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REVIEW

Assessing natural hazards in forestry for risk management: a review

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Abstract We address the problem of how to integrate risk assessment into forest management and therefore provide a comprehensive review of recent and past literature on risk analysis and modeling and, moreover, an evaluation and summary on these papers. We provide a general scheme on how to integrate concepts of risk into forest management decisions. After an overview of the risk management process and the main hazards in forests (storm, snow, insects, fire), the paper focuses on the principal methods used to assess risks from these hazards for commercial forestry. We review mechanistic models, empirical models, and expert systems and consider the needs for different spatial scales of risk assessment, from the regional to the single-tree level. In addition to natural hazards and their secondary effects, we deal with economic aspects of risk analysis. Monte Carlo simulations to deal with volatile timber prices and ways to include risk in classical Faustmann approaches are briefly discussed along with the integration of portfolio theory into forest management decision making and attitude toward risk. Special attention is paid to the implications for risk modeling under climate change.

This is one in a series of articles dedicated to Prof. Dr. Dr. h.c. Gerhard Oesten on the occasion of his 60th birthday.

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Introduction

Integrating risk into long-term forest management means applying the entire risk management process to decisions made about forest ecosystems. This process, which is well established in general business economics and in insurance mathematics (Haimes 2004), is comparatively undeveloped in forestry. With the goal of supporting a general modeling framework for integrating risk as a quantitative measure into long-term forest management, we review the methodologies and results from studies on the natural hazards most prevalent in European forests.

The risk management process comprises three major steps: (1) risk analysis or risk assessment, (2) risk handling, and (3) risk control. The first step is concerned with estimating the probability of a particular event and the severity of its associated outcomes. Whereas the term ‘analysis’ is often associated with industries (like insurance) in which outcomes are routinely denominated in monetary units, the term ‘assessment’ is more frequently encountered in sectors where outcomes may or may not be expressed monetarily. Because of its common use in ecology, we adopt the term ‘assessment’ for this review.

There are differences between financial systems and ecosystems that affect the steps of risk assessment and handling. Two in particular are relevant for forestry: first, the probabilities and effects of natural hazards can vary with spatial scale, and second, forest owners or stakeholders may not share the same aversion to risk (Hummel et al. 2008).

This means that the methods for assessing risk in forest ecosystems are not uniform and that opinions will differ about how to use risk assessment results in management decisions. There are, however, also similarities shared by financial systems and ecosystems, namely, that handling has to do with minimizing risk and calculating total costs while controlling involves evaluating the efficiency of the measures adopted as way to manage unwanted risk. Gardiner and Quine (2000) describe a process, with special emphasis on storm damage, that encompasses the steps of risk management: (1) after assessing risk, including identifying the type of hazard and estimating its likelihood, (2) alternative management strategies and their consequences, in terms of loss, are (3) implemented and evaluated (Gardiner and Quine 2000: 262).

In economic theory, risky decisions have known outcomes with known probabilities (Bannock et al. 1979). In contrast, an uncertain decision has a known number of outcomes, but the probability of each outcome is unknown. According to Kaplan and Garrick (1980), risk assessment tries to find answers to three fundamental questions: (1) what can go wrong; (2) how likely is it that it will happen; and (3) what are the consequences? In this review, we adopt a theoretical construct that accounts for the probabilistic nature of risk. A natural hazard is, for our purposes, an unexpected or uncontrollable natural disturbance event of unusual magnitude that negatively affects either the activities of people or people themselves (www.naturalhazards.org). Risk is a hazard quantitatively expressed in probabilistic terms (Holecy and Hanewinkel 2006). We adopt the expected value approach (Haimes 2004) as a second theoretical construct. The expected value approach is a procedure that quantifies the consequences of an event subject to risk by multiplying the probability of the event with its outcome, thus combining the answers to questions (ii) and (iii) by Kaplan and Garrick (1980). Although Haimes (2004) discusses the pitfalls of the unqualified application of the expected value approach, e.g. if events with low probabilities and catastrophic outcomes are compared with events of high probability but low outcomes, most of the risk modeling in forest ecosystems deals either with the derivation of probabilities for the main disturbances to forests (storm, fire, insects, snow) or with the quantification of the outcomes of different hazards. Heinimann (2002) enlarges the view on risk by citing Sandman (1987) who created the formula: “Risk = Hazard + Outrage” to consider risk aversion, which is a concept to understand the difference between the expected loss and person’s judgment of the loss as a negative utility (Nicholson 1995).

Integrating risk management into forestry will require methods that accommodate the dynamism inherent in ecosystems, particularly since climate change affects forest processes and structure by altering the frequency, intensity, duration, and timing of key hazards like fire, insects, and windstorms (Dale et al. 2001).

Important influences on forest biodiversity include natural, altered and new disturbance regimes, and alien and invasive species. Key challenges and opportunities specific to these threats and quantitative and probabilistic approaches to risk assessment are (i) endpoint selection and calculation of net value change, (ii) probability calculations and stochastic spatial processes, and (iii) evaluation of multiple interacting threats (Kerns and Ager 2007). A general framework for risk management under changing environmental conditions needs to take these aspects into account, especially since there are a multitude of interactions between several (abiotic and biotic) damaging agents (i.e. Radeloff et al. 2000; Kulakowski et al. 2003; Hanewinkel et al. 2008). In addition, the effects of the different hazards, not only on timber production but also on other forest functions such as protective functions and carbon sequestration, have to be considered. As shown by Kurz et al. (2008a), especially mass outbreaks of insects can lead to severe losses in carbon and can initiate feedback loops with the danger of further deteriorating the whole situation (Kurz et al. 2008b).

Figure 1 shows an overview on how to integrate risk aspects into forest management decisions in a schematic way:

The integration of risk has to take place in several steps:

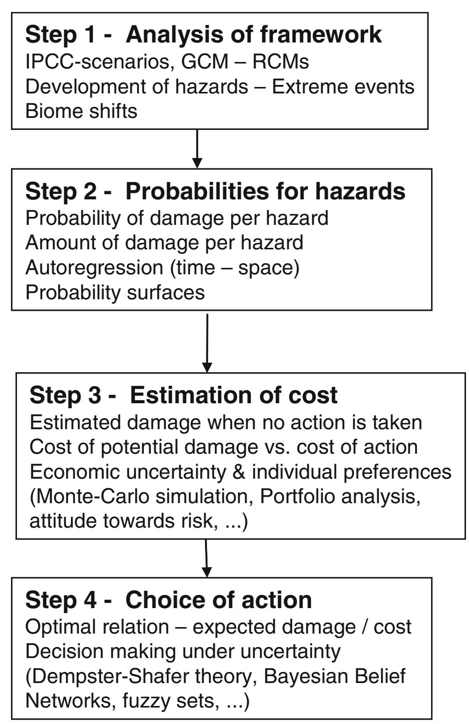

Fig. 1 Steps of the integration of risk into decision making in forestry. *RCM* regional climate model, *GCM* general circulation model

Step 1: analyze the framework for the development of different hazards under changing environmental conditions.

A first step toward integrating dynamism into risk models 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 precipitation or wind speed, 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 the forecast of extreme events. Most of the risk analysis that is undertaken so far under climate change is based on the assumption of a constant change of environmental parameters, e.g. a constant increase in temperature or decrease in precipitation over time. However, for some of the most important damaging agents like storm or fire, extreme events play a much more important role, and knowledge about probabilities and frequencies of potential hazards of this type is of crucial importance.

Within this step, the general situation in terms of risk for major tree species has to be assessed. Therefore, the progress that has been made in modeling plant species distribution under changing climatic conditions (Elith et al. 2006) has to be used and extended to the most important tree species in Europe. However, the shortcomings and uncertainties of these approaches have to be carefully evaluated (Heikkinen et al. 2006). As a first approach, simple bioclimatic envelopes maybe useful (Kölling 2007), but the implementation of very simplistic suitability tables for tree species under changing climatic conditions (Roloff and Grundmann 2008) seems to be not adequate in this respect as they lack dynamic and quantitative aspects.

Step 2: derive probabilities associated with different hazards for a given area.

