information from the declarations to quantify harvest events in the study landscapes. In each landscape, we selected declarations submitted no more than 5 years before the storm event and that indicated clearcutting. We labeled each forest cell in which the declaration polygon indicating clearcutting covered $\geq 50\%$ of its area as harvested (1). We call this variable the *harvest gap size* variable. We then created another variable, the *mean gap size* variable, by assigning a value of 1 to each cell if it was in a harvest gap or if it was classified as non-forest based on the MS-NFI data. We then transformed the harvest gap and mean gap size variables into raster format using the Rook's criterion, and calculated the edge densities and average sizes of both gap types using the *landscapemetrics*-package (Hesselbarth et al. 2019) in R.

Storm characteristics covariates

We used spatially explicit data on maximum daily wind gust speeds to quantify wind speeds during the different storm events. Hereafter, we refer to these data as wind speed data. The wind speed data are based on maximum wind gust speed observations at 10-min intervals from about 150 weather stations, the number of which varies slightly from storm to storm due to changes in the station network, distributed throughout Finland. The daily maximum values of wind gust speed from each station are interpolated to 500 m × 500 m grid cells using kriging with external drift (as in Laapas et al. 2023). The interpolation procedure accounts for the effects of surface roughness length, elevation, and percent of sea and lake cover on wind gust speed. We chose to use the maximum wind gust speed rather than the mean wind speed during the storm event because of the demonstrated relationship between maximum wind gust speed and disturbance severity (Valta et al. 2019). The wind speed data are produced by the Finnish Meteorological Institute and are openly available through an e-service (FMI 2023a). To determine the highest wind gust speed during each storm event, we used the wind speed data for one day before and four days after the recorded date of storm initiation. To do this, we stacked the five daily wind speed maps and created a single map layer composite by taking a maximum value from each overlapping map pixel. Using the composite, we quantified the maximum wind gust speed for each landscape cell and quantified its arithmetic mean value across landscapes to represent the maximum wind gust speed in that landscape during a given storm event. This compositing was done to reduce the effect of potential bias in a single map layer in the analyses (as in Kulha et al. 2024) and to capture the highest wind speed during the storm events.

We used hourly mean wind speeds from ERA5-Land data at 0.1° spatial resolution to quantify the general wind direction and the wind direction during the storm event in each landscape (Muñoz-Sabater et al. 2021). We used this information to determine whether the wind direction during the storm event differed from the general wind direction in a landscape. We considered this variable relevant because trees may be less acclimated to storm winds coming from directions other than the general wind direction. Hereafter, we refer to the ERA5-Land data as wind direction data. We had to use these coarse-scale data because, unlike wind gust speeds, fine-scale wind direction data were not available across Finland at the time of our analysis.

To quantify the wind directions, we obtained the wind direction data across Finland for the years 2011–2020, averaged the hourly v and u vectors to daily means, and converted them to daily wind speeds and directions. We used the wind direction information from the entire 10-year period to define the most frequent wind direction with half cardinal accuracy for each study landscape and used this to represent the general wind direction in the landscape. Then, for each landscape, we extracted the daily wind speeds and directions for the period from 1 day before to three days after the storm event, selected the day with the highest average wind speed, and compared the wind direction on that day to the general wind direction in the landscape. If the storm wind direction differed more than 67.5° from the general wind direction, we marked the storm wind direction as different (1) from the general wind direction in that particular landscape.

Finally, we used existing literature (Laapas et al. 2023) and online sources (FMI 2023b) to label each storm event as either a windstorm (0) ($N=211$; Table 1) or a thunderstorm (1) ($N=90$).

Forest and soil characteristics, topography, and stand size covariates

We used the most recent MS-NFI data possible at the time of storm occurrence to quantify the proportion of *Picea abies* L. (hereafter spruce) and the standard deviation of tree height in each landscape, as increasing proportion of spruce and increasing surface roughness due to tree height variability predispose stands to wind disturbance (Suvanto et al. 2016, 2019). In Finland, the MS-NFI information is updated every two years. For this reason, the time between data collection and storm occurrence varied between the storm events (Table 1). The MS-NFI information is distributed as raster maps with 16 m spatial resolution. We quantified the sum of tree biomass in each landscape cell and divided it by the sum of spruce biomass to represent the average proportion of spruce in each landscape cell, and averaged these proportions to represent the proportion of spruce in the landscape. We used the average of cell-specific standard deviations in tree height to represent tree height variability in the landscape.

