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Integrating the risk of natural disturbances into forest management in Norway

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Academic dissertation

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ABSTRACT

Natural disturbances can rapidly change the structure and species composition of forests. Their effects can also compromise the provision of services and products from forest ecosystems. Therefore, it is very relevant that the risk of natural disturbances is considered when planning forest management prescriptions. This study presents a general framework for integrating risk into long-term forest management, via two main steps: 1) risk assessment (damage characterisation and modelling); and 2) risk management (simulation and optimisation). This research characterises the primary natural disturbances in Norway, and presents occurrence and damage models for the most relevant of these. The results show that the main natural disturbances in Norway are snow, wind and browsing from ungulates. The models identify which stand and site variables are more influential when predicting a forest's vulnerability to damage. The browsing occurrence models show that the most relevant variables to explain stand vulnerability are stand age, size and density. The model predicting snow and wind damage occurrence highlights the importance of the stand density, structure, mean diameter and height, but also site-related variables, such as latitude or altitude. The models predicting the damage rate for snow and wind damage, use covariates, such as stand basal area, height, diameter and slenderness. Snow and wind damage models are used in a stand dynamic simulation to optimise management prescriptions for considering risk. The optimal management schedules for a spruce dominated stand leave lower volumes towards the end of the rotation and shorten the rotation length. This thesis provides relevant information that can be used by managers in considering the risk of natural disturbances in forest management and planning.

Keywords: Hazards, modelling, simulation, browsing, wind, snow.

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Olalla Díaz-Yáñez

LIST OF ORIGINAL ARTICLES

This thesis is based on the following three articles and two manuscripts, which are referred to in the text by the Roman numerals **I**–**V.** Articles **I, II** and **IV** are reproduced with the kind permission of the publishers. Manuscripts **III** and **V** are the author's versions of the submitted manuscripts.

I **Díaz-Yáñez**, **O**. Mola-Yudego, B., Eriksson R., González-Olabarria J.R. (2016). Assessment of the Main Natural Disturbances on Norwegian Forest Based on 20 Years of National Inventory. PLoS ONE 11(8): pp.e0161361–16.
https://doi.org/10.1371/journal.pone.0161361

II **Díaz-Yáñez**, **O**., Mola-Yudego, B. González-Olabarria, J.R. (2017). What variables make a forest stand vulnerable to browsing damage occurrence? Silva Fennica 51(2): 1–11.
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III **Díaz-Yáñez**, **O**., Mola-Yudego, B., González-Olabarria, J.R. (2018). Modelling and mapping occurrence of wind and snow forest damage. Manuscript.

IV **Díaz-Yáñez**, **O**., Mola-Yudego, B., González-Olabarria, J.R., Pukkala, T. (2017). How does forest composition and structure affect the stability against wind and snow? Forest Ecology and Management 401: 215–222.
https://doi.org/10.1016/j.foreco.2017.06.054

V **Díaz-Yáñez**, **O**., Arias-Rodil, M., Mola-Yudego, B., González-Olabarria, J.R., Pukkala, T. (2018). Effects of wind and snow damage on the optimal management of Norwegian spruce forests. Manuscript.

Author's contribution

The author is responsible for the compilation of this thesis. For all the articles, the author was responsible for conceptualisation, formal analyses, visualisations and drafting of the articles jointly with the co-authors. Programming for the data analysis, models, simulator and optimisation was mainly performed by the author.

TABLE OF CONTENTS

ABBREVIATIONS AND DEFINITIONS

Abbreviations

NFI	National Forest Inventory
LEV	Land Expectation Value

Definitions

model	Mathematical description of a real phenomenon described by a hypothesised relationship between variables.
sustainability	Use of the forest ecosystem and resources to meet current demands without compromising future needs.
forest ecosystem service	Benefits for humans provided by forest ecosystems.
tradeoffs	The provision of one ecosystem service is changed by the increased or decreased use of another service.
risk	The probability that an adverse event will occur (e.g., damage by natural disturbance).
risk management	The process of taking decisions considering risk and implementing actions that reduce (or not) the probability of occurrence and damage.

INTRODUCTION

Forests and natural disturbances

Historically, natural disturbances have played a fundamental role in forestry, although their consideration in forest planning and management has been limited until recent years. In the past, most of the research efforts in forest management have been oriented to *classic* silviculture, where natural disturbances were considered external to the system, almost to the extent of being *unpredictable* or *unavoidable* – *catastrophes* that did not have to occur according to plan. This consideration, however, has changed, and today's view is that natural disturbances are an essential part of the forest ecosystem dynamics, are predictable to a certain extent, strongly affect the provision of ecosystem services, and therefore have to be included in forest management approaches. Despite some commonly-held views, their effects are not necessarily only negative; whereas the effects of disturbances put certain forest ecosystem services at risk, others benefit from them (Thom and Seidl, 2015). For example, a decrease in live biomass due to a disturbance can compromise the sustainable provision of timber or the carbon balance, but an increase in dead wood will generally benefit biodiversity (Zubizarreta-Gerendiain et al. 2017).

Boreal forests are exposed to a range of natural hazards, caused by different disturbance agents, which can be classified as abiotic (e.g., storms, drought, landslides, avalanches, flooding and wildfires) or biotic (e.g., insects, ungulates and pathogens). Whichever the case, disturbance regimes and their effects on forests are influenced by several aspects, such as climate, changes in the forest–disturbance interaction, introduction of invasive species, changes in forest species, shifts in land use, or lack of forest management, among others (O'Hara and Ramage, 2013).

Wind and snow are among of the most significant disturbances agents in boreal forests. In fact, in Northern Europe, forests have been recurrently affected by storms (e.g., *Vivian* in 1990, *Gudrun* in 2005 and *Kyrill* in 2007), and, whilst today it is unclear how these disturbance regimes will change (Feser et al. 2015; Mölter et al. 2016), it can be expected that they will play an even a more significant role in the near future. Even assuming no rise in temperatures, frequency or intensity of storms, damage is expected to increase due to forests becoming more vulnerable (Schelhaas et al. 2003) due to the accumulation of growing stocks and older trees. Typical damage caused by snow and wind include the uprooting and breakage of trees. Such damage can rapidly change the structure, products and services provided by forests (Valinger and Fridman, 2011). In Norway, for instance, the wood stock in forests has increased continuously, as the harvested volumes have been below the annual increment – between 1990 and 2014, the growing stock changed from 579 to 929 million m^3.