As a general modeling approach for this step, forest damage of different kinds can be modeled in a three-stage procedure. Initially, the probability of damage has to be assessed. Subsequently, the amount of damage, given that a damage event occurred, must be described. Eventually, autoregressive techniques can be applied to correct the dependence of damage in time and space. Thus, total damage of a given type DT is given as the product of the probability of damage occurrence p(IT = 1) and amount of damage $D_{T|I_T=1}$, given it occurs, including an autoregressive component VART(p), and random noise ε (Hanewinkel et al. 2008: 2252):

$$\mathrm{DT} = \mathrm{p(IT = 1)} \cdot D_{T|I_T=1} + \mathrm{VART(p)} + \varepsilon. \quad (1)$$

This approach is a variant of the expected value approach that is very common in risk modeling (Haimes 2004) and is often used for risk assessment in forest planning models (Gadow 2000). As we will show, there is a wide array of statistical modeling techniques available for the different steps. So far, a multitude of case study-based, locally adapted risk models has been developed. They have to be replaced by models that are based on large-scale data (Schmidt et al. 2009) with a broader spectrum of application or by models that are better able to generalize (Gardiner et al. 2008). Ideally the models are built on a long-term and large-scale database such as national forest inventory data, level I/level II–monitoring data on a European scale or long-term observed research plots (Albrecht 2009). The large disturbances of the recent past should be used to build a common database for risk modeling and risk evaluation. On a European level, Schelhaas et al. (2003) provide a first attempt, which can be continued and enlarged by economic models and linked to similar efforts in North America. In order to take into account spatial aspects, 2-or 3-dimensional probability surfaces may be developed that give an overview of the distribution of probabilities in space. Such a surface may help in identifying centers of vulnerability and risk hot spots.

Step 3: estimate cost of potential damage in relation to risk management actions to be taken.

This step starts with the estimation of the cost of potential damage due to risk if no action is taken. This baseline scenario will then be compared to alternative scenarios with different intensities of risk management and the related costs. Goal of this step is the creation of a family of risk curves where the tradeoffs between the probability of an outcome of a damaging agent and the costs to manage the hazard and its effect on the possible outcome are depicted.

When taking into account economic aspects e.g. when estimating costs of actions or the effects on revenues, beside destruction probabilities that can be expressed in the discussed way, the risk of volatile timber prices should be taken into account. Monte Carlo simulation techniques seem to be a useful tool to integrate different risks in economic calculations (Dieter 2001; Knoke and Wurm 2006). As many authors have reported about subjective aspects of risk (Kaplan and Garrick 1980; Haimes 2004), it is crucial to take into account attitude toward risk, usually in the form of risk aversion (Plattner 2006). As a general economic background, the application of the theory of portfolio selection according to Markowitz (1952, 1959) and the theorem of capital separation according to Tobin (1958) by Knoke and Hahn (2007) are useful extensions of economics to forestry, but underlying assumptions about probability distributions need to accommodate the potential impact of rare events.

Koellner and Schmitz (2006) develop a conceptual framework, based on portfolio theory, that links levels of biodiversity and ecosystem services in the context of riskadjusted performance and show limitations of mean–variance analysis for ecosystem management using the example of grassland ecosystems. They point out the necessity for a new empirical research program to enhance progress in this field. Similar observations can be made for risk models in forestry.

Step 4: choice of action by decision making under uncertainty.

The final step is the choice of the appropriate action that shows the best relation between the expected cost of the damage in relation to the cost of the action itself. This has to include an analysis of the potential effect of an action (or non-action) on damage probabilities on neighboring forest areas. A crucial point in further risk management activities is the integration of uncertainty in this type of decision making. Therefore, a sound theoretical framework has to be built, using adequate theories like the Dempster-Shafer theory of evidence (Shafer 1976) or the theory of fuzzy sets (Zadeh 1965). A general overview of the theoretical background can be found in Beck (2005). Both theories have already been applied to problems of decision making in forest management. Lexer et al. (2000) use fuzzy sets to model ecophysiological suitability of tree species. Iliadis et al. (2002) perform a fire risk classification of forest areas in Greece with the help of fuzzy sets. The application of Bayesian Belief Networks (McCann et al. 2006) also seems to be a promising approach to identify the degree of uncertainty in decision making in ecosystem management. Otherwise, risk management strategies might be conceived with assumptions about frequency and severity of disturbance that: (1) assume that potential outcomes are known, (2) might be wrong about frequency or severity of potential outcomes, or (3) might have been right for current or past conditions but are influenced by changing conditions like climate.

When weighing risk assessment results in forest management, the process by which decisions are reached with the benefit of new information on probabilities and costs is not trivial. Individual people will likely have different perceptions of what the new information implies about risk and different levels of risk aversion, even if they can agree on what risk exists. This matters for contiguous forests in multi-ownership landscapes or for places in public ownership where citizens can participate in decisions.

To manage the risk to standing wood volume in forest ecosystems, it is necessary to quantify both the probability of a hazard and the outcome of it in terms of merchantable timber. Accordingly, we give an overview of the major disturbances in forests and their present and expected importance as hazards in Europe. We then describe some methods for assessing the risk to wood volume associated with these hazards and ways in which assessment results are used in decisions about handling risk. We then discuss the notion of risk in space and time and principle ways of handling risk including economic aspects of risk analysis.

Major disturbances to forests and their future importance

We focus on four major abiotic and biotic disturbances, with an emphasis on how they affect standing wood volume in European forests. Factors like frost, land slippage, and flooding are not included, but others such as pathogen increases are, because we think they will assume greater importance in the future.

Storm

Windstorms are a major disturbance in European forests. Rottmann (1986) provides a comprehensive review of storm damage to standing timber volume before 1980. Over the period 1950–2000, Schelhaas et al. (2003) report an estimated average annual storm damage of 18.7 million m3 of wood. Major storm events in Central Europe in the last three decades include volume damage of more than 100 million m3 (Vivien/Wiebke in 1990), almost 200 million m3 (Lothar/Martin in 1999) and around 75 million m3 (Gudrun in 2005). Since then, Europe has been hit by a series of unusually severe storms ("Kyrill" in the Northern part of Germany in January 2007, "Paula" in Austria in 2008, "Klaus" in France in 2009). Majunke et al. (2008) report increases both in timber damaged due to storms and in large-scale storms in Germany in the decades after 1960. The results of a model study in Sweden (Blennow and Olofsson 2008) dealing with storm damage under a changed wind climate for different climate scenarios do not show a clear tendency toward increased wind speeds in the future, which would cause higher damage to standing volume. While there is, to date, no clear evidence that the number of European storms with high wind speed has increased (Albrecht et al. 2009), two factors suggest increased storm damage in the future: (1) increased standing volumes and (2) climatic conditions that favor storm damage (increased winter precipitations with wet soils and a lack of winter frost) (Majunke et al. 2008). Hanewinkel et al. (2008) detected a periodicity in storm damage of 10–11 years in a long-term time-series in the southern Black Forest in Germany; however, the expected return times for severe storm events like "Lothar" seem to be much longer. Schütz et al. (2006) estimate the return time for such a storm on the stand level between 86 and 113 years for Norway spruce and between 357 and 408 years for European beech.

Two widely acknowledged predisposing factors for storm damage are tree species and tree or stand height.

Other important characteristics such as the relation between diameter and height (h/d-ratio), crown length, root rot, stand density and structure, and other site related characteristics like exposure, exposition, slope, water regime and soil texture also influence the risk of single trees or forest stands to mortality from windstorms. A comprehensive overview of the tested variables in the reviewed studies is given in Table 1. Although some of the listed characteristics–such as crown dimensions and h/d-ratio–are intercorrelated, the tree and stand characteristics appear more important than the site characteristics, based on the simple count of their appearance as damage predicting effects. Meteorological characteristics could not be considered in this context.

Snow

Damage from snow to the standing volume of wood is less important in Europe than windstorm damage. For example, Schelhaas et al. (2003) report around 1 million m3 of snow damage per year in Europe. This figure varies, however, with Nykänen et al. (1997) reporting that snow damage affects an estimated 4 million m3 of timber annually. Snow accumulation on trees is strongly dependent upon weather and climatological conditions. Temperature influences the moisture content and, therefore, the weight of snow, which in turn affects how much snow accumulates which then causes damage by breaking crowns and limbs. Wet snow is most likely to occur in late autumn or early spring. Geographic location and topography influence the occurrence of damaging forms of snow, with the highest accumulations typical in coastal locations and moderate to high elevations. Slope plays a less important role and the evidence on the role of aspect is contradictory. The occurrence of damaging events can vary from every winter to once every 10 years or so depending upon regional climatology. Hanewinkel et al. (2008) detected higher snow damage in a long-term time series every 15 years. Under an assumption of warming temperatures in northern latitudes, the risk of snow damage could increase, because the relative occurrence of snowfall near temperatures of zero could increase. Here, Kilpeläinen et al. (2009a), assume an increase in wet snowfall in winter time in the first phase but then expect a substantial reduction of the risk of snow damage toward the end of this century. In more southern latitudes, especially in low mountain ranges, snow damage is expected to decrease due to a general tendency toward less snowfall with increasing winter temperatures.

