REVIEW PAPER

A review of decision-making approaches to handle uncertainty and risk in adaptive forest management under climate change

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Abstract

· **Context** This review paper provides an overview of approaches to which we may resort for handling the complex decision problems involving uncertainty and risk that climate change implies for forest managers. Modelling approaches that could support adaptive management strategies seem to be called for, not only as climate change denotes increased economic uncertainty but also because new and more reliable information becomes available as time passes and climate changes.

· **Aims** The paper (1) provides a broad overview of state-of-the-art methods for optimal decision making under risk and uncertainty in forestry and (2) elaborates on the possible use of these methods in adaptive forest management under climate change.

· **Method** A survey of the current literature is carried out to identify approaches and developments that may prove most promising in relation to different challenges to the adaptive management of forest ecosystems under climate change.

· **Results** Most studies focusing on changing, typically increasing, risks in forest management under climate change tend to build on existing approaches about changes in risk levels contingent on climate change scenarios.

· **Conclusion** Finally, we discuss what to emphasise in future studies to improve the understanding of adaptive forest management and decision support tools needed to cope with climate change.

Keywords Adaptive forest management · Climate change · Operations research · Market uncertainty · Abiotic and biotic risk

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1 Introduction

Risk and uncertainty is, today, widely included in forest modelling. Recent reviews focus on the modelling of hazards and risks (Hanewinkel et al. 2010) or on the handling of price and other market risks (Hildebrandt and Knoke 2011; Buongiorno and Zhou 2011). However, we are facing a new kind of uncertainties, which has been little addressed in the forest management and decision-making literature and that are those implied by climate change. Climate change is likely to have significant impact on forest ecosystems. A crucial word here is 'likely' because the issue is highly uncertain as there is a lack of complete knowledge or historical parallels. There is uncertainty about the reactions of forest ecosystems to climate change, but more fundamentally, there is considerable uncertainty as to

what degree of climate change we are facing. This has important implications for how we adapt decision-making approaches to the new challenge.

While a few studies do address adaptive decision approaches to forest management faced by climate change (e.g. Huang et al. 1998; Jacobsen and Thorsen 2003; Armstrong et al. 2007), much more is to be learned and considered regarding the potential of many other approaches in the literature on different kinds of uncertainty in decision-making models.

The key objective of the present review is to provide an overview, and hence a better understanding, of approaches and models suitable for handling uncertainty and risk likely to be part of the complex decision problems that climate change implies for forest owners and managers. The dynamic nature and inherent uncertainty of climate change and its impacts on forests are particularly important aspects of these decision problems. It seems that the situation calls for modelling approaches that would support adaptive management strategies because the ecological and economic uncertainty is augmented by climate change and because new and more reliable information becomes available as time passes and climate changes (Prato 2008; Probert et al. 2010). We stress that our aim of the review is to provide a representative overview of approaches relevant to the decision-making problem in focus and not to provide an exhaustive review of all the many different kind of studies that in different ways deal with risk and uncertainty in forestry.

Forest decision making under uncertainty is a large and productive cross-disciplinary research field (Fina et al. 2001; Kangas and Kangas 2004; Hein and van Irland 2006). Thus, even if climate change is a relatively new issue, much can be learned by supplementing a review of climate change literature, with a broader review of forest research literature and some guiding examples from other disciplines, addressing conceptual issues of adaptive decision making under uncertainty (e.g. Albers and Goldbach 2000; Amacher et al. 2005; Weintraub and Romero 2006; Armstrong et al. 2007; Prato 2000, 2008; Probert et al. 2010). Therefore, this review includes examples of approaches from the handling of risk (e.g. Dixit and Pindyck (1994); Heikkinen 2003; Redmond and Cubbage 1988; Scholtens and Spierdijk 2010), over the operational risk assessment (Borchers 2005; Linkov et al. 2006), to the handling of uncertainty and information scarcity (Albers 1996; Benítez et al. 2006; Forsyth 2000; Kaloudis et al. 2005; Regan et al. 2005). In our discussion, we highlight the need for further development of existing methods that better incorporate key risk components and dynamics implied by climate change, which are not yet addressed adequately in the literature.

In order to provide a basic understanding of the decision-making challenge in focus of the review, we start with a description of what characterises the uncertainty associated with climate change and forest management. Then follows what is the main emphasis of the paper: a quantitative analysis and categorisation of more than 100 references. The categorisation is made by focusing on different dimensions and issues of relevance to many of the specific problems of adaptive forest management and should aid anyone interested in investigating specific sub-fields of the literature. We finish the paper with a discussion of how current knowledge and methods can be used in forest management facing the new challenge of climate change.

1.1 A framework for modelling adaptive management under climate change

At the core of adaptive management is the ambition to collect and integrate in forest management the necessary knowledge—as it becomes available—about how ecosystems are likely to respond to alternative management schemes and changing environmental conditions, within a continuous decision process (Prato 2000, 2008; Hahn and Knoke 2010; Probert et al. 2010). This involves a chain of state–dose–response–impacts, where management actions affect all the individual links. The outcome of such a chain of events is a set of flows of forest-based goods and services and, potentially, a final or steady (average) state of the forest ecosystem. A good adaptive forest management strategy is thus designed so as to pursue the best possible expected overall outcome in terms of a specific performance measure. For example, it can be designed to minimise risk (Meilby et al. 2003; Nitschke and Innes 2008) or maximise expected net present value (Yin and Newman 1996; Spring et al. 2005; Jacobsen and Helles 2006; Yousefpour and Hanewinkel 2009), expected overall welfare (Gong and Löfgren 2007; Wintle and Lindenmayer 2008), or a particular multi-criteria objective function (Linkov et al. 2006; Ohlson et al. 2006; Zhou et al. 2008; Ananda and Herath 2009). To meet these objectives, we need adequate descriptions of the forest ecosystem as well as relevant parts of the surrounding socioeconomic system (Hoogstra 2008; Blennow 2008; Hahn and Knoke 2010). What is relevant depends on the issue and objectives of the specific models applied, but it may range from uni-dimensional data in conceptual or stand-level models to multi-dimensional datasets in more complex models, e.g. at the landscape level (Meilby et al. 2003; Ohlson et al. 2006).

