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Recent approaches to model the risk of storm and fire to European forests and their integration into simulation and decision support tools

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Abstract

The aim of this paper is to discuss the different recently developed empirical and mechanistic modelling approaches for assessing the risk of wind and fire damage to forests. Additionally the work will explore possible ways to integrate these approaches, including feedback mechanisms, into growth and yield models and decision support tools used in forestry. The integration of mechanistic and empirical storm risk models, as well as an empirical/mechanistic fire risk model into growth simulators is demonstrated and future challenges and options for risk modelling and for creating complex decision support tools, including growth simulators, meteorological components and risk modules, are discussed.

Key words: storm risk; fire risk; empirical modelling; mechanistic modelling; growth simulators.

Resumen

Enfoques recientes para modelizar el riesgo de tormentas y fuego en los bosques europeos y su integración en herramientas de apoyo a la simulación y toma de decisiones

El objetivo de este trabajo es analizar los diferentes modelos empíricos y mecanicistas que se han desarrollado recientemente para evaluar el riesgo de daños por el viento y el fuego en los bosques. Además, el trabajo explora las posibles formas de integrar estos enfoques, incluyendo mecanismos de retroalimentación, en los modelos de crecimiento y produccion y en las herramientas de apoyo a la toma de decisiones utilizadas en el sector forestal. Se muestra la integración de modelos mecanicistas y empíricos de riesgo a tormentas, así como un modelo empírico/mecanicista de riesgo de incendio en los simuladores de crecimiento y se discuten los retos futuros y las opciones para la modelización de riesgos y para la creación de complejas herramientas de apoyo a la toma de decisiones, incluyendo simuladores de crecimiento, componentes meteorológicos y módulos de riesgo.

Palabras clave: riesgo de tormenta; riesgo de incendio; modelo empírico; modelo mecanicista; simuladores de crecimiento.

Introduction

Decisions made in forestry and forest planning often concern large areas, long time horizons and multiple stakeholders. Therefore, it is of particular importance to consider the risks related to specific management scenarios and expected uncertainties related to forest planning. We define risk as a hazard quantitatively expressed in probabilistic terms (Holecy and Hanewinkel, 2006) and we adopt the expected value approach (Haimes, 2004) that quantifies the consequences of an event subject to risk by multiplying the probability of the event with its outcome (Gadow, 2000). This paper focuses on storm and fire as natural hazards. Determining appropriate management practices for reducing the risk of damage and assessing the risks associated with growth and yield predictions are, however, multidisciplinary issues, and difficult to resolve without models supporting decision making. The probability of damage also changes over time as a consequence of forest dynamics, and thus, changing properties of trees and

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stands, in interaction with management and environmental conditions (Peltola *et al.,* 2010; Zeng *et al.*, 2006, 2010).

Natural hazards cause significant economic losses in forestry in Europe. For example, Schelhaas *et al.* (2003) reported damage to 35 million m^3 timber, on an annual basis, in European forests in the years 1950-2000, of which 54% was caused by storm, 16% by fire and 8% by insects (and 22% by other reasons). Thus, the main hazard to forests in Europe is storm. After the huge storm «Lothar» in 1999 (200 million m^3 of timber damaged), an increasing frequency of large damaging events was detected, as demonstrated by the storms in 2005 («Gudrun», 75 million m^3), 2007 («Kyrill», 100 million m^3) and 2009 («Klaus», 50 million m^3). Forest fires are considered as the second most important natural hazard to forests in Europe, having major economic impacts especially in Mediterranean areas. Wildfires that occurred in Portugal during 2003 (426,000 ha damaged area) and 2005 (338,000 ha) were responsible for economic losses of over 3 billion Euros (EM-DAT, 2009). The economic impact of damage is particularly severe in managed forests, because of the reduction in yield, increased costs of unscheduled harvesting, increase in breeding material for bark beetles, and resulting problems in forestry planning (Zeng *et al.*, 2009). As storm and fire seem to be by far the most important disturbances in European forests, we concentrate our analysis on these two damaging agents.

The vulnerability of forest stands to wind damage is affected by wind climate (*e.g.* average and gusting wind speed and wind direction), tree/stand characteristics (*e.g.* tree species, tree/stand height, slenderness of trees, crown and rooting characteristics and stand density) as controlled by silvicultural management, site characteristics and factors increasing stand exposure (*e.g.* due to topography, upwind clear cuts). Wind damage is also more likely especially in older coniferous stands (*e.g.* Norway spruce, *Picea abies*) situated at the downwind edge of recently clear cut areas, and especially if they have been recently and heavily thinned (*e.g.* Peltola *et al.*, 1999). The vulnerability of forest stands to fire damage will depend on the forest composition, stand density, structural irregularity and stand age, as affected by forest management, the amount and nature of the surface fuel-complex, topography and weather conditions (Agee and Skinner, 2005; González *et al.*, 2007).

There are complicated interactions between factors affecting the vulnerability of tree stands to wind and fire damage. It is therefore not possible, purely based on experimental studies, to determine how the risk (probability of damage) changes over time as affected by forest dynamics, management and environmental conditions. For this purpose, we need tools to support the decision making in forestry, both for the short and long term, related to forest management and planning.

The aim of this review is to discuss the state-of-the-art in modelling the risk of wind and fire damage and ways to integrate these two types of risk into growth and yield model simulations and decision support tools for forestry. Therefore, the integration of two different storm risk models (a mechanistic and an empirical one) and an empirical/mechanistic fire risk model into growth simulators is demonstrated. Future challenges and options for risk modelling and for creating complex decision support tools, including growth simulators, meteorological components and risk modules, are discussed.

State-of-the-art for modelling the risk of wind in European forests

Modelling approaches available for wind risk modelling

Outline

Various approaches for predicting the mechanisms and/or risk of wind damage have been developed in recent decades. Generally speaking these models, dealing with vulnerability and/or risk, can be grouped as being either empirical (statistical) models or mechanistic models. Mechanistic models, such as HWIND (Peltola *et al.*, 1999), ForestGALES (Gardiner *et al.*, 2000, 2008) and FOREOLE (Ancelin *et al.*, 2004), have been developed as generic tools for risk assessment, predicting the threshold (critical) wind speeds (mean speed for 1 hour) needed for uprooting or stem breakage of trees under a range of silvicultural conditions, based on the properties of the trees within single species stands. Especially ForestGALES and HWIND have been widely adopted in a number of different countries and integrated with different methods for predicting the local wind climate in order to calculate the probability of wind damage in the short term (for examples see Gardiner *et al.*, 2008). Recently, they have also been used together with growth and yield model simulations to consider the potential risks of wind damage over time at a regional level (*e.g.* Zeng *et al.*, 2006; Peltola *et al.*, 2010).

Similarly, empirical models have been developed to assess the risk for single trees (Schmidt *et al.*, 2010) or forest stands (Hanewinkel *et al.*, 2004). Ideally the models are built on a long-term view and a large scale database using trial plots (Albrecht, 2009), national forest inventory data (Valinger and Fridman, 1999) or level I/ level II – monitoring data on a European scale. A general problem with many statistical models arises out of the fact that they deal with regionally limited case-studies and, therefore, are difficult to generalize outside the area where they have been developed. In order to do so, they usually have to be re-parameterized using a new dataset. However, considerable progress has been made in methodological approaches used for statistical models (*e.g.* Wood, 2006). Table 1 gives an overview of recently developed mechanistic and empirical models for the risk of storm damage.

Mechanistic modelling for wind risk assessment

For the proper assessment of risks by wind damage related to forest management, we should fully understand both the mechanisms of tree stability and the performance of trees under strong winds (Gardiner *et al.*, 2000). This is possible based on mechanistic modelling of wind induced damage, which helps to understand the mechanism behind uprooting and stem breakage of trees as affected by the wind loading (mean wind and gustiness) and tree/stand characteristics (*e.g.* tree species, tree height and diameter, crown area, rooting characteristics, stand density), as well as site type, upwind gap size, distance from upwind stand edge. Mechanistic modelling can also be used to predict critical wind speed (CWS) causing such damage for management prescriptions to avoid or mitigate the expected damage (see *e.g.* Peltola *et al.*, 1999; Gardiner *et al.*, 2000). Based on the predicted critical wind speeds and the probability of such wind speeds occurring for a local wind climate, it is also possible to calculate the probability or return period of the CWS occurring at the site (see *e.g.* Blennow and Sallnäs, 2004; Zeng *et al.*, 2004, 2006).