The increased presence of uprooted and broken trees can also lead to damage in the remaining trees by other disturbances, such as insect attacks (Bakke, 1989; Schroeder and Eidmann, 1993). In this way, Norwegian forests have suffered extensive damage from bark beetle (*Ips typographus*) outbreaks. The most severe bark beetle outbreaks happened between 1971 and 1981, damaging over 5 million m^3 of timber in an area of 140,000 km^2 (Bakke, 1989). The bark beetle outbreaks were caused by a combination of factors, including a drought and an extensive windthrow, caused by a storm in 1969 that damaged over 2.4 million m^3 (Gardiner et al. 2010). Another important disturbance damaging Norwegian forests is browsing by ungulates, such as moose (*Alces alces*). Whereas moose are very much appreciated for their hunting value, increasing populations represent a threat to forests, and compromise their future (Edenius et al. 2002a). Browsing damage results in economic losses due to the mortality of young stands, reduced growth, changes in species compositions and/or lower timber quality (Persson et al. 2000; Nevalainen et al. 2016).

Risk management and planning

Risk management is the process of identifying, assessing and selecting management options for forested areas that consider the risk of potential losses. Considering risk in forest management and planning has two clear advantages. On the one hand, it can provide more realistic estimations of future ecosystem services (Meilby et al. 2001; González-Olabarria et al. 2008; Zubizarreta-Gerendiain et al. 2017). On the other hand, considering damage allows the inclusion of management prescriptions that can enhance services and products, while reducing the negative impacts from disturbances (Heinonen et al. 2009).

Forest management can have an impact on how natural disturbances affect forests (Päätalo, 2000; Jactel et al. 2009; Pukkala et al. 2016; Subramanian et al. 2016). Including risk in forest management modifies the optimal prescriptions, for example, by changing the rotation age, the thinning intensities or the amount of biomass left in the stand (Meilby et al. 2001; González-Olabarria et al. 2008; Zubizarreta-Gerendiain et al. 2017). Forest resistance to damage is improved by changing landscape structures (Zeng et al. 2007; Zubizarreta-Gerendiain et al. 2017), fostering stand-level resistance (Agee and Skinner, 2005; Jactel et al. 2009; Hanewinkel et al. 2014), or changing species compositions (Roessiger et al. 2011; Jactel et al. 2017). Forest management can also embrace the effects of disturbances on forests (Seidl et al. 2018), or even emulate them (Bergeron et al. 2001) as a means of providing a close to nature management and enhancing certain positive effects of disturbances to ecosystem services (Thom and Seidl, 2015). In general, there is an increasing interest in management that promotes ecosystems that are more diverse and resilient to perturbations (Fahey et al. 2018).

Optimisation methods have proved to be a useful tool for determining the best management alternatives across a range of potential options. There are different approaches to finding optimal management prescriptions that considered the risk from natural disturbances. Previous studies have used anticipatory or adaptive approaches. Adaptive approaches produce management rules that consider economic and environmental changes and therefore improve the decision-making for risky environments (González-Olabarria et al. 2017). Damage has been included with a deterministic (Zeng et al. 2007) and stochastic approaches (González-Olabarria et al. 2008). The consideration of damage as a stochastic variable provides a more realistic estimation of the effects of the disturbance, as it is possible to obtain both the mean value of the disturbance impact and its associated variation (McCarthy and Burgman, 1995). Damage probability has also been considered as an exogenous or endogenous variable to the stand characteristics; in the past, studies have determined optimal stand management prescriptions, by considering the risk as endogenous (Thorsen and Helles, 1998). As more relevant information has become available, it has been easier to calculate the damage probability with an endogenous approach, through damage models that use stand characteristics as predictive variables (Seidl et al. 2011a). In any case, both endogenous and exogenous damage considerations have required a characterisation of the disturbance regimes, an understanding of their effects and occurrence, and a link between their impacts and forest variables.

Risk assessment

The essential aspects of risk assessment are the characterisation of the relevant natural disturbances on forests, and accounting, through modelling, of the endogenous and exogenous factors that influence their occurrence. Long-term analysis of disturbances enhances the understanding of their importance, severity and spatial distributions. Models help to cope with the intrinsic natural disturbance complexity. The modelling of natural disturbance damage has been done at different scales, and by using different statistical approaches. Some damage models have used tree-, plot- or stand-level variables (González et al. 2007; Selkimäki et al. 2012; Nevalainen et al. 2015; Kamimura et al. 2016), while others have approached the modelling from a landscape perspective (Blennow and Sallnäs, 2004; Heinonen et al. 2009; Zeng et al. 2010).

Damage in forests are discrete events that have been modelled using different statistical approaches, such as generalized linear models (Albrecht et al. 2013; Hanewinkel et al. 2014), or logistic- (Fridman and Valinger, 1998; González et al. 2006) or machine-learning-based (Selkimäki et al. 2012; Albrecht et al. 2013) models.

Natural disturbances modelling is challenging because the disturbance agents are difficult to forecast. In many cases, there is not enough available information to predict the presence and intensity of the damaging agents over long periods and across large areas, such as wind intensity, snow load or ungulate abundance. We can improve our understanding of what makes a forest more vulnerable to suffering damage, however, through studying the influence of forest characteristics and their thresholds. Nonetheless, the modelling process is still challenging, as many of the predisposing factors to damage are interconnected. In order to deal with disturbance complexity, we need extensive data to cover the disturbances variability, especially when we are interested in analysing large areas and multiple disturbance agents.

National Forest Inventories (NFIs) provide extensive empirical data across time and space from which is possible to evaluate forest changes and the effects of natural disturbances on forests (Allen, 2001; Wulff et al. 2013). Using permanent plots, we can quantify changes by evaluating a forest's status before and after the damage, for example. NFI data have several advantages: they are able to record different levels of damage without disregarding lower damage levels; they provide information on a large spatial scale and they allow observation of differences across multi-species and multi-aged stands. Moreover, NFIs have proved to be useful in measuring several natural disturbances, and in to predicting their effects on forests (Dobbertin, 2002; González et al. 2006; Vospernik, 2006; Selkimäki and González-Olabarria, 2016).

Through disturbance modelling, we can identify which variables and interactions are the main drivers of forest damage as well as their influence on forest ecosystem services and products. The main variables determining forest vulnerability to ungulates are age, density, species composition and stand size. Young stands are more vulnerable, as they have more food sources at a suitable height (Jalkanen, 2001). Lower stand densities increase the vulnerability because they facilitate the penetration of the ungulate to the stand (Jactel et al. 2009). The stand species composition affects browsers behaviour and browsing damage is different between tree species. The more palatable species include birch (*Betula* spp.), rowan (*Sorbus* spp.), willow (*Salix* spp.)

and aspen (*Populus* spp.); however, ungulates' species preferences change with time, for example, conifers are preferred over broadleaves during winter. The species diversity of the stand also influences the stand vulnerability, with increased risk in more diverse stands (Vehviläinen and Koricheva, 2006). The stand size is also an important variable, as browsing damage is often greater in larger stands, but is also linked to the specific stand structure, location and species palatability (Pietrzykowski et al. 2003).