With climate change development, a new source of change and uncertainty needs attention in adaptive forest management. Climate change can be considered a significant source of exogenous and stochastic 'doses' of changing climatic conditions, variability and associated catastrophic events (Lindner et al. 2002; Prato 2008; Böttcher 2008; Hahn and Knoke 2010). General ecological

effects of changing climate are likely to include changes with regard to growth, competition within and between species, flowering and fructification, regeneration, mortality rates and lifetime. Catastrophic events include windthrow, snow breakage, mortality caused by flooding or severe drought, fire and insect attacks. The 'doses' may also include indirect socioeconomic effects of climate change, such as increased insurance rates and increased fluctuations of market prices, interest rates, taxes and owner's needs for cash income.

The link between the 'doses' and the state of the forest ecosystem is tracked in models of the 'response' of the ecosystem to a given 'dose'. This is the system's intrinsic response, which may be described by a stochastic model emphasising, e.g. forest health decline, dieback, increasing or decreasing growth, and change with respect to regeneration success, mortality, genetic selection pressure, species composition, biodiversity and soil development. Finally, this flow of dose–response will have an impact on the values that owners and society at large derive from forest ecosystems (Knoke et al. 2005; Lien et al. 2007; Hemery 2008; Hyytiäinen and Penttinen 2008; Heller and Zavaleta 2009). By 'forest management', we refer to the whole range of decisions that a decision maker must consider concerning the forest: choice of species, provenances, regeneration approach, thinning and tending practices, harvest age or size, drainage, protection measures, afforestation, deforestation, etc. Management of course directly influences the state of the forest, but it may also affect the dose–response relationship, e.g. susceptibility to windthrow or consequences of drought, and the economic impact of a given ecological response may be modified through management (cutting losses, enhancing benefits). Management decisions are described by actions in time and context (Hahn and Knoke 2010). Individual management decisions may be part of a long-term strategy including a set of pre-planned actions, triggered by basic state variables, such as age or stand density. Typically, such strategies are designed to perform well under a given set of deterministic assumptions about the future, or they are designed to cope with known variability in, e.g. seed production, regeneration risks, storms, etc., and are not subject to adjustment based on climate-induced changes in current trends and fluctuations. Forest owners will likely face hazard risks, growth patterns across species and other important factors to vary and change in the future in ways that cannot be well described by the past, known variation and information about the productivity of species.

By contrast, an adaptive forest management approach taking into account also climate change could include a set of contingent decision rules, specifying a range of different good or optimal decisions for several possible future states of the world (Prato 2000, 2008; Jacobsen and Helles 2006; Zhou et al. 2008; Yousefpour 2009). Hence, using an adaptive management approach, individual decisions are made on the basis of observed trends and fluctuations and resulting beliefs about the future, and since future developments are uncertain, the decisions are not assumed to always lead to perfect results but to outcomes that are, on average, the best possible. Prato (2008) noted that if different stakeholders', depending on their set of preferences for the attributes of ecosystem services, prefer different best adaptation strategies, in this case, a compromise best adaptation strategy would need to be developed using a multi-attribute evaluation.

At this point, a comment is needed on the distinction between risk and uncertainty applied in the remainder of this paper. While it is sometimes common to see these two terms assigned distinctly different meanings in the Knightian sense that the former implies a form of empirically or objectively measure of risk, e.g. probabilities and/or impacts, whereas uncertainty do not (or rely on subjective probabilities). However, this distinction is far from being used consistently in the literature. In fact, many papers and even books (see, e.g. Dixit and Pindyck) apply the term uncertainty about, e.g. variation in prices and similar, but clearly apply empirical (objective) measures and models of this uncertainty (e.g. Thorsen 1999a, b). In fact, one could argue that there's a tendency to use the risk term mainly for downside events like storm and fire and of course in the literature relating strongly to the issue of risk aversion, where risk has the broader definition of variation in outcomes. For this reason, we consider both of the terms risk and uncertainty, which may have been used interchangeably in the literature, and try to remain true to the formulations and applications. We stress, however, that while much of the literature deals with empirically quantifiable risks and uncertainties, we shall argue that the inherent uncertainty about what climate change we face is hardly quantifiable without some use of subjectivity or beliefs about, e.g. future mitigation actions.

A final topic to address here is what rationale to assume on behalf of forest managers and their decision making (Hoogstra 2008). Implicitly, most state-of-the-art models assume forest managers to be rational within the limits of the decision-making model, e.g. knowledgeable about forest growth, risk and uncertainties and impacts of various changes and shocks. However, much evidence suggests that forest managers base their decisions on different sets of information and in ways quite different from those assumed (Ananda and Herath 2005; Couture and Reynaud 2008; Hoogstra 2008). This is a crucial issue as the success of decision making in adaptive forest management depends on managers being aware of changes with regard to state and development of the forest and knowledgeable about available management strategies (Gong 1994; Jacobsen and Thorsen 2003; Linkov et al. 2006; Moore and Conroy 2006; Yousefpour 2009). According to Blennow (2008),

adaptation to forthcoming risks (including extreme events) has not been actively implemented in Swedish forestry, while similar studies of risk management in forestry of other countries appear to be rare as well. While forest owners certainly already applies silvicultural measures to deal with known risks and variability, e.g. in seed production, regeneration risks and variation in prices, there is some evidence (Blennow 2008) that forest owners' belief in their personal adaptive capacity or that of the forest ecosystem and their scepticism regarding climate change may limit their motivation for taking adaptation measures. Research aiming to cope with such deficits is largely lacking in forest research.

Different decision-making models reflecting what could be termed a 'bounded rationality', including bounded sets of information, have been developed and outline different ways of addressing forest managers' use of information and development of expectations regarding the future (Hoogstra 2008; Jacobsen et al. 2010; Probert et al. 2010).

Looking at risk of climate change in the above framework, research into climate change and adaptive forest management should make sure to include (1) risk flow modelling (e.g. modelling endogenous risk for multiple risk types); (2) models allowing for spatial relations and interdependence as well as for the inclusion of values, goods and services other than wood production; (3) methods and techniques enabling the handling of problems at the scale of forests or landscapes; and (4) approaches that explicitly allow for evaluating the effect of learning as future climate unfolds.