Given the demonstrated relationship between wind disturbance occurrence, topography, and soil characteristics (Suvanto et al. 2016, 2019), we wanted to control for the effects of these variables on wind disturbance patterns. Therefore, we calculated the mean elevation and standard deviation of elevation for each landscape using a digital elevation model with a resolution of 25 m, which we obtained from the National Land Survey of Finland (MML 2024). When calculating the mean elevation at the landscape level, we first calculated the mean elevation for each individual cell and then averaged these means over the whole landscape. We calculated the standard deviation of elevation by averaging the cell-specific standard deviations of elevation in each landscape. For soil characteristics, we calculated the most common soil type (fine mineral soil, coarse mineral soil, organic soil) by first quantifying the soil type with the highest coverage in each cell and using the most common soil type at the cell level to characterize the soil in the landscape. We also calculated the soil thickness class with the highest coverage in each cell and quantified the proportion of cells where the soil thickness was <1 m, as we expected these cells to be particularly susceptible to wind disturbance. We obtained the data on soil characteristics from the Geological Survey of Finland (GTK 2024).

In addition to our attempts to use gridding to remove the effect of stand boundaries from the analysis, we wanted to use stand size as a control variable in the analyses. We used spatially explicit, open-access forest stand information downloaded from the FFC e-service (FFC 2019) to quantify average stand size in each study landscape. The downloaded data consist of polygons that delineate forest stands that are consistent with respect to site type, timber stock, and forest management plan. To quantify the average stand size, we extracted overlapping forest stands for each study landscape, and calculated their average size in hectares.

Statistical modeling

We used landscape-scale regression models to address the four research questions posed in this study. In the models, each landscape was treated as a single observation. For each research question, we began the model selection with the same initial set of covariates and interactions (i.e. full model), with the response variable and model type varying depending on the research question being addressed and the distribution of the dependent variable (Table 2). The full models included each covariate listed in Table 2, and the interaction between wind speed and storm type. We chose to keep only this interaction out of all the possible two-way interactions because it was necessary to test our research hypotheses. For each research question, we first fit the full models and, starting with the interaction term, dropped the covariate with the lowest p-value at each iteration until only covariates significant at the 0.05 level remained. The continuous covariates were scaled and centered before model fitting.

To address the first research question, we used beta regression, a method specifically designed for 0–1 bounded data (Geissinger et al. 2022), with a logit link function to model the proportion of wind-disturbed forest out of total forest area, our measure of wind disturbance extent. For this dependent variable, the most parsimonious model was:

$$DP_i = \alpha_{0,ST} + \alpha_{1,ST} WS_i + \alpha_2 MGS_i + \alpha_3 HGS_i + \alpha_4 SDE_i, \quad (1)$$

where DP_i is the logit of the proportion of disturbed forest area in landscape i, $\alpha_{0,\,ST}$ is the storm type-specific intercept, WS_i is the mean wind gust speed during the storm in landscape i with storm type-specific coefficient $\alpha_{1,\,ST}$. Thus, the model includes an interaction between mean wind gust speed and storm type. MGS_i is the mean gap size, HGS_i is the mean size of harvest gaps, and SDE_i is the standard deviation of

Table 2 Covariates describing the study landscapes that were used in all full models

Covariate group	Covariate name	Covariate type	Covariate range	Covariate unit	Number of most parsimonious models that include the variable
Landscape configuration	Mean edge density (ED)	Continuous	4–49.7	m/ha	1
	Edge density of harvest gaps (EDH)	Continuous	0.6–23.0	m/ha	0
	Mean gap size (MGS)	Continuous	3.0–299.6	ha	2
	Mean size of harvest gaps (HGS)	Continuous	1.2–8.9	ha	3
Storm characteristics	Maximum wind gust speed (WS)	Continuous	8.4–31.7	m/s	3
	Storm type (ST)	Categorical	0, 1	Windstorm (0), thunderstorm (1)	4
	Storm direction (SD)	Categorical	0, 1	Storm direction the same as (0) or different from (1) the prevailing wind direction	1
Forest characteristics	Proportion of spruce (SP)	Continuous	5.4–51.2	%	0
	Standard deviation of tree height (SDT)	Continuous	3.5–6.5	m	1
	Stand size (SS)	Continuous	0.8–2.8	ha	0
	Forest proportion (FP)	Continuous	21.3–100.0	%	3
Topography and soils	Mean elevation (ME)	Continuous	3.4–228.6	Meters above sea level	0
	Standard deviation of elevation (SDE)	Continuous	0.01–3.6	Meters	1
	Soil type (SOT)	Categorical	0, 1, 2	Fine-grained mineral soil (0), coarse-grained mineral soil (1), organic soil (2)	0
	Proportion of thin soil (PTS)	Continuous	0–100	Coverage of cells with soil thickness < 1 m of the total landscape area	0

Covariate acronyms are listed in parentheses in the Covariate name column. The same acronyms are used in Eqs. 1–4 elevation in landscape i. $\alpha_{0\text{-}4}$ are the parameters to be estimated.

For the second research question, we used a gamma-distributed generalized linear model (GLM) with a log link function to model the relationship between the wind disturbance patch size and the covariates. In this analysis, the equation for the most parsimonious model was:

$$PS_i = \beta_{0,ST} + \beta_1 MGS_i + \beta_2 HGS_i + \beta_3 FP_i, \tag{2}$$

where PS_i is the log of the mean wind disturbance patch size in landscape i and $\beta_{0,ST}$ is the storm type-specific intercept. MGS_i is the mean gap size, HGS_i is the mean harvest gap size, and FP_i is the proportion of forest in the landscape i. $\beta_{0\text{-}3}$ are the parameters to be estimated.