Previous models have shown that predisposing factors for snow and wind damage are related to exposure (topographic conditions, including altitude, latitude and other proxies), site and soil type (Mitchell et al. 2001; Albrecht et al. 2013; Hanewinkel et al. 2014; Pasztor et al. 2014), and to variables that describe the forest, such as tree height, diameter, slenderness, basal area, density, structure and dominant species (Martín-Alcón et al. 2010; Valinger and Fridman, 2011; Hanewinkel et al. 2014; Pukkala et al. 2016). Other aspects that make forest stands more vulnerable to damage are: the lack or delay of management prescriptions (Päätalo, 2000); the increase of growing stock, forest aging (Peltola et al. 2010) and climate warming (Nykänen et al. 1997; Peltola et al. 1999a).

Framework

Under the prospects of increasingly disturbed forests (Turner, 2010; Seidl et al. 2017), a better understanding is needed of the relationship between disturbances and forest changes, and the finding of sustainable management options to adapt to those changes; however, many important aspects have not been completely understood yet for Norwegian forests, such as: what are the most important natural disturbances in recent years?; how do changes in stand and site characteristics affect the forest vulnerability?; can we use forest management to make forests less vulnerable or more resilient?; and how management can sustain ecosystem services under the risk of disturbances?

In order to ultimately develop recommendations for governance and the decision-making process, we need to integrate several aspects of risk (Fig. 1). First, a characterisation of the natural disturbances that are damaging forests is needed. Second, an identification of the relevant stand and site variables that make a forest more vulnerable to suffering damage and to having higher damage rates, is required. Third, it is necessary to evaluate how management can reduce the forest vulnerability and to analyse the tradeoff between benefits and required investments.

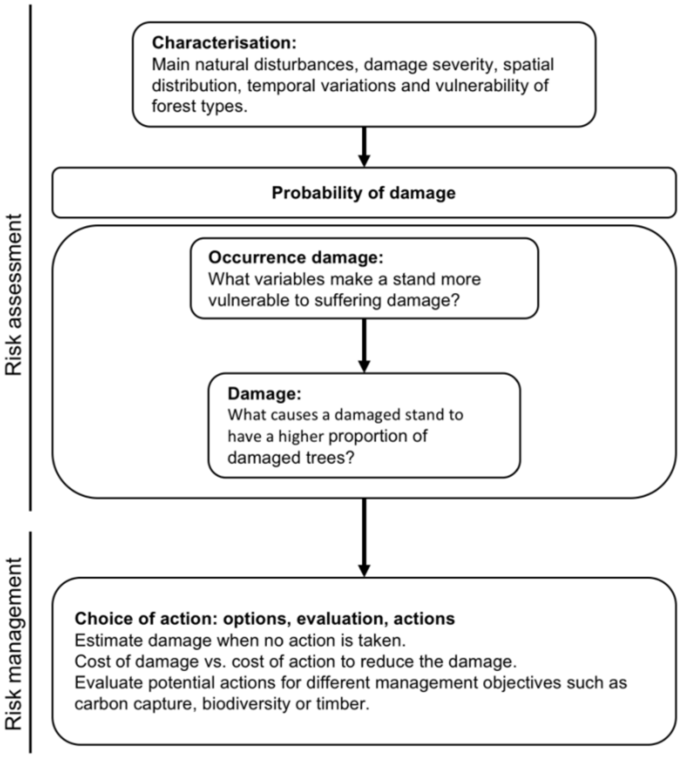

Figure 1. Framework used for including the risk of natural disturbances into forest management

Aims of this thesis

The aim of this thesis is to develop a framework that incorporates natural disturbance risks into forest management and planning in Norway. To achieve this aim, two main steps were taken – 1) risk assessment and 2) risk management. Several damage models were developed to provide the tools for estimating economic and ecological changes caused by disturbance agents at a country level.

The specific objectives were to:

1. characterise the importance, types and temporal evolution of natural disturbances at a country and regional levels (**I**);
2. develop a predictive model for damage occurrence caused by ungulate browsing (**II**);
3. develop a predictive model for the occurrence of wind and snow damage (**III**);
4. develop a damage model to predict the proportion of damaged trees in a snow- and wind-damaged plot (**IV**); and
5. find the optimal management schedules under the risk of damage (**V**).

The hypotheses were:

1. Stand and site variables have an effect on the probability of browsing, snow and wind damage.
2. The proportion of trees damaged by snow and wind is affected by stand and site characteristics.
3. Optimal management changes when the risk of wind and snow is considered.

MATERIAL AND METHODS

Material

Study area

The study area included the whole of Norway, except for the most northernmost county, Finmark (Fig. 2), where the forest inventory had a different plot grid. Forests cover the 30% of the country. About 79% of the forested area is privately owned, with about 9% owned by the state and the municipalities, 6% by the forest industry and companies and 6% by other owners. The main commercial tree species are: Norway spruce (*Picea abies* L. Karst), Scots pine (*Pinus sylvestris* L.) and birch (*Betula* spp.). In boreal forests, the succession dynamics usually follow a rapid colonisation by broadleaves (*Betula* spp. and *Populus* spp.) after a disturbance, but the prevailing industry-oriented forest management has promoted pure conifer forests due to their higher economic value and, on average, higher wood production.

The Norwegian NFI for the period 2011–2014 estimated that the productive forest area was about 7 million hectares, of which up to 30% can be regarded as mountain forests. Productive forest areas are defined in the NFI protocols (Landsskogtakseringens, 2008) as those forest areas that have an expected yield of over 1 m^3 ha^{-1} year^{-1} over bark.

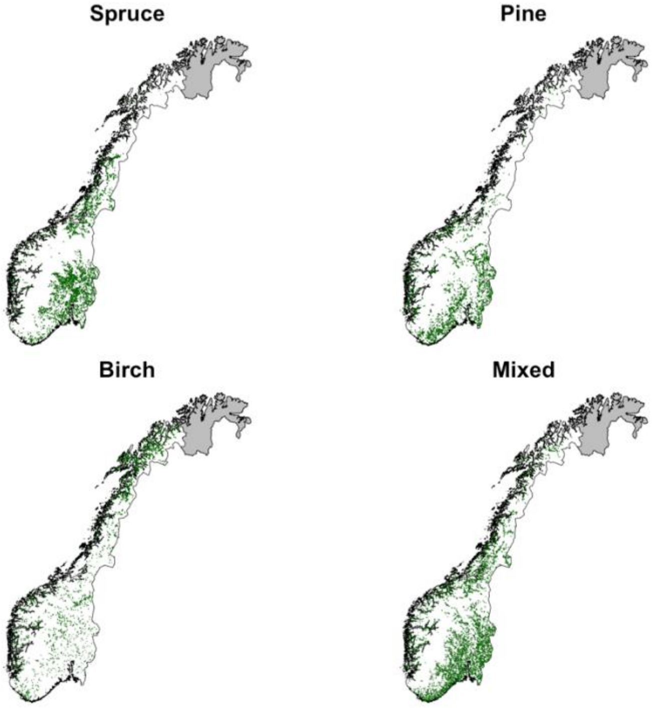

Figure 2. Study area (white) and plots distribution by species (green), during the period 2010–14