2 Materials and methods

To access and collect the papers relevant for this review effort, an extensive literature search was conducted, as illustrated in Fig. 1. A combination of the key words was applied so that at least one word from each of the search terms in boxes (logical OR operator) and at least one term from each box should appear (logical AND operator) either in the title or the abstract of the paper. Five different search engines were used: 'Web of Science', 'Scopus', 'Scirus', 'Science Direct' and 'CAB'. This brute force search resulted in a gross list of about 225 papers, of which 113 were not relevant for the focus of this paper, leaving 112 papers for the review and the quantitative analysis. The selected papers were either representative of decision-making approaches to handle risk and uncertainty in forestry or dealing with adaptive management under climate change. The later applies not only for forest resources but for a broad variety of the biophysical systems like land resources, urban areas, agro-forestry, agriculture and non-renewable resources and, moreover, for different gaols (e.g. conservation, landscape management, resource allocation). A number of deterministic studies came into consideration to mention precautionary approaches in adaptation to climate change. Excluded papers were mainly studies that do not address the thematic of this paper, e.g. from topics like genetics, soil science or meteorology. The selection may subsequently entail a compact analysis for the outlined purposes of this review; however, the quantitative results are just valid for this sample.

The selected papers were all comprehensively reviewed by at least one of the authors of this paper, and a number of characteristics related to forest risk modelling were noted. A summary of the review notes was made in a table for each paper. In the summarising part, characteristics of the study were described together with notes on the investigated issue, the source of risk, the analytical and operational research (OR) techniques used and the paper's implications for future research.
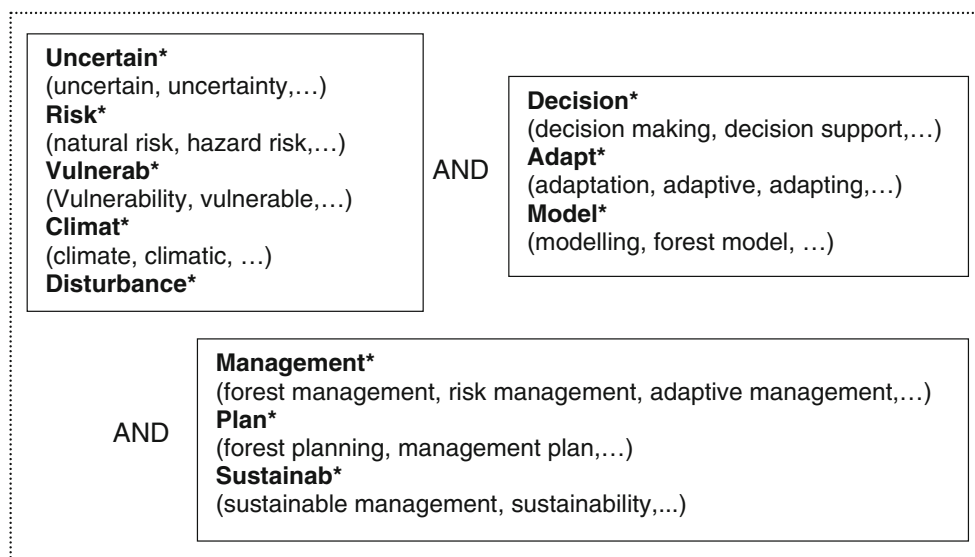
3 Results

Risk modelling in forest management studies has shown an increasing trend over the last two decades (see Fig. 2). While there were just occasional publications on the topics under investigation (cf. Fig. 1) in the early 1990s (one to two publications per year), the number of publications has considerably increased in recent years (i.e. 2005 and thereafter). Most likely, attention to risk analysis in forestry would grow even more in the coming years, as climatic changes and uncertainties will manifest themselves into concrete management challenges, knowledge shortages and decision support needs.

3.1 Classification of reviewed papers

Figure 3 shows the number of contributions categorised into different classes depending on the source of risk and uncertainty in focus. Price uncertainty stands out as the single most studied topic, followed by catastrophic events taken together, here fire (Gonzáles et al. 2005b; 2008), windthrow (e.g. Thorsen and Helles 1998; Meilby et al. 2001, 2003; Hanewinkel 2005; Insley and Lei 2007), ice (Goodnow et al. 2008) and biotic risks. In much of the literature on catastrophic events, risk levels depend entirely on exogenous factors, biotic and climatic. Exceptions do exist, e.g. Thorsen and Helles (1998) explicitly model risk as partially endogenous to stand treatment. This approach has also been extended to fire risk (Gonzáles et al. 2005a). While these sources all address the stand level, focusing on specific stands or trees, some risks depend on the spatial context. Studies addressing decision making under risk at forest or landscape levels include Reed and Errico (1985, 1986, 1987), Lohmander (1987, 2000), Gonzáles et al.

Uncertain*
(uncertain, uncertainty,…)
Risk*
(natural risk, hazard risk,…)
Vulnerab*
(Vulnerability, vulnerable,…)
Climat*
(climate, climatic, …)
Disturbance*

AND

Decision*
(decision making, decision support,…)
Adapt*
(adaptation, adaptive, adapting,…)
Model*
(modelling, forest model, …)

AND

Management*
(forest management, risk management, adaptive management,…)
Plan*
(forest planning, management plan,…)
Sustainab*
(sustainable management, sustainability,...)

(2005b) and Eriksson (2006). However, except for Lohmander (1987), these studies essentially use a single-stand approach, and the forest-level models are, in practice, simple aggregates of stand-level models where interdependence exists only through forest-level constraints. More recent studies have developed forest and landscape-level models, including spatial interdependence between individual forest stands with respect to risks (Meilby et al. 2001, 2003; Gonzáles et al. 2005b). These studies show that considerable challenges remain regarding large-scale analyses, related to the dimensionality of stochastic optimisation models involving a large number of time steps and interdependent states.

Price uncertainty has been in focus in many studies, either as a part of a net present value (NPV) calculation or separately. An early example is Brazee and Mendelsohn (1988), but numerous studies followed (e.g. Teeter and Somers 1993; Gong 1994, 1999; Plantinga 1998; Zhou

1999; Thorsen 1999a; McGough et al. 2004; Zhou and Buongiorno 2006; Penttinen 2006; Chladná 2007; Manley and Bare 2001).

