Journal of Environmental Management 246 (2019) 706–716

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Climate change and the provision of biodiversity in public temperate forests – A mechanism design approach for the implementation of biodiversity conservation policies

Andrey Lessa Derci Augustynczik*, Rasoul Yousefpour, Marc Hanewinkel

Chair of Forestry Economics and Forest Planning, University of Freiburg, Tennenbacherstr. 4, 79106, Freiburg, Germany

ARTICLE INFO

Keywords:
Forest biodiversity
Mechanism design
Forest optimization
Conservation planning
Forest birds

ABSTRACT

The provision of forest biodiversity remains a major challenge in the management of forest resources. Biodiversity is mostly considered a public good and the fact that societal benefits from biodiversity are private information, hinders its supply at adequate levels. Here we investigate how the government, as a forest owner, may increase the biodiversity supply in publicly-owned forests. We employ a mechanism design approach to find the biodiversity provision choices, which take into account agents' strategic behavior and values towards biodiversity. We applied our framework to a forest landscape in Southwestern Germany, using forest birds as biodiversity indicators and evaluating the impacts of climate change on forest dynamics and on the costs of biodiversity provision. Our results show that climate change has important implications to the opportunity cost of biodiversity and the provision levels (ranging from 10 to 12.5% increase of the bird indicator abundance). In general, biodiversity valuations needed to surpass the opportunity cost by more than 18% to cope with the private information held by the agents. Moreover, higher costs under more intense climate change (e.g. Representative Concentration Pathway 8.5) reduced the attainable bird abundance increase from 12.5 to 10%. We conclude that mechanism design may provide key information for planning conservation policies and identify conditions for a successful implementation of biodiversity-oriented forest management.

1. Introduction

The provision of biodiversity remains a major challenge in the management of forest resources. Biodiversity has been continuously declining worldwide during the past decades, despite its recognized importance to human well-being, ecosystem functioning and ecosystem resistance and resilience under climate change (Díaz et al., 2006; Isbell et al., 2015; Tilman et al., 2014). A main constraint to the implementation of biodiversity conservation strategies is the fact that biodiversity is mostly considered a public good, and in the absence of markets or policy mechanisms to promote its provision, there are incentives for free riding and undersupply. One option to tackle this issue, is to enhance biodiversity goals in public forests. The government, as a forest owner and aiming to promote an efficient use of forest resources, may raise funds and apply biodiversity-oriented management solutions in these areas. Thereby, it is possible to mitigate the discrepancy between current and efficient biodiversity supply, promoting sustainability and increasing social welfare (Kemkes et al., 2010).

The promotion of biodiversity in forest landscapes demands a cost-benefit analysis of biodiversity-oriented management strategies, compatible with societal preferences for multiple forest goods and services. This requires that both social costs and benefits related to biodiversity are known. The quantification of costs is a straightforward task, e.g. through the computation of the opportunity costs of biodiversity-oriented forest management or the value of contracts for biodiversity amelioration (Rosenkranz et al., 2014). Conversely, the evaluation of biodiversity benefits involves indirect assessments, predominantly applying choice experiments, where participants are asked how much they would be willing to contribute towards an increased biodiversity supply or by eliciting their preferences for bundles of ecosystem services (e.g. Meyerhoff et al., 2012; Getzner et al., 2018; Iranah et al., 2018). A key issue when considering biodiversity benefits, is the fact that the preferences for biodiversity are private information, and policy makers may have at hand only prior beliefs (e.g. the probability distribution of these preferences), in terms of the willingness-to-pay (WTP) for biodiversity. This means that agents may have the incentive to misrepresent their true preferences when asked to contribute towards the cost of biodiversity provision, hindering the implementation of

* Corresponding author.
E-mail address: andrey.lessa@ife.uni-freiburg.de (A.L.D. Augustynczik).

https://doi.org/10.1016/j.jenvman.2019.05.089
Received 4 February 2019; Received in revised form 13 May 2019; Accepted 21 May 2019
Available online 18 June 2019
0301-4797/

biodiversity conservation programs.

Mechanism design is arguably the best tool to address problems of this nature. Mechanism design is a sub-field of game theory, also known as inverse game theory. This framework searches for the design of games (e.g. auctions and voting schemes) that will lead to a desired outcome, such as welfare maximization or other economic goals (Nisan and Ronen, 2001). In this sense, mechanism design can be applied to a variety of natural resource management problems that involve asymmetric information. Formally, a mechanism is composed by a social choice function and a payment rule ensuring agents have incentive to participate in the mechanism and are not better-off by misrepresenting their true valuations. The mechanism designer can then make use of these functions to decide upon the implementation of management solutions.

Here we use this framework to tackle the increase in biodiversity supply in public forests, taking into account the societal preferences for biodiversity and the strategic behavior of the agents. In our setting, the government proposes a mechanism to raise capital to cover the costs of an increased biodiversity supply. According to Rands et al. (2010), to increase the success of conservation policies it will be necessary to prioritize the management of biodiversity as a public good, to integrate biodiversity in both public and private decision-making and to facilitate policy implementation. These priorities may be combined under the mechanism design framework. Thereby, we are able to characterize the supply levels that can be actually realized under the private information held by the agents and what the minimum conditions are, in terms of the social benefit, that enable the implementation of conservation policies without the need of external funding. This is crucial to create more resilient forest landscapes in the future.

A variety of mechanisms have been studied for the private supply of public goods. For example, Güth and Hellwig (1986) and Csapó and Müller (2013) provide a framework for defining social choice functions and payment rules for the private supply of public goods. Bierbrauer and Hellwig (2016) and Grüner and Koriyama (2012) analyze the provision of public goods in voting mechanisms. Güth and Hellwig (1986) highlight that a further difficulty in the supply of public goods arise when a large number of participants are involved, which is typically the case for the implementation of biodiversity conservation policies. The same authors show that in this case, the probability that a single participant affects the supply of the public good is small, leading them to reduce their willingness-to-pay and contributions toward the cost of the public good. Hellwig (2003) addressed this issue and reported that in the case that the supply level of the public good is bounded, the costs are independent of the number of agents and the number of participants is sufficiently large, then the public good is eventually provided.

Traditionally, voluntary mechanisms to increase biodiversity provision in forest landscapes have been addressed by game theoretical models. These include, for example, auctions to assign forest reserves (e.g. Hartig and Drechsler, 2010) or auctions for bundles of ecosystem services (Roesch-McNally et al., 2016). Despite the large body of literature dealing with the characterization of mechanisms for the provision of public goods, and their suitability to address a range of natural resource management problems involving the private supply of public goods, mechanism design applications are still largely missing.

Apart from the private information regarding the valuations for biodiversity, a further challenge for the implementation of biodiversity-oriented management refers to the uncertainty induced by climate change on the dynamics of both forest and forest biota. Climate change is expected to modify a variety of forest processes and interactions, e.g. forest growth rates, species composition and disturbance activity (Lindner et al., 2014). These processes are closely related to forest profitability and are therefore predicted to cascade to the opportunity costs of biodiversity-oriented management. These novel environmental conditions will demand new management solutions to anticipate climatic impacts. Therefore, a sensible analysis of mechanisms targeting biodiversity provision needs to consider future forest development and its impacts on the implementation of conservation policies.

Still there is a major gap in the literature regarding the definition of adequate provision levels of forest biodiversity taking into account social costs and benefits. Moreover, the strategic behavior of agents towards contributions to implement biodiversity-oriented management is usually neglected. Here we tackle these issues by integrating ecological and economic aspects of forest biodiversity, using the machinery of mechanism design. We build upon the frameworks developed by Hellwig (2003) and Csapó and Müller (2013), and consider the provision of biodiversity in publicly owned forests in a temperate forest landscape under climate change, using a coupled ecological-economic framework. We addressed in this study the following research questions:

- What are the opportunity costs of biodiversity-oriented management in a temperate forest landscape under climate change?
- What are the minimum conditions for a feasible implementation of biodiversity-oriented forest management in terms of societal benefits?
- What are the impacts of climate change on the social choice function and what are the optimal management solutions to realize an increased biodiversity supply?