For the third research question, we used a GLM with a negative binomial distribution and a log link function to model the relationship between the number of disturbance patches and the covariates. Here, the equation of the most parsimonious model was:

$$PN_i = \gamma_{0,ST} + \gamma_{1,ST} WS_i + \gamma_2 ED_i + \gamma_3 FP_i \tag{3}$$

where PN_i is the log of the number of wind disturbance patches in landscape i and $\gamma_{0,\ ST}$ is the storm type-specific intercept. WS_i is the mean wind gust speed during the storm in landscape i with storm type-specific coefficient $\gamma_{1,\ ST}$, ED_i is the mean edge density and FP_i is the proportion of forest in landscape i. $\gamma_{0\text{-}3}$ are the parameters to be estimated.

To address the fourth research question, the spatial distribution of disturbance patches, we used beta regression with a logit link function to examine the relationship between this variable and the covariates. Here, the equation for the most parsimonious model was:

$$\begin{aligned} DPC_i = {} & \delta_{0,ST} + \delta_{1,ST} WS_i + \delta_2 HGS_i + \delta_3 SDT_i \\ & + \delta_4 FP_i + \delta_5 SD_i, \end{aligned} \tag{4}$$

where DPC_i is the logit of the wind disturbance patch clustering in landscape i, $\delta_{0,\ ST}$ is storm type-specific intercept, WS_i is the mean wind gust speed during the storm in landscape i with storm-type specific coefficient $\delta_{1,\ ST}$, HGS_i is the mean harvest gap size, SDT_i is the standard deviation of tree heights, FP_i is the proportion of forest, and SD_i is the storm direction landscape i. $\delta_{0\text{–}5}$ are the parameters to be estimated.

We also fitted quasi-likelihood models with different variance functions to test the performance of alternative model formulations. Since their results were similar compared to the models reported here (Tables S1–S4), we retained the models presented in Eqs. 1–4 on the grounds that they represent the standard families of distributions developed for the different types of response variables, and because a fully specified distribution, as opposed to the quasi-likelihood, allows the models to be incorporated directly into a stochastic disturbance generator, which is useful for the future development of disturbance simulation models.

Results

On average, 1.7% of the total forest area in the study landscapes was disturbed during windstorms and 2.6% during thunderstorms, with disturbed proportions ranging from 0.03 to 9.9% for windstorms and 0.31 to 9.3% for thunderstorms (Fig. 1A). The mean wind disturbance patch size was 6.7 ha for windstorms and 8.8 ha for thunderstorms, with mean wind disturbance patch sizes varying from 1.0 to 79 ha for windstorms and 2.4 ha to 106.9 ha for thunderstorms (Fig. 1B). The average number of wind disturbance patches per landscape was 18 for windstorms and 22 for thunderstorms, with the number of wind disturbance patches ranging from 1 to 62 for windstorms and from 1 to 73 for thunderstorms (Fig. 1C). For both storm types, >98.5% of the studied landscapes showed clustering of disturbance patches, with the average unscaled clustering value being higher for thunderstorms (0.60) than for windstorms (0.56) (Fig. 1D).

Landscape configuration covariates were related to each of the response variables, with the specific covariate depending on the response variable (Fig. 2). Harvest gap size was related to every response variable except number of disturbance patches, was the only landscape configuration covariate that was related to the wind disturbance patch clustering, and was the only covariate that increased disturbance patch clustering ($\delta_2 = 0.09$) (Fig. 2D). Mean gap size had the largest contribution to the proportion of wind-disturbed forest and the size of wind disturbance patches among the landscape structure covariates ($\alpha_2 = 0.16$ and $\beta_1 = 0.19$, respectively) (Fig. 2A, B),

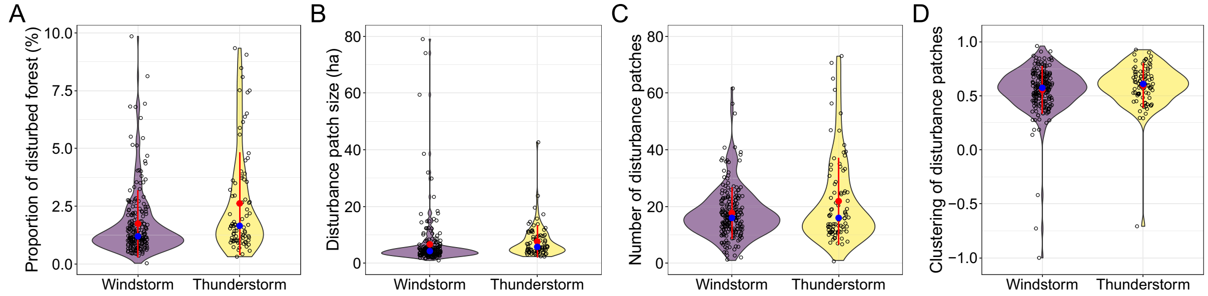

Fig. 2 The distributions of the response variables, proportion of disturbed forest **A**, disturbance patch size **B**, number of disturbance patches **C**, and clustering of disturbance patches **D**, shown with colored violins and with original the original data as black dots. The red dots are the mean and the blue dots are the median of the data, and the length of the red lines is one standard deviation in either direction from the mean. In **B**, a thunderstorm landscape with a mean disturbance patch size of 106.9 ha has been omitted for clarity