The severity of snow damage is related to tree characteristics. Stem taper and crown characteristics are important factors conferring stability in trees. Forest management can alter the probability of damage through choice of regeneration, tending, thinning and rotation (Nykänen et al. 1997). A summary of the literature identifies risk factors for snow damage in the following descending order: (1) conifers (for some authors, the evidence on species differences is less clear due to the interaction with location) (2) pole stands (young to mid-aged) (3) high h/d (this parameter is very well acknowledged, in contrast to windthrow), (4) wet/heavy snow (meteorological conditions: around 0°C, no wind; appropriate elevation asl for those conditions) (Petty and Worrel 1981; Rottmann 1985; Valinger and Lundqvist 1992; Slodicák 1995; Nykänen et al. 1997; Peltola et al. 1997; 1999; Jalkanen and Mattila 2000; Päätalo 2000; Müller 2002).

Fire

Fire is a major disturbance to forests all over the world. The estimated area affected by fire in Europe from 1961 to 2000 was at 213,000 ha with a damaged volume of 5.5 million m3 per year (Schelhaas et al. 2003). The costs of suppressing wildfires in the United States exceeded USD$1 billion for the first time in 2000 and did so again in 2002 and 2003 (Donovan and Brown 2007). There is evidence that the periodicity and severity of forest fires are influenced by the effects of climate (Swetnam and Betancourt 1998; Ehle and Baker 2003; Hessl et al. 2004). As temperatures increase, especially in the Mediterranean areas, an increase in fire activity can be expected. Fire is often related to drought, and after extreme years like 2003 drought appears as a disturbance that significantly affects forests. Ciais et al. (2005) estimate a 30% reduction in gross primary productivity over Europe after the year 2003. As with fire, extreme drought events are expected to increase with increasing temperatures. Even in northern latitudes, the risk of fire is expected to increase toward the end of this century (Kilpeläinen et al. 2009b).

Insects

After windstorms and fire, insects damage the most timber volume in European forests. According to Schelhaas et al. (2003) 2.9 million m^3 of damaged timber per year can be assigned to bark beetles (mainly *Ips typographus* (L.)) for the period 1950–2000. Other insects that historically caused large damage do not have the same impact as bark beetles nowadays (e.g. *Lymantria monacha* (L.), 135 million m3 in the period 1845–1865, Plochmann and Hieke 1986, ex Schelhaas et al. (2003). Bark beetle outbreaks are closely linked to storm events (Nykänen et al. 1997a, Bebi et al. 2003). Many studies confirm that insect outbreaks occur as a consequence of previous abiotic disturbances, especially for storm events (Rottmann 1986; Müller 2002; Becker et al. 2004; Hanewinkel et al. 2008). The vulnerability of trees that had previously suffered from snow

Table 1 Studies concerning storm damage and tested variables

Study	Tree and stand characteristics									Site characteristics	
Authors (year)	Species	Height (or age or diameter)	Crown properties	h/d-ratio	Density/ structure	Stand edge	Thinning characteristics	Root properties	Root rot	Orographic exposure (exposition/ slope)	Soil (water regime, soil texture)
Agster and Ruck (2003)					o	o					
Aldinger et al. (1996)	o	o			o		o	o			o
Cremer et al. (1982)			o	o	o		o				o
Cucchi et al. (2005)		o	o	o			o				o
Dobbertin (2002)	o	o			o		o			o	o
Dobbertin et al. (2002)	o	o			o		o			o	o
Dunham and Cameron (2000)		o	o	o							o
Dupont and Brunet (2008)					o	o					
Gardiner (1995)		o	o		o						
Gromke and Ruck (2008)			o		o						
Hanewinkel et al. (2008)	o	o			o		o			o	o
Hanewinkel (2005)	o	o			o					o	o
Hautala and Vanha-Majamaa (2006)					o	o					o
Hütte (1967)								o		o	o
König (1995)	o	o			o		o		o	o	o
Lanquaye-Opoku and Mitchell (2005)		o					o			o	o
Lohmander and Helles (1987)	o	o					o			o	o
Mayer (1988)										o	o
Mayer et al. (2005)	o	o								o	o
Moore et al. (2003)			o	o		o					
Morse et al. (2003)					o	o					
Müller (2002)	o	o	o	o	o		o		o		o
Nagel and Diaci (2006)	o	o									
Nicoll et al. (2005)					o			o		o	
Peterson (2000)	o	o							o	o	o

Table 1 continued

Study	Tree and stand characteristics									Site characteristics	
Authors (year)	Species	Height (or age or diameter)	Crown properties	h/d-ratio	Density/ structure	Stand edge	Thinning characteristics	Root properties	Root rot	Orographic exposure (exposition/ slope)	Soil (water regime, soil texture)
Peltola et al. (1999)	o	o	o	o		o	o	o			o
Quine (1995)					o		o			o	o
Saidani (2004)	o	o		o	o		o			o	o
Schmid-Haas and Bachofen (1991)	o	o	o		o		o	o	o	o	o
Schmoeckel (2005)										o	o
Schütz et al. (2006)	o	o		o	o		o			o	
Scott and Mitchell (2005)		o	o	o	o	o				o	o
Valinger and Fridman (1997)		o		o							
Wangler (1974)	o	o							o	o	o
Zhu et al. (2006)	o	o			o					o	o

damage is also subsequently increased for insect or fungal attacks (Nykänen et al. 1997). Forest stands showed a higher vulnerability toward bark beetle outbreak after fires and vice versa (Kulakowski et al. 2003), and there was a clear interaction between insect defoliation and fire on a landscape level (Radeloff et al. 2000).

There is evidence that an already damaged forest stand shows a higher vulnerability toward further damage than an undamaged one (Hinrichs 1994; König 1995). The total damage caused by the gale "Lothar" in southwest Germany added up to more than 30 million m3 of timber (FVA 2003). In the aftermath of this storm, more than 7 million m3 of salvage cuttings followed due to bark beetle activity. However, these patterns of interaction between disturbance agents like fire and spruce beetles (*Dendroctonus rufipennis*) (Bebi et al. 2003) have been difficult to quantify in magnitude and over time and, therefore, to incorporate into risk models. Seidl et al. (2007) developed and integrated a sub-model of disturbances by *Ips typographus* in an existing hybrid forest patch model. Calculating cross-correlation between storm and insect damage, Hanewinkel et al. (2008) found out that storm events typically provoke subsequent insect outbreaks between 2 and 6 years later. Klimetzek and Yue (1997) found a distinct cyclic pattern for bark beetles on spruce in southern Germany with intervals of 5–8 years between peaks for major damage and a common cyclical pattern for pine insects with recurrent periods of 10.2 and 32.3 years.

The degree of disturbance caused by insects in North America exceeds by far that of Europe. Kurz et al. (2008b) report on an area infested by mountain pine beetle (*Dendroctonus ponderosea*, Hopkins) in western Canada that cumulatively reached >100,000 km^2 by the year 2006 and an additional large area infested by spruce budworm (*Choristoneura fumiferana*) in eastern Canada. Together with a strong impact of wildfires, natural disturbances have turned Canada's forests, which cover around 7% of the world's forest area, from a source to a sink of carbon dioxide (Kurz et al. 2008a). With increasing temperatures insect damage, especially bark beetle damage is expected to increase. Insects now living in warmer areas are supposed to move into colder areas. One example for such a shift of a habitat area is Oak Processionary moth (*Thaumetopoea processionea)*, a moth infesting central European oak species, that has for a long time been rather negligible in Central European forests. In the last two decades with increasing temperatures and drought, this insect that affects human health (Bogenschütz et al. 1986), has populated large areas and has been subject to several mass outbreaks. There will also be "losers" among insects under a predicted climate change. Species like *Lymantria spec*. in Europe that showed mass outbreaks in the past will suffer from higher winter temperatures and are expected to lose importance as damaging factors.

Pathogens

No confirmed figures exist for the amount of damage from fungi on standing wood volume in Europe; however, pathogens influence forest management. Metzler and Kublin (2003) estimate that in southwest Germany an annual loss of 10 Million Euro is due to the infection of Norway spruce with *Heterobasidion annosum*. This fungus causes root and stem rot that leads to decreases in timber quality and the share of valuable lumber grades and to losses in harvestable timber volume and an increase of harvesting costs. The risk of infections increases when Norway spruce is established on former non-forested land, on sites containing free $CaCO_3$ in the upper soil, with high stand densities and thinnings taking place in autumn and after injury to root collars and roots (Wangler 1974; Schmid-Haas and Bachofen 1991; König 1995; Müller 2002; Metzler and Kublin 2003). A general overview on *Heterobasidion annosum,* its biology, impact and management can be found in Woodward et al. (1998). Recent investigations by Möykkynen and Pukkala (2009) deal with the optimization of the management on *Heterobasidion*-infected sites.

