Climate Change and Decision-Making Under Uncertainty

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Abstract This paper highlights the main risks and uncertainties associated with climate change in forest management. The overarching challenge is the deep uncertainty about the future direction of changes in climate denoted by representative concentration pathways (RCPs). Moreover, climate change poses new sources of risk from frequent, more intensive, and even novel disturbances in forest ecosystems. Adaptation strategies have been developed to guarantee resistance of forests to climate change and impacts, but they are mostly valid for a restricted set of climate outcomes in the future. Therefore, alternative decision-making approaches should be found to overcome the deep uncertainty about future climate development and adapt forests to future environmental conditions. We propose two decision-making approaches; portfolio diversification and robust decision-making (RDM) to solve both problems. Portfolio management is an established concept in forest utilization and requires diversification of forest structures by e.g., admixing new species, or applying different sets of silvicultural interventions. Robust decision-making is a unique approach to deal with the deep uncertainty in general, but has rarely been applied to forest management. Recent adaptations of RDM to risk management under climate change provide a good basis for

application in forestry. We outline the details of RDM to this end with an example, and highly recommend its application. Finally, a consensus among politicians on a climate target, e.g., Paris agreement, may diminish the deep uncertainty about the degree of climatic change at the end of the century. However, actions pathways, i.e., scenarios to meet the climate target would stay deeply uncertain for long.

Keywords Adaptive management · Climate target · Forest growth · Climate risks · Forest econometrics

Introduction

Forest management is used to cope with uncertainty inherent in forestry. However, climate change exceeds the previous level of risk and uncertainty and poses a major novel challenge to forest management. Climate directly affects forest growth and productivity through the photosynthesis process, phenology of deciduous and conifer trees, and stressing forest ecosystems under extreme climatic conditions. Moreover, the frequency and magnitude of damage to forests via hazards is increasing as climate changes [1, 2]. However, climate change may also positively affect forest ecosystems by enhancing conditions for forest growth, e.g., increasing CO₂ availability in the atmosphere [3••], and gaining new areas suitable for forest vegetation types in higher latitudes [4] and altitudes [5]. These major impacts of climate change pose a higher quantity of uncertainty (climate change as a new source of uncertainty) and novel quality of uncertainty (changing patterns and magnitude of damages) to forest resource management.

The most challenging uncertainty related to climate change effects on forest ecosystems, however, remains the difficulty of identifying a single scenario to predict the climate development pathway in coming decades to deal with its particular

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impacts and uncertainties. Decision-making under this kind of deep uncertainty is one of the most crucial and still unresolved problems in the management sciences and economics. There is a set of plausible climate change scenarios based on assumptions about population growth, fossil fuel consumption, and land use changes in the twenty-first century resulting in a low or high global warming [6, 7•]. Though, any consensus among politicians on a climate target, e.g., Paris agreement to allow for a max. 1.5–2 °C change in the global average surface temperature at the end of the century, may diminish the deep uncertainty about the degree of climatic change. However, actions to meet the climate target and their pathways as target-oriented scenarios would stay deeply uncertain.

Scenario-based approaches are widely applied to produce a series of recommendations for forest management under climate change. Ensemble projections with the aim to produce stochastic climate projections by incorporating a range of outcomes from different global climate models may capture modeling uncertainty about realization of climate change scenarios [8]. However, there is huge uncertainty about the range of scenarios being able to represent all future changes and which scenario is the more probable one among others. This adds to the uncertainty of decision-makers facing different potential futures with their underlying suitable management strategies. We introduce two main approaches to cope with these deep uncertainties using (i) a pragmatic decision on the diversification of strategies to ensure the partial resistance of forests to upcoming climatic changes and impacts, and (ii) a robust decision-making approach to ensure a certain minimum level of outcomes regarding forest health and productivity that are independent of future climatic conditions.

In the following, we first clarify the nature of uncertainty inherent in climate change and its impacts on forest ecosystems and, subsequently, review the decision-making approaches so far applied in the domain of climate change management to deal with the problem. We highlight that more research is crucially needed on the topic to assist implementation of climate change management strategies in forestry.

Climate Change Uncertainty

Future possible climate development trends are highly related to the socio-economic evolution of the global population, industries and energy consumption, economic growth, and the sustainability governance of global natural resource. Assuming a certain set and sequence of these socio-economic factors and their changes (forcings) would frame a scenario for climate trajectory models to predict future possible climate states. IPCC [6, 7•] reports and follow up by experts have made an exhaustive effort to encapsulate these forcings in a few major scenarios, the so-called RCPs (Representative Concentration Pathways). The main

outcomes of RCPs are the pathways toward an explicit climate condition at the end of twenty-first century [7•].