while the mean edge density had the largest contribution to the number of disturbance patches ($\gamma_2 = 0.18$) (Fig. 2C).

Among the storm characteristics covariates, storm type was related to each of the four response variables examined (Fig. 2). The interaction between storm type and wind speed was related to each response variable except for disturbance patch size, with the interaction between wind speed and thunderstorm having the largest relative contribution to proportion of disturbed forest, number of disturbance patches and clustering of disturbance patches ($\alpha_1 = 0.48$, $\gamma_1 = 0.52$, $\delta_1 = -0.38$, respectively) (Fig. 2). Storm direction was only related to the clustering of disturbance patches (Fig. 2D).

Among the forest characteristics and stand size covariates, forest proportion was related to each response variable except for the proportion of disturbed forest (Fig. 2), and the standard deviation of tree height was related to the clustering of disturbance patches (Fig. 2D).

Increasing mean gap size increased the proportion of wind-disturbed forest, the increase being slightly more pronounced for thunderstorms than for windstorms (Figs. 2A, 3A1). For example, the proportion of disturbed forest was 1.6% for windstorms and 3.2% for thunderstorms when mean gap size was 20 ha, but increased to 2.0% and 4.1% for windstorms and thunderstorms, respectively, when mean gap size was 100 ha (Fig. 3A1). The proportion of disturbed forest also increased as a function of increasing wind speed, the increase again being more pronounced for thunderstorms than for windstorms (Figs. 2, 3B1). For example, when the wind speed was 13.0 m/s, the proportion of disturbed forest was approximately 1.4% for windstorms and 1.7% for thunderstorms, but when the wind speed increased to 23 m/s, the proportion of disturbed forest increased to 2.0% for windstorms and 5.6% for thunderstorms (Fig. 3B1), with the other variables set to their arithmetic means.

Mean gap size and the size of harvest gaps both increased wind disturbance patch size (Figs. 2B, 3A2–3B2), the increase in both cases being more pronounced for thunderstorms than for windstorms. For example, the average disturbance patch size was 4.9 ha in windstorms and 7.2 ha in thunderstorms when mean gap size in the landscape was 20 ha, increasing to 6.7 ha in windstorms and 9.9 ha in thunderstorms when mean gap size increased to 100 ha (Fig. 3A2). Similarly, the average disturbance patch size in windstorms was 5.0 ha in windstorms and 6.5 ha in thunderstorms when the average harvest gap size in the landscape was 1.5 ha, increasing to 6.9 ha in windstorms and 8.7 ha in thunderstorms when the average size of harvest gaps increased to 4.0 ha (Fig. 3B2).

Increasing mean edge density was positively associated with the number of wind disturbance patches for both windstorms and thunderstorms (Figs. 2C, 3A3). For example, the number of disturbance patches was 13 for windstorms and 18 for thunderstorms when the mean edge density was 10 m/ha, and increased to 21 for windstorms and 30 for thunderstorms when the mean edge density was 35 m/ha (Fig. 3A3). The number of disturbance patches also increased with increasing wind speed, the increase being faster for thunderstorms than for windstorms