To answer the research questions, we applied our mechanism design framework to a temperate forest landscape in southwestern Germany. To account for climate impacts on forest development and opportunity cost, we used the process-based forest growth model 4C under three different climate change scenarios and applied five management strategies: 1) biodiversity provision; 2) biomass production; 3) business-as-usual (BAU); 4) climate adaptation and 5) no management. We built an optimization model to maximize forest Net Present Value (NPV) in an 80-years planning horizon. To define the mechanism, we considered biodiversity valuation data from an extensive choice experiment conducted in Germany, defining the thresholds for the supply of biodiversity under climate change, in terms of the social value of biodiversity. We consider the case where the designer represents the federal state (responsible for the management of forest resources) and agents represent the six administrative regions the study area, negotiating on behalf of their population and deciding upon the contribution towards the biodiversity supply cost. Although we conduct our analysis in a temperate forest landscape in Germany, the framework proposed is flexible and can be easily adapted to different biomes and conservation practices, as long as cost and benefits related to biodiversity supply are available.

2. Material and methods

We conducted our analysis following three steps. Initially, we applied a climate-sensitive growth model to evaluate forest growth dynamics under climate change, assessing the opportunity cost of biodiversity-oriented forest management with the help of an optimization model. Subsequently, we computed the social benefits of biodiversity, applying the results of a choice experiment conducted in our research area and derived a social choice function for the implementation of biodiversity-oriented forest management. Finally, we evaluated climate impacts on the social choice function and how the required increase in biodiversity supply can be realized through forest management.

2.1. Data

To evaluate forest development under climate change, we used forest inventory data from 98 1-ha plots located in publicly-owned forests in Southwestern Germany, following two design gradients of forest cover (< 50%, 50–75% and > 75 in 25 km^2 radius) and forest structure (< 5 habitat trees/ha, 5–15 habitat trees/ha and > 15 habitat trees/ha). The forest inventory recorded tree species identity, the DBH of all trees (with DBH > 7 cm), height of 7% of the trees. Moreover, lying and standing deadwood amounts were assessed. These plots were used to estimate the average forest responses for each forest age class. Based on these responses, we performed the optimized forest planning of 17503 publicly owned forest stands in the southern Black Forest, covering an area of 54227 ha. The forest in the region is dominated by Norway spruce (*Picea abies* (L.) H. Karst.), European beech (*Fagus sylvatica* L.) and silver fir (*Abies alba* Mill.).

To assess biodiversity, we used the German Biodiversity Strategy indicator, given by the abundance of 10 forest bird species (from which seven were present in our research area), in relation to the abundance in the 1970's (BMUB, 2015). We computed the responses of the bird assemblage to different forest management alternatives in each of our plots applying the hierarchical Bayesian model developed in Augustynczik et al. (2019) for the same study area.

The preferences for biodiversity were based on the results from the choice experiment conducted by Weller and Elsasser (2017), assuming homogeneous preferences. The authors computed the WTP from an increase in the forest biodiversity indicator used in the German Biodiversity Strategy, i.e. an increase in the abundance of 10 indicator bird species. For assessing the affected population, we retrieved the population statistics from the national ministry of statistics (Statistiches Bundesamt, 2016).

We computed forest profitability in terms of the Net Present Value in an 80-years planning horizon. We discounted harvesting revenues with a 1.5% market interest rate (Müller and Hanewinkel, 2018). This rate represent the typical return on capital in the region and is compatible with the average long term interest rates in Germany during the past 10 years (ECB 2019). Harvesting and planting costs were retrieved from Härtl et al. (2013) and for timber revenues we used the average market wood prices in Baden-Württemberg in 2016. Therefore, prices and costs were assumed to be deterministic in our analysis.

2.2. Forest simulation and biodiversity supply

To evaluate forest development under climate change, we used the process-based forest growth model 4C (Lasch et al., 2002). 4C describes forest processes at tree and stand scale under changing environmental conditions and is capable of simulating a variety of management interventions, including thinning, planting and final harvesting (Lasch et al., 2005). A detailed description of the model is available in the model webpage (www.pik-potsdam.de/4c/). Since our plots spanned over more than one forest stand, we used the growth model Sibyla (Fabrika, 2007) to estimate the average age of each plot and subsequently computed the average responses of each forest age class based on the plot average age. Sibyla is an individual-tree model that uses the stand generator STRUGEN (Pretzsch, 1997) to generate a forest stand according to individual tree input data, enabling to derive the average age of each species in the stand.

We considered in our simulations five management strategies and three climate change scenarios. The management strategies were defined as: 1) Biodiversity conservation: increase current rotation age in 10 years, apply a thinning intensity of 10% of the standing volume and replace Norway spruce stands by European beech stands; 2) Biomass production: decrease current rotation age by 20 years, apply a thinning intensity of 25% of the standing volume and convert spruce stands to Douglas-fir (*Pseudotsuga menziesii*) stands; 3) BAU: maintain current rotation age, species composition and a thinning intensity of 17% of the standing volume; 4) Climate adaptation: decrease current rotation age by 10 years, apply a thinning intensity of 20% of the standing volume and convert spruce stands to Scots pine (*Pinus sylvestris*) and 5) No management: no thinning, harvesting or conversion. Each plot and management alternative was simulated under three climate scenarios, given by the combination of the Global Climate Model (GCM) HadGEM2-ES and the Representative Concentration Pathways (RCP) 2.6, 6.0 and 8.5, bias-corrected by ISIMIP (https://www.isimip.org/). We refer to these scenarios in the remainder of this manuscript as Had2.6, Had6.0 and Had8.5.

To assess the increase in biodiversity provision through forest management, we used the biodiversity index of the German Biodiversity Strategy, which is computed based on the abundance of 10 forest birds, used as indicator species. We used the outcomes of the forest growth model to predict the abundance of these indicator forest birds under different management options. Biodiversity supply was then evaluated as a flow of benefits along the simulation period. The bird abundance data was collected using a point count protocol with three repetitions in 2017, which was used to fit an N-mixture Bayesian hierarchical model (Eq. (1)). In the model, the community process was modelled using a Bernoulli distribution, the abundance of the species was described by a zero-inflation Poisson distribution and the detectability was evaluated through a Binomial observation model (for details see Augustynczik et al., 2019). Moreover, we set the abundance of microhabitats to its average value, due to limitations on the detail of input data to estimate this parameter. To provide more robust projections, we also reduced one standard deviation from the mean estimate of the parameter related to the conifer share, due to the high sensitivity and uncertainty related to this parameter.

$$\lambda_i = \varphi_i \exp(b_{0i} + b_{1i}Slope + b_{2i}Altitude + b_{3i}BA + b_{4i}ConiferShare + b_{5i}Dvol + b_{6i}NDead + b_{7i}TMHA) \quad (1)$$

Where: λ_i: abundance of species (N/ha); ϕ_i: zero inflation coefficient; Slope: plot slope (°); Altitude: plot altitude (m a.s.l.); BA: plot basal area (m^2/ha); ConiferShare: share of conifers (%); Dvol: deadwood volume (m^3/ha); NDead: number of snags (N/ha); TMHA: tree microhabitat abundance (N/ha).

2.3. Costs of biodiversity provision and optimal management under climate change

Based on the forest responses obtained in each climate change scenario, in terms of wood production and biodiversity, we quantified the costs of biodiversity provision using an optimization approach. We constructed a linear programming model to maximize forest profitability while increasing biodiversity provision thresholds (for details see Appendix A). Thereby, it was possible to establish a Pareto frontier between NPV and bird abundance and to derive the total cost related to this increase in biodiversity supply. The total cost was defined by the difference in NPV between the baseline scenario (maximum NPV and no biodiversity requirement) and scenarios including biodiversity requirements (increase in bird abundance).

2.4. Biodiversity benefits

To identify efficient biodiversity supply levels, besides the computation of costs, it is necessary to quantify its social benefits. Here we considered solely the non-use value of forest biodiversity, i.e. existence and bequest values. The biodiversity benefits were established using data from an extensive choice experiment conducted by Weller and Elsasser (2017). The authors computed the WTP for an increase in the forest biodiversity index used in the German Biodiversity Strategy. In this experiment, the authors asked the participants to choose preferred landscape structures and corresponding contributions towards a landscape fund, according to the landscape selected. The authors subsequently used conditional logit models assuming homogeneous preferences to estimate the WTP for an increase in forest biodiversity, measured through the biodiversity index. Specifically, the WTP for an increase in the biodiversity index in 5 and 25 points compared to the current levels was estimated. This corresponds to a 5% and 25% increase in the abundance of the 10 indicator species compared to baseline (1970's abundance), respectively. We used these data to calibrate a constant elasticity of substitution (CES) utility function (Eq. (2)) for wood and biodiversity. This function was subsequently used to derive the benefits of intermediary biodiversity supply levels.