Previously, a comparison of the HWIND, ForestGALES and FOREOLE models showed good agreement at newly created stand edge conditions (see Ancelin *et al.*, 2004; Gardiner *et al.*, 2000, 2008). This was found despite the fact both the GALES and FOREOLE models were designed originally to calculate the critical wind speed within the stand, whereas the HWIND model was designed to calculate the critical wind speed at the newly created stand edge. On the other hand, the basic structure of these models is quite similar, although they show differences in the methods used for calculating each step of the model simulation (for further model details see, *e.g.* Ancelin *et al.*, 2004; Gardiner *et al.*, 2000, 2008; Peltola, 2006). However, in HWIND and ForestGALES, the critical wind speed is calculated using the mean tree and stand characteristics. Whereas, in FOREOLE model, critical wind speeds can also be predicted for individual trees within a coniferous stand (however this approach has not yet been validated).

Table 1. Examples of recently developed mechanistic and empirical models for storm damage to forests. GL(M)M = generalized linear (mixed) models, GAM = generalized additive models. Additional hazards included in the model are shown in parenthesis related to description of model type

Model name/type (reference)	Type of model (add. hazard)	Country/species/remarks
ForestGALES (Gardiner *et al.*, 2000, 2008)	Mechanistic	Great Britain/most European commercial coniferous species
HWIND (Peltola *et al.*, 1999)	Mechanistic (snow)	Finland/Scots pine, Norway spruce, birch spp.
FOREOLE (Ancelin *et al.*, 2004)	Mechanistic	France/Norway spruce
WINDA (Blennow and Sallnäs, 2004)	Mechanistic	Sweden/Scots pine, Norway spruce, birch spp.
FORGEM-W (Schelhaas *et al.*, 2007)	Mechanistic	Netherlands/Douglas fir
GLM (Lanquaye-Opoku *et al.*, 2005)	Empirical	British Columbia, Canada/no species specific models
GLMM, Cross Correlation, Spectral Analyses (Hanewinkel *et al.*, 2008)	Empirical (snow, insects)	Black Forest (Germany) conifers + hardwoods, long term series
GLM, GAM (Schmidt *et al.*, 2010)	Empirical	South-West Germany, large scale NFI-data, Lothar

All mechanistic models are sensitive to model inputs and parameter values, and thus, any inaccuracies in the input tree characteristics (*e.g.,* dbh, height, crown depth and width) and parameters that control the magnitude of the wind loading (*e.g.,* gust factor, drag coefficient, crown streamlining) or the resistive bending moments of trees can have a large influence on the predicted critical wind speed for uprooting and stem breakage (see *e.g.* Zeng *et al.*, 2006). Thus, they require accurate input data, but also further model parameterization (*e.g.* based on tree pulling tests, supporting wind tunnel experiments and/or airflow simulations) and validation if they are applied in other conditions than for which they have been originally developed. However, compared to purely empirical models, mechanistic models show a greater ability for generalization. On the other hand, these models have been found to simulate bending moments and critical wind speeds needed to cause uprooting or stem breakage in agreement with the corresponding outputs of regression equations for extensive tree pulling data and with wind speeds known to cause actual damage to similar kinds of trees. Thus, despite the possible limitations of these tools, they can be used to help to evaluate the risk linked to a particular regime of management (Gardiner *et al.*, 2008), which is rarely the case for empirical models due to a lack of an adequate database.

However, as the current versions of HWIND and ForestGALES predict the risk for the mean tree within a stand or at its newly created edge, it should be noted that this approach is well adapted only for regular, single species stands. In heterogeneous stands different trees will not necessarily have equal risk. This model limitation should be considered in future model development work. Furthermore, these models do not capture the process of wind damage in real stands (*e.g.* from newly created stand edge to inside the stand). In reality, the failure of one tree alters the wind regime for its neighbours and may make it more liable to damage. In this sense, Schelhaas *et al.* (2007) showed one of the first attempts to incorporate neighbour interactions into risk model development.

Empirical (statistical) modeling for wind risk assessment

Empirical wind damage risk models are statistical models that relate the presence or magnitude of wind damage to variables (*e.g.* tree/stand characteristic, topography, stand exposure, site conditions etc.) measured following a damage inventory. However, as wind damage is a rare event, these models typically assign a probability value to the occurrence of damage (*e.g.* Lanquaye-Opoku and Mitchell, 2005). Such empirical modeling is most suitable for stands with complex and variable structure and composition, and where topography and soils are heterogeneous. It should be noted, however, that a large sample size is needed to fit and test empirical models. In the strict sense, empirical models can only be used in locations with site conditions and management similar to the area used to build the models, unless properly re-fitted, which limits their application. Despite the fact that unlike mechanistic models, empirical models do not define causal links between wind loading, tree/stand variables and the probability of damage, they still can offer tools for classifying the overall susceptibility of forest stands growing on specific sites. Lanquaye-Opoku and Mitchell (2005) are among the first to have used a relatively large dataset as the basis for logistic regression models to predict stand level risk based on variables including wind, in addition to topographic, ecosystem, stand and edge exposure factors. They also found that such models may be applicable in other forest regions where synoptic weather systems produce damaging winds.

Recently models that integrate non-parametric smoothers in regression models such as generalized additive models (GAM) have been used for risk modeling, *e.g.,* Schmidt *et al.* (2010) use a GAM to model spatial trends in the damage caused by the storm «Lothar». Especially compensating for the lack of independent observations, mixed modeling techniques such as generalized linear mixed models (GLMMs, *e.g.* Hanewinkel *et al.*, 2008) and generalized additive mixed models (GAMMs, see Wood, 2004) allow the partitioning of variance into a fixed effects part on the one hand, which is explained by the predictor variables, and a random part on the other hand, which is explained by a hierarchical (also referred to as clustered or nested) data structure.

Additionally, classification and regression trees (CART) have recently been used as robust and easy-to-use analysis methods in risk modeling and for an explorative data-analysis of large databases in order to identify significant predictors (see *e.g.* Olofsson and Blennow, 2005; Kamimura *et al.*, 2008). They do not require distributional assumptions and can accommodate correlated observations and missing values. Recently, Kamimura *et al.* (2008) built classification trees based on the integrated use of empirical datasets (*e.g.* tree height, stand density, slenderness, upwind gap size, direction of wind exposure, slope, aspect) and mechanistic modeling for wind damage (predicting the critical wind speeds) together with the probability of such wind speeds. Olofsson and Blennow (2005) used a classification tree approach to build a decision support tool for the identification of stand edges with a high probability of wind damage in Norway spruce forests.

Integration of mechanistic storm risk models with growth and yield models and decision support tools

In the future, mechanistic models should be integrated, as sub-modules, into growth and yield models and forest planning tools with a feedback mechanism between these component models to support risk assessment related to forest management decision making. This is crucial, especially under changing climatic conditions in which such risks are expected to increase. The risk of wind damage is also changing over time related to forest dynamics as affected by forest structure, environmental conditions (climate, site) and management, and thus, without integrated tools risk assessment over a long time period would be difficult. Zeng *et al.* (2006, 2007) presented the first attempts of regional level risk assessment over a long time period by integrating model simulations using the HWIND model and the growth and yield model SIMA (a stochastic gap type model), which can be used to predict stand dynamics over time as controlled by environmental conditions (climate, site) and forest management. Similarly, Peltola *et al.* (2010) have used these models together to assess the potential wind risks to forest resources in forest inventory plots throughout Finland as affected by climate change and management. Recently, Blennow *et al.* (2010) have also demonstrated, based on an integrated use of WINDA and growth modeling, how possible changes in wind climate and forest dynamics may affect, under changing climate, the probability of critical wind speeds in Sweden at the management unit level. However, in these previous studies, the outputs of growth models have been used as inputs to mechanistic risk models without any feedback mechanism, demonstrating thus, in this sense, only potential risks over time.