Degree of Changes

RCPs are employed to represent a wide but closed set of climate change scenarios and provide a common source of forcing for earth system models (ESMs) to simulate climate trajectories. However, the RCP scenarios applied to different ESMs may result in different outcomes, e.g., trends in mean global surface temperature, precipitation, and drought patterns. Figure 1 below illustrates the four main RCPs scenarios applied to different ESMs to predict anomalies in global surface temperature. RCP8.5 is a no-climate-policy scenario resulting in severe changes in climate and RCP2.6 represents a rigorous climate policy mostly to limit greenhouse gas (GHG) emissions and, accordingly, low climate change impacts. RCP4.5 and RCP6.0 are intermediate scenarios with moderate GHG emissions and CO₂ concentrations in the atmosphere. Although there is a clear difference among these four RCP scenarios, there is substantial uncertainty among models to predict the climate properties forced by each of these RCPs. Therefore, the analysis of the impacts of climate change would depend on the model applied (e.g., forcings of RCPs by MPI-ESM as presented in [8]).

Climate Change Impacts

Forest decision-makers' awareness and precaution about climate change is highly affected by their direct observation about natural variability of climate and the regional weather cycles and indirectly by observing impacts of climate change on forest health, productivity, and risks [10]. Forest decision-

Fig. 1 Projected changes in global surface temperature during the twenty-first century applying ESMs (the number in parenthesis is the number of participating models) in CMIP5 Project (Coupled Model Inter-comparison Project Phase 5). (Used with permission. Source: [9])

makers have been observing new patterns in forest growth and productivity that are different from historical records [5]. On the other hand, there are new sources of risk to forests either from changes in natural hazard intensity [2, 11], e.g., windthrow frequency and damage [11], or novel kinds of risk [1], e.g., higher mortality from drought stress in European beech (*Fagus sylvatica*) stands [12].

Impacts on Forest Growth and Productivity

Recent and future changes in forest growth and productivity are driven by an increasing concentration of CO₂ in the atmosphere, nitrogen deposition from the atmosphere and associated changes in climate properties, e.g., temperature and precipitation. CO₂ is a vital GHG in the photosynthesis process and its increased availability positively affects tree growth. Tree growth in forest sites with no nutrient limitation would largely benefit from increased CO₂ availability [3••]. Changes in temperature and precipitation may affect forest growth positively by increasing tree growth (due to longer growing season) or suitability of new areas for the establishment of forest vegetation [5]. Examples of these effects are shown for enhanced growth of Norway spruce (*Picea abies*) in forest productivity studies in Sweden and Finland [4]. However, negative effects have been observed on poor sites, decreasing growth [13] or increasing mortality of trees [14] especially under heat or drought stress [15], as a combined effect of temperature (increase) and precipitation (decrease).

Impacts on Forest Risks and Hazards

Natural hazards have long been recognized as natural phenomena affecting forest vegetation dynamics [5]. For example, mortality is a common regulating mechanism in forest ecosystems that controls forest stand density, species composition, and regeneration establishment in mature closed stands. There are multiple examples emphasizing the vital role of natural hazards, e.g., forest wildfires for facilitating a new generation of seedlings to grow and reach sunlight.

However, we face new patterns in the frequency, intensity, and geographical distribution of these damage agents. During the past decades, there have been increasing reports (higher frequency) of large-scale and intense damage to forests such as winter storms in central Europe [11], forest fires in Spanish oak forests [16], and windthrow in southern Sweden [17]. Moreover, there are regionally novel sources of disturbances (e.g., fire in central Europe) and post disturbance spread of biotic agents (e.g., insect calamities after windthrow) affecting forest health and productivity. Bark beetle attack on Norway spruce forests in most regions of Europe is a typical example of such a disturbance in a new large-scale [2]. Furthermore, there are other disturbance mechanisms, as direct outcomes of climatic change, such as drought affecting forest health [1, 15].