Other approaches, based on NPV measures or other measures of profitability, have also been taken to investigate effects of price uncertainty including addressing forest investment analysis in the framework of the Capital Asset Pricing Model (e.g. Redmond and Cubbage 1988; Washburn and Binkley 1990, 1993; Wagner and Rideout 1991, 1992; Lundgren 2005; Scholtens and Spierdijk 2010) and also studies relying on the expected mean–variance rule or similar simulation based decision criteria, e.g. Yoshimoto and Shoji (1998) using a binominal option pricing model, Reeves and Haight (2000) and Knoke et al. (2001). Other sources of uncertainty, such as interest rate (Alvarez and Koskela 2001; Buongiorno and Zhou 2011), climate change effects (Jacobsen and Thorsen 2003; Bodin and Biman 2007) and society's preferences for non-market values, e.g. Abildtrup and Strange

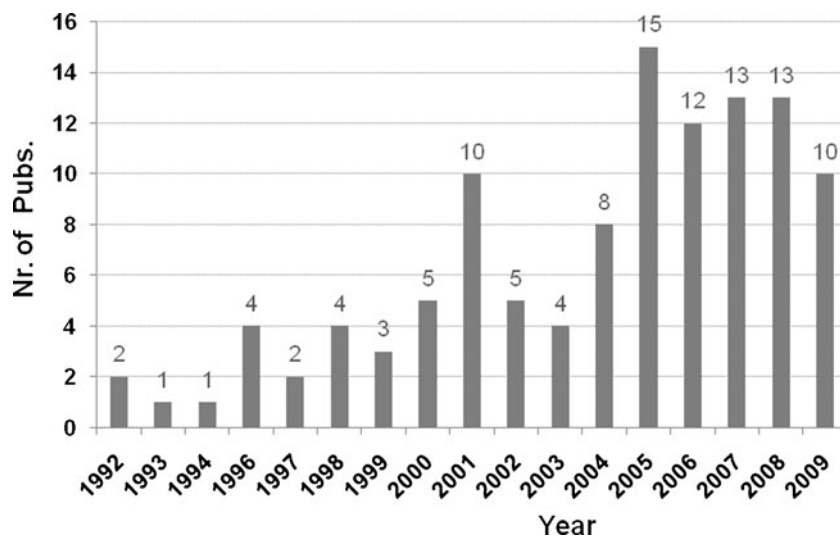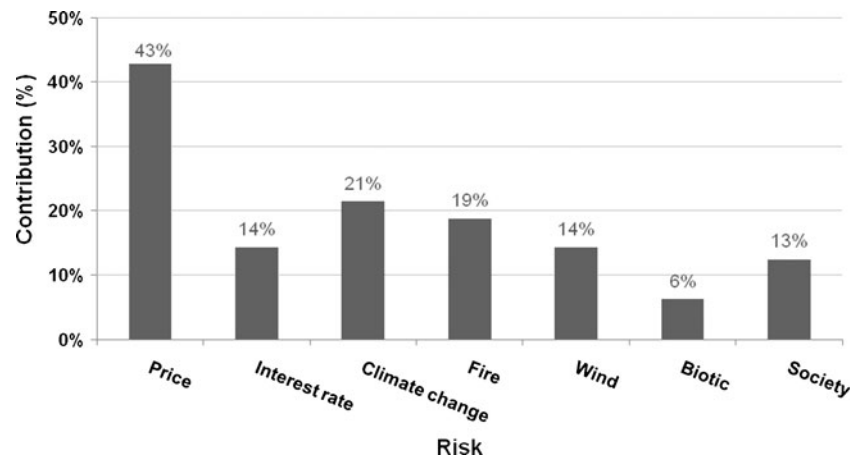**Fig. 2** Number of publications on forest risk modelling over the last 17 years

Fig. 3 Prevalence of different sources of risk and uncertainty in the literature

(1999) and Ananda and Herath (2005), are much less common.

3.2 Models of risk analysis

There are various ways to include different types of risk in decision-making models. Figure 4 shows the observed frequency of different approaches to the modelling of forest-related risks in the reviewed literature. The Geometric Brownian Motion (GBM) dominates in forest risk analysis and is applied in 19% of the papers, in particular those looking at stochastic price or NPV changes (e.g. Willassen 1998; Thorsen 1999b; Sødal 2002; Duku-Kaakyire and Nanang 2004; Malchow-Møller et al. 2004) and also studies on other types of values, e.g. Bulte et al. (2002). The GBM is a simple model of how a stochastic process may develop over time. For example, the paper by Jacobsen and Thorsen (2003) presents a model of the decision problem of choosing between two species, which may be favoured or disfavoured by forthcoming climate change. Changes in growth trends are subject to stochastic increases or decreases following a

random walk (a discrete Brownian motion) adding to or detracting from the empirical growth function. The risk element is based, however, on assumptions, whereas the impact on each of the two spruce species is based partly on physiological evidence. The paper shows that with uncertainty about future climate change and impacts on growth, it is worthwhile keeping both species longer in mixed stands than in the absence of uncertainty. While this decision approach certainly has significant merits, the paper has an important limitation: The modelling of forthcoming climate change is at the same time overtly simple and yet assumes knowledge about direction and variance of possible impacts. This requires assigning known probabilities to the outcome of specific combinations of state and action. With the direction and speed and variance of climate change and its impacts on forests being unknown, this is a difficult requirement often replaced by strong assumptions.

Alternatives used in the literature include the autoregressive process, (AP), (e.g. Plantinga 1998; Gong 1999; Gjolberg and Guttormsen 2002) and vector AP (VAP), e.g. Gong and Yin (2004) and Jacobsen and Helles (2006).