Figure 1 shows a simplified layout for integrated risk modelling, in which a mechanistic wind risk model (*e.g.* HWIND) thereby enabling its use together with a process-based growth and yield model (*e.g.* the FinnFor model, see Kellomäki and Väisänen, 1997)

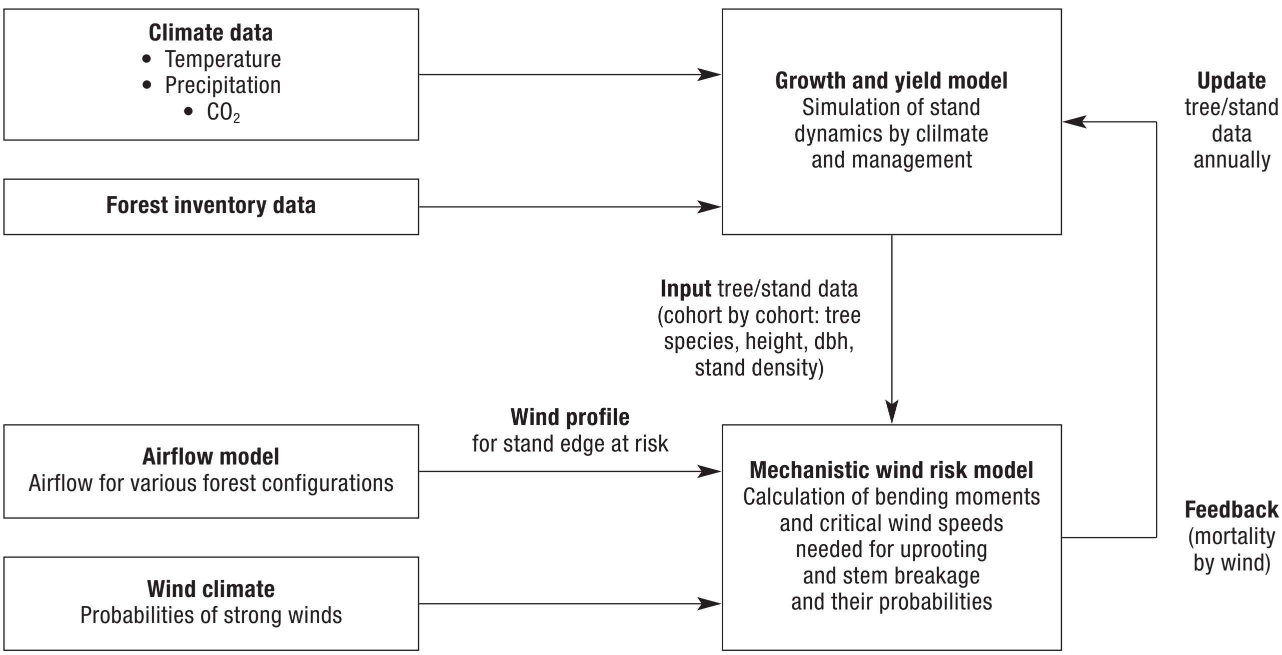

Figure 1. Outline for integrated wind risk modelling by employing a mechanistic wind risk model (*e.g.* HWIND) and growth and yield model (*e.g.* FinnFor model) with feedback mechanism between their simulations.

with a feedback mechanism between these component models in order to properly consider the additional mortality of trees caused by wind extremes in the simulation of forest dynamics over time. More precisely, in this integrated risk modeling approach, local climate data (*e.g.* monthly means for temperature and precipitation and wind probabilities), forest inventory data (tree/stand characteristics) and forest management guidelines are used as inputs for the simulations by the forest ecosystem model. At the end of each year, the simulated tree/stand characteristics (*e.g.* for mean characteristics of tree stand or separately different tree cohorts) are used as inputs to the mechanistic wind risk model. Depending on the predicted critical wind speeds and their probabilities, the number of trees could then be decreased in a stand (or cohort by cohort), and the updated tree/stand characteristics used as input for the following year's growth simulation etc. This procedure could be repeated annually until the final cut.

If single tree stand simulations are used, the kind of conditions expected over time at the upwind the stand edges thought to have a risk should be considered, as this affects the mean wind profile at the stand edge (and gust and gap factors). In this context, two-dimensional airflow models (*e.g.* Aquilon model, see Foudhil *et al.*, 2005) could offer useful tools to provide mean horizontal wind profiles for various stand configurations (*e.g.* at the stand edge of a newly created gap with various perimeter lengths or at the downwind edge of a shorter sheltering stand). These mean wind profiles, *e.g.* at the upwind the stand edge, can then be used as inputs to mechanistic risk model simulations. In a similar way, the development of forest resources could be predicted at a regional level (*e.g.* on national forest inventory plots), while considering the risk of damage. It would be ideal, however, if these integrated model simulations could be used in landscape level risk assessment in forest planning.

Currently, further model development is needed to install a feedback mechanism between growth and yield models (*e.g.* FinnFor/SIMA, see Kellomäki and Väisänen, 1997; Kellomäki *et al.*, 1992) and mechanistic modeling (*e.g.* HWIND) (see Fig. 1, Peltola *et al.*, unpublished). In this context, two-dimensional airflow model simulations could also provide, for the mechanistic model, the mean horizontal wind profiles at the downwind stand edge considered to have an influence on risk under various forest configuration cases. Current empirical equations in mechanistic models derived from wind tunnel studies for gust and gap factors could also possibly be replaced based on these airflow simulations. These modifications are crucial, because previous wind tunnel and airflow modeling studies have shown that the structure of the stand affects the shape of the wind profiles with implications for the wind loading of individual trees under different forest configurations (Gardiner *et al.*, 2005; Dupont and Brunet, 2008).

Figure 2 shows an example of the integrated use of SIMA and HWIND models to predict how the proportion of Norway spruce, and the occurrence of various critical wind speeds in forest inventory plots, could change in southern Finland over time under the current (1971-2000) and changing climate. The climate change scenario used for this purpose was the A1B climate scenario for 2010-2099 based on the ACCLIM project by the Finnish Meteorological Institute (*i.e.* providing estimates for the expected climate change in Finland for the adaptation studies). The scenario projects an average +4°C increase in mean temperature and a 10-30% increase in precipitation for Finnish conditions until the end of the 21st century (see Jylhä *et al.*, 2009). For simplicity, the feedback mechanism between SIMA and HWIND predictions was not used here. Additionally in the HWIND simulations all the stands were expected to be situated at the edge of newly clear cut areas, which indicated maximum risk. Furthermore, the occurrence of birch (*Betula* spp) in coniferous stands was actively controlled by pre-commercial thinning following the current forest management guidelines for Finnish forests.