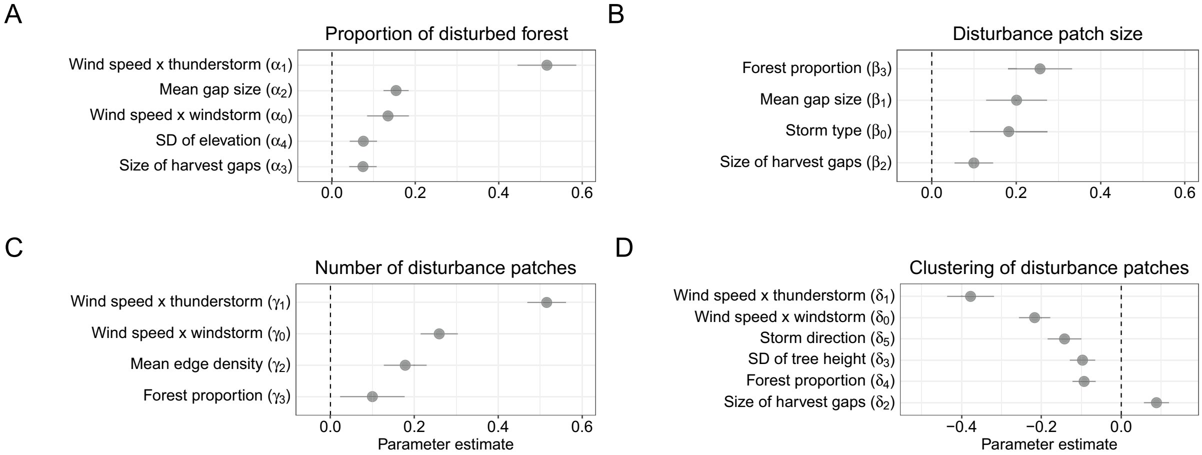

Fig. 3 Regression model parameter estimates for the scaled and centered covariates from the model explaining the proportion of wind-disturbed forest (**A**), wind disturbance patch size (**B**), number of wind disturbance patches (**C**), and clustering of wind disturbance patches (**D**). The covariates are ranked from top to bottom in the order of the magnitude of their contribution to the examined dependent variable. Error bars indicate the 95% confidence intervals for the estimates. The symbols in parentheses refer to those used in Eqs. 1–4. In **B**, the storm type represents a thunderstorm. In **D**, the storm direction represents an event where the storm direction was different from the general wind direction. Note the different range of the x-axis in **D**. Numerical parameter estimates are reported in Tables S1–S4. In **A** and **D**, SD refers to standard deviation

(Figs. 2C, 3B3). For example, at a wind speed of 13.0 m/s, the average number of disturbance patches was 11 for windstorms and 15 for thunderstorms, increasing to 23 for windstorms and 59 for thunderstorms when the wind speed increased to 23 m/s (Fig. 3B3).

The clustering of wind disturbance patches increased with the increasing the size of harvest gaps (Figs. 2D, 3A4). For example, the clustering was 0.79 for windstorms and 0.74 for thunderstorms when the harvest gap size was 1.5 ha, increasing to 0.83 for windstorms and 0.77 for thunderstorms when the harvest gap size was 4 ha (Fig. 3D2). The clustering of disturbance patches decreased with increasing wind speed, the decreasing being faster for thunderstorms than for windstorms (Fig. 3B4). For example, at a wind speed of 13.0 m/s, the clustering of disturbance patches was 0.85 for windstorms and 0.84 for thunderstorms, decreasing to 0.76 for windstorms and 0.65 for thunderstorms when the wind speed increased to 23 m/s (Fig. 3B4).

In terms of model validation, the model residuals did not show a linear trend when plotted against the fitted values (Fig. S3) or against the continuous model covariates (Fig. S4; Fig. 4).

Discussion

The influence of landscape configuration on wind disturbance

Landscape configuration was related to every aspect of wind disturbance occurrence examined, suggesting that wind disturbance responds to and creates patterns in forest landscapes. For example, increasing landscape complexity due to increasing non-forest and harvest gap sizes and increasing edge density between forest and non-forest, and between forest and harvest gaps had a positive relationship with the proportion of wind-disturbed forest. While the importance of landscape configuration on disturbance occurrence and extent has long been recognized (Turner 1989) and empirically demonstrated for certain disturbances such as fire (Niklasson and Granström 2000; Pinto et al. 2020), its effect on the spatial patterns of wind disturbance has remained unquantified. Instead, recent research has mostly focused on identifying the drivers of wind disturbance susceptibility at individual tree (Schmidt et al. 2010; Zanotto et al. 2024) and stand scales (Ruotsalainen et al. 2023), as well as