Data

The Norwegian NFI was established in 1919 with strip sampling. The implementation of circular permanent plots started in 1986, and the continuous forest inventory was introduced between 1994 and 1999. All of the permanent plots are re-measured every five years, covering 20% of the plots across the whole country each year (Tomppo et al. 2010). The inventory design is a 3 × 3 km grid, except for the northernmost county, Finmark, where the inventory started to use a different grid in 2011. There are more intensive plot distributions across the country, in protected areas, for instance. In this study, we used the 3 × 3 km grid of permanent plots collected from 1995 to 2014, excluding Finmark. The area of each plot is 250 m^2 and, in each plot, all the trees above 5 cm of breast height diameter were measured. In this thesis' studies, only the plots that were located on productive forests were considered.

Damage variables, such as the presence or absence of damage, are measured around the centre of the plot (1000 m^2) according to the inventory protocols (Landsskogtakseringens, 2008). Damage occurrence was recorded if the damage was evaluated to have had an effect on the future economic development of the stand, representing a significant reduction in the volume increment or regeneration, and the overall damage rate was above 5%. The damage rate was defined using different criteria according to the damaging agent. In a plot damaged by ungulate browsing, the overall damage rate was defined by the percentage of trees that were injured; in a wind-damaged plot, it was defined by the volumetric proportion of blown-down trees; and in a plot damaged by snow, by the number of trees that had stem breakage. We combined wind and snow damage during the modelling for two reasons: 1) the wind and snow records used different approaches to measure the injury rate (uprooted and broken trees), and this differentiation could have led to the overlooking of the real reason behind the damage; and 2) boreal forests damage is typically caused by a combination of both snow and wind (Fridman and Valinger, 1998; Valinger and Fridman, 1999; Päätalo, 2000).

Across all of the studies, the plots were divided according to their dominant species into four forest types: spruce (spruce > 70%), pine (pine > 70%), birch (birch > 70%) and mixed forests (no single species accounted for more than 70% of the basal area). According to the NFI instructions, the plots were also categorised by their development class into young, intermediate and mature plots.

Methods

The methods used were selected to move from the data and theory of damage to choosing an optimised management prescription that considered the risk of damage. Fig. 3 shows the step-by-step schema that starts with the *data* and *theory* that was used to *model* damage, as a simplified description of the damage phenomena. The damage models and other stand dynamics models were then used to describe the evolution and dynamics of the stand in a *simulator*, according to changes in the values and objectives of the treatment variables. The simulator is a step-wise algorithm, used to search through the different alternatives and provide a value for the selected objective (e.g. land expectation value, LEV). These results were then optimised with an optimisation algorithm (*solver*) to find what combination of assigned values provide the best solution – for example, the highest revenues.

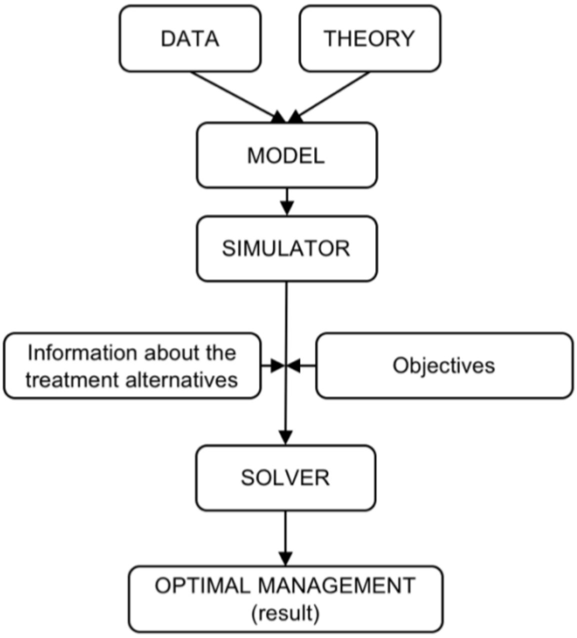

Figure 3. Scheme of steps followed, from data to optimisation

Polynomial models were developed for each disturbance to analyse their temporal trends. The identification of areas with higher damage was analysed using a geo-statistical method based on adaptive kernels. Finally, the differences in damage frequencies across forest types, and the development classes, were studied using a contingency table and a chi-squared test. The chi-squared test was calculated to evaluate significant differences in damage frequencies among forest types and development classes.

Damage occurrence models were created for browsing, snow and wind damage. A damage occurrence model is a discrete-event model that predicts whether the disturbance occurred or not. This binary model predicts the probability of damage occurrence, given certain levels of the causal variables. In order to consider a higher number of predictive variables, we used two machine-learning approaches – classification and regression trees (CART) for the model predicting browsing damage occurrence, and boosted regression trees (BRT) for the models predicting snow and wind damage occurrence.

Machine-learning methods have several advantages, compared to more traditional modelling approaches: they can handle different types of predictor variables and deal with missing data, and they can describe complex non-linear relations, handle interactions between the predictors, and summarise the model in a meaningful and understandable way. The two machine-learning approaches used, were based on classification and regression trees. These models relate the response variable and predictors by recursive binary splitting. The main difference between the two approaches is that BRT combine multiple regression trees to provide an improved predictive performance; these additional trees are created to recursively fit the residuals of the model, and therefore they are focusing on the hardest observations to predict in a stage-wise process. Both approaches provide an analysis of the variable importance calculated based on the goodness of the splits in CART (Breiman et al. 1984), and considering the number of times the variable was used for splitting and the improvement it provided to the following model in BRT (Elith et al. 2008).

The damage models predicted the proportion of uprooted or broken trees in a damaged plot. The predicted variable was a count of damaged trees and undamaged trees. Count data models are an extension of binary models, in which the measure of the observation is a count of occurrence (damaged trees) within a plot.

The response variable in the damage models was the number of trees that were broken or uprooted as a proportion of the number of trees that were alive in the previous measurement. The best distribution for this type of data is the binomial distribution. Binomial distribution is used for discrete proportions that arise from the number of 'successes' of a finite number of Bernoulli trials, and therefore was suited to our data. An important aspect is that we assumed that the trees were independent, and that each tree had the same probability of being damaged. The damage models were defined as follows:

$$Y_{ij}\text{: total number of damaged trees in } n_{ij} \text{ trees}$$
$$Y_{ij} \sim \text{binomial } (n_{ij}, \pi_{ij})$$

where, n_{ij} is the number of trees in the plot measurement i at measurement time j, and π_{ij} is the probability of a tree being damaged in plot i at time measurement j. We used the link function (logit link), modelling the log odds of the probability of damage as a function of the k explanatory (plot-level) variables, $\boldsymbol{X}_{ij} = (X_{ij,1}, X_{ij,2}, \dots X_{ij,K})$.