Based on our simulations, under the changing climate the proportion of Norway spruce (*i.e.* % of total stem volume) could be clearly lower in 2070-2099 than under the current climate in 2070-2099 (Fig. 2). Especially under the changing climate in 2070-2099, birch would replace both Scots pine (*Pinus sylvestris*) and Norway spruce. However, this happens also, to some degree, under the current climate for the same period (compared to current situation). At the same time, the occurrence of the lowest critical wind speeds (expected in autumn time, birch without leaves) could also increase, to some degree, in southern Finland from the first period of 2010-2039 (with a quite similar picture regardless of climate) to the final simulation period of 2071-2099. An increase will be, to a certain extent, also higher under the changing climate (see Fig. 2). The wind speeds in the two lowest critical wind speed classes are nowadays present once or twice every 10 years in southernmost Finland under the current climate. Fortunately, strong

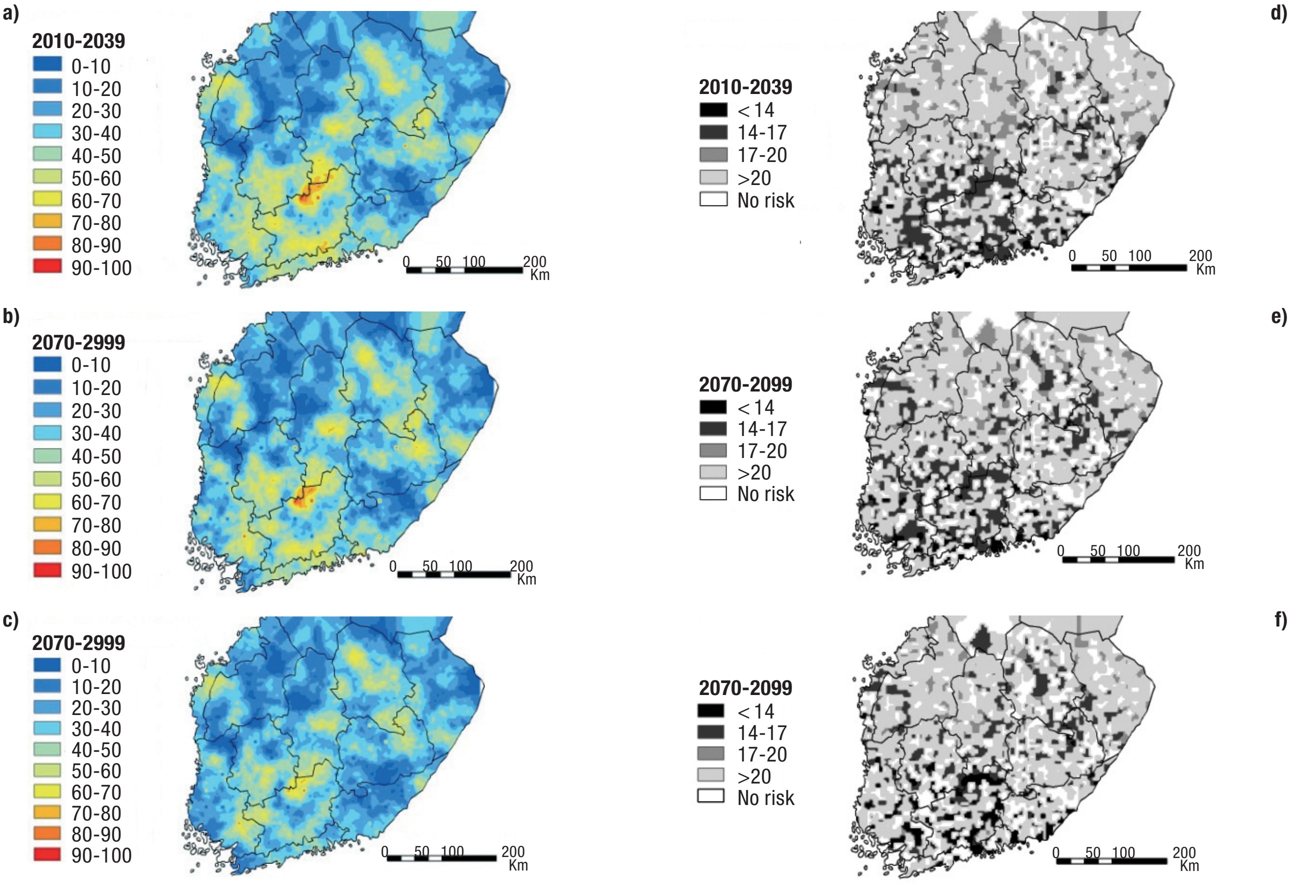

Figure 2. Example of the integrated use of HWIND and SIMA simulations: The maps on the left show the proportion of Norway spruce (% of total stem volume) in southern Finland a) in 2010-2039 and b) in 2070-2099 under the current climate and c) in 2070-2099 under the changing climate. The maps on the right shows the occurrence of different critical wind speeds for same cases (d, e and f), respectively.

winds/storms are not expected to increase significantly in Finland until the end of the 21st century (Gregow and Ruosteenoja, unpublished). However, the risk of damage could still be expected to increase in the future due to a significant decrease in the frozen soil period under the warming climate (strongest winds blow from autumn to early spring in Finland). Therefore, integrated tools such as those demonstrated above are crucial for future risk assessment related to forest management decisions.

Integration of empirical storm risk models with empirical growth simulators

The «Lothar Storm model» that is used here as a demonstration example is an empirical model that is based on individual tree damage data dating back to the «Lothar» gale (winter 1999) in Baden-Württemberg, Germany (Equation 1, see Schmidt *et al.*, 2010). The model was developed to estimate the risk of storm damage for individual trees. The data were compiled from the National German Forest Inventory. The model attempts to separate the effects of tree-specific variables, topography, site conditions and flow field-related effects on damage probability. The crucial problem of missing information on the actual flow field parameters was solved by applying a generalized additive model (GAM), which enables the simultaneous fit of a spatial trend function. The model is already used for decision support in forest risk management in south-west Germany. Tree species, four different parameters indicating the exposure of the terrain in four wind-directions (the modified Topex-to-Distance index by Scott and Mitchell, 2005) and species-specific dbh, as well as tree height effects, were integrated into the model, in addition to the spatial trend function.

Equation 1 (Schmidt *et al.*, 2010):

$$g(\pi_{ijk}) = \text{species}_{ijk}^{T}\ \beta_{1\,\text{species}} + \log\left(\frac{\text{dbh}_{ijk}^{\ \text{species}_{ijk}^{T}\ \alpha_{1\,\text{species}}}}{\text{height}_{ijk}^{\ \text{species}_{ijk}^{T}\ -\gamma_{1\,\text{species}}}}\right) + \beta_2\ \text{Top\_to\_Dist1}_{ij} +$$
$$+ \beta_3\ \text{Top\_to\_Dist2}_{ij} + \beta_4\ \text{Top\_to\_Dist3}_{ij} + \beta_5\ \text{Top\_to\_Dist4}_{ij} +$$
$$+ f_1(\text{north}_{ij};\text{east}_{ij})$$

Species = an indicator vector for tree species group (Picea abies, Abies alba/Pseudotsuga menziesii, Pinus sylvestris/Larix spec., Fagus sylvatica/Quercus spec., other broad-leaved tree species with high or low life expectation).
Dbh = diameter at breast height (1.3 m) in 1999 (cm).
Height = tree height in 1999 (m].
Top_to_Dist1 = sum of modified Topex-to-Distance indices on directions 270 and 240 (Fig. 1) (gradient multiplied by 10).
Top_to_Dist2 = sum of modified Topex-to-Distance indices on directions 90 and 60 (Fig. 1) (gradient multiplied by 10).
Top_to_Dist3 = sum of modified Topex-to-Distance indices on directions 320 and 190 (Fig. 1) (gradient multiplied by 10).
Top_to_Dist4 = sum of modified Topex-to-Distance indices on directions 140 and 10 (Fig. 1) (gradient multiplied by 10).
North = northing Gauss-Krüger-coordinate (m).
East = easting Gauss-Krüger-coordinate (m).
α, β, γ = (vectors of) regression coefficients.
f_1 = a two-dimensional smooth function.

where $g(\pi_{ijk})$ is the expected probability of storm damage for tree$_{ijk}$ (Schmidt *et al.,* 2010).

What makes the model particularly interesting for the integration into an empirical single-tree growth model is that it delivers tree-species-specific damage probabilities taking into account essential dendrometric parameters such as dbh and height that are regularly used by growth models.