A specific risk with fungi arises when pathogens are being introduced in new areas with potential new hosts. This may lead to epidemics that can change whole landscapes. Prominent examples for these epidemics are the decline of *Ulmus spec.* due to Dutch elm disease (*Ophiostoma ulmi*) all over Europe, in North America the destruction of large forest areas with chestnut (*Castanea dentata*) in the Appalachians due to chestnut blight (*Cryphonectria parasitica*) or of *Pinus strobus* due to *Cronartium ribicola* (Heiniger 2003). With an increase of global traveling and exchange of goods, the risk of this type of invasion of pathogens–including invasive species of plants and insects–will continue to increase. With increasing temperatures and warmer and moister winters, the risk of infections with fungi is expected to increase. In Europe, tree species like *Alnus spec.,* but also *Fagus sylvatica,* are more and more affected by *Phytophtora spec.* (Brasier and Jung 2003). On the west coast of the United States of America, *Phytophtora ramorum* causes sudden oak death over extensive areas (Frankel et al. 2008). There are risks such as e.g. pinewood nematode or cherry leaf roll virus, which might be of increasing importance in the future. In order to keep forest owners informed about the actual status of pests, organizations such as the European and Mediterranean Plant Protection Organization maintain quarantine or alert lists (EPPO 2009).

Pests and diseases are particularly linked to structure and species composition of the forests they are connected with. Mainly highly productive species such as Norway spruce have been introduced to many sites all over Europe beyond their original range and are now subject to increasing biotic risks especially when grown under conditions of monocultures (Spiecker et al. 2004). This situation is expected to aggravate with increasing temperatures. Other species like Douglas fir have been "imported" to Europe without their specific antagonists, which might be a mid-term advantage when introducing them today. In the long run it will be important to monitor how especially

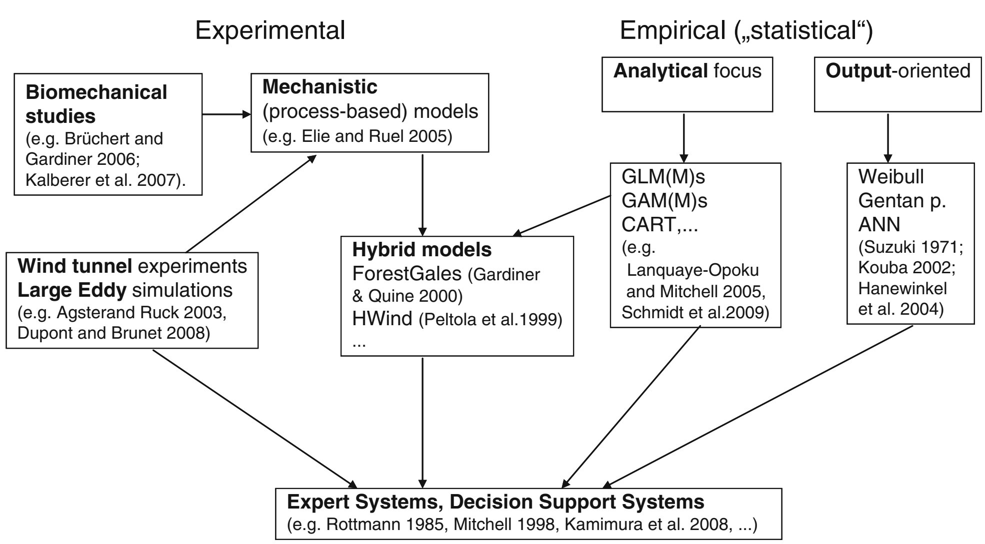

Fig. 2 Overview of methodological approaches for risk assessment and modeling using the example of storm damage. *GL(M)Ms* generalized linear (mixed) models, *GA(M)Ms* generalized additive (mixed) models, *CART* classification and regression trees, *ANN* artificial neural network

biotic hazards have to be subject to risk management under changing environmental conditions.

Methods for assessing and modeling risk

Figure 2 gives an overview of the main methodological approaches to model storm risk. In our review, we include mechanistic models, together with those that are a hybrid between empirical and mechanistic models, in the general category of experimental models (Fig. 2).

Experimental methods: mechanistic models

Windtunnel studies as well as large eddy simulation studies give further insight into aerodynamic properties of forest canopies and the airflow and turbulences at forest edges. They were originally designed to reconstruct the relationship between wind gusts, pressure coefficients and small-scale model forests under experimental conditions, since findings about gusts–as the most damaging winds–are almost impossible to derive under field conditions, especially under stormy ones (Fraser 1964; Chen et al. 1995; Gardiner et al. 1997; Agster and Ruck 2003; Brunet et al. 2003; Morse et al. 2003; Dupont and Brunet 2008; Gromke and Ruck 2008).

There are other investigations dealing with mechanistic/mechanical properties concerning modulus of rupture, bending moments, tree swaying (e.g. Guitard and Castera 1995; Milne 1995; Brüchert et al. 2000; Brüchert and Gardiner 2006; Kalberer et al. 2007) that are meant to describe vulnerability of trees toward storm damage based on wood or tree properties. All these basic experimental approaches served as a basis for the development of mechanistic models.

An overview of mechanistic models, also sometimes referred to as “process-based” models, with a special emphasis on wind damage is given by Gardiner et al. (2008). The purpose of mechanistic storm damage models is to analyze physical processes behind stem breakage or turnover of trees due to wind and/or snow and then to use the principles found in the processes such as critical wind speed (CWS) for management prescriptions. Mechanistic models such as HWIND (Peltola et al. 1999), ForestGALES (Gardiner and Quine 2000) or WINDA (Blennow and Sallnäs 2004) have been developed as generic tools for risk assessment and—in the case of HWIND and ForestGALES—tested against each other (Gardiner et al. 2000). Both of these tools require test arrangements such as tree pulling, dynamic rocking or wind tunnel experiments and are primarily meant to be used to evaluate the risk linked to a particular regime of management. The main idea behind these models is to develop Wind Risk Management tools (WRM) that compare model outputs such as CWS to overturn or break trees with the expected wind speed derived from local climate models and to calculate the probability of exceeding the CWS occurring at the geographic location of the trees. As most of these models are not able to depict fully the physical processes behind stem-breakage or turnover they contain empirical aspects and are therefore often called hybrid empirical/mechanistic models. The critical empiricism of these models is usually the derivation of a gust factor (Gardiner et al. 2008). Other investigations dealing with mechanistic approaches for storm damage assessment are: Nicoll et al. (2005), Mason (2002), Cucchi et al. (2003), Ancelin et al. (2004), Cucchi et al. (2005), Achim et al. (2005), Elie and Ruel (2005),

Component models integrate the risk assessment on different levels, from single trees to stands and whole regions (Talkkari et al. 2000). They usually combine mechanistic models with meteorological components such as wind speed or airflow modeling (König 1995; Lekes and Dandul 2000) and thereby seek to improve the performance of the risk assessment. An overview of different model approaches for risk assessment until the end of the 1990s that is accessible via the World Wide Web is given by Miller et al. (2000).

Differences between fire management in Europe and North America influence the focus of model development. In the United States and Canada, for example, the strategy for forest fire management has shifted from fighting all fires to letting some fires burn (e.g., Shea 2008). This strategic shift is being prompted by increases in the costs of suppression and the area burned (Donovan and Brown 2007) and advances in understanding the role of fire and other disturbances in forest ecosystems (e.g.: Parker et al. 2006; Spies et al. 2006). A direct outcome is an increasing emphasis on coordinated, interagency investment (e.g.: JFSP 2007) in mechanistic models and in decision support systems that can aid forest managers in predicting fire behavior and effects and in identifying assets at risk over extensive geographic areas (Andrews 2007). In contrast, fire management strategies in more densely populated Europe emphasize suppression and, because ignition sources are often human rather than lightening, include demographic information in model development and decision support systems (Catry et al. 2009).

There are mechanistic models for pests and diseases such as CLIMEX that are able to describe the potential development of a large amount of biotic damaging agents under changing environmental conditions and that are already integrated in expert systems for pest risk assessment (Sutherst et al. 2009).

Empirical models

There are two general groups of empirical or statistical models which can be divided according to their focus: the first group on analysis and the second on output. Models in the first group aim at finding out significant predictors related to the type of damage to be modeled.

