Forest Ecology and Management 401 (2017) 215–222

Contents lists available at ScienceDirect

Forest Ecology and Management

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

How does forest composition and structure affect the stability against wind and snow?

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ARTICLE INFO

Article history:
Received 8 February 2017
Received in revised form 23 June 2017
Accepted 25 June 2017

Keywords:
Risk modelling
Forest management
Picea abies
Betula sp.
Pinus sylvestris
Mixed stands
Damage

ABSTRACT

The risk of snow and wind damage should be considered when deciding forest management actions, as it can greatly change forest development and its accompanying services. In this study, we develop models that predict snow and wind damage using management related variables as predictors. The plot level models are based on the extensive data available for Norwegian forests from four consecutive measurements of the national forest inventory along the period 1995–2014. The snow and wind risk is assessed in pure stands (pine, spruce and birch) as well as for mixed stands. Separate models are constructed for predicting the probability of a tree to be damaged, broken or uprooted. The models' descriptors include: mean diameter, mean tree slenderness, mean height, basal area and a portfolio of variables related to stand structure and composition. The models are based on generalized linear models assuming binomial or quasi-binomial distributions resulting in nine models. Mixed stands are the stands most commonly affected by snow and wind damage followed by spruce dominated stands. Spruce stands with more heterogeneous structures are less prone to suffer breakage of trees, and increasing stand height have a big impact on the risk of tree breakage. The models presented in this study can be used to create management prescriptions considering the risk of snow and wind damage. These models also help to better understand which variables make a forest more vulnerable to snow and wind damage.

1. Introduction

Snow and wind damages play a key role explaining forest ecology and dynamics. The ecological importance of snow and wind associated disturbances on forest relates, for example, to the increment of biodiversity as a result of changes in the forest structure (e.g. opening of gaps) (Quine and Gardiner, 2007) or the creation of new habitat niches (e.g. standing broken trees or lying dead wood) (Lain et al., 2008). On the other hand, they also result in substantial economic impacts, as their damage compromises the achievement of forest management goals and the implementation of a pre-scheduled sequence of management operations (Gadow, 2000). In this sense, studying the impact snow and wind have on forests not only helps to increase our knowledge on forest dynamics, but it is essential for defining forest management alternatives adapted to this source of risk.

Norwegian forests have not faced big catastrophic snow and wind damages during the last decades (Díaz-Yáñez et al., 2016). The absence of catastrophic snow and wind damages can be the consequence of the removal of susceptible trees after the extensive damages occurred in the 70s (Bakke, 1989; Økland and Berryman, 2004) or due to a lower frequency of intense storms during the last three decades. However, this relative stability of Norwegian forest against storm damage does not have to be permanent. In this sense, some authors argue that even assuming no trend suggesting a rise in storms' intensities and frequencies, snow and wind damage is expected to increase due to forests becoming more vulnerable (Schelhaas et al., 2003). In fact, it is expected that the forests will become more vulnerable to snow and wind damages, as the total growing stock increases every year and trees become older (Peltola et al., 2010). In addition, changes in climatic conditions can also increase the risk of snow and wind damage; for instance, rises in temperature result in an increase in trees' susceptibility to be uprooted since the period the soil is frozen gets shorter (Peltola et al., 1999), and a raise in humid snow increases the risk of branches and stem breakage, due to accumulation on tree crowns (Nykänen et al., 1997). These suggest that, despite the effect of other external factors, it is necessary to identify which variables make forests vulnerable to wind and snow damage; this

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http://dx.doi.org/10.1016/j.foreco.2017.06.054
0378-1127/

knowledge can contribute to develop mitigation strategies, so as to reduce the risk and severity of snow and wind damage, and to generate future scenarios that consider their effects on forests.

The assessment of the potential impact of snow and wind damage on forest resources has previously relied on controlled experiments (growth and yield trials) and simulated data (Päätalo, 2000; Päätalo et al., 1999; Peltola et al., 1997), using mechanistic and empirical models (Päätalo, 2000; Jalkanen and Mattila, 2000), observing the impact of large and catastrophic events (Canham et al., 2001; Cucchi and Bert, 2003; Mayer et al., 2005) or measuring the damage from multiple events over an extended period of time (Dhubhain et al., 2001; Jalkanen and Mattila, 2000). From the latest approach, studies using national forest inventories (NFIs) data are gaining relevance (Dobbertin, 2002; Fridman and Valinger, 1998; Martín-Alcón et al., 2010). Although using repeated measurements from NFIs limits the possibility of including reliable information on some factors such as wind speeds and snow loads, as measurements are taken on fixed time intervals and cannot be assigned to specific damage events, it also provides advantages for management purposes that cannot be neglected.