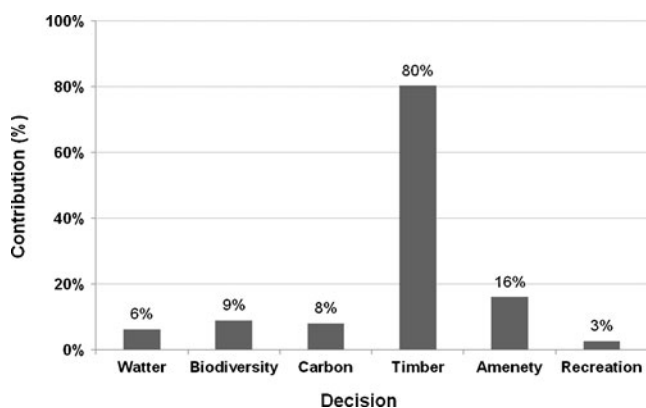**Fig. 4** Frequency of different risk models applied in forest risk analysis
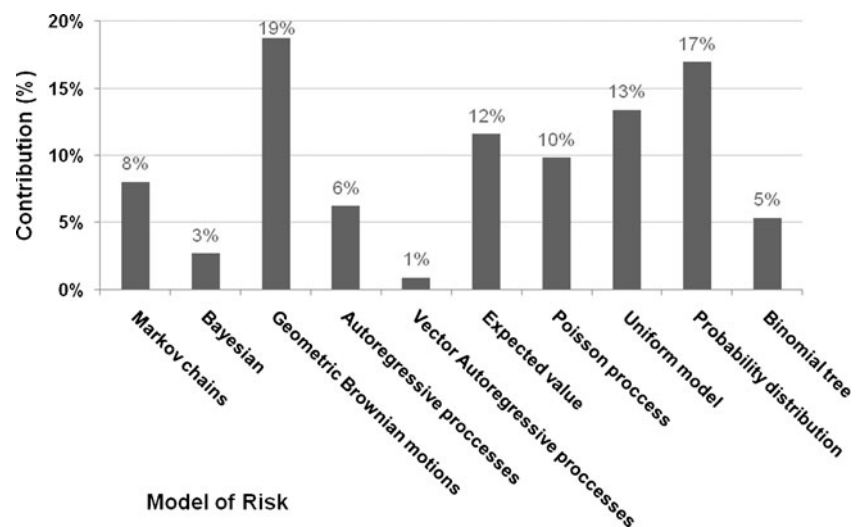
Fig. 5 Attention to different categories of products and services in the literature on decision making under risk

Compared with the GBM and other models of stochastic processes, a simpler competing risk model, with a much wider application space, is the specification of static probability distributions (PD) for key variables. This approach, however, fails to handle the potential correlation in the time domain of stochastic variables like prices. This approach is used in 17% of the papers and hence mainly in papers dealing with other sources of risk, though it was essentially used also in Brazee and Mendelsohn (1988).

Turning to other sources of risk, forest analyses use the Poison process (PP) to model risk of fire and windthrow directly (e.g. Reed 1984; Yin and Newman 1996; Fina et al. 2001; Ohlson et al. 2006; Armstrong et al. 2007; Jacobsen 2007) or in modified and more complex versions (e.g. Thorsen and Helles 1998) and also the simple uniform distribution (Uni, e.g. Amacher et al. 2005; Gong et al. 2005; Zhou et al. 2008). Other approaches and models like Markov chains (MC, e.g. Knoke et al. 2001; Meilby et al. 2003; Spring et al. 2005; Zhou and Buongiorno 2006), Bayesian (By) approaches (e.g. Prato 2000, 2009; Kangas et al. 2000), and binominal trees (BT, e.g. Gove and Fairweather 1992; Duku-Kaakyire and Nanang 2004; Yoshimoto 2009) were applied only in a few studies.
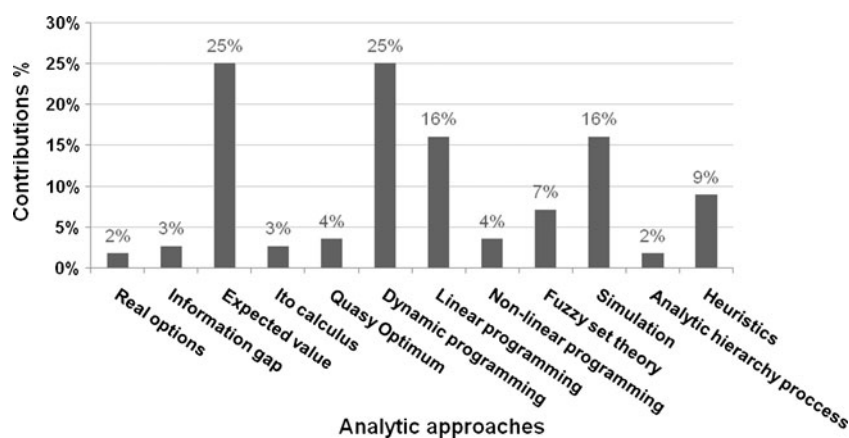
Climate change will affect many types of risk and uncertainty, which may be captured using many of the approaches found here. The change in these risk variables, as well as many other state variables describing the forest, will likely follow the development in core climate variables like temperature, precipitation, and wind patterns. However, the modelling of this should likely differ from that found in the literature reviewed: It seems likely that it should reflect a transition from current climate, growth and risk dynamics to a new, yet unknown but hopeful by then stable, climate, with related growth and risk dynamics. Thus distributions of all variables can be thought of as non-stationary in means and higher orders for a considerable period, but not in a way adequately captured by, e.g. GBM processes or similar as these do not have the important tendency of mean reversion, which we generally are accustomed to find for a stable climate. An alternative model for possible future scenarios of climate development could be to model the development of core variables with some form of trend-stationary process, potentially with a heteroscedastic, time-dependent variance.

3.3 Variables in the objective functions

The goal or objective functions of the bulk of studies have emphasised traditional objectives, i.e. timber production and non-timber products and services like biodiversity, water, carbon, recreation and amenities. Maximisation of present values from timber production under risk was the most common objective, in particular of course in studies evaluating price or other market value risks, and 80% of the papers included this as one of the main aims (Fig. 5). Amenity was also included in a considerable part of the literature (16%) compared with other objectives (Pukkala and Miina 1997; Prato 2000; Bulte et al. 2002; Alvarez and Koskela 2007a; Zhou et al. 2008). However, non-timber products and services like biodiversity, carbon, wildlife and water were only considered in a smaller number of studies

Fig. 6 Technical solutions applied in forest risk analysis

(Huang et al. 1998; Creedy and Wurzbacher 2001; Bulte et al. 2002; Spring and Kennedy 2005; Spring et al. 2008; Galik and Jackson 2009; Yousefpour 2009), which made up 9%, 8% and 6% of the papers. The least common objective in forest risk management was recreation, addressed in only 3% of the papers.