Based on the CES utility function (Eq. (2)), we calculated the WTP per unit (% increase in bird indicator abundance) (Eq. (3)) and the sum of benefits for our research area, correcting the WTP of the affected population by the income in the region. To establish the level of biodiversity benefits, they were discounted and aggregated along the 80-year planning horizon, using a 1.5% pure time preference rate, following the HM treasury (Treasury, 2003). This rate expresses the preference of agents for consuming now rather than in the future. We weighted the biodiversity supply in public forests according to the total forest area in the study region and finally we defined the benefits based on Eq. (3) and the level of biodiversity provision.

$$U = \left[\alpha w^{\frac{\theta-1}{\theta}} + (1-\alpha)B^{\frac{\theta-1}{\theta}}\right]^{\frac{\theta}{\theta-1}} \quad (2)$$

$$MB = \frac{-B^{\left(\frac{\theta-1}{\theta}-1\right)} w^{\left(1-\frac{\theta-1}{\theta}\right)}(\alpha-1)P}{\alpha} \quad (3)$$

where: U: utility; MB: WTP for biodiversity (per unit); B: biodiversity supply level; w: wood consumption; θ : elasticity of substitution between wood and biodiversity; α: preference parameter for wood over biodiversity.

2.5. A second-best mechanism for biodiversity provision

To handle the asymmetric information on the biodiversity valuations, we applied a mechanism design approach. We considered that biodiversity is supplied as a single indivisible unit. The government then defines a discrete level of biodiversity to be supplied in public forests and designs a mechanism to levy funds to cover the costs of the biodiversity-oriented forest management. We assumed that the agents display quasilinear utilities and are risk neutral.

A mechanism can be defined as triple$\mu(A, q, p)$, consisting of a set of agents' strategies$A$, a social choice function q and a payment rule$p$. Let$i = 1, \ldots, N$be agents that hold private information on their preferences for biodiversity, which is defined by their type θ_i(here the type expresses the WTP of an agent). The types are independently drawn from the same probability distribution $F(x)$ with density function$f(x)$, which is assumed to have a monotone hazard rate (the ratio $\frac{f(x)}{1-F(x)}$ is monotone increasing in x). The prior information on the distribution of types is common knowledge. Moreover, the agents know the realization of their own typeθ_i, but do not know the types of other agents. The government, as a designer, selects a social choice function and a payment rule, so that the social choice function maps the vector of types in the decision of supplying biodiversity in publicly-owned forestland q: $\theta \rightarrow [0,1]$ and the payment rule maps the vector of types into the vector of payments performed by the agents$p$: $\theta \rightarrow \mathbb{R}_+^N$. Since biodiversity is a public good, the government can only enforce agents to contribute towards the cost of biodiversity supply by threatening not to implement biodiversity-oriented forest management, in case the levied agents' contributions are not sufficient. It can be shown that given some conditions, the mechanism design problem can be simplified to the selection of the social choice function q (see details in supplementary I).

In addition to the above mentioned assumptions, further constraints need to be included in the mechanism proposed. Specifically, agents need to derive non-negative benefits when participating in the mechanism (in the interim phase), referred to as interim individual rationality constraint. Additionally, the mechanism needs to be Bayes-Nash incentive compatible, i.e. in expectation, reporting their true types is a dominant strategy for the agents (agents cannot be better-off by misrepresenting their type). Finally, the mechanism needs to be ex-ante budget balanced, meaning that in expectation the funds levied by the mechanism need to cover the cost of implementation of biodiversity-oriented management.

Table 1
Description of parameters and functions used in the second-best mechanism.

Parameter/Function	Description
N	Number of agents
θ_i	Type of agent i
θ	Profile of agents' types
$q(\theta)$	Social choice function
c	Cost of provision
$F(\theta)$	Cumulative probability density of agents' types
λ^S	Lagrange multiplier of the ex-ante budget balance constraint
$f(\theta)$	Probability density function of agents' types
$R(\theta)$	Sum of virtual valuations of profile θ

In a first-best mechanism, biodiversity is provided whenever the sum of benefits is greater than the cost. This mechanism, however, imposes a loss on the supplier, due to the asymmetric information on the biodiversity valuations (Güth and Hellwig, 1986; Börgers, 2015). This requires the application of a second-best mechanism, which undersupplies biodiversity but is implementable without external funding. Güth and Hellwig (1986) propose such mechanism, where the designer selects a choice function that maximizes social welfare, under the condition that no external funding is needed to cover the implementation costs. This mechanism can be described by the maximization of Eq. (4) (for a description of the parameters and functions see Table 1). In this setting, the sum of biodiversity valuations need to cover the cost of implementation, plus a fraction of the sum of virtual valuations. The virtual valuations appear in the second term of Eq. (4) and are the maximum surplus that the designer can extract from the agents in the mechanism.

$$MaxZ = \int q(\theta)\left(\sum_{i\in N}\theta_i - c\right)dF(\theta) + \lambda^S \int q(\theta)\left[\sum_{i\in N}\left(\theta_i - \frac{1-F(\theta_i)}{f(\theta_i)}\right) - c\right]dF(\theta) \quad (4)$$

When many agents are involved, valuations are reduced, due to the fact that each agent has a decreasing influence on the final decision and expects that the public good will be provided anyways. Hellwig (2003) shows that the valuation of an agent is corrected by the probability that the agent is focal to the decision of supplying the public good. This probability approximates $1/\sqrt{N}$ and the expected revenue of the mechanism is proportional to Eq. (5):

$$R(\theta) = \frac{1}{\sqrt{N}}\sum_{i\in N}\left(\theta_i - \frac{1-F(\theta_i)}{f(\theta_i)}\right) \quad (5)$$

(Hellwig, 2003).

Here we adopted a numeric optimization approach to solve the mechanism design problem. If we replace the continuous type space of agents $\mathbb{R}^N$ by a discrete approximation and add a dummy type of 0 with probably 0, the optimization problem of the mechanism designer admits a Linear Programming (LP) representation (Vohra, 2012). Using this framework, we constructed an optimization model to find a second-best mechanism, as proposed by Güth and Hellwig (1986). We used an Integer Linear Program, based on the optimization approach introduced by Csapó and Müller (2013). Here we aimed to find a second-best mechanism that maximizes social surplus, while respecting *ex-ante* budget balance, interim individual rationality and Bayes-Nash incentive compatibility:

$$MaxZ = \sum_{\theta\in\Theta}\pi_\theta q_\theta\left(\frac{1}{\sqrt{N}}\sum_{i\in N}\theta_i - c\right) \quad (6)$$

Table 2
Sets, variables and input data used in the mechanism design model.

Sets	Description
Θ	Set of profile realizations
N	Set of agents
Variables	
q_θ	Binary variable that takes value 1 if profile θ is included in the solution and value 0 otherwise
Data	
θ	Profile of agents' types
π_θ	Probability of observing profile θ
c	Opportunity cost of biodiversity provision
$R(\theta)$	Sum of virtual valuations of profile θ

$$\sum_{\theta\in\Theta}\pi_\theta q_{\theta_i}-\sum_{\theta'\in\Theta}\pi_{\theta'}q_{\theta'_i}\geq 0 \qquad \forall\ i\in N,\ \forall\ \theta,\theta'\in\Theta|\theta_i>\theta'_i \tag{7}$$

$$\sum_{\theta\in\Theta}\pi_\theta q_\theta(R(\theta)-c)\geq 0 \tag{8}$$

$$q_\theta\in\{0,1\} \qquad \forall\ \theta\in\Theta \tag{9}$$

The objective function (Eq. (6)) maximizes the expected social surplus, given by the sum of valuations minus the cost of implementation, over the type space. Constraint (Eq. (7)) ensures Bayes-Nash incentive compatibility and interim individual rationality, enforcing monotonicity of the choice function in respect to the agent's type. Interim individual rationality constraints enforce that agents receive a nonnegative utility for participating. Bayes-Nash incentive compatibility ensures that agents have no incentives to misrepresent their types. Constraint (Eq. (8)) enforces *ex-ante* budget balance, which requires that, in expectation, the costs of biodiversity provision are covered by the contributions of the agents and (Eq. (9)) ensures that the choice function takes binary values. For a description of sets, variables and data used in the optimization models see Table 2.