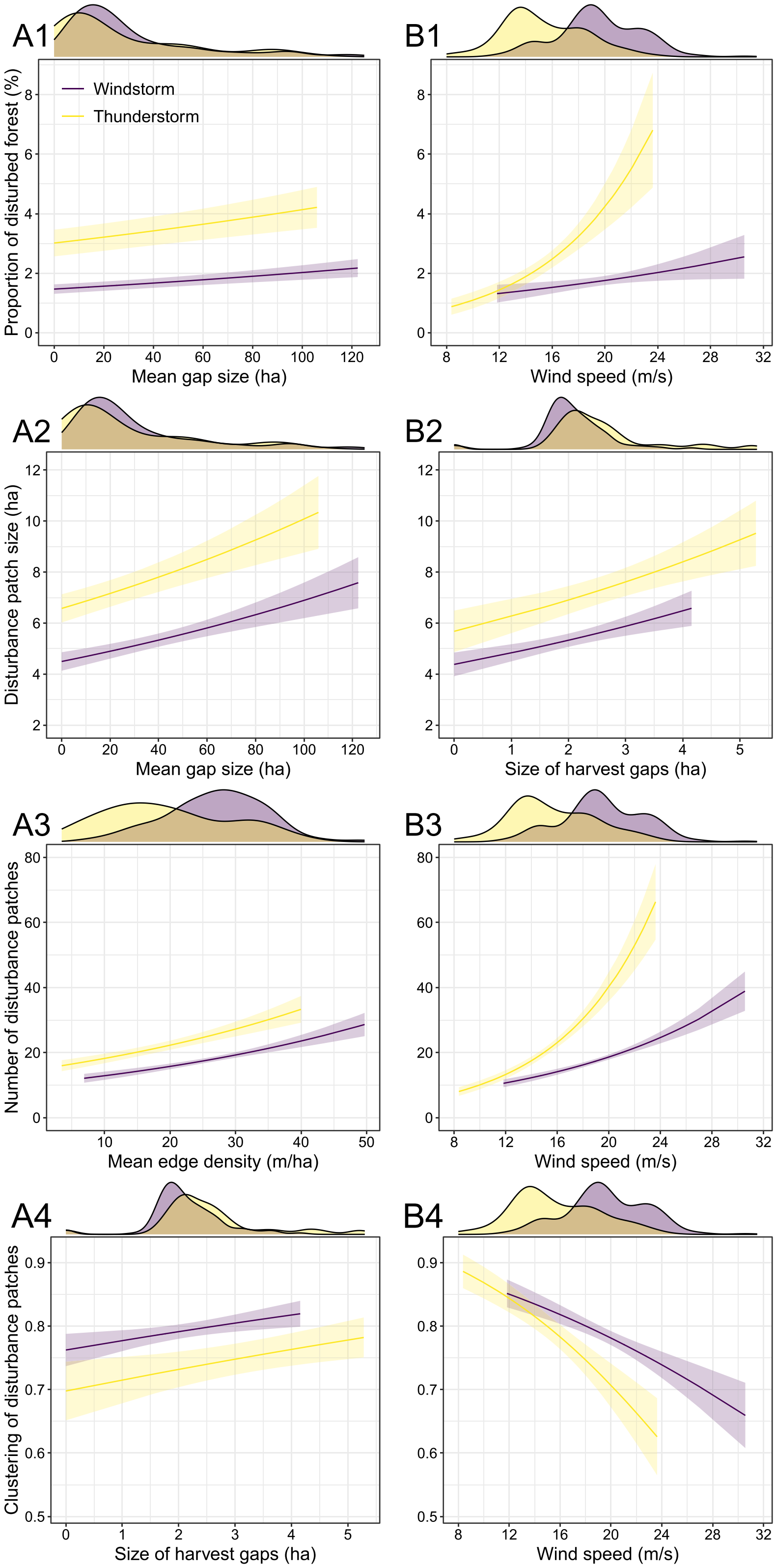

Fig. 4 Model predictions as a function of landscape configuration (**A**) and storm characteristics (**B**) covariate with the highest contribution in the regression models with proportion of disturbed forest (**A1–B1**), disturbance patch size (**A2–B2**), number of disturbance patches (**A3–B3**), or disturbance patch clustering (**A4–B4**) as response variables, plotted separately for windstorms and thunderstorms. For disturbance patch size, the two landscape structure covariates with the highest contribution are shown because no continuous storm covariates were related to disturbance patch size (**A2–B2**). For each panel, the variables other than the one used in the prediction were set to their arithmetic mean. In the predictions shown in panels **A4–B4**, the storm direction was set to be different from the general wind direction. The shaded areas are the standard errors of the predictions, and the marginal histograms show the density distributions of the covariate used in the prediction. **B2** and **A1** show the predictions plotted with mean gap size values < 95th quantile (127.0 ha) to exclude outlier gap sizes. Predictions for other covariates included in the models are shown in Fig. S5

spatial representations of wind risk based on these susceptibilities (Suvanto et al. 2019). Our results show that understanding the influence of landscape configuration is also important for understanding the occurrence of wind disturbance in forest landscapes (Franklin and Forman 1987; Honkaniemi et al. 2020).

Increasing gap size increases wind disturbance patch size

Increasing non-forest and harvest gap sizes were positively related to the proportion of disturbed forest for both wind and thunderstorms. The positive relationship was manifested as larger disturbance patches in landscapes with larger non-forest and harvest gaps, while the number of wind disturbance patches varied independently of non-forest and harvest gap sizes. The observed relationship could be because increasing the size of non-forest and harvest gaps increases the wind fetch and consequently the wind load on trees at gap edges, thereby increasing the severity of wind disturbance at gap edges (Panferov and Sogachev 2008; Peltola 1996; Yang et al. 2006). The increased wind load may also cause windthrows to occur farther from the gap edges because higher wind loads allow the wind to penetrate deeper into the canopy (Dupont and Brunet 2008) and because the relative magnitude of the wind moment peaks some distance away from the absolute gap edge (Yang et al. 2006).