Figure 3 shows how such a statistical storm damage model can be integrated into a model chain containing an empirical growth simulator and a general/regional circulation model (GCM/RCM) projecting future changes of windfields under climate change. Typically, the dendrometrical information concerning dbh and height, and their interrelation, is assessed using forest inventory plots. In south-west Germany a system of permanent inventory plots in a 200 m × 100 m grid is

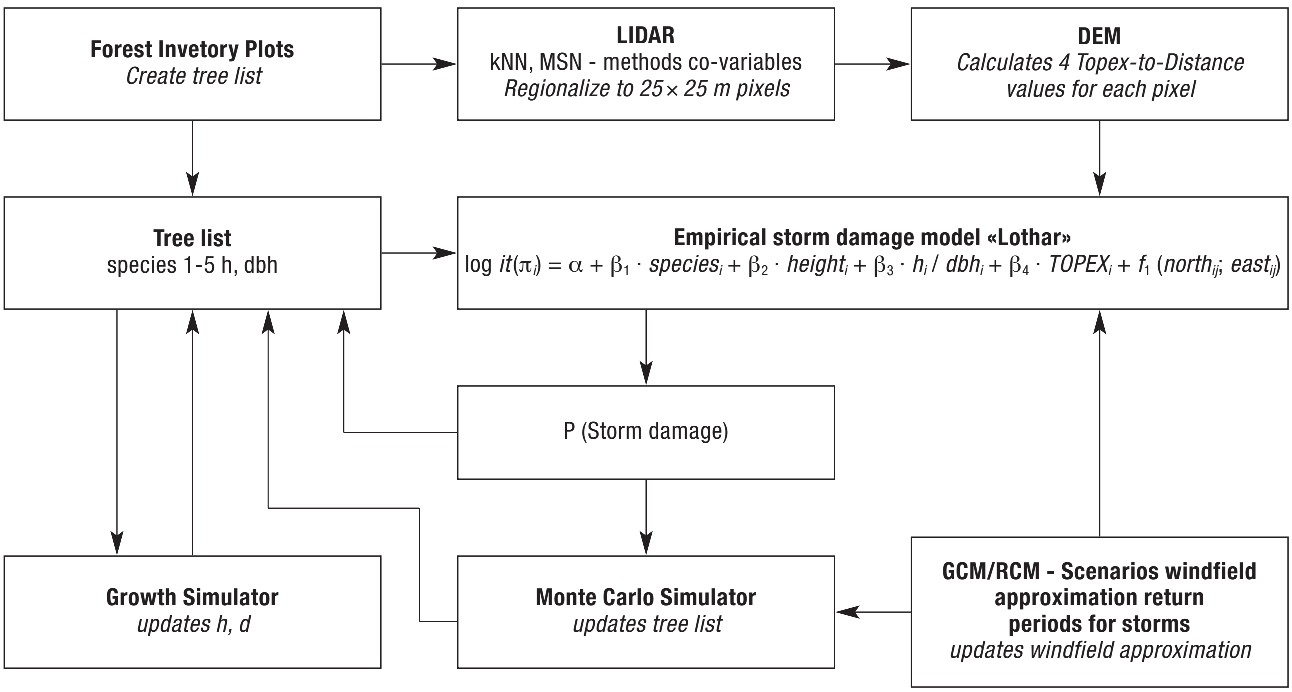

Figure 3. Scheme showing the integration of the empirical storm damage model «Lothar» into a model chain encompassing a growth simulator. DEM: digital elevation model. LIDAR: Light Detecting and Ranging. *h*: height, *dbh*: diameter at breast height. GCM/RCM: general/regional circulation model. kNN: k-nearest neighbor, MSN: most similar neighbor.

available in public forests. As the storm damage model takes into account the exposure of the trees, the dendrometrical information has to be regionalized to 25 m × 25 m pixels. A method to realize this has been developed by Nothdurft *et al.* (2009). They show how, based on co-variables issued from airborne laserscanner data (LIDAR), information from regular sample plot inventory data can be regionalized down to the forest stand level tessellated into high-resolution subunits using most similar neighbor (MSN) and k-nearest neighbor (k-NN) approaches. For these subunits the required 4 different topex-to-distance values are then calculated using a digital elevation model. From the plot information a tree list, containing species, height and diameter is generated. For each tree an initial storm damage probability is calculated using the spatially explicit dendrometrical and the terrain related parameters taking into account either the original airflow conditions of the storm «Lothar» as depicted by the spatial trend function or an assumed geographic position of the forest within a winter storm by varying the northing/easting-values in the model. Such a regionalization can also be used to take into account the landscape aspect of risk modeling that is disregarded when exclusively using stand-level risk models.

The tree list with the initial storm damage probability for each tree is then processed using an empirical growth simulator. For south-west Germany at least two growth simulators, the model Silva (Pretzsch, 2001) and the model BWinPro (Nagel, 1997), can be utilized to integrate a storm damage module. The growth simulator updates height and diameter and creates a new tree list where trees were removed by silvicultural interventions or internal mortality. This tree list is then updated using a Monte Carlo simulator that eliminates trees according to their storm damage probability. There are several ways regarding how this Monte Carlo simulator can intervene in such a process: the most common is that an array of random numbers is created and compared to the individual storm damage probability of each tree. If the random number exceeds the probability, the tree is removed. The Monte Carlo process is activated intermittently according to the assumed return period of the storm events. The updated tree list is then again inputted to the storm damage model, subsequently the storm damage probabilities are recalculated and the process restarts.

There are different ways for a dynamic implementation of this process. A first step towards integrating dynamic feedbacks into risk models that are useful for forest management is to downscale the projections for IPCC scenarios of general circulation models (GCM) and regional circulation models (RCM) to a level relevant for forest management decisions. For some climate parameters, such as wind speed or precipitation, this is still a major challenge because the appropriate scale at which to assess and model the probabilities needed for risk management is not always known. A crucial point when improving predictions for climate change scenarios in terms of risk will be to make progress in forecasting extreme events.

Figure 4 shows a projection for the relative change of gust wind speed using a GCM-RCM model chain (Rauthe *et al.*, 2010).

Such a projection can be used as a dynamic input for the risk model/growth simulators in two ways: (i) it can influence the wind field approximation of the storm damage model by modifying the geographic position of the forest stand to be simulated from *e.g.* a more remote position to a more central position within the storm as projected by the RCM; (ii) it can be used to influence the parameters of the Monte Carlo simulator. The range of the random numbers to be produced can be modified according to the severity of the storm that is projected, as well as its geographical position. In the case of an extreme storm event, the random number will be close to 1 resulting in a total loss of the simulated stand.

State-of-the-art for modelling the risk of fire in European forests

Modelling approaches available for fire risk modelling

Outline

Various approaches for predicting fire damage have been developed. The models dealing with vulnerability of forest to fire can be grouped, generally speaking, as being either empirical (statistical) models or physical models. Table 2 gives an overview of examples of models developed or used in Europe for fire damage assessment. Fire spread models were also included if they were thought to be capable of predicting the initiation and spread of crown fires (Dupuy and Morvan, 2005; Cruz *et al.*, 2008)

