Forest Ecology and Management 381 (2016) 17–28

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Forest susceptibility to storm damage is affected by similar factors regardless of storm type: Comparison of thunder storms and autumn extra-tropical cyclones in Finland

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ARTICLE INFO

Article history:
Received 19 April 2016
Received in revised form 5 September 2016
Accepted 6 September 2016
Available online 15 September 2016

Keywords:
Wind damage
Forest damage
Winter storm
Windthrow

ABSTRACT

Wind storms are a major source of disturbance in European forests and changes in climate are expected to further increase the amount of damage. The aim of this study was to compare the factors affecting forest susceptibility to storm damage between two storm types, autumn extra-tropical cyclones and thunder storms, to find out whether similar factors expose forests to damage in storms with different meteorological characteristics. We used two storm damage data sets collected after two autumn storms in November 2001 and four thunder storms in summer 2010 in Finland. The damage caused by these storms was documented after the storms on plots of the Finnish National Forest Inventory. We used generalized linear mixed models to study the probability of storm damage in different types of forest stands. Explanatory variables in the models described stand characteristics, recent forest management operations, soil type and topography. The models were able to discriminate between the damaged and non-damaged plots (AUC_{autumn} = 0.724, $AUC_{thunder}$ = 0.808). The autumn storm model also had some discrimination power for predicting the storm damage in the thunder storm data set ($AUC_{thunder2}$ = 0.675). These results suggest that similar factors affect stand susceptibility to storm damage in both storm types. The potential use of the models was demonstrated by using the autumn storm model to calculate damage probabilities for stand simulations and to create a forest storm damage susceptibility map for Southern Finland.

1. Introduction

Storms are a major source of disturbance in European forests (Schelhaas et al., 2003). Although in Finland the extent of damage has so far been smaller than in Central Europe, substantial forest damage have been caused in recent years by, for example, a series of thunder storms in 2010 and severe autumn storms in 2001 (Ihalainen and Ahola, 2003; Viiri et al., 2011). In addition to the trees felled by storms, further damage can be caused after the storm event, as dead-wood left in forests increases the risk of bark beetle outbreaks (Bouget and Duelli, 2004; Komonen et al., 2011). By causing extensive damage, the storms have a major effect not only on wood production but also on other ecosystem services provided by forests, such as carbon sequestration from the atmosphere (Lindroth et al., 2009; Seidl et al., 2014).

Wind damage in forests can be divided into endemic and catastrophic damage. Endemic damage typically affects the most vulnerable trees, for example trees on newly created stand borders, and can be triggered by frequently recurring wind speeds. In contrast, catastrophic damage is caused by exceptionally high wind speeds (Gardiner et al., 2008). In this study we focus on catastrophic damage caused by the thunder storms in summer 2010 and two extra-tropical cyclones in autumn 2001.

In Europe, the majority of forest storm damage is caused by winter storms, which are usually strong extratropical cyclones (Gardiner et al., 2010). However, in Finland soils are typically frozen during winter and provide good anchorage for trees. Therefore, storms cause more damage during autumns when soils are unfrozen (Laitakari, 1952; Gregow et al., 2008). In this type of conditions, storm damage consists mainly of uprooting of trees whereas stem breakage occurs typically during storms accompanied with snowfall and during summer thunderstorms (Laiho, 1987; Gregow et al., 2008, 2011).

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http://dx.doi.org/10.1016/j.foreco.2016.09.005
0378-1127/

Compared to extra-tropical cyclones occurring in autumn and winter, thunder storms often have a smaller spatial and temporal extent and, thus, a smaller total impact on forests (Gardiner et al., 2010). However, their effects can also be substantial, as demonstrated by the series of thunder storms in 2010 that felled over eight million cubic meters of wood in Southern and Central Finland (Viiri et al., 2011). The dynamics of thunder storms differ from winter and autumn storms. The damage in thunder storms is caused by strong downbursts. In fact, Uotila et al. (2015) suggest that because of the high wind speeds during downbursts, it is not possible to prevent thunder storm related damage with forest management practices. However, limited research is available on thunder storm related forest damage, as the research on forest storm damage in Europe has concentrated on winter storms (e.g., Gardiner et al., 2010; Schmidt et al., 2010; Schindler et al., 2012; Kamimura et al., 2016).

Wind damage in forests is affected by the susceptibility of trees to damage as well as meteorological factors such as wind speed, direction and gustiness. The susceptibility to damage varies between tree species as well as within a species, and is affected by characteristics such as the age, size and form of the tree (Laiho, 1987; Lohmander and Helles, 1987; Peltola et al., 1999b; Albrecht et al., 2012; Hanewinkel et al., 2013). The local abiotic environment also has an effect on the damage probability. For example, topography, forest edges and the proximity of water areas or other open areas can affect the wind speed and, thus, cause high variability in wind conditions even within short spatial distances (Peltola et al., 1999b; Dupont et al., 2008; Schindler et al., 2012).