Decision-Making Under Climate Change

Managing forests under climate change requires decisions dealing not only with the uncertainty related to the nature of changes, e.g., deep uncertainty about climate change scenarios, but also the uncertainty about the actions to cope with the new conditions and climate change impacts. However, experience with new alternative management strategies and their effectiveness to increase resistance and resilience of forest ecosystems is not sufficient so far. Moreover there are multiple options to reach forest management goals [18, 19] and their utility is highly dependent upon the underlying climate change scenario. Therefore, in the following, we outline the issues related to the selection of alternative management solutions and two main decision-making approaches to solve the problem of selecting the best decision at a given point in time, given what is currently known, and what is currently anticipated in terms of alternative possible climate trajectories.

Forest Management Alternatives to Deal with Climate Change

Adapting state of the art forest management strategies to climate change may demand broadening the range of activities beyond traditional silvicultural interventions to realize an effective adaptation [19]. Therefore, preparing a set of alternative solutions besides a business as usual (BAU) strategy is an essential step to explore the decision space and search for an optimal decision. Adaptive strategies may be implemented in a large forest area as a unique solution or specified for a small forest area to satisfy adaptation goals in combination with other management strategies. The latter is, furthermore, recommended to meet multiple forest management objectives and restrictions [18].

Novel Solutions and Strategies

Silvicultural interventions are one of the main tools for forests' adaptation to climate change [19] by changes, for example, in thinning regimes and intensities [15], changes in silvicultural systems and species composition [18], exploring new ways to establish favored regeneration [20]. Moreover, forest structural changes may ensure adaptation by introducing new endemic or exotic species being insensitive, or more adjusted, to climate change [21]. Moving from monocultures toward mixed forests and from even-aged forestry systems to uneven-aged are further alternative strategies for establishing resilient forests [22]. Economic decisions such as finding the optimal rotation age under change can also improve the adaptability of the forest sector to the risks of climate change, e.g., forest fires [23]. Therefore, it is essential to search for a new set of alternatives that are able to deal with the local effects of climate change, and to assess their outcomes.

Combined Effects of Management and Climate

Traditional assessment of management alternatives based on empirical knowledge (e.g., using yield tables) is not appropriate to simultaneously analyze management actions and climate effects [24••]. It is crucial to identify physiological responses to adaptive management interventions using climate driven, e.g., process-based, forest growth models. The evaluation results of the combined effect of management and climate can be used to identify effective adaptation strategies. The next step is to identify the most efficient strategies with the highest adaptive capacity and lowest costs subject to a set of climate change scenarios.

Dealing with Deep Uncertainty of Climate Change

Making decisions under climate change uncertainty requires approaches that safeguard stability of optimal solutions and should take into account the dynamic nature of this decision-making process. Forest decision-makers may not realize the reduction of uncertainty about climate change (i.e., reduction in the number of feasible future scenarios) very soon [24••] because there is no consensus among politicians about a climate target [6] or about a unique pathway to achieve the climate target of a maximum of 2 °C according to the Paris agreement. They should rely on the available information about the current and future state of the climate and suitable adaptive decisions, and update this pool of knowledge at any decision point [25]. However, it remains unresolved how to decide upon a wide range of decision alternatives, each optimal under certain climate conditions. In the following, we refer to two main approaches, debated in the arena of climate change risk management, namely portfolio management and robust decision-making. The former is already applied in forestry to deal with different sources of risks and the latter is rather novel and needs detailed elaboration.

Diversification of Management Strategies

A simple and effective strategy to cope with climate change is to build a portfolio of adaptation strategies and measures, e.g., planting different tree species [20]. Integrating sufficient flexibility about switching from one strategy to another in a dynamic decision-making process can provide the basis for staying, at least partly, adapted and getting advantage of potential opportunities in the future. Diversification of management actions and sequences over time as forests are aging is not a new concept to forestry. It is applied to simultaneously reach multiple goals [18] and reduce risks [26] and has been an evolving common strategy for forest management in the last decades. The downside of this strategy may be the difficulty in finding optimal solutions for multi-objectives and constrained decision problems [27].

Robust Decisions to Tackle Climate Change Uncertainty

Making decisions robust to the uncertainty of climate change and its impacts may be the ultimate goal in different sectors including forestry. However, this robustness may be achieved at the cost of optimality, e.g., moving away from maximum production and benefit. Therefore, there is a dilemma between the degree of robustness and reduction in uncertainty inherent in climate change. A robust decision-making (RDM) process would result in a good decision, continuously performing satisfactorily under all climate change scenarios, but not necessarily in the optimal decision (relevant to a subset of scenarios).