The link function is:

$$g(\pi) = logit(\pi) = log\left(\frac{\pi}{1-\pi}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k \qquad \text{(Eq. 1)}$$

The simulation was developed using a step-wise algorithm that contained stand dynamic models and the snow and wind damage models (**III**, **IV**). The simulator followed these steps: 1) predict growth (Bollandsås et al. 2008); 2) calculate stand variables – basal area, dominant species, basal area of the trees larger than the tree of interest, percentage of basal area in the stand of the subject species, tree height (Sharma and Breidenbach, 2014), tree volume (Braastad, 1966; 1967; Vestjordet, 1967); 3) estimate natural competition mortality; 4) estimate damage-induced mortality (**III**, **IV**); and 5) if it was a harvesting year: apply harvesting and calculate revenues (Blingsmo and Veidahl, 1992). During the simulation, we performed a sensitivity analysis for uncertain variables, such as the discount rate, taking 1, 2 and 3% values.

Damage was considered from both a deterministic and a stochastic approach. In both approaches, we calculated the damage occurrence, $\widehat{Poc}$, by using the models presented in **III** transformed to a 5-year probability, and the predicted damage probabilities of any tree in the stand being uprooted and broken ($\widehat{Pup}$ and $\widehat{Pbr}$) by using the models presented in **IV**.

When using the deterministic approach to calculate damage, we estimated the probability of damage for each 5 year in the rotation. The probability of damage occurrence was multiplied by the predicted probability of any tree in the stand being uprooted and broken. The resulting value was multiplied by the number of remaining trees in the stand to obtain the number of damaged trees.

When using the stochastic approach, randomness was considered: 1) only at the plot level; and 2) at the plot and tree levels. When the stochasticity was only considered at the plot level, we determined whether there was damage by comparing the predicted probability of damage occurrence, transformed to a 5-year probability, to a random number generated using a random realisation of a binomial distribution. The probability of damage occurrence, $P_{oc\,stoc}$, was then obtained for one trial and using, as the probability of success, the estimated probability of occurrence $\widehat{Poc}$:

$$P_{oc\,stoc} \sim B(1, \widehat{Poc})$$

If the $P_{oc\,stoc} = 1$, we calculated the damaged trees as in the deterministic approach but substituting $\widehat{Poc}$ by $P_{oc\,stoc}$. If the $P_{oc\,stoc} = 0$ then no trees were damaged in that stand and rotation year.

When using the stochastic approach, with stochasticity both at plot and tree level, we first determined whether there was damage occurrence or not. If there was a damage occurrence at plot level, then we estimated whether each tree of each representative tree, *n*, was actually damaged or not (first for uprooted: $P_{n\,i\,up\,stoc}$) by using a random realisation of a binomial distribution where the probability of damage was obtained for one trial, and using, as the probability of success, the estimated probability of uprooted damage, $\widehat{Pup}$, multiplied by the observed damage distribution by diameter class, $P_{n\,up\,DC}$:

$$P_{n\,i\,up\,stoc} \sim B(1, \widehat{Pup} * P_{n\,up\,DC})$$

The sum of all $P_{n\,i\,up\,stoc} = 1$ is the total number of uprooted damaged trees for each representative tree, *n*. Then, the same process was performed to estimate whether the remaining alive representative trees were broken or not by calculating $P_{n\,i\,br\,stoc}$:

$$P_{n\,i\,br\,stoc} \sim B(1, \widehat{Pbr} * P_{n\,br\,DC})$$

The optimisation was performed using the differential evolution method as described in Pukkala (2009) and Arias-Rodil et al. (2015), having the LEV as the objective function. The initial stand in the simulation was a representative young stand dominated by spruce trees.

RESULTS

Assessment of the main natural disturbances

Snow, wind and browsing by ungulates were the agents causing most of the damage observations and impact on Norwegian forests across the studied period, but had different frequencies across time (Fig. 4) and space. Browsing damage frequency remained relatively constant, with different peaks during the studied interval. Areas with higher browsing damage frequencies were around the most productive forests in the country, located in the south-west. On the other hand, wind and snow damage occurrence declined over time, but suffered an increase in 2012–2014. Wind and snow damage were mainly concentrated in mountainous areas, with no major spatial differences between north and south. According to the NFI-protocols measurements, the mean browsing damage rate was 27%, while for snow and wind it was 11%.

In relation to forest types, birch forest was the most affected, followed by mixed and spruce forests. Birch and mixed forests were mainly damaged by browsing, and wind and snow, while spruce forests were more affected by wind and snow. According to the contingency tables and chi-squared tests, the observed damage frequency was higher than expected for snow damage to mature and intermediate birch forests. It was also higher than expected for wind damage on mature spruce forests, and browsing damage frequencies for all young forests, except on spruce-dominated forests.

Browsing damage

The five most important variables that predict browsing damage were: age, development class, basal area, stand size and density (proving hypothesis 1). The models indicated that young stands with low tree densities had higher probabilities of damage occurrence. Plots with higher species diversity were also more prone to suffering damage. On the other hand, the stand size did not have a clear predictive effect across all the models. Other variables, such as dominant species and Shannon index, indicated that stands dominated by mixed species, pine or more diverse species,

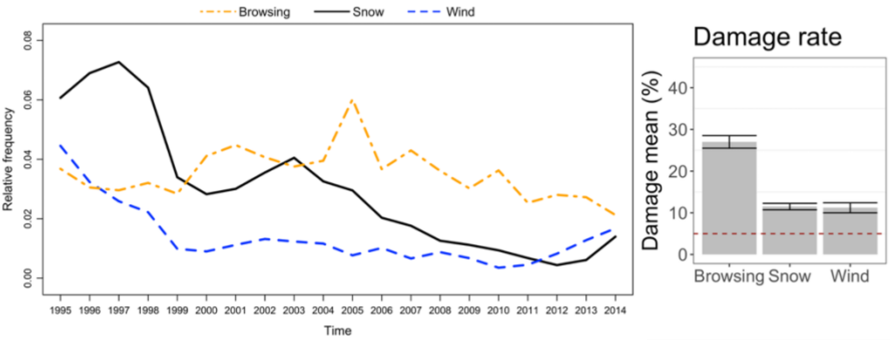

Figure 4. Characterisation of damage time-series, and rates of browsing, and snow and wind damages, as collected in the NFI data.

were more susceptible to damage. Moreover, increasing proportions of deciduous, birch or pine also increased the probability of browsing damage occurrence.