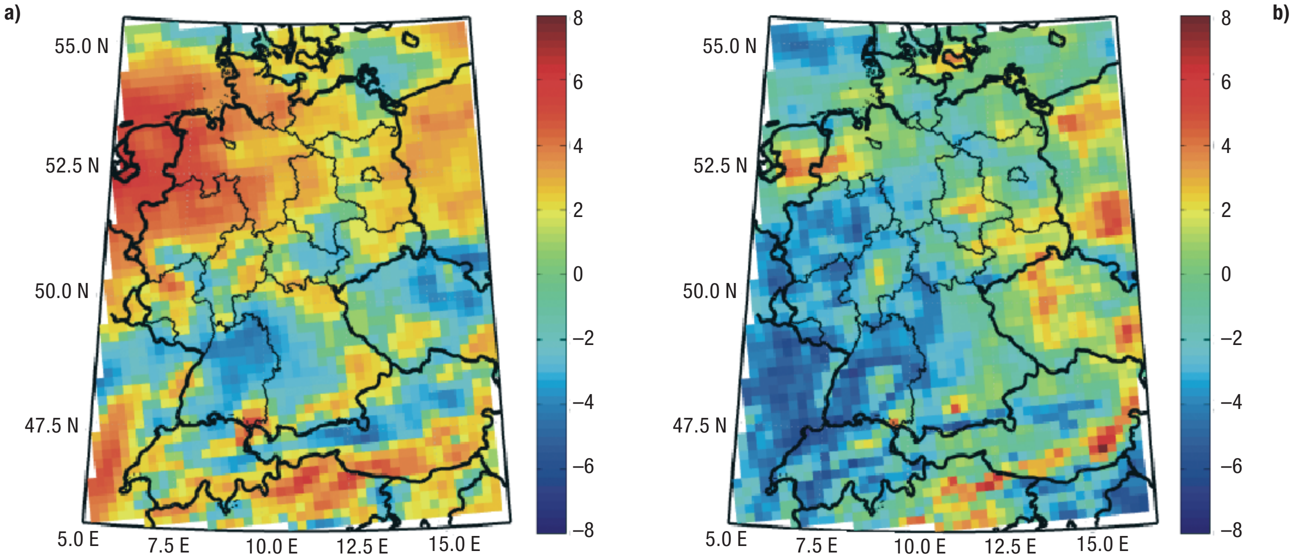

Figure 4. Projection of the relative change of gust-wind speeds for an A1B *vs* C20 scenario for Germany using an ensemble of GCM-RCM model predictions for an assumed return period of 10 years a): mean, b) standard deviation (Rauthe *et al.*, 2010).

Physical modelling for fire risk assessment

Historically, fire behaviour simulators have been based on empirical and semi-physical models, which are able to predict surface fire spread and intensity with accuracy. These models usually require, as input data, information about the local weather conditions during the fire simulation period, and the amount and moisture of fine and dead fuels (Rothermel, 1983). Regarding the effect of fires on tree mortality, most of the studies can be divided in two groups (Fowler and Sieg, 2004): ones that consider the amount of observed tree tissue damage as a predictive variable (*e.g.* Rigolot, 2004), and those that consider the intensity of fire as a predictor (*e.g.* McHugh and Kolb, 2003). Both types of mortality models are empirical in nature, but rely on fire behaviour simulators to obtain the variables (tissue damage, fire intensity) needed to predict the mortality of a tree in the future. For forest planning purposes, these models have limitations, especially

Table 2. Examples of recently developed mechanistic and empirical models for fire damage to forests. Legends: CL-CV = Classification and cross validation with existing fire spread models; BL = binary logistic models; GLM = generalized linear models

Model name/type (reference)	Type of model	Country/species/remarks
FIRETEC (Dupuy and Morvan, 2005)	Physical	USA/adapted for pine stands in Europe
CL-CV (Mitsopoulos and Dimitrakopoulus, 2007)	Semi-physical	Greece/Alepo pine/crown fire potential
CL-CV (Fernandes, 2009)	Semi-physical	Portugal/conifers, hardwoods/fire behaviour, NFI data
BL (Fernandes *et al.*, 2008)	Semi-physical	Europe/pines/post-fire mortality
BL (Rigolot, 2004)	Empirical	S- France/Mediterranean pines
BL (Sidoroff *et al.*, 2007)	Empirical	Finland/Scots Pine/low intensity prescribed burnings
GLM, BL (González *et al.*, 2007)	Empirical	Catalonia (N-E Spain)/conifers and hardwoods/ long period, large scale, NFI data
BL (Moreira *et al.*, 2007)	Empirical	South Portugal/cork oak/post fire survival
PPPY (Cruz *et al.*, 2008)	Empirical, semi-physical	—/pine plantations

when dealing with landscape-level planning, as most fire behaviour simulators require data on surface fuel accumulation, weather scenarios and location of the fire ignition point, that are difficult to accurately predict over long term periods (Rothermel, 1991). Additionally, the computational requirements of these models are still large, reducing the possibility of running multiple scenarios to assess the variability of fire spread and landscape change over the length of a planning period (Bettinger, 2010). Therefore, the inclusion of such models in decision support systems is difficult, or at least highly dependent on a limited number of specific fire simulations.

Empirical modelling for fire risk assessment

Modelling fire damage presents one important limitation in comparison to the damage caused by other hazards. This limitation arises from the fact that some of the most important features determining the fire behaviour and intensity in a forest stand are difficult to measure after a fire. For example, the amount of dead and fine fuels, and even small trees, are variables that define the intensity of a fire, but their consumption by a fire makes the reconstruction of a proper inventory of these variables impossible after the fire occurred. However, the use of experimental fires, and an analysis of their effects, can overcome this problem (Fernandes *et al.*, 2004; Sidoroff *et al.*, 2007). It should be noted, however, that reproducing the conditions of a high intensity fire in a experimental fire as Fernandes *et al.* (2004) did, is extremely difficult due to the risk of fire escaping, as well as the social unrest that the experiment may cause. For this reason, most of the studies based on experimental fires, especially in Europe, only deal with low intensity fires (Sidoroff *et al.*, 2007). In order to link the forest structure and composition, prior to the occurrence of a fire, and the potential fire damage caused by it, other approaches have been considered. For example, Pollet and Omi (2002) and Ritchie *et al.* (2007) collected historical records and commercial inventories of treated stands that subsequently were affected by a wildfire, which allowed them to see the effect of stand structure on post-fire damage. Another option is to compare changes in plots affected by fire from national forest inventories (González *et al.*, 2007). The study of González *et al.* (2007) utilized a large number of permanent plots and perimeters of fires occurring within the interval of the inventory measurement, making it possible to generate a generalized linear model (GLM) model to predict the proportion of dead trees following the fire, and a binary logistic (BL) model to predict the survival probability of individual trees. Other studies have also used national forest inventories to assess the probability of fire occurrence. For example, González *et al.* (2006) created a BL model to predict the probability of fire occurrence for stands in Catalonia depending on the stand structure, composition, and location.

A new approach that has recently been introduced in Europe is to generate fuel types that consider forest structure, making it possible to make predictions about potential fire intensity depending on the development of the stand, and therefore on its management. These new «stand level» fuel types are classified on the basis of the amount, type and arrangement of surface and canopy fuels. For example, Mitsopoulos and Dimitrakopoulus (2007) generated fuel types for Pinus halepensis stands in Greece, while Fernandes (2009) generated fuel types for a wide range of species using the Portuguese national forest inventory. These two studies can be considered semi-physical, as they rely both on field measurements and simulations from pre-existing fire behaviour models as input data for classification. These models predict the initiation and spread of a crown fire which is essential for fire modelling (*e.g.* Scott and Reinhardt, 2001; Cruz *et al.*, 2004, 2005).

Linking empirical fire damage models with growth models and integration into a DSS

The post-fire damage model

The model of González *et al.* (2007) is an empirical fire effects model developed to predict the proportion of dead trees («Pdead» s. equation 2) in burned stands in Catalonia, Spain. The model was developed using data from plots of the Spanish National Forest Inventory affected by fire between the 2nd and 3rd repetition of the inventory. The model tried to identity if variables representing stand composition, structure and topographical position had an effect on the potential post-fire damage. Additionally, a tree-level survival model was developed to determine which trees will survive in a stand depending on the damage at stand-level and the size of the trees.

The formulation of the models is as follows (González *et al.*, 2007):

Equation 2:
Stand level damage model

$$Pdead \text{ (proportion of dead trees)} = \frac{Exp\left(Y_{Pdead}\right)}{\left(1+Exp\left(Y_{Pdead}\right)\right)}$$

$$dY_{Pdead} = -6.131 - 0.329G + 0.060\,Slope + 2.266\,Pine + $$
$$+4.319\left(\frac{G}{D_q+0.01}\right)+6.718\left(\frac{s_d}{D_q+0.01}\right)+e$$

G = stand basal area in $m^2 * ha^{-1}$.
Slope = percentage of altitude change per distance (%).
Pine = dummy variable which equals 1 if the stand is dominated by pines (> 50 % of basal area is pine) and 0 otherwise.
s_d = standard deviation of the breast height diameters of trees (cm).
D_q = is the quadratic mean diameter (cm) of trees.
e = standard deviation of the residual (in stochastic simulation it can be used to generate variation in the level of damage).