Recent studies on RDM algorithms, e.g., [28•, 29] concentrate on maximizing expected utility from management outcomes in combination with the conditional value at risk (CVaR). The aim of RDM may be defined as (1) simultaneous maximization of a weighted average of expected utility and CVaR, which is the utility in the worst case future, (limited degree of confidence (LCD) criterion), or (2) maximizing expected utility subject to CVaR, as a certain minimum level of achievement in the worst cases, (safety-first (SF) criterion) in dealing with deep uncertainty in climate change. A very rare application of RDM to forest management under climate change [28•] defined RDM as “reasonably likely to be effective in achieving objectives, over a range of uncertainties,” incorporating deep uncertainty about future conditions. To find more flexible solutions than the current status quo forest management strategy, the authors asked experts to judge the robustness of decision alternatives for post disturbance forest land management. However, the RDM concept was applied without further development of associated algorithms and decision criteria, e.g., LCD.

As an example of the application of RDM in forestry, we refer to some figures simulated by Yousefpour et al. (2014) for a stylized forest species selection problem in central European conditions [25]. The authors summarized the expected economic performance of different species, based on their land expectation value (LEV), under climate change scenarios (see details in Table 1). According to these figures, there is an optimal species, i.e., with the highest economic performance, for each climate change scenario (e.g., beech subject to climate change scenario III with LEV of 679 €/ha/year). As this optimality is scenario-specific, we apply the same

Table 1 Average economic performance (land expectation value) of four species and subject to climate change scenarios I–III for a low, moderate, and a high change in future climate (numbers are all in €/ha/year)

Species/climate change scenario	I	II	III
Beech (<i>Fagus sylvatica</i>)	294	517	679
Scots pine (<i>Pinus sylvestris</i>)	479	452	432
Norway spruce (<i>Picea abies</i>)	412	548	670

evaluation results to find robust decisions with LCD and Safety-First criteria as described above. An LCD based robust decision will chose Norway spruce for plantation with a land expectation value (LEV) of 541 €/ha (with an equally weighted average of min 412 €/ha/year + max 670 €/ha/year). Safety-First based robust decision results depend on the CVaR constraint. In the example below, if we aim for a minimum performance of at least 430 €/ha, the optimal robust decision is Scots pine because it outperforms Norway spruce and Douglas fir with the maximum performance of 479 €/ha/year. In this case, beech is excluded from the decision space as it does not satisfy the constraint and may impose a high economic loss in the worst case, i.e., 138 €/ha/year (with LEV of 294 €/ha/year compared to Scot pine with min. LEV of 432 €/ha/year).

Discussion

Decision-Making Approaches and Climate change Uncertainty

Future decisions on forest management under climate change may tend toward either scenario-specific adaptation or scenario-unrestricted robust decisions. Adaptation has been the focus of forest management studies under climate change during the last decades [19, 21, 24••]. Decision-making approaches, especially optimization, have been widely used to recommend the most suitable adaptive strategies [10, 20]. However, adaptive strategies are usually optimized to be applied under a historical [18] or a specific future climate scenario [30], which is a very deliberate assumption. Therefore, it is necessary to optimize the forest investment portfolio by applying simultaneously a diversity of adaptive actions to reduce income risk (see the “[Dealing with Deep Uncertainty of Climate Change](#)” section) or apply, as we recommend, different search algorithms to identify adaptation strategies that are robust to climate development outcomes and will not pose a great loss to forests if the deliberate assumption fails. We recommend in this review an explicit integration of robust decision-making and outline the most suitable developments adopted from the climatology and risk management literature [28•, 29].

If there is an ensemble of global climate models for future climate predictions, probability distribution functions (PDF) of prediction results should be used to incorporate model uncertainty in a stochastic analysis [28•, 31]. Though, the main idea behind RDM regardless of its deterministic (integrating a single climate projection) or stochastic nature (integrating modeling uncertainty of climate projections) remains to reduce the sensitivity of decision outcomes to deep uncertainty about scenarios (e.g., climate change). This aim can be achieved by making cautious decisions that operate satisfactorily under all possible sets of circumstances but that are

not certainly optimal for each individual circumstance. Technically, robustness is defined as ensuring a minimum level of achievement under worst case conditions and simultaneously finding the robust decision maximizing the outcome under all other conditions. If the minimum outcome level (CVaR) is treated as a constraint in the decision-making process, the Safety-First criterion is chosen. An alternative approach is to choose the LCD criterion and maximize a weighted average of the expected outcome and a minimum level of outcome in the worst case (CVaR). An actual application of these explicit robust decision-making approaches to forest management problems under climate change, however, is missing.