Analytical models

Wind The predictors that are found to be significant in the models such as height, tree species, height/diameter ratio or site qualities in the case of wind damage are then used for expert systems or directly for management prescriptions. Ideally, these predictors (often called independent variables, although many of them are not really independent) can be expressed in terms of critical values, e.g. if dominant height of a forest stand exceeds a critical level, the risk of wind damage increases exponentially. The models of this first group, often called "statistical models" use data of historical damage occurrences, large-scale inventory data or regionally limited case study data to predict future risk events or to classify forests according to their vulnerability toward risks. The standard tool to predict risk for forests or forest stands is usually a variant of a regression model. Thereby, the logistic regression model has been utilized as the most common statistical approach to examine wind damage to forests (Hinrichs 1994; König 1995; Fridman and Valinger 1998; Valinger and Fridman 1999; Jalkanen and Mattila 2000; Mitchell et al. 2001; Lanquaye-Opoku and Mitchell 2005; Schütz et al. 2006). This technique was mainly successful when it was applied for numerically analyzing influential factors causing wind damage. Hanewinkel et al. (2004) use the logistic regression as a baseline model to be compared with an artificial neural network. The different factors that were analyzed in the different studies vary widely.

A lot of progress has been made in the design of statistical models. Instead of standard regression approaches that often show problems with heteroscedasticity and independence of observations or predictors, additive and mixed modeling techniques have been applied to storm damage analyses. Recently, models that integrate non-parametric smoothers in regression models such as generalized additive models (GAM) were developed for risk modeling. Schmidt et al. (2009) use a GAM to model spatial trends in the damage caused by the storm "Lothar". Especially compensating the lack of independence of observations, mixed modeling techniques such as generalized linear mixed models (GLMMs) or generalized additive mixed models (GAMMs) 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 (Singer 1998; Collett 2003; Browne et al. 2005; Littell et al. 2006; Nothdurft et al. 2006; Meng et al. 2008). Classification and regression trees (CART) can be used in risk modeling for an explorative data analysis of large databases in order to identify significant predictors. As quite robust and easy-to-use analysis methods they do not require distributional assumptions and they can accommodate correlated observations and missing values (Therneau and Atkinson 2002, Venables and Ripley 2002. pp. 251–270, Maindonald and Braun 2007, pp 259–280). Due to their rugged character the CART methods are often referred to as 'machine learning' and 'data mining' methods. For example, Dobbertin and Biging (1998) used a binary classification tree to predict mortality for ponderosa pine (*Pinus ponderosa*) and white fir (*Abies concolor*) and Kamimura et al. (2008) integrate regression trees in a decision support system to reduce storm damage on sugi (*Cryptomeria japonica)* forests in Japan.

As a classifier for wind damage to forests, however, linear regression models did not always perform as well as one might hope. Their ability to predict damage to forest stands decreases, especially when the number of undamaged and damaged stands in the sample data set to which the logistic regression model is fitted, differs significantly. The study of Fridman and Valinger (1998), for example, showed that with the specific data set used in that investigation, the predicted proportion of damaged plots was highly over-estimated. Although the best model, using tree, stand, and site variables, correctly classified 81.1% of the undamaged and 81.8% of the damaged plots, it over-predicted the proportion of damaged plots (21.3%), compared to the observed proportion of 3.8% (Fridman and Valinger 1998: 348). The low performance of the logistic regression models necessitates efforts to find new approaches to classify wind damage to forests. The predictive power of the model used by Schütz et al. (2006) was rather low as well. One of the reasons for the sometimes poor performance of statistical models in predicting risk classes may be that it is difficult to combine the analytical abilities of a model in finding significant predictors and the ability of the model to generalize and deliver a reliable prognosis. A general problem when using data from a single damaging event is the validation of the data with an independent dataset. After huge storm events it is often difficult to mobilize workforce to assess damaged trees before they are harvested as this type of work is assigned with a rather low priority in the forest enterprise and access to the damaged areas for scientists is limited.

Fire The fire growth simulation model FARSITE (Finney 1998) uses spatial information on topography and fuels along with weather and wind files to project short-term (2–3 days) fire behavior, while FlamMap (Finney et al. 2003) is a fire behavior mapping and analysis program that computes potential fire behavior characteristics (spread rate, flame length, fireline intensity, etc.) over an entire FARSITE landscape for constant weather and fuel moisture conditions. LANDFIRE (Rollins and Christine 2006) produces geospatial data products that describe existing vegetation composition and structure, potential vegetation, surface and canopy fuel characteristics, historical fire regimes, and fire regime condition class. With inputs of fuel characteristics, lighting patterns, fuel conditions, and meteorological attributes, CONSUME outputs fuel consumption and emissions by combustion phase. FSPro (Fire Spread Probability) is a spatial model used to calculate the probability of fire spread over a specified time period from a given geographic point. Model inputs include forest surface fuels and canopy characteristics, plus site aspect, elevation, and slope. Combining the FARSITE or LANDFIRE data layers (crown base height, bulk density, etc.), current weather projections, historical weather scenarios, fuel moisture classifications, fire history, and wind speed and direction, FSPro can push fire projections out as far as 30 days. The model is designed for situations when managers do not have a high level of confidence in weather projections, or for periods when long-term weather projections are not available.

Models predicting the probability of fire useful for forest management typically represent easily measurable forest characteristics like elevation, tree size, stand structure and species composition. For example, in a model developed by Gonzalez et al. (2006) the probability of a forest stand to burn increased with lower altitudes, smaller diameters, larger basal areas, higher proportion of coniferous species and increasing variation in tree diameter. Including previous fire events as an explanatory variable in a Poisson model in order to predict forest fires significantly increased the reliability of the incorporated fire index (Mandallaz and Ye 1997). There is a relationship between the spatial distribution of forest fuels and fire hazards. Therefore, Gonzalez et al. (2005) include fire risk into numerical forest planning by taking into account the spatial distribution of risky and non-risky forest stands.

Insect Apart from wind and fire, most of the other damaging agents are modeled using empirical approaches. Insect damage is more difficult to assess and model as both vulnerability of the trees as well as the development of the insect population must be taken into account. The approach that is applied is a combination of a pre-disposition assessment together with a thermo-energetic model. Seidl et al. (2007), in order to model the susceptibility of stands to damage by *Ips typographus*, combine a comprehensive assessment system of stand and site related predisposition (PAS) (Netherer and Nopp-Mayr 2005) with a phenology model of *Ips typographus* (Baier et al. 2008). This approach is mostly empirical but has mechanistic elements. Predictive risk models for the mountain pine beetle (*Dendroctonus ponderosae*) currently rely on stand susceptibility indices, but efforts are underway to incorporate ecological knowledge about infestation dynamics (Nelson et al. 2008).

Output-oriented empirical models

The second group of empirical models has a focus on output. This group of models either uses statistical approaches with a very limited set of predictors to derive transition probabilities (Suzuki 1971) or they rely on nonparametric approaches such as artificial neural networks (Hanewinkel et al. 2004; Hanewinkel 2005), that do not offer any analytical opportunities due to a black-box character but instead have other advantages compared to parametric models (such as a robustness against redundant or "noisy" data). Neural networks have also been used to model biome shifts (Guisan and Zimmermann 2000). A classic deterministic approach within this second group of empirical models is to derive transition probabilities for age classes of stand types on defined site units. The theory behind these models has mainly been developed by Suzuki (1971) based on the theory of Markov- chains. This approach has been widely applied in eastern Germany to derive survival probabilities for age classes of forests dominated by Norway spruce (Kurth et al. 1987) and has lead to a modification of the normal forest model into the so-called "target forest model" (Kurth et al. 1987; Klocek and Oesten 1991). Transition probabilities are often modeled with the help of probability distributions. A practical application of the Weibull probability distribution, in the analysis of forest management risk has already been demonstrated by Kouba (2002) and Gadow (2000). Kouba (2002) expresses the uncertainty at a given age with the aid of the theory of random processes by the probability of destruction of a forest stand or an age class. The focus of this approach is on estimation of the mean number of years of future forest life in correlation to the current age (Kouba 2002: 211). A similar model has been used as a basis for an insurance model by Holecy and Hanewinkel (2006).

Table 2 shows a summary overview of risk assessment and modeling approaches by methodological category, type of hazard, specific aspects and region.