3.4 Operations research methods

Risk analysis integrated into decision-making under uncertainty can either be done using analytical approaches, e.g. Itô calculus, or OR (operations research). Using simply the expected value (EV) as the decision basis was common in the investigative phase of analysis in many papers, e.g. Thorsen (1999a). Apart from that, as shown in Fig. 6, stochastic dynamic programming (SDP) was the most common technical tool used to deal with risk in forestry. The studies are closely related to the real options literature as shown by Plantinga (1998) and with examples like Thorsen (1999a, b), Abildtrup and Strange (1999), Duku-Kaakyire and Nanang (2004), Gjolberg and Guttormsen (2002) and many others. To a large extent, this group of studies correlates with the literature considering uncertainty in terms of the stochastic evolution of future prices (Brazee and Mendelsohn 1988; Thomson 1992; Gong 1994; Yoshimoto and Shoji 1998; Gong et al. 2005), present value measures (Norstrøm 1975; McCarthy et al. 2001; Abildtrup and Strange 1999; Malchow-Møller et al. 2004), stochastic interest rates (Alvarez and Koskela 2001, 2003; Buongiorno and Zhou 2011) and similar, but not exclusively. For example, SDP has also been applied in various versions to analyse decision making under risk of hazards as windthrow (Meilby et al. 2003; Hanewinkel 2005; Heinonen et al. 2009) and fire (Reed 1984; Boychuk and Martell 1996; Amacher et al. 2005; Gonzáles and Pukkala 2007; Prestemon and Donovan 2008; González et al. 2008).

Common to all of these problems and decision approaches is the ability of the researcher to validly describe the stochastic process for the uncertain variables in a way that allowed for a known and stationary state transition matrix within a confined state and time matrix (e.g. Buongiorno and Zhou 2011). This is a strong feature of the real options approach, which is essentially also at the heart of the reservation price literature. Similar approaches have only rarely been used to climate change and uncertainty about the effect on, e.g. growth patterns of species under climate change. This has, however, so far been in the form of essentially non-stationary processes, e.g. a branch-out binomial or trinomial tree (Jacobsen and Thorsen 2003). They lend themselves reasonably well to SDP algorithms, but as stressed also in Section 3.2, the effects of climate change are not likely to be well described by the type of non-stationary processes and changes in core climate variables implied by the models of these studies. Rather, we are in the midst of a stochastic transition from one, known, stable climate (equilibrium) with considerable variability, but nevertheless fairly stable and stationary (cyclic), to a new but largely unknown climate, which we may expect or not to stabilise (in a cyclic equilibrium). Although the later statement is conjecture, it gives an essential opportunity to explore options to adapt to possible future climate states via management (considering more future equilibriums may alleviate the assumption). Thus, the change is non-stationary in a way that does not offer the researcher a firm fundament for, e.g. setting up even a stationary state transition matrix, or even a time bounded non-stationary such. Assessment of transition probabilities will change as new information about the transition and its implications arise.

Taking a wider look into the literature, linear programming (LP) and simulation analysis techniques (applying probabilistic modelling of risk without integration in OR techniques) were also frequently used to solve or analyse problems involving decision making under risk (Reed and Apaloo 1991; Buongiorno 2001; Yousefpour and Hanewinkel 2009). Evolutionary techniques like genetic algorithms, simulated annealing and taboo search were all included in the heuristics category and were present in 9% of the literature (Kangas et al. 2000; Zeng et al. 2007; Yousefpour 2009). Other techniques like mathematical and numerical determination of optimal stopping in the real options literature (including also Itô calculus), information gap and the analytical hierarchy process were all less common (e.g. Thorsen 1999a, b; Insley 2002; Duku-Kaakyire and Nanang 2004; Rocha et al. 2006; Jacobsen 2007; McCarthy and Lindenmayer 2007).

Again, most of these OR methods make rather strong assumptions on the ability of the decision maker to assign stable and well-defined probability structures to the

Table 1 Prevalence of different characteristics and aspects of studies emphasising climate change and associated risk

		Climate change and risk
		Contribution (%)
NPV maximum		7
Risk		8
	Fire	6
	Wind	4
	Biotic	5
	Social	1
Non-timber		15
Scale	Stand	4
	Forest	9
	Landscape	9

different outcomes and dynamics of stochastic events and variables. The most flexible but also simple approach is the simulation analysis techniques, which—because of their often computational low requirement—typically offer themselves better to, e.g. analysis of the effects of varying stochastic parameters and the like over decision time span. What this method is often lacking is a procedure for reflecting knowledge update and knowledge contingent decision making. A possible alternative here, which appears largely unexplored in the forest management literature, is the use of Bayesian methods (Kangas et al. 2000; Prato 2000, 2008 and 2009; Jacobsen et al. 2010). Kangas and Kangas (2004) noticed that application of Bayesian approach was suffering from computational difficulty until recently and advancements in simulation methodology.

4 Discussion of climate change focus

The literature on various aspects of risk, uncertainty and decision making in forest management is a rather comprehensive. We have not included all studies in this review, but have selected a large sample representing the development in the research on handling uncertainty and risk if forest, which appeared relevant for the design of adaptive management approaches under climate change. More than a hundred (112) publications dealing with risk analysis in forest modelling were included, but only some of them explicitly take into account climate change and related environmental impacts (21%=24 of total 112 references, Fig. 3). We also examined which risks and changes were the main focus.

Table 1 shows the occurrence of different aspects of risk analysis in the study of climate change and forest modelling from selected pool (112 references). It reveals that only 7% (eight references) of the studies focusing on NPV maximisation used some type of risk model to solve a forest management problem under climate change. Risk of biotic and abiotic hazards and the impact of climate change on these were also rarely investigated, making up only 4–6% of the studies (five to seven studies). Social risk analysis, or taking into account the possible changes in the preferences of society, in studies emphasising climate change amounted to only 1% (i.e. one study). It thus appeared to be the least studied aspect of risk analysis in forestry.