To build our optimization problem, we assumed that agents' valuations were composed by 5 types $\Theta=\{1,2,3,4,5\}$ that were uniformly distributed inside the confidence interval of biodiversity valuations established in section 2.4. Moreover, we considered 6 agents$N=\{1,2,3,4,5,6\}$, each representing an administrative region with an equal share of the population (negotiating on its behalf) that need to agree on the implementation of biodiversity conservation policies in public forests. Each agent also needs to contribute towards the cost of the increased biodiversity supply, representing fund transfers in a fiscal federalism framework (Bönke et al., 2013). Finally, we analyzed the implementation of 6 levels of bird indicator abundance increase$B=\{2.5\%, 5\%, 7.5\%, 10\%, 15\%, 17.5\%\}$. Besides the uncertainty regarding the realization of the vector of valuations of the agents, the government must also consider that the costs of biodiversity-oriented management are uncertain and contained in$C=\{c_{Had2.6}, c_{Had6.0}, c_{Had8.5}\}$. In our analysis, we investigated the social choice on the expected cost $\bar{c}=(c_{Had2.6}+c_{Had6.0}+c_{Had8.5})/3$ and on each climate scenario as a sensitivity analysis (Barbieri and Malueg, 2014). We disconsidered the trivial cases, where biodiversity should never be provided (the costs are lower than the sum of valuations if all agents have the lowest type) and never be provided (the costs are higher than the sum of valuations if all agents have the highest type). We solved the optimization model using the software Gurobi8.1 (http://www.gurobi.com/products/gurobi-optimizer).

3. Results

3.1. Costs of biodiversity provision under climate change

We perceived that up to a 10% increase in the current bird indicator abundance at the end of the century, the opportunity costs increased almost linearly with the biodiversity requirements, whereas for

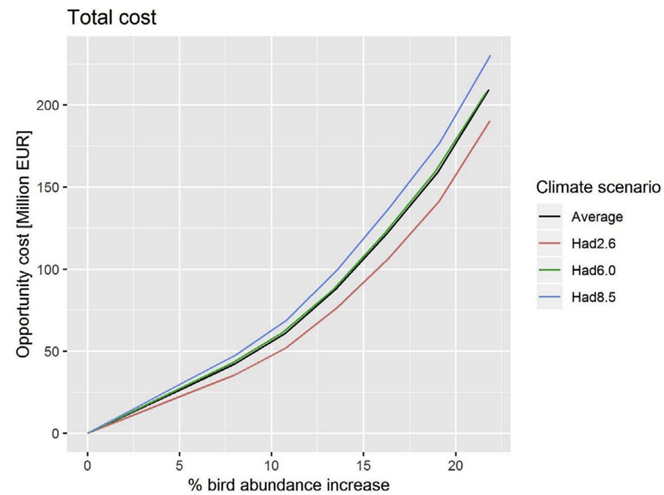

Fig. 1. The figure shows the total opportunity cost for increasing bird abundance levels at the end of the century for each climate change scenario.

abundance increases above this threshold, it was necessary to strongly compromise forest profitability. This behavior is depicted in the cost curves (Fig. 1), where we noticed a sharp opportunity cost increase for high levels of bird abundance. This was a result of the limits on the conversion of highly profitable spruce by beech stands (with lower growth rates and wood value) for increasing the share of broadleaved forests in the region and the need to reduce the area of more profitable management strategies.

Climate change had important implications for the total cost of biodiversity provision. The increase in forest growth rates under higher atmospheric CO_2 concentration, in combination with sufficient precipitation, led to an increase in forest growth rates and consequently higher forest profitability and opportunity cost. This was determinant for the attainable level of biodiversity supply under the mechanism design approach, since the total supply cost was required to be met by the contributions of the agents considered in our analysis.

In addition to climate impacts, the cost behavior was also related to the biodiversity responses to forest management in our model. We used the N-mixture model described in section 2.2 to estimate the bird abundance under novel forest structures generated by the alternative management regimes applied in our analysis. Three main parameters used to estimate bird abundance were affected by management: the basal area of the stand, the share of conifers and the number of snags. Among these parameters, the bird assemblage was most responsive to the share of conifers and responded marginally to the number of snags and the basal area of the stand. Given that the increase in the snag number has important economic implications due to the reduction in thinning revenues, the increase in the share of broadleaves was the most cost-effective management practice to increase biodiversity supply and reach the levels required by the mechanism. This management action, however, also reduced forest profitability due to conversion costs.

3.2. Second-best mechanism for biodiversity provision

The first step taken in the analysis of the mechanism was the identification of the trivial cases, in which biodiversity is never provided or always provided (the social choice function always equal to 1 or 0 regardless of the profile realization), based on the lowest and highest possible sum of valuations. For the average cost scenario, the non-trivial case yielded a bird abundance increase of 12.5% at the end of the century (Fig. 2) and bird abundance increases below this value were nearly always provided.

The optimal choice function, i.e. the threshold related to the sum of

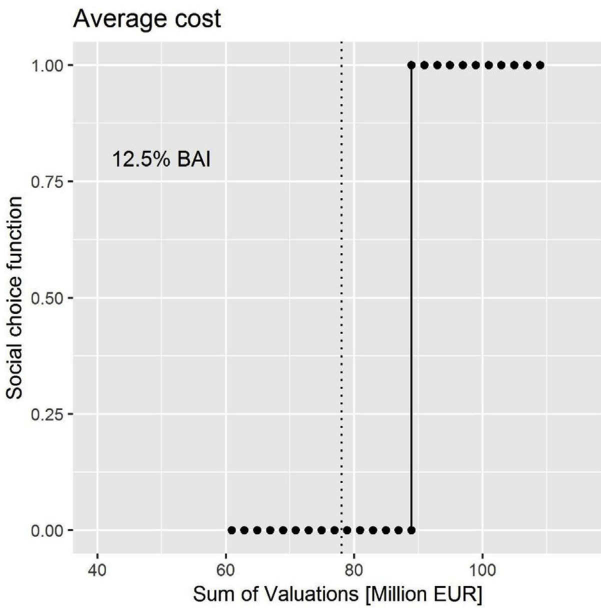

Fig. 2. Social choice function value for the average cost across the climate scenarios. BAI stands for the level of bird abundance increase in the non-trivial provision level. The dotted vertical line shows the opportunity cost for the corresponding increase in bird abundance.

valuations that would lead to the implementation of biodiversity-oriented management is depicted in Fig. 2. As expected, the second-best mechanism undersupplied biodiversity. We perceive that the social choice function was only activated if the sum of valuations surpassed 89 Million EUR, whereas the first-best mechanism would implement biodiversity-oriented management for valuations above 78 Million EUR. Thus, the sum of valuations was required to exceed the cost of implementation by more than 14%, taking into account the agents described in our model. This was a result of the information rent held by the agents on their valuations. Under these conditions, the probability of implementation of biodiversity-oriented management was 24%, i.e. in 24% of profile realizations the social choice function would be activated. Additionally, to maintain Bayes-Nash incentive compatibility and interim individual rationality, the payment rule would require agents with types 1, 2, 3, 4 and 5 to contribute with an equivalent of 100, 90, 86, 83 and 81 % of their WTP, respectively. We perceived that biodiversity-oriented management was mainly implemented for profiles with a combination of high biodiversity valuations (e.g. types 4 and 5, with the two highest biodiversity valuations according to the distribution used in our analysis). This requirement yielded a reduced probability of implementation, since all agents displayed simultaneously high valuations in a limited number of profile realizations. On the other hand, if the first-best solution was considered and external funding was feasible, the probability of implementation would increase to 84%, due to the lower threshold of implementation.

In our model, we required the mechanism to be budget balanced in expectation. This condition, however, does not guarantee that the funds raised will cover the costs of implementation in all profile realizations. This also caused an undersupply compared to the first-best solution, which affected the expected surplus of the mechanism. The first-best case, disregarding the budget balance condition, would yield an expected surplus of 7.5 Million EUR for the agents, whereas for the second-best case this figure amounted to 3.8 Million EUR. We highlight that, despite the lower expected surplus, this mechanism still produces a larger social benefit than the profit maximization mechanism (expected surplus of 1.9 Million EUR).

Although the optimization models generated through the mechanism design model had high dimensionality, with 15.625 binary variables and 165.625 non-zeros, the optimal solution could be efficiently computed, with processing time inferior to 1 s. We emphasize that the problem size may become computationally prohibitive when the number of types and agents is large, since the number of profile realizations is proportional to $|T|^{|N|}$. In such cases, heuristic solutions may be required to compute the optimal mechanism.