Integrating knowledge of risk using expert- or decision support systems

Looking back at the literature on risk assessment of the last decades, one major problem is obvious: there are only a

Table 2 Studies of multiple hazards, methodological category, special features, region

Authors (year)	Methods–category	Hazard	Special features	Region
Abetz and Kramer (1976)	Empirical–analytical	Storm	Descriptive statistics	D
Achim et al. (2005)	Experimental	Storm	Mechanistic modeling	Quebec, CDN
Agster and Ruck (2003)	Experimental	Storm	Wind tunnel	D
Aldinger et al. (1996)	Empirical–analytical	Storm	Root architecture	D
Baier et al. (2008)	Phenological	Insects	Thermo-energetic model	A
Blennow and Sallnäs (2004)	Experimental	Storm	Mechanistic modeling–WINDA	S
Brüchert and Gardiner (2006)	Empirical	Storm	Biomechanical wood properties	UK
Brüchert et al. (2000)	Empirical	Storm	Biomechanical wood properties	D
Chen et al. (1995)	Experimental	Storm	Wind tunnel, surface roughness	BC, CDN
Cremer et al. (1982)	Empirical–analytical	Storm	Review–descriptive statistics	NZ
Cucchi et al. (2003)	Experimental	Storm	Mechanistic modeling	F
Cucchi et al. (2005)	Experimental	Storm	Mechanistic modeling, ForestGALES_France, growth model CAPSIS	F
Dobbertin (2002)	Empirical–analytical	Storm	Classification and Regression Trees	CH
Dobbertin and Biging (1998)	Empirical–analytical	Storm	Classification and Regression Trees	CH
Dobbertin et al. (2002)	Empirical–analytical	Storm	Descriptive statistics	CH
Dunham and Cameron (2000)	Empirical–analytical	Storm	Statistical modeling, biomechanical wood properties	UK
Dupont and Brunet (2008)	Experimental	Storm	Large eddy simulation, gust factors	F
Elie and Ruel (2005)	Experimental	Storm	Mechanistic modeling, ForestGALES_Quebec	Quebec, CDN
Finney et al. (1998)		Fire		
Finney et al. (2003)		Fire		
Fraser (1964)	Experimental	Storm	Wind tunnel, surface roughness	UK
Fridman and Valinger (1998)	Empirical–analytical	Storm, snow	Generalized Linear Model	S
Gadow (2000)	Empirical–output-oriented	General risk	Weibull transition probability	
Gardiner (1995)	Empirical–analytical	Storm	Swaying and movement of 4 trees	UK
Gardiner and Quine (2000)	Experimental	Storm	Review	UK
Gardiner et al. (2008)	Experimental	Storm	Review of mechanistic modeling	Northern hemisphere
Gardiner et al. (2000)	Experimental	Storm	Mechanistic modeling–HWIND and ForestGALES	UK, Scandinavia
Gardiner et al. (1997)	Experimental and empirical	Storm	Field assessments and wind tunnel	UK
Gonzalez et al. (2006)	Empirical–analytical	Fire	National forest inventory data	E
Gromke and Ruck (2008)	Experimental	Storm	Wind tunnel–aerodynamic modeling	D
Guitard and Castera (1995)	Experimental	Storm	Simulation analysis, tree swaying	F
Hanewinkel (2005)	Empirical–output-oriented	Storm	Artificial Neural Network	D
Hanewinkel et al. (2008)	Empirical–analytical	Storm, insects	Generalized Linear Mixed Model	D
Hanewinkel et al. (2004)	Empirical–output-oriented	Storm	Artificial Neural Network	D
Hautala and Vanha-Majamaa (2006)	Empirical–analytical	Storm	Retention patches	SF
Holecy and Hanewinkel (2006)	Empirical–output-oriented	Storm and general risk	Weibull transition probability	D
Hütte (1967)	Empirical–analytical	Storm	Descriptive statistics	D
Iliadis et al. (2002)	Fuzzy sets	Fire	Risk classification	GR
Jalkanen and Mattila (2000)	Empirical–analytical	Storm, snow	Generalized Linear Model	SF

Table 2 continued

Authors (year)	Methods–category	Hazard	Special features	Region
Kalberer et al. (2007)	Experimental	Storm	Mechanistic modeling and biomechanical wood properties	CH
König (1995)	Empirical–analytical	Storm	Generalized Linear Model	D
Kouba (2002)	Empirical–output-oriented	General risk	Weibull transition probability	D
Lanquaye-Opoku and Mitchell (2005)	Empirical–analytical	Storm	Statistical modeling, portability	BC, CDN
Lohmander and Helles (1987)	Empirical–analytical	Storm	Statistical modeling–Generalized Linear Model	DK
Mandallaz and Ye (1997)	Empirical–output-oriented	Fire	Statistical modeling–Poisson models	EUR
Mason (2002)	Experimental	Storm	Mechanistic modeling–review	UK
Mayer (1988)	Empirical–analytical	Storm	Expert system	D
Mayer et al. (2005)	Empirical–analytical	Storm	Statistical modeling–Generalized Linear Model	EUR
Mickovski et al. (2005)	Empirical–analytical	Storm	Statistical modeling–expert system	UK, F
Milne (1995)	Experimental	Storm	Mechanistic modeling	USA, CDN
Mitchell et al. (2001)	Empirical–analytical	Storm	Statistical modeling–Generalized Linear Model	BC, CDN
Morse et al. (2003)	Experimental	Storm	Simulation analysis, multi-methodology	UK
Moore et al. (2003)	Empirical–analytical	Storm	Review, retention system	USA, CDN
Müller (2002)	Empirical–analytical	Storm, root rot	Statistical modeling–Generalized Linear Model	D
Nagel and Diaci (2006)	Empirical–analytical	Storm	Statistical modeling–Generalized Linear Model	SLO
Nelson et al. (2008)	Phenological–mechanistic	Insects	Meta-analysis	USA, CDN
Netherer and Nopp-Mayr (2005)	Empirical	Insects	Predisposition assessment system	High Tatra
Nicoll et al. (2005)	Experimental	Storm	Mechanistic modeling–gust factor	UK
Nielsen (1990)	Experimental	Storm	Mechanistic modeling—anchorage moment	D, DK
Nilsson et al. (2004)	Empirical–analytical	Storm	Short communication–descriptive statistics	S
Nykänen et al. (1997)	Empirical–analytical	Snow	Descriptive statistics	EUR
Päätalo (2000)	Empirical	Snow		SF
Peltola et al. (1999)	Experimental	Storm, snow	Mechanistic modeling–HWIND	SF
Petty and Worrel (1981)	Experimental	Snow, storm	Biomechanical wood properties	UK
Quine (1995)	Empirical	Storm	Review, probabilistic vs. deterministic systems	UK
Rollins and Christine (2006)		Fire		
Rottmann (1985, 1986)	Empirical–analytical	Storm, snow	Expert system	D
Saidani (2004)	Empirical–analytical	Storm	Statistical modeling–airborne survey	D
Schmid-Haas and Bachofen (1991)	Empirical–analytical	Storm	Statistical modeling	CH
Schmidt et al. (2009)	Empirical–analytical	Storm	Statistical modeling–Generalized Additive Model	D
Schmoeckel (2005)	Empirical–analytical	Storm	Statistical modeling–orographic focus	D
Schütz et al. (2006)	Empirical–analytical	Storm	Statistical modeling–Linear Model	CH
Scott and Mitchell (2005)	Empirical–analytical	Storm	Statistical modeling–Generalized Linear Model	BC, CDN
Seidl et al. (2007)	Empirical	Insects	Phenology model and predisposition assessment	A
Slodicak and Novak (2006)	Empirical–analytical	Storm, snow	Descriptive statistics	SLO
Talkkari et al. (2000)	Experimental	Storm	Mechanistic and airflow modeling	SF
Valinger and Fridman (1999)	Empirical–analytical	Storm, snow	Statistical modeling–Generalized Linear Model	S
Wangler (1974)	Empirical–analytical	Storm	Descriptive statistics	D
Zhu et al. (2006)	Empirical–analytical	Storm, snow	Statistical modeling	CN

few studies covering large areas and working on a comprehensive database that allows for a generalization of the findings for larger areas. One exception might be the study by Schmidt et al. (2009), covering the whole Southwest of Germany and working on the national forest inventory database. Most of the studies work on a very regionally limited spatial level and only cover one major damaging event such as a storm or a catastrophic snow breakage. In order to make the findings of these studies available to decision makers and to integrate the knowledge on risk assessment, expert systems have been designed. For the German-speaking community, Rottmann (1985, 1986) has developed two expert systems for storm damage and snow damage to forests. The storm damage systems is based on a literature review for storm damage in Europe from 1802 to 1985 and provides for a scheme to evaluate the risk of storm damage including 18 elements (height, crown length, exposure) in 4 categories: climate, site, stand, management. The risk for each element is expressed by scores and the importance of each element is expressed by weights. The output of the system is the grade of vulnerability reaching from stable to unstable. The system for snow damage provides for a literature review of snow damage in Europe from 1865 to 1983. The principle of the system is again a scheme to evaluate the risk of snow damage including seven elements (tree species, age, h/d, crown length, mixture, plantation spacing, thinning). The risk for each element is expressed by scores and the output is a grade of vulnerability calculated as the sum of scores reaching from no danger to very high danger.