4.1 Impacts in focus of risk analyses

Traditionally, timber production and its value is the main, or at least one of the main, objectives of forest management modelling and studies of decision making under risk (e.g. Gong 1994; Weintraub and Bare 1996; Pukkala and Miina 1997; Vettenranta and Miina 1999; Buongiorno 2001; Chang 2005; Zhou et al. 2008). However, social and

environmental services of forest ecosystems are becoming more and more important in forest management and must therefore be integrated into forest modelling procedures. Several studies address this challenge and apply techniques and approaches of relevance to multi-functionality (e.g. Albers 1996; Weintraub and Bare 1996; Creedy and Wurzbacher 2001; Krcmar et al. 2001; Bulte et al. 2002; Zhou and Gong 2004; Fernandez 2005; Gong et al. 2005; Spring et al. 2005; McCarthy and Lindenmayer 2007; Ananda and Herath 2009; Heller and Zavaleta 2009). In the present review, just 15% of the studies emphasised climate change and associated risk considering non-timber forest products and services like biodiversity, carbon, water, amenity values and recreation. The inclusion of non-timber products and services requires a valuation measure of operational relevance, which, together with other quantitative measures, can be linked to the utility and welfare to be maximised (Gong and Yin 2004; Yousefpour and Hanewinkel 2009). This is especially true when there is no real market for them. For example, this is the case for biodiversity, carbon sequestration, oxygen production, improvement of local wind climate and soil preservation. Furthermore, the review observed only few investigations of the real impacts of biotic hazards on forest utilisation (5%), and the economics of biotic risk in forest management was emphasised by only Wilson and Baker (2001) and Xu et al. (2009).

Most studies focusing on changing, typically increasing, risks in forest management under climate change tend to build on existing approaches and then make assumptions about (or more rarely model) changes in risk levels contingent on climate change scenarios (Jacobsen and Thorsen 2003; Yousefpour 2009). Thus, the studies do not adequately deal with the issue that the uncertainty about what climate scenario will become real may be much more important for significant decision than the actual changes in known risk levels for given climate change (Cordonnier et al. 2008). However, the precautionary principle from environmental management (see Rogers et al. 1997) and for adaptation to the risk in forestry, e.g. climatic changes, has been taken into account in some studies applying appropriate silvicultural interventions (Knoke et al. 2001, 2005; Knoke and Wurm 2006; Knoke 2008; Jacobsen et al. 2004; Yousefpour 2009). For instance, Yousefpour (2009) examined adaptation to climate change in the Black Forest area of south-western Germany by the conversion modelling of Norway spruce monocultures towards mixed spruce beech forests subject to multiple goals and found an optimal solution asking for diversified silvicultural interventions.

4.2 Spatial scale in climate change studies

Climate change is considered a regional or global phenomenon rather than a local one, even if observed locally

(Lindner et al. 2002; Spring et al. 2005; Böttcher 2008; Galik and Jackson 2009; Xu et al. 2009; Heller and Zavaleta 2009). Therefore, one could argue that the scale of climate change studies should be at landscape or at least forest enterprise level to reasonably address the effects of changing environment on forest structure. The present review reveals that in fact most of the investigations of forest risk modelling under climate change (21% of 112 selected studies) were conducted either at landscape (9%) or forest level (9%) and that only a few studies (3%) considered the risk of climate changes solely at the stand level. For analysis of uncertainty and risk associated with climate change, it appears crucial to be able to handle problems defined at the forest or landscape level. It should, however, be noted that decision problems at landscape level are often complex, multi-dimensional integer optimisation and are therefore difficult to solve for optimal solutions, even in a static setting. Adding uncertainty and a long time perspective further complicates the issue, and most likely landscape-level models require substantial simplification of the adaptive decision problems (see Jacobsen et al. 2010; Meilby et al. 2001, 2003 for complex examples of aggregating from stand to forest level). While this may seem like a limitation—not making use of the full underlying information—it will be useful to illustrate some spatial aspects of the uncertainty, which can then, at first in a qualitative way, be handled together with more complicated but deterministic landscape models. However, Heller and Zavaleta (2009) warn that problems of scaling may raise uncertainty, including scaling-down global climate models to fit maenagment scales or scaling-up empirical observations to predict larger scale processes. This is even more crucial when attributes like biodiversity, mainly indicated non-linearly (Yousefpour 2009), are under consideration of adaptive management.

4.3 Model and solution approaches relevant for climate change

From a technical point of view, it is always a challenge to integrate risk into the modelling procedures. Finding a solution to sophisticated risk-including models is itself a comprehensive scientific task, where there is no general analytical solution to most of the relevant formulations and problems. Furthermore, if a solution at the operational level is demanded, numerous technicalities and modelling challenges will be faced to find numerical solutions. However, Kangas and Kangas (2004) conclude that the most important point is not to ignore uncertainty and to take it into account in decision making one way or another and to make the decision makers be aware of that. Weintraub and Romero (2006) agree that incorporating risk and uncertainty in OR models in agriculture and forestry is crucial, and there is a

need to adapt methods and concepts specifically conceived for the particulars of the forestry and agriculture sector.

In the present review, SDP was the most frequently applied technique to solve the above-mentioned problems (25% of the literature, see Fig. 5). The SDP algorithm guarantees an optimal solution within the problem formulation. In spite of its advantages, the SDP also suffers from heavy increases in computational complexity as the dimensionality of the problem grows. Along with SDP, the E-V analysis approach was also a widely used (25%) methodology, but it does not comprise an optimal solution as such. This also applies to simulation techniques (16%), which are used to explore the solution space for different management scenarios without producing any concrete suggestions in the form of optimal solutions, but which may lead to a plethora of good solutions. Another approach that offers a real global optimum solution within the problem formulated is LP. Unfortunately, LP involves rigorous assumptions regarding the linearity of objectives and constraints (Weintraub and Bare 1996; Insley and Rollins 2005; Weintraub and Romero 2006; Yousefpour and Hanewinkel 2009), which hampers its wider application. Furthermore, flexible formulations of dynamic decision problems under uncertainty are difficult to obtain within LP formulations of a reasonable size. LP was applied in 16% of the literature and might be combined with SDP. Other techniques were less commonly represented, possibly because of their ambiguous application [fuzzy, information gap theory, non-linear programming, Heuristics, real options, Ito (ito calculus), analytic hierarchy process (AHP) and quasy optimum]. However, it seems that due to the increasing importance of society's preferences in forest risk analysis (Kangas and Kangas 2004; Ananda and Herath 2005; Hoogstra 2008) and in order to legitimise decisions regarding the governance of forest ecosystems (Satake et al. 2007), solution methods like AHP or similar techniques that are able to integrate socio-economic analysis into the decision-making process should be more commonly applied in future studies (Kangas and Kangas 2004; Weintraub and Romero 2006; Heller and Zavaleta 2009). Hahn and Knoke (2010) stress that adaptation is fundamentally about human needs and not about nature aiming to decrease vulnerability in forest ecosystems, and measures carried out should be depending on both ecological and socio-economic understanding.