Snow and wind damage

Both site and forest stand variables were relevant for predicting snow and wind damage occurrence (proving hypothesis 1). The most important site-related variables were latitude, altitude and slope. The models indicated that plots located on steeper slopes, at more northerly latitudes and higher altitudes had higher probabilities of suffering snow and wind damage. The most important forest stand-related variables were tree density, mean diameter, dominant height and structure (Gini coefficient); however, the ratio between height and diameter, slenderness, did not play a relevant role in the damage occurrence predictions. Moreover, the relative importance of each of the variables changed across each of the forest-type models, and the variable dominant specie made a low contribution to the model for all the species together.

In the occurrence models, the pairwise interactions among the predictive variables were different for each forest type (Fig. 5). The strongest interactions on spruce-dominated stands were between density, dominant height and site index, and between Gini coefficient and altitude, but their interaction values were lower compared to the other forest types. In the selected model for birch-dominated stands, the strongest interaction values were between the Gini coefficient and the stand mean diameter. Finally, in the selected model for mixed stands, the interactions with higher values were between latitude and the Shannon index, and between latitude and altitude, although the combined latitude and altitude effect did not necessarily increase the damage probability.

Forest characteristics were also relevant when predicting the proportion of damaged trees, such as stand basal area, mean diameter, height and slenderness (partly

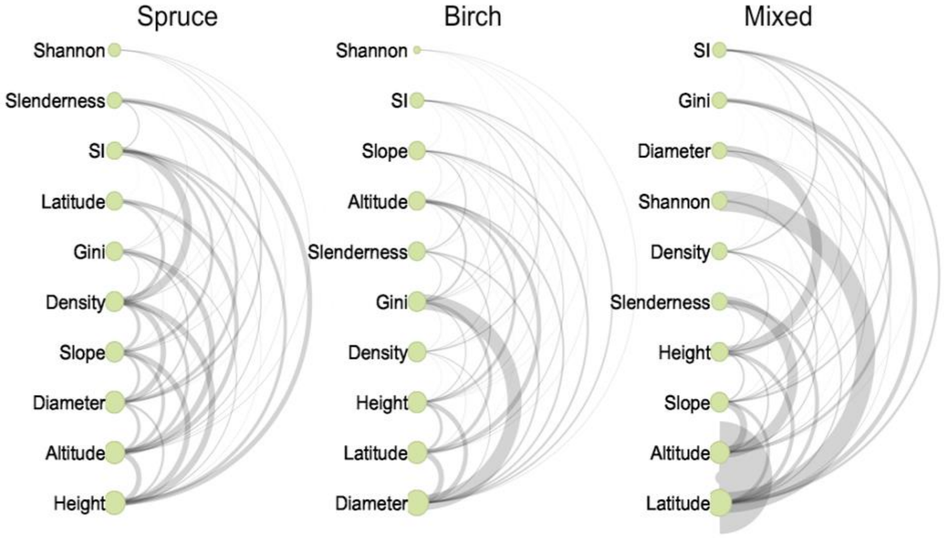

Figure 5. Interactions and importance of variables for snow and wind damage occurrence models by forest type. Wider lines represent a stronger interaction among variables. The size of the node corresponds with the variable importance in the model (larger nodes indicating more importance).

proving hypothesis 2). After accounting for the effects of all the variables included in the model, increasing basal area resulted in less vulnerable stands. Increasing mean diameter increased damage for all forest types, except for mixed stands. Increasing height increased the probability of broken trees; however, taller trees were less susceptible to being uprooted. On spruce-dominated stands, increasing slenderness indicated that trees were more prone to breakage but, it indicated the opposite in the model predicting the proportion of uprooted trees, where increasing slenderness lowered the probability of damage.

Simulation and optimisation

The consideration of snow and wind damage did have an effect on the optimal management of a spruce-dominated stand (proving hypothesis 3) (Fig. 6). Optimal management without considering the risk of damaged produced higher LEVs than when the risk was considered. Stock volume was lower across time, when risk was considered in the management, particularly towards the end of the rotation. Considering risk also shortened the rotation, or maintained equal for most of the optimisation cases, and increasing the discount rate meant a decrease in the stand basal area and shorter rotation lengths.

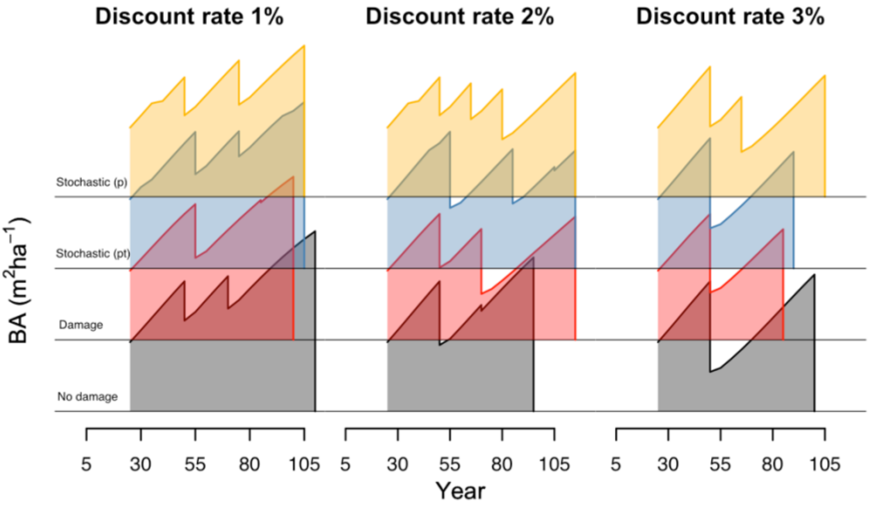

Figure 6. Optimal management prescriptions and basal area dynamics across time for a spruce-dominated stand at 1, 2 and 3% discount rates, with an establishment cost of 1500€ ha^{-1} and considering the risk of damage using four different approaches: 1) stochastic at plot-level (*Stochastic (p));* 2) stochastic at plot- and tree-level (*Stochastic (pt)*); 3) deterministic simulation of damage (*Damage*); and 4) without considering the risk of snow and wind damage (*No damage*).

DISCUSSION

The studies included in this thesis analysed the different aspects required to include natural disturbances risk into forest management in Norway. They focused on two abiotic damage (snow and wind) and one biotic damage (browsing by ungulates). These damaging agents were selected due to their importance in Norway over the studied period (**I**). The developed framework followed two mains steps: 1) a risk assessment (natural disturbances characterisation and modelling); and 2) a risk management (simulation and optimisation). Although both biotic and abiotic damage are highly dependent on the exposure to the damaging agents (size of the ungulates population, snow load or wind intensity), understanding the reasons behind a more vulnerable stand enables us to incorporate the risk of damage into forest management and planning (**II, III, IV, V**).