3.3. Sensitivity analysis and management solutions

Climate change had a substantial effect on the choice function due to the varying implementation cost (Fig. 3). For the Had2.6 and the Had6.0 climate scenarios, the same level of bird abundance increase was observed (12.5%). Nevertheless, for the Had2.6 scenario, the lower opportunity cost led to a probability of implementation equal to 66%, whereas for the Had6.0 it reduced to 16%. Similar to the average cost scenario, a higher probability of implementation was observed for the first-best case (> 99% for the Had2.6 and 76% for the Had6.0 scenario). Considering the Had8.5 scenario, the increase in bird abundance amounted to 10% at the end of the century, with a probability of implementation of 76% in the second-best case. Under such conditions, biodiversity-oriented management would be implemented if the sum of the valuations surpassed 76 Million EUR, whereas in the fist-best solution the social choice function would be activated for profiles with valuation above 63 Million EUR.

The optimal portfolio for increasing levels of bird abundance in each climate scenario is shown in Fig. 4. We observed that the increase in bird abundance requirements caused a reduction in the area under BAU and biomass-oriented management, whereas the biodiversity management strategy largely increased. Hence, depending on the costs of biodiversity supply, the allocation related to the second-best mechanism differed. For example, the Had2.6 scenario would require the biodiversity strategy in approximately 28% of the total area, whereas for the Had8.5 climate scenario, the biodiversity strategy would be reduced to 21% of the total area. Additionally, for a same level of bird abundance increase, climate change required tailored management regimes. The optimal portfolio under the Had2.6 scenario applied the no management strategy in 6% of the total area, whereas the same figure was reduced to 2% in the Had6.0 scenario. In general, more intense climate change led to a reduction in the area under no management and an increase in the area of the biomass production strategy.

4. Discussion

Here we analyzed how the government may implement biodiversity-oriented forest management in public forests, in order to reduce the gap between efficient and current levels of forest biodiversity in temperate ecosystems. We computed the costs of biodiversity provision and applied a mechanism design approach to account for the strategic behavior of agents related to the contribution towards this cost. We defined social choice functions for biodiversity supply in public forests under climate change and computed optimal management solutions to realize the required biodiversity indicator increase.

4.1. Costs of biodiversity provision under climate change

The total costs of biodiversity provision were moderate with up to a 10% increase in bird abundance at the end of the century, ranging approximately between 892 and 1180 EUR/ha, whereas for the maximum biodiversity provision within our modelling framework increased by up to 4346 EUR/ha. Since the conversion to broadleaved forests is bounded by the current area of Norway spruce, it was necessary to increase the abundance through less efficient management interventions and increasing the opportunity cost, e.g. applying management with low thinning intensity to increase mortality and snags availability. Rosenkranz et al. (2014) evaluated the implementation costs of the Habitats Directive in Germany and reported average loss of income

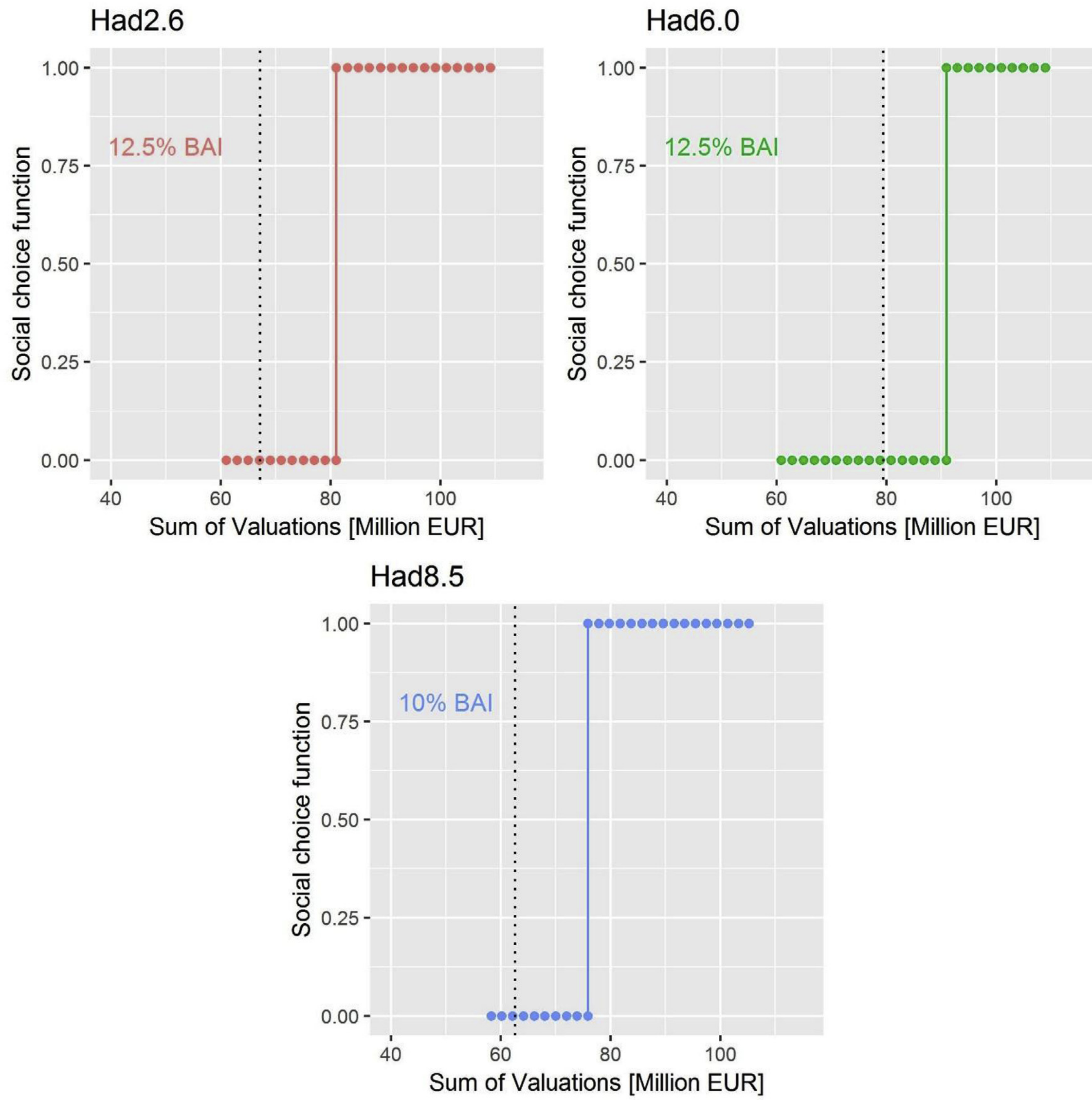

Fig. 3. Sensitivity of the social choice function according to the climate trajectory. BAI stands for the level of bird abundance increase in the non-trivial provision levels. The dotted vertical line shows the opportunity cost for the corresponding increase in bird abundance.

ranging from 1958 to 2496 EUR/ha, depending on the management applied and discounted with a 1.5% interest rate. Hily et al. (2015) analyzed the cost effectiveness of Natura 2000 contracts in France, with an average cost of contracts approaching 1900 EUR/ha.

Climate change and its implications to forest dynamics were also important drivers of the costs of biodiversity provision and, thus, cascaded to the mechanism implementation. Climate scenarios with increased forest productivity showed higher opportunity cost, since the profitability of conifer stands increased. An important aspect of forest development under climate change not investigated here refers to the occurrence of forest disturbances. Disturbances may modify forest profitability and interact with forest biodiversity, altering conservation costs (Hanewinkel et al., 2013; Seidl et al., 2017), and affecting the probability of biodiversity supply. In this sense, a closer investigation of disturbances under climate change and its effects on forest biodiversity and profitability is encouraged.

A dynamic updating on possible climate realizations and on the social value for forest biodiversity will help to reduce the range of costs and benefits, improving the efficiency of biodiversity-oriented forest management when new information becomes available. Adaptive forest management in combination with Bayesian updating provide a natural framework to dynamically update forest strategic plans in the face of new information and may be employed to tackle this issue (e.g. Yousefpour et al., 2013). Such information may help to identify not only optimal conservation actions, but also identify the optimal timing for its implementation and avoid that thresholds related to ecosystem functioning are surpassed.