The first advantage of using NFIs is that they are large resource assessment programs that aim to capture all the representative conditions over a whole country. The second advantage is that NFI due to their measurement protocols are able to capture different levels of damage without neglecting the smaller levels, often disregarded and not recorded with remote sensing tools. Finally, by using measurements based on permanent NFI plots, it is possible to provide a temporal framework to the observed damage. The combination of these NFI advantages allows us to generate predictions on the potential damage from storms, for multiple forest types and stages of stand development, dependent on a stand's structure and composition. We can produce these predictions in a static way or during an extended period, if we simulate the development of a managed or unmanaged stand.

Damage caused by snow and wind manifests as uprooted and broken trees. Some studies have measured wind and snow damage by considering together the number of trees with broken branches, broken trunks and uprooted trees (Schmidt et al., 2010; Valinger and Fridman, 1999), others have differentiated into two damage types: broken and uprooted trees (Päätalo, 2000; Päätalo et al., 1999). The type of damage, broken or uprooted trees, has also been used to differentiate the cause of the damage (snow or wind) (Valinger and Pettersson, 1996).

The aim of this research is to develop predictive models of forests vulnerability against snow and wind damage that support forest management decisions in Norway and understand better the variables effect on the stand vulnerability. We consider snow and wind damage together due to the specific climatic conditions in the Nordic areas that make the cause of tree damage the combination of both agents (Valinger and Fridman, 1999), but we split the type of damage between broken or uprooted trees. The data we use rely on a large pool of empirical observations based on Norwegian national forest inventories and the models include variables whose value can be modified through forest management.

2. Material and methods

2.1. Data

The data used originated from the Norwegian National Forest Inventory (NFI) collected during the 7th, 8th, 9th and 10th measurements, corresponding to the period 1995–2014 (Fig. 1). The Norwegian NFI is a systematic inventory with permanent circular plots of 250 m^2 in a 3×3 km grid. Only complete plots were included; those divided by a stand boundary were excluded from the analysis. Permanent plots were located on forest land all over the country, except for the most northern county Finnmark, that was excluded from the analysis due to having a different grid and records period. Plots were categorized by their dominant species, based on the percentage of basal area per species present in each plot: spruce (>70% was spruce), pine (>70% was pine), birch (>70% was birch) or mixed (all other combinations).

Following the inventory protocols (Skoglandskap, 2007), the occurrence of natural disturbances was evaluated at stand level (1000 m^2 around the permanent plot center); plots with any record of snow or wind damage in that area were considered to have presence of damage. In this study, we merged trees damaged by snow and wind and only those plots with presence of snow or wind damage occurrence were included in the analysis. Damage by snow and wind was estimated at tree level inside the plot. In each plot, damage was calculated by dividing the number of damaged trees by the number of trees that were alive and undamaged in the previous measurement of the same plot minus the trees that were considered out. Trees considered out were those trees that had disappeared, moved outside the plot area or were removed for other reason than the impact of snow or wind (e.g. harvested). All trees presenting damage were grouped in three categories: *damaged trees*, *broken trees* and *uprooted trees*. *Damaged trees* included all the trees damaged or dead (either standing or downed); *broken trees* only considered trees that were standing but had a part broken off (dead or alive) and *uprooted trees* included those trees that were downed and lying in the ground (dead or alive). Trees that were damaged in the previous measurement were not considered in following measurements, neither as undamaged nor as damaged trees. Salvaged trees forced by the impact of snow or wind (e.g. blowdown trees) were also included as damaged trees in those cases where the reason for removing a tree was stated as snow bent tree, uprooted tree or tree with mechanical damage.

A portfolio of potential predictors was compiled to explain the damage (Table 1). The predictors were chosen among stand and site characteristics at plot level. Statistics of those variables are presented in Table 2. Most of the variables were directly obtained from the NFI or as a result of calculations based on the available NFI data combined with other sources. However, the available sources did not include measurements of the snow or wind intensity. To fill this gap, different proxies for snow and wind intensity were assessed (Table 1) adapting the approached taken in Hanewinkel et al. (2014) and Martín-Alcón et al. (2010), three different proxies for snow and wind intensity were estimated: the first one was the mean damage of the neighboring plots within a 5000 m distance of each plot (excluding their own value), and the second and third were based on kernel analysis. In these cases, the kernel values were calculated following Díaz-Yáñez et al. (2016) and the methods were based on Seaman and Powell (1996) and Worton (1989). The intensity levels were defined calculating the marked kernels (damage per unit area) or calculating the kernel probability (damaged points per unit area) at 4500, 6500 and 10,000 m.

2.2. Statistical methods

Damage models were prepared for each of the defined forest types (spruce, pine, birch and mixed forest) and for each of the three types of damaged trees: damaged, broken and uprooted. The predicted variable was the probability of a tree to be damaged (referred to as damage). The criteria to include the predictors in the models were: the resulting model had to be parsimonious, with good predictive power, all predictors had to be significant at the 0.05 level and the residuals had to indicate a non-biased model. The same variable portfolio (Table 1) was tested in all models, in order to allow comparisons among them. In all cases, alternative