Increasing mean harvest gap size was positively related to the proportion of disturbed forest and disturbance patch size, but the relative contribution of harvest gap size was less than that of permanent gaps and harvest gaps combined (i.e. the *mean gap size* variable). This suggests that while increasing gap size led to an increase in wind disturbance extent and disturbance patch size, gap type also influences the outcome of wind disturbance. Trees can acclimate to their general wind environment by, for example, altering compression wood formation (Wohlgemuth et al. 2022), crown geometry (Wade and Hewson 1979), and stem taper (Brüchert and Gardiner 2006) to better match their local wind environment. However, if the local wind environment changes suddenly, for example due to harvesting, trees may not have time to acclimate to the new wind environment, potentially increasing wind-related tree mortality (Tang et al. 1997; Zeng et al. 2004).

Increasing edge density increases the number of wind disturbance patches

Increasing the mean edge density was positively related to the number of wind disturbance patches, but varied independently of the proportion of disturbed forest. This suggests that increasing gap shape complexity does not increase the extent of wind disturbance, but rather results in a higher number of small disturbance patches. In a forest landscape with high gap shape complexity, a higher number of stands are located at the wind sensitive gap edge compared to a landscape with simple shaped canopy gaps, potentially resulting in increased disturbance severity with increasing gap edge density (Lohmander and Helles 1987; Tang et al. 1997). Similarly, increasing gap shape complexity may also indicate increased forest fragmentation (Slattery and Fenner 2021), suggesting an increased number of disturbance patches due to an increased number of separate forest patches. However, increasing gap complexity does not increase wind fetch as much as increasing gap size (Panferov and Sogachev 2008), limiting the wind load on trees adjacent to a complex but small canopy gap. In this light, the lack of relationship between the proportion of disturbed forest and gap edge density, as well as disturbance patch size and gap edge density, seems logical.

Increasing harvest gap size increases wind disturbance patch clustering

Increasing mean harvest gap size had a positive relationship with the clustering of wind disturbance patches. Disturbance events consist of environmental forcing interacting with ecosystem properties (Peters et al. 2011). In the context of wind disturbance, harvesting alters the ecosystem properties by increasing the susceptibility of stands adjacent to the harvest gaps to wind disturbances by predisposing unacclimated trees to high wind loads (Suvanto et al. 2016; Tang et al. 1997). The larger the harvest gaps, the greater the wind load during a storm event because larger gaps allow for higher wind speeds and thus higher disturbance severities (Dupont and Brunet 2008; Panferov and Sogachev 2008). For this reason, landscapes with large harvest gaps may exhibit high clustering of wind disturbance patches. In addition to harvest, natural disturbances can also influence the probability of wind disturbance by altering the ecosystem properties. For example, wind disturbance patches may exhibit spatial (Schulte et al. 2005) and temporal (Dupont et al. 2015; Runkle 1985) autocorrelation, such that an existing wind disturbance patch increases the probability of wind disturbance in a neighboring stand during a consecutive or even the same storm event. Our results are indicative of both types of autocorrelation, as the newly formed wind disturbance patches tend to cluster in landscapes with larger recent harvest gaps. This clustering is also relevant to disturbance interactions, as clustering of wind disturbances near harvest gaps can promote the formation of new wind disturbance patches in the same neighborhood, and further catalyze compounding disturbances such as bark beetle outbreaks (Peltonen 1999).

The influence of storm characteristics on the occurrence of wind disturbances

Increasing wind speed increases wind disturbance extent

Increasing wind speed was positively related to the proportion of disturbed forest and the number of disturbance patches, with increases more pronounced for thunderstorms than for windstorms. Storm type was also associated with disturbance patch size, with thunderstorms producing larger disturbance patches than windstorms. Consistent with our results, increasing wind speed has been shown to covary with disturbance severity in boreal forests of northern Europe (Valta et al. 2019) and elsewhere (Pawlik and Harrison 2022; Usbeck et al. 2010). Our results suggest that the relationship between disturbance severity and wind speed differs by storm type, and that in a managed forest landscapes, increased wind disturbance severity is manifested as a greater number of disturbance patches rather than a greater size of disturbance patches. In contrast to windstorms, which occur in fall to spring in our study region (Laurila et al. 2021), thunderstorms typically occur in late summer. This means that thunderstorms occur when trees have leaves and the ground is not frozen, which increases wind loading on deciduous trees and decreases tree anchoring, respectively, increasing tree vulnerability to high winds (Gregow et al. 2011) and potentially explaining the higher severity of thunderstorms compared to windstorms. While our data indicate that the wind speeds were lower during thunderstorms than during windstorms (Fig. S6), the coarse resolution of the weather station network may not capture the high wind speeds that occur locally during thunderstorms (Laapas et al. 2023). Therefore, it is possible that the higher proportion of forest disturbed during thunderstorms compared to windstorms is at least partially explained by high the wind speeds during thunderstorms.

Although the wind speed covariates had the largest contribution in three out of our four models, previous studies have shown that wind speed alone is insufficient to predict the probability of wind disturbance (Laapas et al. 2023). This notion was also highlighted in our results, as the magnitude of the relative contribution of landscape structure covariates was similar to that of wind speed, and disturbance patch size varied independently of wind speed. The influence of variables unrelated to the storm, such as landscape configuration, may play a large role in disturbance occurrence, especially when the disturbances are of moderate intensity and wind speeds are mostly below the critical wind speed (Turner and Gardner 2016), regardless of storm type (Suvanto et al. 2016).