4.2. Second-best mechanism for biodiversity provision

The expected agents' surplus in the second-best mechanism design approach, as expected, was inferior to the first-best, where biodiversity is provided whenever the sum of benefits surpasses the costs of implementation. This occurs due to the *ex-ante* budget balance requirement, ensuring that no external funding is needed for an increase in biodiversity supply. The social choice function required, in general, that valuations surpassed the costs by more than 18%. Yet, under voluntary participation, the second-best mechanism provides a powerful framework for the provision of forest biodiversity, when external funding is undesirable. Through this approach it is possible to derive not only the thresholds for biodiversity provision, but to attach probabilities of success, once the distribution of valuations is known.

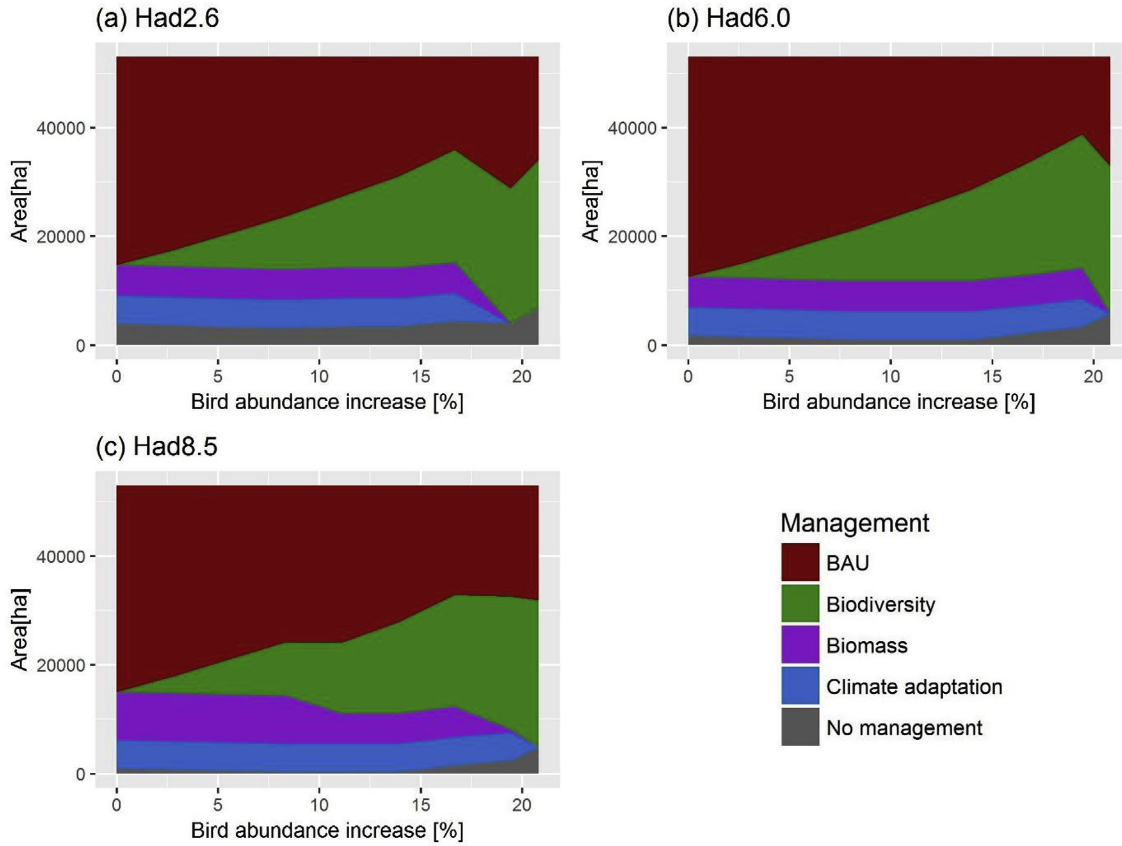

Fig. 4. Optimal management portfolio for each climate scenario under increasing levels of bird abundance at the end of the century.

The mechanism considered here refers to the case where the government acts to maximize social welfare and does not have any additional constraints apart from the budget balance. The mechanism designer, however, may have different goals. A large body of literature is dedicated to the supply of public goods when the designer has the objective of maximizing profits (e.g. Csapó and Müller, 2013), where the public good is only provided if the sum of virtual valuations cover the costs of implementation. Moreover, the government may have additional budget targets and minimum amounts of funds to be raised that would modify the mechanism. The formulation of the mechanism design problem as an integer linear model allows to seamless integrate such additional requirements in the decision-making process, e.g. by adding extra constraints (Vohra, 2012). This may provide valuable information when closed-form solutions for the models are not readily available.

The weight placed on the sum of virtual valuations decreased when the costs of biodiversity-oriented management approached the upper limit of the sum of valuations, approximating the first-best mechanism. This was accompanied, however, by a substantial decrease in the probability of implementation, since biodiversity-oriented management was only applied if the profile of valuations was composed by the highest types. Börgers (2015) shows this behavior of the thresholds for the second-best mechanism considering the supply of a public good, in which the threshold approaches the first-best criteria for costs near upper bound of valuations. In our analysis, when the cost was close to the maximum sum of valuations in the average cost and Had2.6 scenarios, there was an approximation to the first-best threshold.

In our study, we computed the optimal choice function for the non-trivial cases, considering the implementation cost in the average case and in each climate change scenario. One may consider the case where the designer wishes to guarantee the performance of the mechanism in the worst-case scenario. This would require that regardless of the climate realization, the feasibility of the mechanism is preserved. Hence, one may consider robustness criteria, e.g. by designing the mechanism based on the highest possible cost, so that in any climate realization the expected revenue is higher than the cost of implementation (Had8.5 in our analysis). The topic of robust mechanism design is currently an area of active research. For example, Bandi and Bertsimas (2014) formulate an auction problem using robust optimization, in which uncertainty sets are used instead of probability distributions to characterize the agents' valuations. Koçyiğit et al. (2018) developed an integer linear programming model for auction design in the case where the seller is ambiguity-averse. Such analyses may improve the success of mechanism under deep uncertain settings.

We investigated the application of a direct second-best mechanism, where agents announce their valuations and contribute towards the costs of biodiversity provision. There are a number of alternative mechanisms dealing with the supply of public goods described in the literature. For example, Bierbrauer and Sahm (2008) investigate democratic mechanisms, where taxes are introduced to finance the public good provision and participants vote to express their preferences for the public good supply. Van Essen and Walker (2017) note that theoretical optimal mechanisms, did not always produce the desired outcomes in experimental studies and propose a simple market-like mechanism that always yield a feasible allocation. In their mechanism, the contribution of the participants is given by the per capita cost of provision corrected by the individual valuation compared to the average valuation. Such experimental evaluation of mechanisms for biodiversity provision are still scarce in the literature and deserve further investigation.

4.3. Optimal forest management

In order to provide biodiversity at a minimum cost, it was necessary to apply tailored management strategies to the set of forest stands in our study area. A combination of management practices will be required in the future to balance the provision of products and ecosystem services in temperate forests. Gutsch et al. (2018) also show that forests in different regions show potential to fulfill optimally different ecosystem services in Germany under climate change, according to its structure and species composition. Naumov et al. (2018) report similar patterns studying forest landscapes in Northern Europe. In this context, den Herder et al. (2017) propose a framework for balancing the provision of forest goods and services, including economic, environmental and social indicators using multi-criteria analysis. Hence, a sound landscape management will ask for the consideration of local forest conditions on the strategic planning of forest use, allowing to achieve the desired goals more efficiently, in terms the provision of multiple ecosystem goods and services.

Our solutions indicate that the conversion of spruce stands to broadleaved forests was the most efficient practice to increase biodiversity provision, measured through the abundance of bird indicator species. We highlight here that the indicator species had a similar response to the management actions considered. It is important to consider, however, that other taxa may have different requirements regarding forest habitats. Particularly, saproxylic organisms require old-growth forest attributes, such as deadwood and habitat trees and connectivity among habitats at a finer scale (Müller et al., 2016; Thomaes et al., 2018). These aspects deserve to be further investigated and both spatial planning models and benefit assessments regarding these taxa are needed.

4.4. Limitations

We conducted our analysis based on the age class of each stand. If forest inventory data is available for each stand in the forest area, we may increase the accuracy of forest production forecasts and tailor management prescriptions to the specific stand structure. Moreover, an important aspect of forest dynamics under climate change refers to the occurrence of disturbances and how these interact with forest productivity and forest taxa (Hanewinkel et al., 2013; Greenville et al., 2018). A coupling of forest growth, disturbance and population dynamics models are recommended for future studies.