Tree-level survival model

$$Psur \text{ (probability of survival)} = \left(1+e^{-(2.224+0.110d-7.117P_{dead})}\right)^{-1}$$

d = diameter of the tree (cm).
Pdead = proportion of dead trees in a stand.

The stand-level damage model is based on constant variables, such as slope, or variables regarding stand structure and composition that can be predicted for the future using growth models. At the same time once the expected damage is defined or calculated at the stand level, the probability of a specific tree surviving the fire can be estimated based on its diameter, an essential variable in any growth model.

Integration of the fire damage model in an empirical growth simulator

A stand-level approach to study the effect of fire on forest management alternatives

Figure 5 shows how a fire damage model can be integrated into a stand level simulator where different

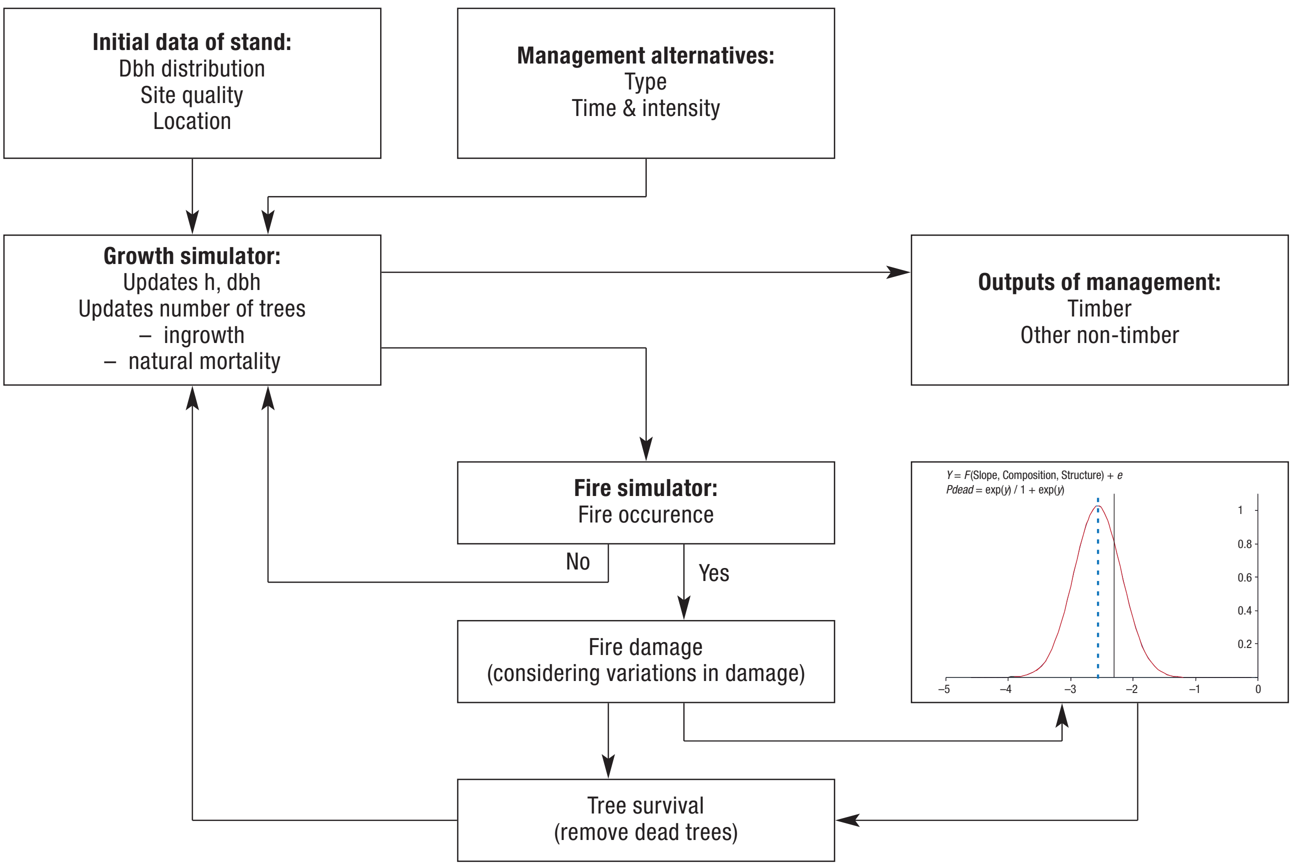

Figure 5. Scheme showing the integration of a fire damage model into a stand level simulator.

management alternatives can be tested in order to address the effect of management on fire risk, or the combined effect that management and fire risk have on the development of the stand and the production of forest goods.

The initial input of the state of the forest, required to run this type of simulator is easily obtained from inventories, additionally the management alternatives can be selected by the forest manager. Once these data are included the simulation can be run using the most accurate forest growth model for initial conditions. Different growth models have been developed for Catalonia for even-aged (Palahí *et al.*, 2003) and uneven-aged stands (Trasobares *et al.*, 2004a, 2004b), which can be used for this purpose. One aspect of this type of simulation is the need to define the fire occurrence probability to be applied during the simulation. The fire occurrence probability can be either constant, it is then obtained from the fire return interval for similar stands in the study region, or vary according to the stand's characteristics (González *et al.*, 2006). If fires are simulated in a stochastic way, using the fire occurrence probability, it should be considered that the occurrence/non-occurrence of a fire in a specific moment of the simulation will have a large impact on the results. For this reason, if the use of these simulators is to estimate the overall effect of fire and management on forest goods, the mean result of multiple simulations and the extreme values can be considered useful information for selecting an optimal management schedule, whereas an analysis of the complete set of simulations would provide an idea of the level of uncertainty affecting our choice.

In a simulation-optimization system, such as RODAL (González *et al.*, 2009), for example, the way the damage model interacts with the growth models is the following: at each step of the growth simulation, the simulator estimates the probability of fire occurrence (Pocurr), using the model of González *et al.* (2006), and creates a random number that, when compared with Pocurr, results in a simulated fire if it is found to be a lower number. If no fire is simulated the forest follows its normal development according to the growth models. If a fire is simulated in any step of the simulation, the proportion of dead trees is estimated using the model of González *et al.* (2007). Using the proportion of dead trees and the diameter of the trees and the application of a survival model, the dead trees are selected and removed (Fig. 6). Subsequently, the remaining surviving trees are used to update the tree list in the simulator database, and the simulation continues. Another aspect of this simulation system is that it allows the generation of stochastic