Wind disturbance patches were clustered for both windstorms and thunderstorms. Increasing wind speed decreased the clustering of disturbance patches for both storm types, but the decrease was more pronounced for thunderstorms than for windstorms. This, together with the increasing proportion of disturbed forest and number of disturbance patches with increasing wind speed, suggests that wind disturbances become more spatially stochastic with increasing storm wind speed. Storm wind speeds vary spatially during a storm event (Laapas et al. 2023). This, combined with varying stand wind susceptibility may cause the disturbance patches to cluster in areas where the wind speeds and/or stand susceptibility are the highest. However, when the wind speed is very high, disturbances begin to occur across the forest landscape, regardless of stand vulnerability (Gardiner 2021; Valta et al. 2019). During such storms, critical wind speeds required to break or uproot trees occur across the landscape, causing disturbances even in stands with low wind susceptibility and potentially reducing the clustering of disturbance patches (Gardiner et al. 2008). Our observation of decreasing disturbance patch clustering with increasing wind speed during thunderstorms is in contrast to that of Frelich and Lorimer (1991). This may be explained by the different study extents. At scales broader than 5 km, which was the radius of our study landscapes, the clustering of thunderstorm patches along storm tracks is visually evident also in our data (Fig. S1).

Challenges of research data

The declarations used in this study provide a large, spatially explicit dataset on forest management activities in Finland. From the perspective of disturbance research, it is important to note that the declarations do not indicate disturbance events per se, but rather management responses to a disturbance (i.e. salvage logging). Therefore, declarations are not submitted from areas where salvage logging is not practiced, such as certain nature reserves, which may bias the data. Forest owners' objectives, willingness and other factors, such as logistical considerations, may also influence their decision to salvage log, provided that the amount of damaged timber remains below the levels defined in the Finnish Damage Prevention Act (1087/2013). In addition, certain other characteristics hamper the use of the declarations for disturbance research purposes. Importantly, the declarations do not contain information on the severity or distribution of the disturbance within the stand. Although the law requires salvage logging to be conducted when a certain volume of disturbance-damaged timber is reached, a salvage logging declaration can also be submitted for disturbances of lesser severity, which are commonly observed in our study area due to wind (Kuuluvainen and Aakala 2011). The occurrence of low-severity disturbance probably explains why 14% of the validated stands showed no evidence of wind disturbance on aerial photographs. The absence of data on the severity of disturbances currently precludes the use of declarations to examine wind disturbance severity on and within stand scales. Nevertheless, our validation procedure indicates that the declarations are able to capture the actual disturbance patterns relatively well at broader spatial scales. In this study, we attempted to reduce the effect of the uncertainty associated with the unknown distribution of disturbance within the stand by gridding the declarations. Declaration data that separate salvage logging are also mostly available from 2010 onwards, limiting the temporal scope of the analyses. Despite these shortcomings, we consider the declarations to be a valuable novel data source for studying forest disturbances. They also provide a solution to the challenge of disturbance agent separation, a common problem in remote sensing of disturbances (Sebald et al. 2021; Tomppo et al. 2021).

Conclusions

Our landscape-scale analyses showed that wind disturbances respond to and create patterns in forest landscapes, but the precise effects of these disturbances depend on landscape configuration, such as the size and shape of canopy gaps, and storm characteristics, such as wind speed and/or storm type. However, forest characteristics, such as forest cover or tree height, and topography played a minor role. In terms of landscape configuration, increasing mean size of canopy gaps, both permanent gaps such as lakes and open peatlands, and recent harvest gaps, had a positive association with disturbance extent and disturbance patch size. Gap complexity, as measured by edge density, increased with the number of wind disturbance patches. With increasing wind speed, wind disturbances became more spatially stochastic, as evidenced by the increasing number and decreasing clustering of disturbance patches with increasing wind speed. These results not only help to understand how landscape configuration drives wind disturbance and thus forest dynamics, but also support the formulation of more realistic disturbance simulation models, which, due to a general lack of spatially explicit disturbance intensity data, often rely on proxies such as landscape configuration to predict disturbance effects.

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Author contributions Mikko Peltoniemi, Juha Honkaniemi, Niko Kulha and Susanne Suvanto developed the original research idea. Jonathan Holder compiled the declaration data and Niko Kulha compiled the other research data with the help of Mikko Laapas and Susanne Suvanto. Niko Kulha, Juha Heikkinen, Mikko Kuronen and Mikko Peltoniemi developed the analytical framework. Niko Kulha performed the analyses and wrote the first draft of the manuscript. All authors commented on earlier versions of the manuscript and read and approved the final manuscript.

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Data availability The data compiled and analyzed in this study are available at: https://doi.org/10.6084/m9.figshare.26028778.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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