Forest management also affects forest wind damage probability. The increased forest damage in storms has been largely attributed to intensified forest management (Schelhaas et al., 2003; Nilsson et al., 2004; Seidl et al., 2011). Therefore, the actions aiming to mitigate damage probability should focus on management practices. This underlines the need for accurate information and operational management tools (Gardiner and Quine, 2000; Zeng et al., 2007; Heinonen et al., 2009).

Storm related forest damage is expected to increase in future due to the changes in climate (Blennow et al., 2010; Gregow et al., 2011; Seidl et al., 2014). In Finland, this increase is related to changes in the wind, frost and snow conditions. A major cause for increasing forest damage is decreased soil frost during autumn and winter storms and, thus, a weaker anchorage of trees (Peltola et al., 1999a; Gregow et al., 2011). Increases in storminess in Northern Europe are possible, although the uncertainties in the prediction are still high (Gregow et al., 2012; Mölter et al., 2016). In addition, as the susceptibility to wind damage varies between tree species, changes in species composition may also alter the damage risk (Peltola et al., 2010).

The aim of our study was to (1) examine the factors that affect the stand-level forest susceptibility to damage during storms and (2) compare these factors between two storm types: autumn extra-tropical cyclones and thunder storms. To achieve this, we used two empirical data sets, where storm damage was recorded at the National Forest Inventory plots after two severe series of storms: two autumn storms in 2001 and four thunder storms of 2010.

2. Materials and methods

2.1. Storms

The storm data used in this study consist of two data sets collected after exceptionally severe storms in years 2001 and 2010. In November 2001, two extratropical cyclones (storms Pyry, 1.11. and Janika, 15.11.) hit south-western Finland and caused tree damage in large areas. Mean wind speed (10 min) on land areas ranged from 16 to 18 m s^{-1} (Ihalainen and Ahola, 2003), while the strongest gust measured on land area was 27.8 m s^{-1}. The main wind direction during the storms was north (Pellikka and Järvenpää, 2003). The damage to forest was further increased because of unfrozen soils during the storms and snowfall associated with the storm Pyry (Zubizarreta-Gerendiain et al., 2012). The amount of damaged wood for the two storms was estimated to be approximately 7.3 million cubic meters (Ihalainen and Ahola, 2003). These storms are hereafter referred to as autumn storms.

In June and August 2010 a period of warm weather ended with a series of thunder storms (storms Asta 29.7., Veera 4.8., Lahja 7.8. and Sylvi 8.8.). Storms were associated with strong downbursts that damaged forests on large areas (Viiri et al., 2011). For example, in storm Asta wind speed in the strongest measured gusts reached 29 m s^{-1} while gusts of 20 m s^{-1} were measured at several weather stations (Finnish Meteorological Institute, 2010). The four thunder storms caused damage of approximately 8.1 million cubic meters of wood in Southern and Central Finland (Viiri et al., 2011).

In the area affected by the storms is characterized by rather low variation in elevation, the study plots are located in elevations ranging from 0 to 229 m above sea level and slopes are generally gentle (Table 1). Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst) are the most common tree species (Table 2).

Table 1
Mean and standard deviation of the independent continuous variables used in models. Values are given for plots with no damage, damaged plots and all plots. To account for the stratified sampling design of the 2010 data, the observations were weighted based on the represented area of each plot.

	Autumn storms 2001						Thunder storms 2010					
	No damage		Damage		All		No damage		Damage		All	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Proportion of spruce (%)	28.7	35.6	39.8	39.5	32.9	37.5	25.2	34.3	26.6	36.1	25.4	34.5
Stand age (years)	71.1	35.0	78.3	30.4	73.8	33.5	64.9	36.6	56.4	28.9	63.6	35.7
Basal area (m^2 ha^{-1})												
Scots pine stand	17.7	7.4	16.9	7.4	17.4	7.4	20.6	7.2	21.6	5.6	20.8	7.0
Norway spruce stand	22.3	8.0	23.9	8.5	23.0	8.3	25.2	7.1	25.9	5.8	25.3	6.9
Other	18.5	9.4	16.6	6.4	18.2	9.0	17.1	7.7	21.6	3.9	17.5	7.5
DBH (cm)												
Scots pine stand	19.0	7.2	19.4	6.8	19.1	7.0	19.4	6.5	19.6	7.2	19.4	6.6
Norway spruce stand	21.9	6.5	25.2	5.9	23.4	6.5	22.8	6.9	22.3	5.9	22.7	6.7
Other	16.7	5.8	18.1	6.0	16.9	5.9	15.2	6.2	21.8	3.3	15.8	6.2
Slope (degrees)												
Shelter side	4.8	3.7	4.1	3.2	4.5	3.5	5.2	4.0	4.8	2.2	5.2	3.9
Wind side	2.9	3.3	3.2	3.8	3.0	3.5	3.5	4.6	3.4	3.1	3.5	4.4