Future Research Development

The challenge associated with climate change uncertainty offers a unique opportunity for innovation in developing new decision-making tools. Traditional decision-making approaches are mostly based on past experiences, which may not be applicable in the future or reach the desired outcomes. Novel experiences may assist in understanding the details of forest responses to climate change in the short term, but may, however, not be reliable for long-term application until climate is stabilized. In addition, there is no consensus about the degree of changes in the future and therefore, a set of possible scenarios are proposed [6]. The facts about climatic changes and the uncertainty about the direction of changes, demand dynamic decision-making approaches, i.e., making use of novel information becoming available over time. Accordingly, novel decisions should revisit the former decisions and regard new knowledge and commitments about climate protection, i.e., CO₂ mitigation in forests, in making relevant and adapted decisions. Moreover, irreversible forest decisions may be postponed to a point in the future, when the knowledge pool suffices to make more certain decisions, e.g., about forest conversion from even-aged to uneven-aged structure [24••].

Change in Framework by Consensus About Target Global Warming Degree at the End of the Twenty-First Century

Internationally binding agreements on the climate target (e.g., Paris agreement) would reduce the deep uncertainty about the degree of climate change at the end of twenty-first century. The decision-making problem afterwards would be to find the most cost-effective strategy for adaptation to the pathway leading to the target climate. However, there may be more than a single pathway to achieve the climate target, and so, the agreement does not eliminate the deep uncertainty. Figure 2 illustrates the climate sensitivity of global surface warming to two hypothetical pathways toward the 2 °C target (according to the Paris agreement) and the deep uncertainty about the realization of these pathways in the future.

Fig. 2 Realized projection of changes in global surface temperature during the twenty first century (see details in Fig. 1, Source: [9]) and the hypothetical pathways (blue and green dashed lines) to meet the 2 °C global surface warming target of Paris agreement. (Used with permission. Source: [9])

The modeling uncertainty about the projection of future climate could be considered by referring to the median and variability (PDF) of the projections by an ensemble of global earth system models [31]. However, modeling uncertainty about the response of forest ecosystems not only to climate but also to management remains unsolved. Advances in computation capacities and novel knowledge about growth processes and forest dynamics may reduce the modeling uncertainty to a large extent. Technical improvements may assist in providing more precise tools for forest inventory and measurements and provide a less uncertain dataset for the analysis of the status quo and as an input for model calibration and validation. Therefore, we may conclude that the overall uncertainty about forest management under climate change may be reduced in the future depending on international cooperation and commitments along with technological advancements. This conclusion highlights the value of learning and obtaining novel knowledge about climate change [32] by monitoring forest responses to a combined effect of climate and management, and the necessity to consider robust decisions and avoid high economic loss (see an example in the “[Dealing with Deep Uncertainty of Climate Change](#)” section). It is worth highlighting that the difficulty in modeling extreme climate events and the imposed high impacts on forests health and productivity remains a challenging issue as there is no historical parallel to build the climate model predictions upon [33].

Conclusion

Implementing a portfolio of adaptive options is an appropriate way to deal with the uncertain world with changing climate and socio-economic demands on forest resources and reducing the

vulnerability of these resources to the current and future impacts of climate change [24••, 26, 34]. Furthermore, applying RDM either conceptually at the stage of the appraisal of management alternatives or explicitly for identifying the most desirable robust decision is highly recommended to guarantee a satisfying level of forest ecosystems’ health and provisioning of ecosystem goods and services in the future. Furthermore, we are currently in the transition phase and lack a set of scenarios for the prediction of climate development in the twenty-first century toward potentially effective political targets at the end of the century. Therefore, we recommend taking into account the current climate change scenarios, e.g., RCPs [7•], and, moreover, most extreme climate development scenarios to explore the entire solution space on forest decisions. As RDM is a missing methodology in the forestry literature, future studies should deliver good and easily implementable examples of RDM applications to solve a diverse set of forest management problems at different levels of complexity. Finally, a consensus among politicians on a climate target, e.g., the Paris agreement, is a great step forward to reduce the deep uncertainty about the degree of climatic change at the end of the century. However, actions pathways, i.e., scenarios, to meet the climate target would stay deeply uncertain providing needs for robust decision-making.

Compliance with Ethical Standards

Conflict of Interest Drs. Yousefpour and Hanewinkel have no conflicts of interests to declare.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by the author.

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