Recent advances in computational capacity may allow applying more sophisticated techniques like heuristics to solve comprehensive decision problems (Kimmins et al. 2008; Yousefpour 2009; Jacobsen et al. 2010). Most of the above approaches, as stressed earlier, have so far been used in the climate change and forest management literature, in ways that do not incorporate the fact that the degree and speed of climate change are both highly uncertain, yet crucial to the analysis of any of the derived changes in otherwise known risks.

5 Conclusion with a focus on future research needs

Looking across all the studies reviewed here, we find that there are two important challenges that need to be addressed to be able to break new ground with respect to decision-making models for adaptive forest management under climate change.

The first challenge is the modelling of uncertainty related to climate change. In the literature reviewed, uncertainty is modelled in ways that usually assume that the parameters of the probability distributions or applied stochastic processes are known (Gove and Fairweather 1992; Weintraub and Bare 1996; Palma and Nelson 2009). The important implication is that even if future states and events are unknown and need to be assessed as stochastic, the models can explicitly assign a (treatment conditional) probability to any model outcome in model state space and time. The stochastic models often base their parameterisation on empirical observations of, e.g. windthrow or fire risks and price behaviour. However, the uncertainties and risks related to climate change cannot be observed historically. There is an inherent uncertainty about the future probability space for climate development, which does not offer itself to simple parameterisations. Rather, model developments will need to address the challenge of handling non-stationary and perhaps even belief-based parameters of stochastic processes and probability distributions, like Bayesian updating (Kangas et al. 2000; Prato 2000, 2009). Kangas and Kangas (2004) and Prato (2000, 2008) admit the suitability of knowledge management approaches like probability theory of Bayes and evidence theory of Dempster–Shafer for coping with non-stationary risks in adaptive management of forest resources. Probert et al. (2010) introduce an adaptive modelling applying Bayesian theory combined with optimization algorithms

with an example of conservation planning for a threatened species Tasmanian Devil, *Sarcophilus harrisii*.

The second challenge concerns the need for simple but valid forest growth models that (1) can provide good estimates of timber production and preferably also other goods and services as a function of stand level characteristics, (2) are constructed in ways that allow them to react to changes in climate with respect to, e.g. two parameters, temperature and precipitation, (3) are able to link together stand output functions to form forest and landscape levels models and (4) are simple enough to provide good conditional predictions of key state variables and flows at low computational costs, hence allowing for evaluation of numerous decision alternatives. Looking into the literature, it appears that most climate-sensitive models are computationally very demanding, e.g. process-based models. These are good models for advanced studies of ecosystem dynamics at a very detailed level (i.e. high complexity and precision, green area along the X-axis of Fig. 7), but their usefulness for decision analysis is quite limited as they are considered to embody too many uncertainties and require too many (poorly known) parameters for their application to be as reliable in practice as empirical models (e.g. Böttcher 2008; Galik and Jackson 2009; Yousefpour 2009). Thus far, they have not been able to predict the effect of different management prescriptions as required for adaptive forest management (less decision diversity, green area along Y-axis of Fig. 7). Furthermore, because of their often heavy computational demands (in terms of run time, etc.), they do not form an attractive basis for the more advanced decision modelling approaches, which are themselves either computationally demanding (e.g. SDP) or at least require numerous stochastic runs of the models under varying assumptions, e.g. Bayesian updating with simulation.

In comparison, a large amount of research conducted in economic risk modelling of forest management applied substantially more advanced approaches to decision modelling. This research especially emphasised timber price, interest rate and rotation period, and it has been based mostly on Faustmann formulations (high risk decision diversity, brown area along the Y axis in Fig. 7). The field is closely related to the real options literature as shown by Plantinga (1998) and with examples like, e.g. Thorsen (1999a, b), Abildtrup and Strange (1999), Duku-Kaakyire and Nanang (2004), Gjolberg and Guttormsen (2002) and many others. The main limitation but also advantage of these types of studies is that they usually apply empirically based models to predict forest development or development in prices over time (e.g. Brazee and Mendelsohn 1988; Gong 1994; Pukkala and Miina 1997; Willassen 1998; Thorsen 1999b; Buongiorno 2001; Jacobsen and Thorsen 2003; Orois et al. 2004; Zeng et al. 2007; Alvarez and Koskela 2006, 2007a, b; Yoshimoto 2009). The advantage
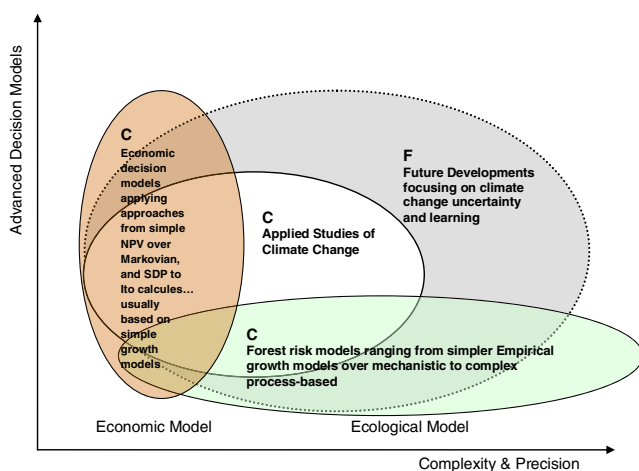

Fig. 7 Chart illustrating current (C) and future (F) situations in research emphasising adaptive forest management modelling

is that these models are often easy to implement in more complex decision models, and they have low computational demands. The disadvantage and limitation is the fact that, by their very nature, empirical models are based on historical evidence, and although the climate has also varied historically, so that empirical growth models may include effects of annual weather, the effects of short-term fluctuations of the weather on growth, regeneration and mortality are likely to differ considerably from the effects of long-term climate change.

Developing operational growth models that are based on (stand-level) empirical information and include causal components would solve the problem and facilitate development of adaptive management schemes. Moreover, future studies should attempt to bridge the gap between comprehensive ecological models and economic models to assist forest decision makers with appropriate and complete modelling tools.

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