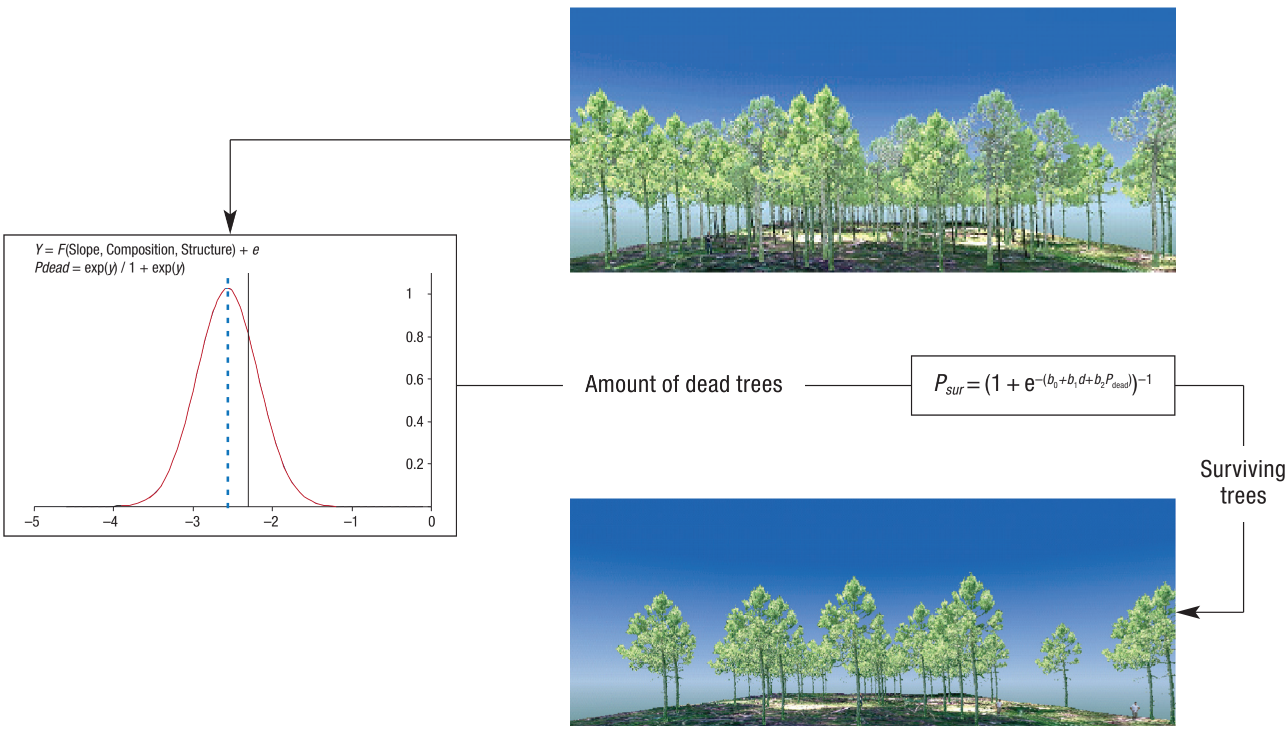

Figure 6. Effect of fire on a simulated stand.

variations in the degree of damage by considering the residuals of the damage model (Fig. 6), meaning that the effect of change in important variables not included explicitly in the model (such as weather conditions or fine fuel accumulation) are considered in a general way in the simulations. Additionally, it includes the possibility of introducing a threshold for the fire damage; once surpassed the simulation calls for the complete re-establishment of the stand.

Discussion and conclusions

Integration of risk models into growth and yield model simulations and decision support tools-overview and outlook

To date, the effects of forest dynamics on the risk of wind damage have been typically considered using time series of tree and stand characteristics as inputs in risk models without considering the feedback mechanism between them (see *e.g.* Zeng *et al.*, 2006; Gardiner *et al.*, 2008). However, a major task for future risk modelling will be the integration of risk models into existing growth and yield models and simulation tools, such as risk modules, *i.e.* to support decision making in forestry. Such work should also be considered for mechanistic risk models.

Examples of models that already include risk modules are PICUS (Seidl *et al.*, 2007) that contains a module for insect damage, as well as the Carbon Budget Model of the Canadian Forest Sector, CBM-CFS3, that explicitly simulates beetle-caused mortality, and fire-caused mortality (Kurz *et al.*, 2008). Furthermore, programs such as RODAL and MONTE, integrate fire occurrence and damage models into the simulation of the stand development, with the intention of optimizing the management schedule at the stand (González *et al.*, 2009) or landscape level (González *et al.*, 2005) under fire risk conditions.

Most of the available growth and yield models, which are capable of simulating stand dynamics, as controlled by environmental conditions (climate, site) and management, contain a module that simulates tree mortality caused by competition (*i.e.* internal factors, Nagel, 1997). However, they do not typically consider mortality caused by biotic or abiotic damages (*i.e.* external factors), and would thus, in this sense underestimate the total mortality. In order to solve this problem, the prediction of mortality by biotic and abiotic damages by the risk models should also be integrated into such growth and yield models for more accurate predictions. This would be crucial especially for long-term predictions, in which such errors will propagate and clearly affect the validity of model's predictions.

The inclusion of risk can be done in different ways: i) a probability of a specific risk can be assigned to a single tree. In a stochastic approach, a random number can be drawn and the decision whether the tree will be damaged is taken by comparing the probability to the random number. In order to achieve stable results, the simulations have to be repeated. This approach is already realized in the mortality module of many growth models (*e.g.* Silva, Pretzsch, 2001) and should be extended to other causes of mortality; ii) Probabilities that are assigned to whole stands can either be distributed to the single tree level by randomly selecting trees or by applying rule based algorithms including expert knowledge. For that purpose, new approaches for combining tree- and stand-level growth models (Yue *et al.,* 2008) may be promising. Damage probabilities of whole stands can also be transformed into transition probabilities for age classes and thus lead to successively smaller areas in older stands based on a Markov approach (Suzuki, 1971). In order to apply these models on a larger scale, the database for the risk model should be large enough, and future trends of expected changes of the different disturbances should be captured.

Future challenges and options for risk models

The main challenge in future risk modelling is the integration of extreme events in existing management models. Within the investigation of climate change, significant progress has been made in the assessment of the effect of a gradual change of environmental conditions. However, the main drivers of change for ecosystems such as forests are large scale extreme events. Within climate change scenario modelling, it will be vital to link expected gradual changes to related extreme events (Zimmermann *et al.*, 2009). Additionally, it will be of increasing importance to integrate the stochastic nature of risk in any modelling endeavours. This can be done by interpreting distributions of outcomes of models using Monte Carlo simulation techniques (Kurz *et al.*, 2008) rather than mean values. When designing adaptive forest management strategies to mitigate the effects of risk, it is crucial to include uncertainty in decision making.

In the future, mechanistic wind risk modelling should be improved to also deal with more complex forest structures and to predict the wind damage risk of individual trees within stands over time through the integration of risk models with forest growth and yield models within a geographical information system framework. For this purpose, individual trees may be identified within a stand with the help of *e.g.* LIDAR technologies. However, such assessment of damage probabilities of individual trees according to their properties could only be possible provided that the airflow above and within a structurally uniform stand could also be predicted with sufficient accuracy. This could even allow forest managers to evaluate the effects of management (*e.g.* thinning, final cutting) on the risk of damage both at the stand and individual tree level, in addition to regional level (*e.g.* spatial and temporal risks). Future trends in statistical modeling of wind risk also include a further integration of spatial (and timely) autocorrelation as well as cross-correlations of different damaging agents and an analysis of the frequency of disturbances by means of spectral analysis of long-term time series (Hanewinkel *et al.*, 2008).

Future studies in fire risk modelling should consider the effect of adjacent stands (Agee *et al.*, 2000; Yoder, 2004) in defining the potential damage at the stand-level. At the landscape level, mapping the effect of forest growth on the long-term probability of fire occurrence can be a meaningful way to incorporate fire risk into spatially explicit decision support systems. In order to achieve that goal, it would be necessary to integrate knowledge about spatio-temporal analysis of fire regimes, fire ignition modelling, and fire spread principles, always having in mind that the temporal scale of this integration should fit with that of the forest growth modelling. For this purpose, the use of remote sensing technologies should be of great help to obtain information about the structure, condition and spatial distribution of forest fuels. For example LIDAR technologies, can be used to produce information about the geometry of forest fuels. LIDAR information can be combined with information obtained from imaging spectrometry to further discriminate fuel types and moisture conditions.

The effect of climate change on fire probability still needs more in-depth research. Fire probability will increase if the occurrence of severe drought and heat is more common as many studies assume (Ciais *et al.*, 2005). Currently this process is too complex to be directly included in models, as the interaction with changes in vegetation due to water stress must be taken into account.

Growth and yield models are the most widely applied model type in management planning. Integrating disturbances may improve these tools, however, they might not necessarily be the ideal choice, especially if large landscapes under dynamically changing environmental conditions are the subject of our planning activities. Including disturbances more fully in our management decision making may result in a paradigm shift where we do not «force» disturbances into the tools we have been using all along, but where we have to develop new tools such as landscape management models taking into account the spatial aspect in a much more explicit way.

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