Mitchell (1998) has developed a diagnostic framework for windthrow risk estimation in Canada that is very similar to an expert system. Berger and Dorren (2007) present a tool that calculates the Probable Residual Rockfall Hazard (PRH) under a forested slope. Another two examples of decision support tools in the field of risk assessment are the British “Windthrow Hazard Classification” (Quine 1995) and the Slopes Decision Support System (SDSS) by Mickovski et al. (2005). They both provide the user with an estimation of windthrow in the form of binary classification. They can be seen as expert systems due to their character involving qualitative risk assessment, although the SDSS contains biomechanical features.

Risk in space and time

Scales of risk analysis

The level of risk models reaches from single tree over forest stands to forest enterprises, regions and whole landscapes. Single tree models can be developed based on permanent plots of national forest inventories (Jalkanen and Mattila 2000; Schmidt et al. 2009). However, inventory plots do not allow identifying the influence of management strategies as this is not reflected in the systematically spaced plots. A general problem with many statistical models arises due to the fact that they deal with regionally limited case studies and, therefore, are difficult to generalize outside the area where they have been developed (Hinrichs 1994). In order to do so, they usually have to be re-parameterized using a new dataset. The ability of mechanistic models to generalize is usually better (Gardiner et al. 2008); however, to enlarge the coverage of the models to new tree species or completely different site conditions requires considerable investments in new experiments. The standard level of risk assessment is the forest stand level (Hinrichs 1994; Hanewinkel et al. 2004), as this is in many areas the level where forests are managed. However, reliable data on risk on a forest stand level are hard to get. Often single-tree level risk models are therefore applied to stands that are characterized by a mean tree (Gardiner and Quine 2000), which is in a way unsatisfying as interactions between trees (Schelhaas et al. 2007) are not taken into account. Transition probabilities are usually applied on the level of sustainably managed working circles or model stands and thus are often used to evaluate the influence of risk on economic parameters or management prescriptions such as rotation age (Dieter 2001).

Databases

Usually the usage of a risk model is determined by the database that was available to parameterize the model. There are many retrospective studies dealing with long-term reconstructions of disturbances such as fire; however, investigations concerning forest risks based on long-term historical data sets of disturbances series are rare. Records of storm damage in Swedish forests over a century are reported (Nilsson et al. 2004) and a quantitative overview of the role of natural disturbances in European forests from 1850 to 2000 is presented by Schelhaas et al. (2003). There are extensive literature reviews until the middle of the 1980s for snow damage to conifers (Rottmann 1985) and for wind and storm damage (Rottmann 1986). However, a model incorporating interaction in time was not built based on their data. Long-term time-series of fire disturbances were investigated for Ponderosa pine (Ehle and Baker 2003) and were linked to climatic variability (Hessl et al. 2004). Repeated fire disturbances were found to determine landscape diversity (Romme 1982). Multicentury, tree-ring reconstructions of drought, disturbance history, and tree demographes revealed climatic effects across scales and ecological responses such as regionally synchronized fires, insect outbreaks and changes in tree demography (Swetnam and Betancourt 1998). Spatial and temporal patterns of fire, snow avalanches and spruce beetle outbreaks were investigated in a long-term time series using dendrochronological techniques (Veblen et al. 1994).

Permanence instead of absolute or relative stability

A promising approach that enlarges the perception of risk management is proposed by Cordonnier et al. (2008). They apply the concept of permanence instead of system equilibrium to the notion of risk. Permanence describes the capacity of a system to remain within a range of satisfactory values. As there is no absolute stability, it is indeed more important to keep a system for the longest possible time in a risk-minimized state, meaning in a state where the system is able to cope with the disturbances to be expected. According to Cordonnier et al. (2008) permanence appears to be a better alternative than temporal indices such as temporal stability or temporal variability because permanence concentrates on meaningful periods and not simply on a general tendency. Thorsen and Helles (1998) use a model to analyze the effect of changing resistance and ability to recover from disturbances caused by thinnings, measured as changes in the susceptibility to windthrow. They found that a decrease in resistance or resilience makes it optimal to increase the number of thinnings, while at the same time making each thinning less intense.

Temporal: spatial autocorrelation

Kerns and Ager (2007) see in the inclusion of stochastic spatial processes one major challenge of quantitative risk assessment. Schmidt et al. (2009) include spatial autocorrelation in their storm damage model. Many studies dealing with optimal spatial forest management under risk (e.g. Meilby et al. 2001) point at the necessity to include spatial aspects into risk assessment. Temporal autocorrelation is taken into account in the model by Hanewinkel et al. (2008). Indeed, the introduction of spatial and temporal autocorrelation in risk models seems to be a major issue of risk assessment. Spatial aspects are also more and more important in economic analyses (Anselin 1988) and will therefore be of increasing importance when valuing different risks.

Risk handling

Cause-oriented measures

Measures of risk handling can be divided into cause-oriented or effect-oriented. Cause-oriented measures aim either at avoiding damage by abandoning risk-prone activities (risk avoidance) or at reducing the probability of damage by adopting preventive measures (risk prevention). Risk avoidance in forest management could mean stopping harvesting or thinning activities due to a temporary increase in the probability of damage (Nielsen 1995). Risk prevention includes all measures aiming at increasing the stability of forests such as early thinnings to influence the h/d-value of the trees (Abetz and Kramer 1976; Slodicak and Novak 2006), or choosing tree species that are less prone to abiotic or biotic damage. Thus, the development of bioclimatic envelopes for major tree species under different climate scenarios (Kölling 2007) can be looked upon as a way to support practitioners in risk prevention. The possibilities of directly influencing damage probabilities with the help of preventive measures are limited. Examples include removing bark beetle infested trees to reduce additional insect damage or treating stumps to avoid infection with *Heterobasidion annosum.* According to Metzler and Kublin (2003) 230,000 ha of spruce forests are treated annually in Europe with fungicides against *Heterobasidion annosum*. From an economic point of view, Ehrlich and Becker (1972) were the first to be interested in the mechanisms of risk prevention that they called self-insurance and self-protection. An approach to apply these ideas to the forestry sector can be found in Brunette (2009).

There is a long tradition in Germany to optimize the "spatial order" of forest areas, which means that foresters install a spatial distribution of forest stands according to their age such that the damage to standing volume from storms is minimized. Forest management systems designed to address this need (Wagner 1928) have been applied to large forest areas in Central Europe over the past several decades. Losses in standing volume in recent decades indicate, however, that this goal has largely failed. Forest management still tries to influence the risk of storm damage to forests through the choice of tree species, adequate rotation times and early thinnings in order to stabilize trees. However, thinning can increase vulnerability of forest stands for storm damage, especially in older stands, which may lead to a severe destabilization and under extreme conditions to the decision not to thin forests at all (Nielsen 1990, 1995). In the United States, advances in ecological understanding about landscape-scale disturbances like windstorms and fire are influencing approaches to managing natural hazards (Mitchell et al. 2002). The emphasis on managing within-stand forest structure is being augmented with knowledge about among-stand patterns of structures that interact with disturbance processes on a landscape scale. Knowledge about the frequency, intensity and severity of disturbances (and their interactions) that can form a basis for designing, implementing and evaluating thinning regimes is still limited, however. In the northeastern US, Seymour (2002) report that windstorms of stand replacement severity occur with a frequency of centuries and affect a mean area of 14–93 ha.

Effect-oriented measures

Effect-oriented risk handling measures aim to reduce the amount of damage, but do not reduce the probability of damage. One such measure is the transfer of risk to a third party, e.g. to an insurance company. For example, a state can assume the risk associated with large natural hazards. Despite a tradition in Europe of insuring against fire, insurance for windstorms is embryonic. An insurance model for forests in the southwest of Germany was developed by Holecy and Hanewinkel (2006) and Brunette and Couture (2008) investigated the influence of public compensation for windstorm damage on possible insurance solutions. Holthausen (2004) investigated the readiness of forest owners to buy insurance policies and reported about the hindrance of public subsidies for market solutions.

Risk reduction implies that the potential magnitude of the damage is reduced while the probability of damage remains the same. This is the case when a forest enterprise diversifies its products. The application of the portfolio theory by Knoke et al. (2005) to introducing mixed stands instead of pure stands illustrates this type of risk reduction. Reducing harvesting costs after a storm event by leaving uprooted or broken trees in the forest and not replanting and waiting for natural regeneration (Holthausen et al. 2004) may also be considered as a way of reducing risk. Securing the flexibility of a forest enterprise to be able to adapt to newly emerging situations may also be seen as a way of risk reduction.