The studies covered large areas and worked with a comprehensive database that allowed for a generalisation of the findings over larger areas, dealing with a major problem of most of previous studies, that have only worked on regionally very limited spatial levels (Hanewinkel et al. 2011). The NFI data used, contained observations from 20 years and at country level. Data from NFIs also has its limitations, for example it can only provide information within the boundaries of available forest management which might limit the understanding of alternative management methods. Despite their limitations, the NFIs have proved to be a relievable source of data for understanding disturbances and creating predictive models (Dobbertin, 2002; Vospernik, 2006; Selkimäki and González-Olabarria, 2016).

An understanding of what makes one specific stand more vulnerable than another is complex, as many of the relevant variables are connected and interrelated. In order to model natural disturbance dynamics, we need to consider multiple variables, at different levels, and their interactions. Although models are a simplification of the reality, they do allow the quantitative study of the effects of complex events, such as disturbances (Seidl, 2017). The developed models have provided several advancements in the risk assessment of damage in Norwegian forests, and identified key factors of stand vulnerability to browsing, snow and wind damage.

Major advancements in developed damage models

The damage and occurrence models covered a knowledge gap, as these models had not been developed in Norway, and were scarce for boreal forests. The models used easily measurable variables that had already been collected from large databases, such as NFIs, as predictors. The damage models were based on extensive data, and they enhance the understanding of natural disturbances and forest vulnerability. They can also be used to consider damage in various scenarios, and investigate damage effects under changing conditions.

The major contributions of the occurrence and damage models are: 1) they establish the vulnerability of a stand to suffering damage occurrence, based on site and forest characteristics, and determine which of the variables has a higher impact on increasing the probability of damage from ungulate browsing (**II**), and snow and wind (**III**); and 2) snow and wind damage models predict the damage proportions using stand variables (**IV**).

The damage models from this study are a first attempt to create country-level models for boreal conditions. The predictions from the occurrence models can be used to provide a regional- or country-level information on which areas are more prone to suffer damage. Predictions that consider larger areas and the spatial heterogeneity contribute better to sustaining the future of ecosystem services and their tradeoffs (Turner et al. 2012; Seidl et al. 2018). On the one hand, disturbances are spatially diverse, and require a landscape-level consideration (Senf and Seidl, 2018), and on the other hand, management might not work in the same manner across the space, and therefore it would be less appropriate to apply spatially-uniform prescriptions to large spatial areas.

The occurrence models were developed using machine-learning approaches. This method allows the consideration of a high number of predictive variables, which is generally complex and not possible using more traditional approaches, such as logistic models, and so providing a better understanding of their relative significance and interaction levels. Machine-learning methods can also provide a superior predictive performance compared to other traditional methods (Elith et al. 2006; Leathwick et al. 2006; Elith et al. 2008). Previous studies that predicted snow and wind damage to forests have used a mechanistic approach (Gardiner et al. 2008), or an empirical approach (Valinger and Fridman, 2011, Albrecht et al. 2013), to the modelling. Although empirical approaches have the disadvantage of providing limited insights into the mechanistic processes, they are able to fully account for the dataset complexity, and identify the key factors that lead to snow and wind damage (Mitchell and Ruel, 2015).

Key factors of stand vulnerability to browsing damage

Browsing was one of the most relevant disturbances in Norwegian forests across the study period, both in terms of occurrence frequency and damage importance. The models predicting browsing damage occurrence showed that the most important variables for defining damage vulnerability were the stand age, development class, basal area, stand size and density (**II**). The stand age and development class indicated that young stands have higher probabilities of suffering damage, as they have more forage at a suitable height (Jalkanen, 2001). Stand density also had an important role in the damage probability. Lower tree densities increase the damage probability, as they facilitated the accessibility to the stand (Andren and Angelstam, 1993; Jactel et al. 2009).

Several studies have discussed about the importance of the stand size. On the one hand, small stands are more attractive to ungulates, as the distances between foraging and shelter areas are decreased (Edenius et al. 2002b). On the other hand, larger stands are more damaged because ungulates spend more time browsing (Nevalainen et al. 2016). In our study, stand size was also a key factor in defining browsing damage probability; however, it did not show a clear trend.

The dominant species and species diversity play an important role in determining stand vulnerability to browsing. Previous studies have also found that stands dominated by birch, mixed species and pine are more vulnerable than those dominated by spruce (Jalkanen, 2001; Edenius et al. 2002b). In relation to stand species diversity, our results showed that more diverse stands are more prone to suffer browsing damage and, according to other studies, to suffer higher damage impacts, as ungulates have a larger range of browsing options, and browse from both preferred and less preferred tree species (Milligan and Koricheva, 2013; Nevalainen et al. 2016).

The model defining browsing damage occurrence provides a relevant analysis of how site and forest stand variables affect stand vulnerability. The developed model could be used to see how much influence can be gained from forest management, and to what degree landscape patterns could be managed to enhance stand resistance, by, for example, considering the role of the stand size at the landscape level.

Key factors of stand vulnerability to wind and snow damage

The wind and snow damage models showed that both site and forest stand variables contain predisposition factors for damage (**III, IV**). Location and site variables were relevant when predicting damage occurrence (**III**). Variables such as latitude, altitude and slope had an important contribution in the models. Increasing latitude and altitude typically means an increase in exposure to snow and wind; in contrast, trees located at more northerly latitudes and higher altitudes might be more adapted to the exposure (Nicoll et al. 2008), and therefore, better able to resist higher levels of the damaging agents. Contrarily, other studies have found a negative relationship between altitude and damage (Albrecht et al. 2013). It is always challenging to analyse these site factors separately, since other relevant variables could have an influence, e.g. the proximity to an stand border with a different forest structures (Lanquaye-Opoku and Mitchell, 2005; Zubizarreta-Gerendiain et al. 2017).

The lack of inclusion of site characteristics in damage models (**IV**) contradicts previous findings (Jalkanen and Mattila, 2000; Scott and Mitchell, 2005), which is explained by the fact that, in this case, only damaged stands were considered, and they were already spatially defined (**I**).

The forest stand predisposition factors for damage occurrence were stand density, mean diameter, dominant height and structure (Gini coefficient); however, the relative importance of each of the variables and their interaction values changed for each individual forest type. Forest characteristics were also relevant when predicting the proportion of damaged trees, such as basal area, mean diameter, height and slenderness. Slenderness was an interesting variable, as it showed different predictive effects in the occurrence and damage models. In the model developed for a spruce-dominated forest, slenderness did not play a relevant role, although it agreed with the idea that increasing slenderness or tree height, increases the probability of damage, as discussed in other studies (Fridman and Valinger, 1998; Peltola et al. 1999b). On the other hand, in the models predicting the probability of a tree to being uprooted or broken, slenderness played an important role, showing that with increasing slenderness, the risk of uprooting decreases. This finding, contradicts previous results (Päätalo et al. 1999), but agrees with the idea that more slender trees are more prone to breakage than uprooting (Peltola et al. 1999b; Päätalo, 2000).