We restricted our analysis to a limited set of management options, agents and types. Our framework, however, can be easily extended to encompass a larger set of management options and valuations to provide more accurate estimates. These need to be balanced with the problem size generated, especially regarding the number of types and agents, as the possible combinations increase exponentially and the resulting matrix of the optimization problem has a large number of non-zeros.

We have included here relevant uncertainty aspects at the strategic planning level, with a focus on climate change and biodiversity valuations. In this sense, we did not consider here all the relevant sources of uncertainty to the supply of biodiversity in public forests. The uncertainty in the biodiversity responses to management practices may significantly affect the operationalization of conservation actions. This uncertainty will have stronger influence with an increase in the sensitivity of the model and larger standard deviation of the management-related parameters. For example, in our analysis, the share of conifers showed the largest influence on the summed abundance, compared to other management actions. Thus, this uncertainty may affect the total cost of conservation (increasing the cost if the observed response had lower magnitude or decreasing the cost otherwise). Similarly, uncertainty in economic parameters (e.g. wood price and interest rate) may affect the opportunity costs of an increased biodiversity supply and deserve further investigation.

Here we considered independent valuations for forest biodiversity. The framework proposed by Csapó and Müller (2013) allows for the relaxation of this condition and is easily adaptable to our study. The authors accommodate dependent valuations by modifying the virtual valuation of agents, according to the joint probability distribution of the dependent random variables.

5. Conclusions

Biodiversity conservation remains a complex and important forest management problem. The coupling of ecological and economic models is key to find efficient conservation solutions and correct the provision of forest biodiversity, aiming to create resilient forest landscapes. Mechanism design offers a powerful framework to account for the strategic behavior of agents towards the public good provision and provides information on the conditions for a successful implementation of conservation programs. This will ultimately depend on the relationship between the social value and costs for providing forest biodiversity, as well as the capacity of the government to levy funds to finance an increased biodiversity supply. The creation of such mechanisms will be key to maintain the provision of multi-functionality of temperate forests in the face of climate change.

Acknowledgements

We acknowledge the funding of this research to the German Research Foundation, ConFoBi project (number GRK 2123).

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.05.089.

Appendix A. Forest optimization model.

A description of sets, data and variables used in the optimization model is provided in Table A1 hereafter.

$$MaxZ = NPV \tag{A1}$$

$$\begin{aligned} NPV \leq & \sum_{i \in S} \sum_{j \in M} \sum_{t \in PH} \sum_{k \in T} vol_{ijtk} x_{ij} price_{tk} \frac{1}{(1+ir)^t} \\ & + \sum_{i \in S} \sum_{j \in M} \sum_{k \in T} volfin_{ijk} x_{ij} price_{PHk} \frac{1}{(1+ir)^{PH}} \\ & - \sum_{i \in S} \sum_{j \in M} \sum_{k \in T} volini_{ijk} x_{ij} price_{1k} - \sum_{i \in S} \sum_{j \in M} \sum_{t \in PH} planting_{ijt} x_{ij} \frac{1}{(1+ir)^t} \\ & - \sum_{t \in PH} fixed_t \frac{1}{(1+ir)^t} \end{aligned} \tag{A2}$$

$$\sum_{i \in S} \sum_{j \in M} bio_{ijPH} x_{ij} \geq Biodiversity \tag{A3}$$

$$\sum_{i \in S} \sum_{j \in M} \sum_{k \in T} vol_{ijtk} x_{ij} \geq 0.7\, b \qquad \forall\, t \in PH \tag{A4}$$

$$\sum_{i \in S} \sum_{j \in M} \sum_{k \in T} vol_{ijtk} x_{ij} \leq 1.3\, b \qquad \forall\, t \in PH \tag{A5}$$

$$\sum_{i \in S} \sum_{j \in M} \sum_{k \in T} volini_{ijk} x_{ij} \leq \sum_{i \in S} \sum_{j \in M} \sum_{k \in T} volfin_{ijk} x_{ij} \tag{A6}$$

$$\sum_{j \in M} x_{ij} \leq area_i \qquad \forall\, i \in S \tag{A7}$$

$$\sum_{i \in S} x_{i1} \leq 0.5 totarea \tag{A8}$$

Table A1
Sets, variables and input data used in the forest optimization model.

Sets	Description
S	Set of stands
M	Set of management regimes
PH	Set of periods
T	Set of tree species
Variables	
NPV	Total NPV of forest management
x_{ij}	Area of stand i to be management under regime j
b	Wood production bound
Data	
vol_{ijtk}	Volume of species k produced in period t in stand i under management j
$price_{tk}$	Price of species k in period t
ir	Interest rate
$volfin_{ijk}$	Final volume of species k in stand i under management j
$volini_{ijk}$	Initial volume of species k in stand i under management j
$planting_{ijt}$	Planting cost of stand i under management j in period t
$fixed_t$	Fixed cost in period t
bio_{ijt}	Bird indicator abundance in stand i under management j in period t
Biodiversity	Total bird indicator abundance bound
$area_i$	Area of stand i
totarea	Total forest area

The objective function (Eq. (A1)) targets the maximization of forest NPV. Constraint (Eq. (A2)) assigns to the variable *NPV* the total NPV of the forest investment along the planning horizon, computed trough the discounted sum of thinning revenues, the difference in standing stock value at the beginning and at the end of the simulation period, the planting costs and administering costs. Constraint (Eq. (A3)) requires that the bird indicator abundance at the end of the period is higher than the bound*Biodiversity*. Constraints (Eq. (A4)) and (Eq. (A5)) are wood flow constraints (Bettinger et al., 2016) and enforce that the harvested volume in every period respects a ± 30% variation compared to the endogenously determined volume bound*b*. The bound *b* was a free variable in the optimization model, enabling to achieve the highest NPV while maintaining the wood flow stability. Constraint (Eq. (A6)) requires that the standing volume at the end of the simulation period to be at least equal to the standing volume at the beginning of the simulation period, i.e. a sustainability criteria regarding the forest utilization rate. Constraint (Eq. (A7)) guarantees that the managed area of each stand is bounded by the stands' total area. Constraint (Eq. (A8)) requires that the conversion of Norway spruce to European beech stands do not extend over the 50% of the total forest area, which is the forest cover of Norway spruce in the study region.

We constructed the optimization model in Lingo 17.0 optimizer (https://www.lindo.com), solving it multiple times, increasing the required level of bird abundance (*Biodiversity*), and establishing the efficient frontier between NPV and biodiversity. The cost for biodiversity provision was subsequently calculated based on the NPV loss to attain an increased bird indicator abundance, compared to the maximum attainable NPV. The solution process to the optimization problem described by Eq. (A1) to Eq. (A8) was obtained in 7 min and 30 s for each bird abundance level enforce by constraint Eq. (A3).

References

Augustynczik, A.L.D., Asbeck, T., Basile, M., Bauhus, J., Storch, I., Mikusiński, G., et al., 2019. Diversification of forest management regimes secures tree microhabitats and bird abundance under climate change. Sci. Total Environ. 650, 2717–2730.

Bandi, C., Bertsimas, D., 2014. Optimal design for multi-item auctions: a robust optimization approach. Math. Oper. Res. 39 (4), 1012–1038.

Barbieri, S., Malueg, D.A., 2014. Increasing fundraising success by decreasing donor choice. J. Public Econ. Theory 16 (3), 372–400.

Bettinger, P., Boston, K., Siry, J.P., Grebner, D.L., 2016. Forest Management and Planning. Academic press.

Bierbrauer, F.J., Hellwig, M.F., 2016. Robustly coalition-proof incentive mechanisms for public good provision are voting mechanisms and vice versa. Rev. Econ. Stud. 83 (4), 1440–1464.

Bierbrauer, Felix, Sahm, Marco, 2008. Optimal Democratic Mechanisms for Taxation and Public Good Provision, Preprints of the Max Planck Institute for Research on Collective Goods, No. 2008, vol. 9 Max Planck Inst. for Research on Collective Goods, Bonn.

BMUB, 2015. Indikatorenbericht 2014. Available at : https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/indikatorenbericht_biologische_vielfalt_2014_bf.pdf, Accessed date: 20 September 2014.

Bönke, T., Jochimsen, B., Schroeder, C., 2013. Fiscal Federalism and Tax Administration–Evidence from Germany. DIW Berlin Discussion Paper No. 1307.