Economic aspects of analyzing risk

Classical Faustmann approach

The inclusion of risk in the economic analysis of forest management has a long tradition. In this paper we concentrate on direct links of economic aspects of risk analysis to forest management and focus on some recent developments. Economic risk is often expressed as standard deviation or variance of expected returns/net present values (Dieter et al. 2001; Knoke and Hahn 2007), but an important methodological deficiency of that approach is that positive variation is also included, while resulting damage is only a negative variation. Mills and Hoover (1982) first addressed this problem. Deegen et al. (1997) use the “my-sigma-rule” for economic modeling of the choice of tree species under uncertain temperature trends. The need for new methodological approaches as future fields of research is stated by Knoke and Hahn (2007).

The classical Faustmann model assumes that timber and input prices and timber yield are known and are constant over the rotation (Klemperer 1994: 200; Navarro 2003; Tahvonen and Viitala 2007). Timber and input prices, however, are subject to periodic fluctuations and the forecasted timber yield is subject to various hazards identified in this paper. Similarly, the assumption that the interest rate is known and constant over the period may not hold. Thus, forest investments take place in an environment of risks and uncertainties. Schwarzbauer (2006) for example, investigates the influence of salvage cuttings on timber prices. Economic efficiency criteria such as net present value or internal rate of return can be used to assess the financial implications of the occurrence of such risks and determine whether it is worth to control them (Klemperer 1994). However, the basic economic model and most of the modified versions of it do not consider the possibility of occurrence of these risks (Reed 1984).

Economic analysis of risk control weighs net present values of expected forest income without damage due to risk against net present values with uncontrolled damage. Usually, the analysis of financial implications is achieved by the addition of a premium to the discount rate to take into account risk. For example, Reed (1984) investigated the effects of fires and other unpredictable catastrophes on the optimal rotation period. He showed that the policy effect of a fire risk is equivalent to adding a premium to the discount rate that would be operative in a risk-free environment and presented a modification of the Faustmann model to consider such risks. Amacher et al. (2005) investigate the importance of self-insurance activities (risk prevention) in a risky environment. Although the limits of a Faustmann model for this type of investigation are obvious (Brunette 2009: 27), they found that the standard result that fire risk reduces the optimal rotation age does not hold when landowners use fuel management.

Monte Carlo simulation: portfolio theory

In some situations, the integration of risks in economic analysis is achieved by using computer simulation such as Monte Carlo simulation to generate probability distributions of net present value at various risk levels for the investment (Dieter 2001). For instance, in a study to investigate how an effective flexible harvest strategy may be applied to mixed forests to reduce the risk of insect damage, Knoke and Wurm (2006) used Monte Carlo simulation to evaluate the effects of market and hazard risks in management of mixed forest. Using the portfolio theory developed by Markowitz and Sharpe, (Markowitz 1952, 1959), Knoke et al. (2005) evaluate mixed forest management and compare it to single species forest management with a focus on mixtures of Norway spruce and European beech. They use the Monte Carlo simulation method to simulate expected financial returns and their dispersion under risk. Knoke and Hahn (2007) provide the conventional "Faustmann approach" with financial risk and risk correlation generated by Monte Carlo simulation. This enables both, the application of the theory of portfolio selection according to Markowitz and the theorem of capital separation according to Tobin (1958) to derive e.g. the optimal tree species composition. Beinhofer (2008) determines optimal rotation ages for forest stands taking risk of failure and the volatility of timber prices into consideration applying a utility function for risk adverse decision makers. There are alternative ways to express uncertainty concerning timber prices. The stochastic dynamic programming model by Teeter and Caulfield (1991) employs a price state transition matrix constructed using a cumulative density function for price based on time series data for national forest pine stumpage values. Lohmander (2000) uses as well stochastic dynamic programming to investigate decisions in the presence of stochastic market prices.

Attitude toward risk- time preference

A general approach to extend economic models with the notion of risk is the introduction of the attitude toward risk, namely risk adversity into economic calculations (Mills and Hoover 1982; Dieter et al. 2001). Knoke et al. (2008: 97) show a formal way how to calculate the economic value of different forests for risk aversion. Core of the calculus is a constant α depending on the attitude toward risk that is approximated based on the reciprocal value of the initial investment, e.g. the cost of the plantation. Pukkala and Kangas (1996) develop a planning method to integrate risk as well as attitude toward risk into forest planning based on Saaty's eigenvalue. An overview on how to include risk and risk preference in economic models can be found at Knoke et al. (2008: 95). Plattner (2006) emphasizes that in risk evaluation there is often a discrepancy between a rationale analytical and an intuitive approach when risk aversion is taken into account. From a general economic point of view, Mossin (1968) investigates how attitude toward risk influences risk prevention such as the demand for insurance. Brunette et al. (2008) extend this approach to the forestry sector.

A general problem, when taking into account risk in decision making is the time preference of the decision makers and thus, which type of discounting to apply. Viscusi et al. (2008) estimated rates of time-preference for environmental quality and found the rate of time preference was very high for immediate benefits and substantially dropped off thereafter, which was consistent with hyperbolic discounting. When analyzing climate change under this aspect, Dasgupta (2008) discusses the idea of social discount rates under growing uncertainty. In a recent essay, Samuelson (2008) deals with choices of people who live mostly for the present against those who think now about different future outputs and the problem on how to actually discount future events.

Still, a general problem remains: in an area of increasing uncertainty, there is no general recipe on how to deal with risks in a changing environment. Even though our knowledge on probabilities or probability distributions on different biotic and abiotic hazards may increase, the remark by Samuelson (2008: 114) still holds true, that "(…) actual economic history is not ever what mathematicians call a "*stationary* probability distribution". There are thus no exact simple rules to learn how to benefit from knowledge of the past. None at all."

Future needs of risk management: an outlook

As climate changes, the probability increases that major tree species will shift biomes. This is due to changing living conditions with increasing temperature and/or a change in the water regime. Thuiller (2007) estimates that each 1°C of temperature change moves ecological zones on Earth by about 160 km. Many references deal with the assessment and modeling of this type of risk that will influence the future distribution of the tree species all over the world and will thus determine the future impact of disturbance regimes.

Biome shifts for tree species are usually modeled based on a presence/absence approach using national forest inventory data and climate parameters such as (mean) temperature, (mean) precipitation, radiation and soil-related parameters (water balance, etc.). Climate parameters are taken from statistically downscaled regional climate models (RCM) based on the results of general circulation models (GCM) and predicted in the future for different climate scenarios. A similar approach to model biome shifts for the main tree species in Switzerland is discussed by Zimmermann and Bugmann (2008). This type of modeling is generally linked to large uncertainties that can be related to the choice of the GCM, the results of different RCM and the related statistical downscaling, the selection of the climate variables and their interaction and general problems with the presence/absence data that show large human influences and often reflect competition but not physiological thresholds. Guisan and Zimmermann (2000) give an overview of methods and background of predictive habitat modeling.

Potential impacts of projected climate change on tree species distribution are usually assessed using single-species bioclimatic envelope models (Heikkinen et al. 2006). There is an increasing interest in this technology with global change and new methods to model distribution (Elith et al. 2006) are applied and future challenges to predict the impact of the expected change to plant distribution are being addressed (Thuiller et al. 2008). A key challenge for future research in general plant distribution modeling is the integration of factors like land cover, direct CO2 effects, biotic interactions and dispersal mechanisms (Heikkinen et al. 2006) as well as the adaptation potential of long living organisms like trees. Kölling (2007) has published basic climate envelopes for 27 tree species in Germany and has initiated a discussion on the validity and usefulness of this methodology as a tool for forest management (Bolte et al. 2008). Although simple bioclimatic envelope models may have a number of advantages (e.g. they are rather easy to understand for practitioners), they need to be applied only when users of the models have thorough understanding of their limitations and uncertainties (Heikkinen et al. 2006: 751). A major challenge in the development of new bioclimatic envelopes under climate change will indeed be the integration of uncertainty in these models.

Biome shift models have principal limits when applied to changing environmental conditions due to their empirical nature. In order to successfully apply them to larger areas, a database encompassing a large climate gradient (e.g. for Europe from the very southernmost to northern climatic conditions) is necessary, otherwise the models will quickly reach an extrapolation range resulting in a very restricted applicability. However, these models can serve as a basis for the assessment of future expected risks of our tree species.

A general need of future risk management activities is the integration and combination of component models that include climate modeling and downscaling and the usage of these models as general drivers for other more specific risk models for different hazard types. The interaction between different hazards such as storm and insects or fire and insects will be another important aspect. In general, risk models have to be made sensitive to dynamic aspects of future environmental conditions (e.g. climate, changing site and other environmental conditions). We used biome shift modeling as an example of such a general dynamic aspect. Beside the analysis of vulnerability, potential resilience of different tree species should also be in the focus of future risk management activities. In order to build holistic decision support tools expert interviews concerning attitude toward risk of decision makers are necessary. They would help to integrate risk management into decision making as presented in our general framework (Fig. 1).

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