In addition, the contribution of the variable *dominant species* was very limited in the damage occurrence models for all the species together. Other predictive variables showed different behaviours in each of the forest type models. We assumed that the dominant species would represent the species-based differences (e.g., rooting of crown shape) (Albrecht et al. 2012); however, the low importance of this variable, and the different effects of other predictive variables, could indicate that detailed variables describing relevant tree species shape could also be included as predictor variables.

Forest management under the risk of wind and snow damage

The integration of risk assessment into forest management presents several challenges, but a lack of consideration of risk can lead to losses and undesired outcomes. The integration of risk management into forestry requires of methods that can quantify the stochasticity and dynamism inherent in natural disturbances and forest dynamics.

Several studies, on Norwegian conditions, have tried to find optimal management actions by considering ecosystem services, such as timber or carbon, as management objectives (Eid et al. 2002; Raymer et al. 2009; Buongiorno et al. 2012), but none of them included the risk of disturbances. We found that a lack of consideration of risk led to an overestimation of the revenues and a shortening of the rotations lengths (**V**), as reported by other studies (Zubizarreta-Gerendiain et al. 2017).

Economic losses caused by natural disturbances are caused by the intrinsic link between these and productivity (Reyer et al. 2017). Disturbances' damage might have a positive effect if, for example, a reduction in the stand density acted as a thinning, thereby reducing tree competition; however, when the disturbance exceeds a certain limit, for example if a reduction in stand leaf area is too high, it will diminish the productivity of the stand. There is also a temporal relationship between productivity and disturbances, as certain development phases are more vulnerable to suffering damage, for example, those stages when trees are taller and therefore more vulnerable to wind damage (Peltola et al. 1999b), or have low densities, making them more prone to suffer browsing damage (Andren and Angelstam, 1993). How productive the stand is will also determine how long it stays in the most vulnerable stages, the time needed to recover after a disturbance damage event and the time required to reach more productive stages.

Forest management can reduce the losses caused by wind and snow, as demonstrated by previous research (Wallentin and Nilsson, 2014; Pukkala et al. 2016). In order to improve economic revenues, we found that management actions, such as reducing tree densities earlier, when the trees are economically viable, leaving lower volumes towards the end, and shortening the rotation length, reduced the losses from wind and snow damage; however, timber production was the only management objective considered in this study, and if other services were also to be included, this management recommendation would likely change (Liski et al. 2001).

Timber prices and discount rates are subject to periodic fluctuations, affecting the forecasting of expected revenues, and increasing the uncertainty associated with such predictions (Pukkala and Kellomäki, 2012). The stochastic nature of disturbances also increases the uncertainty in the expected revenues, therefore it is crucial to establish priorities to consider the variations of the damage, and not only the mean values (McCarthy and Burgman, 1995). Furthermore, a stochastic consideration of damage allows the inclusion of the attitude of the manager towards risk (Pukkala and Kangas, 1996).

Abiotic disturbance regimes and intensities are highly related to climate change, but it is not clear how disturbance dynamics are going to change in Northern Europe (Feser et al. 2015; Mölter et al. 2016). Several studies have pointed to a relationship between a change in climate and an increase in specific types of disturbance (Schelhaas et al. 2010; Seidl et al. 2011b). In boreal forests, rises in temperature reduce the period during which the soil is frozen, and increase wet snow, consequently increasing susceptibility of trees to be uprooted (Peltola et al. 1999b) and their branches and stems to be broken (Nykänen et al. 1997). Even assuming no rise in temperatures, and storms frequency or intensity, damage from snow or wind are expected to increase due to an increasing forest vulnerability (Schelhaas et al. 2003); growing stocks in forests increase every year, and forests become older.

Future prospects

The main ambition of the developed models was to benefit from the vast amount of data available across space and time. The limitations of the models' development raised several issues that will need further study; for example, the inclusion of damage interactions across space and time, or the consideration of relevant climate data to enable a better understanding of how potential future changes in climate will affect risk. For the biotic damage model (browsing occurrence), it is necessary to develop a model to predict the impact of the damage in the stand. Moreover, it would be interesting to explore how a tree-level model could complement the current developed models. Finally, according to the results, mixed- and broadleaf-dominated stands were more damaged than coniferous stands, and showed interesting interactions among variables and threshold values that are worth further exploration.

The risk simulations, and finding of optimal management prescriptions improved the current understanding of how risk changes management, and evaluated to what degree the proposed managements would enhance the desired ecosystem services. The simulation and optimisation presented here were a first attempt using a simplified approach, and therefore have several aspects that could be improved in future studies. In the stand dynamic simulation, we only managed towards one ecosystem service – timber production; however, forest changes are driven by multiple aspects (e.g., disturbances, changes in climate, societal values or ecological shifts). With increasing uncertainty, it is then even more relevant that we evaluate whether the selected management actions can or cannot truly mitigate the undesirable losses. These become more complex when considering the interactions between drivers of forest change and the tradeoffs among different ecosystem services. The dynamic stand simulator from this study could easily be implemented for the quantification of other ecosystem services, such as biodiversity and carbon capture. Therefore, it would be possible to estimate to what degree management actions have an effect on improving these ecosystem services, and what the tradeoffs are.

Few studies have covered large areas and worked with extensive datasets that allow generalisation of the findings to larger areas. The probabilities of damage and effects that natural disturbances have on forests can vary in space. The developed models can quantify for spatial changes, and therefore they could also be used in future studies. For example, a landscape approach would allow us to understand which areas can be managed for mitigation of the effects of the disturbances on services and products, and which areas can be left unmanaged to embrace the disturbance effects, for example to promote biodiversity.

This thesis presents a general scheme of how to integrate risk into long-term forest management. The modelling and simulations provided an understanding of key damage mechanisms. The framework used ultimately aimed to integrate disturbances dynamics and risk assessment, as a part of future forest management under changing scenarios, and to deliver useful information to decision-makers.

A general problem still remains, however, as there is no perfect step-by-step framework for how to deal with risk and how to benefit from past data knowledge, particularly under the uncertainty of future changing climatic conditions.

Nevertheless, it is clear that natural disturbances must be considered when making forest management plans, and therefore we should carry on seeking for, and improving our, knowledge on disturbance dynamics, their interactions and ecosystem service tradeoffs, while expanding our approaches and methodologies to confront new challenges in forest management.

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