Börgers, T., 2015. An Introduction to the Theory of Mechanism Design. Oxford University Press, USA.

Statistiches Bundesamt, 2016. Statistiken zur Einwohnerzahl in Deutschland. Available at : https://www.tagesschau.de/inland/einwohnerzahl-deutschland-107.html, Accessed date: 25 July 2018.
Csapó, G., Müller, R., 2013. Optimal mechanism design for the private supply of a public good. Games Econ. Behav. 80, 229–242.
den Herder, M., Kurttila, M., Leskinen, P., Lindner, M., Haatanen, A., Sironen, S., et al., 2017. Is enhanced biodiversity protection conflicting with ambitious bioenergy targets in eastern Finland? J. Environ. Manag. 187, 54–62.
Díaz, S., Fargione, J., Chapin III, F.S., Tilman, D., 2006. Biodiversity loss threatens human well-being. PLoS Biol. 4 (8), e277.
ECB (European Central Bank), 2019. Statistical data warehouse. Available on. https://sdw.ecb.europa.eu/browse.do?node=9691124, Accessed date: 26 April 2019.
Fabrika, M., 2007. Simulátor Biodynamiky Lesa SIBYLA, Koncepcia, Konštrukcia a Programové Riešenie, Habilitačná Práca. Technická univerzita vo Zvolene, pp. 328.
Getzner, M., Meyerhoff, J., Schläpfer, F., 2018. Willingness to pay for nature conservation policies in state-owned forests: an Austrian case study. Forests 9 (9), 537.
Greenville, A.C., Burns, E., Dickman, C.R., Keith, D.A., Lindenmayer, D.B., Morgan, J.W., et al., 2018. Biodiversity responds to increasing climatic extremes in a biome-specific manner. Sci. Total Environ. 634, 382–393.
Grüner, H.P., Koriyama, Y., 2012. Public goods, participation constraints, and democracy: a possibility theorem. Games Econ. Behav. 75 (1), 152–167.
Güth, W., Hellwig, M., 1986. The private supply of a public good. J. Econ. 46 (1), 121–159.
Gutsch, M., Lasch-Born, P., Kollas, C., Suckow, F., Reyer, C.P., 2018. Balancing trade-offs between ecosystem services in Germany's forests under climate change. Environ. Res. Lett. 13 (4), 045012.
Hanewinkel, M., Cullmann, D.A., Schelhaas, M.J., Nabuurs, G.J., Zimmermann, N.E., 2013. Climate change may cause severe loss in the economic value of European forest land. Nat. Clim. Change 3 (3), 203.
Hartig, F., Drechsler, M., 2010. Stay by thy neighbor? Social organization determines the efficiency of biodiversity markets with spatial incentives. Ecol. Complex. 7 (1), 91–99.
Härtl, F., Hahn, A., Knoke, T., 2013. Risk-sensitive planning support for forest enterprises: the YAFO model. Comput. Electron. Agric. 94, 58–70.
Hellwig, M.F., 2003. Public-good provision with many participants. Rev. Econ. Stud. 70 (3), 589–614.
Hily, E., Garcia, S., Stenger, A., Tu, G., 2015. Assessing the cost-effectiveness of a biodiversity conservation policy: a bio-econometric analysis of Natura 2000 contracts in forest. Ecol. Econ. 119, 197–208.
Iranah, P., Lal, P., Wolde, B.T., Burli, P., 2018. Valuing visitor access to forested areas and exploring willingness to pay for forest conservation and restoration finance: the case of small island developing state of Mauritius. J. Environ. Manag. 223, 868–877.
Isbell, F., Craven, D., Connolly, J., Loreau, M., Schmid, B., Beierkuhnlein, C., et al., 2015. Biodiversity increases the resistance of ecosystem productivity to climate extremes. Nature 526 (7574), 574.
Kemkes, R.J., Farley, J., Koliba, C.J., 2010. Determining when payments are an effective policy approach to ecosystem service provision. Ecol. Econ. 69 (11), 2069–2074.
Koçyiğit, Ç., Bayrak, H.I., Pınar, M.Ç., 2018. Robust auction design under multiple priors by linear and integer programming. Ann. Oper. Res. 260 (1–2), 233–253.
Lasch, P., Badeck, F.-W., Lindner, M., Suckow, F., 2002. Sensitivity of simulated forest growth to changes in climate and atmospheric CO2. Forstwiss. Cent.blatt 121 (Suppl. 1), 155–171.
Lasch, P., Badeck, F.W., Suckow, F., Lindner, M., Mohr, P., 2005. Model-based analysis of management alternatives at stand and regional level in Brandenburg (Germany). For. Ecol. Manag. 207 (1–2), 59–74.
Lindner, M., Fitzgerald, J.B., Zimmermann, N.E., Reyer, C., Delzon, S., van der Maaten, E.,, et al., 2014. Climate change and European forests: what do we know, what are the uncertainties, and what are the implications for forest management? J. Environ. Manag. 146, 69–83.
Meyerhoff, J., Angeli, D., Hartje, V., 2012. Valuing the benefits of implementing a national strategy on biological diversity—the case of Germany. Environ. Sci. Policy 23, 109–119.
Müller, F., Hanewinkel, M., 2018. Challenging the assumptions of a standard model: how historical triggers in terms of technical innovations, labor costs and timber price change the land expectation value. For. Policy Econ. 95, 46–56.
Müller, J., Simon, T., Roland, B., Khosro, S.T., Barimani, H.V., Sebastian, S., et al., 2016. Protecting the forests while allowing removal of damaged trees may imperil saproxylic insect biodiversity in the Hyrcanian beech forests of Iran. Conserv. Lett. 9 (2), 106–113.
Naumov, V., Manton, M., Elbakidze, M., Rendenieks, Z., Priednieks, J., Uhlianets, S., et al., 2018. How to reconcile wood production and biodiversity conservation? The Pan-European boreal forest history gradient as an "experiment". J. Environ. Manag. 218, 1–13.
Nisan, N., Ronen, A., 2001. Algorithmic mechanism design. Games Econ. Behav. 35 (1–2), 166–196.
Pretzsch, H., 1997. Analysis and modeling of spatial stand structures. Methodological considerations based on mixed beech-larch stands in Lower Saxony. For. Ecol. Manag. 97 (3), 237–253.
Rands, M.R., Adams, W.M., Bennun, L., Butchart, S.H., Clements, A., Coomes, D., et al., 2010. Biodiversity conservation: challenges beyond 2010. Science 329 (5997), 1298–1303.
Roesch-McNally, G.E., Rabotyagov, S., Tyndall, J.C., Ettl, G., Tóth, S.F., 2016. Auctioning the forest: a qualitative approach to exploring stakeholder responses to bidding on forest ecosystem services. Small-scale For. 15 (3), 321–333.
Rosenkranz, L., Seintsch, B., Wippel, B., Dieter, M., 2014. Income losses due to the implementation of the Habitats Directive in forests—conclusions from a case study in Germany. For. Policy Econ. 38, 207–218.
Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., et al., 2017. Forest disturbances under climate change. Nat. Clim. Change 7 (6), 395.
Thomaes, A., Dhont, P., Dekeukeleire, D., Vandekerkhove, K., 2018. Dispersal behaviour of female stag beetles (Lucanus cervus) in a mosaic landscape: when should I stay and where should I go. Insect Conserv. Divers. 11 (6), 523–533.
Tilman, D., Isbell, F., Cowles, J.M., 2014. Biodiversity and ecosystem functioning. Annu. Rev. Ecol. Evol. Syst. 45, 471–493.
Treasury, 2003. The Green Book. Appraisal and Evaluation in Central Government.
Van Essen, M., Walker, M., 2017. A simple market-like allocation mechanism for public goods. Games Econ. Behav. 101, 6–19.
Vohra, R.V., 2012. Optimization and mechanism design. Math. Program. 134 (1), 283–303.
Weller, P., Elsasser, P., 2017. Ökonomische Bewertung der kulturellen Ökosystemleistungen des Waldes. In: Fick, J., Gömann, H. (Eds.), Wechselwirkungen zwischen Landnutzung und Klimawandel. Springer, Berlin Heidelberg New York (in press).
Yousefpour, R., Temperli, C., Bugmann, H., Elkin, C., Hanewinkel, M., Meilby, H., et al., 2013. Updating beliefs and combining evidence in adaptive forest management under climate change: a case study of Norway spruce (Picea abies L. Karst) in the Black Forest, Germany. J. Environ. Manag. 122, 56–64.