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Minimising the relative regret of future forest landscape compositions: The role of close-to-nature stand types

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ABSTRACT

Increasingly uncertain decision outcomes prevail in forest management and hamper choosing a single optimal management alternative. Confronting all management alternatives with multiple future scenarios and selecting an alternative minimising the regret under the worst scenario may provide suitable guidance under such uncertainty. Here, we search for future forested landscape compositions using regret minimisation for different objectives. We consider even-aged and uneven-aged stand types (called close-to-nature stand types) as management alternatives. Close-to-nature forest stand types supported the minimisation of regret for all objectives (represented by financial return, volume increment, C-storage, and two biodiversity indicators). However, close-to-nature stand types covered 18 % to 43 % of the future forest landscape in our study, which shows that even-aged stands are also necessary. For example, supporting biodiversity or multiple objectives simultaneously required large proportions of light-demanding and climate-change-tolerant Oak stands (even aged). Such Oak stands are difficult to achieve under shady conditions with limited canopy openings, which is typical for uneven-aged systems. Building on robust Pareto frontiers, we show a substantial trade-off between supporting biodiversity and maximising financial return but only a moderate trade-off between supporting biodiversity and maximising the C storage in a forest landscape. We suggest that such landscape-level trade-offs be quantified and discussed more intensively.

1. Introduction

The role of different silvicultural systems is under increasing forest political discussion, given the dramatic global changes (Gills and Morgan, 2023), the associated enormous damage to forests (Seidl et al., 2018; Thom and Seidl, 2016), and the diverging expectations concerning the ecosystem services that forests shall provide (Biber et al., 2015; Sotirov et al., 2021). A recent European-level study found, “One third of the forest area was subject to declining condition, signalled by a reduction in soil organic carbon, tree cover density and species richness of threatened birds …” (Maes et al., 2023). Binding forest restoration targets are a political response to this situation, as suggested for European forests (European Union, 2022). To combat climate change and biodiversity loss in Europe (Lier et al., 2022), nature-based forest management alternatives are commonly prioritised (Larsen et al., 2022).

Nature-based forest management is an example of integrated forest management (Aggestam et al., 2020). Given that clear-cut restrictions are becoming more common in some new European forest laws (Nichiforel et al., 2020), integrated forest management that excludes clear-cutting will implicitly be favoured. Integrated forest management aims to satisfy “… multiple societal demands in a limited spatial context (e.g., a forest stand) rather than maximising individual objectives in separate plots, such as at a larger forest landscape or even country level …” (Aggestam et al., 2020). However, it is unclear if such stand-level integrated forest management alternatives can better provide multiple uncertain ecosystem services than forest landscapes consisting of several stand types (nature-based and conventional).

The silvicultural literature has intensively discussed nature-based forest management strategies and the worldwide practised systems as alternatives to conventional forest management regimes. According to

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Puettmann et al. (2015), nature-based forest management is synonymous with continuous-cover management in Northern Europe, close-to-nature forest management in Central Europe, and forest ecosystem management in the USA. Here, we will use the Central European term close-to-nature forest management to describe our alternative silvicultural regime integrating tree species mixtures and irregular age structures (uneven-aged structures).

Forest stands managed under close-to-nature silvicultural regimes differ from conventional even-aged forest plantations, which commonly consist of only one tree species and are often clear-cut at the end of the production period (O'Hara, 2016). Brang et al. (2014) have established silvicultural principles supporting climatic change adaptation of forests, which partly correspond to principles of close-to-nature forest management. These include increased tree species richness, structural and genetic diversity, and relatively low timber stocks. Building on the principles of close-to-nature forestry but widening the scope, the European Commission has recently issued more nuanced guidelines for "closer-to-nature forest management" (European Commission, 2023) based on a policy brief published by Larsen et al. (2022). Those commission guidelines have extended the management principles compared to close-to-nature forestry, for example, by including "… a variety of silvicultural systems based on natural disturbance patterns of the region" (see Aszalós et al., 2022 for the possible role of disturbances as management guidelines).

Supporting the prioritization of close-to-nature forests, some studies have shown that such forests can best provide multiple ecosystem services (Eyvindson et al., 2021; Pukkala, 2016). For example, Pukkala (2016) confirmed that such forests offer a broader range of ecosystem services and perform better in their provision, even when management strictly focuses on financial return. Other studies have also shown that close-to-nature forestry is economically attractive (Assmuth et al., 2021; Knoke et al., 2023a; Malo et al., 2021; Tahvonen and Rämö, 2016).

Against this backdrop, our paper elucidates the impact of allowing for various silvicultural systems, conventional even-aged and close-to-nature uneven-aged, in non-spatial multiple objective optimisations at the landscape scale. By performing landscape optimisation, we identify desirable forest compositions as landscape portfolios containing target shares of future stand types. Using a similar approach, Chreptun et al. (2023) showed forest landscape portfolios where close-to-nature forest stand types played a prominent role. Our optimisation builds on minimising the maximum relative regret for not selecting the best composition (Yager, 2004) by considering several decision criteria, each representing different forest ecosystem services. Regret is the disappointment of a decision-maker when realising that a non-optimal alternative was chosen, even if this alternative may previously have appeared optimal, given the available information (Bell, 1982).

Here, we define regret as a shortfall compared with an expected outcome. More specifically, regret is the relative distance between the highest expected and the achieved outcome, computed for many future scenarios, considering single or multiple decision criteria. Accounting for many possible outcome scenarios is essential, as the future is uncertain. Our decision criteria measure the contribution of a stand type to an ecosystem service and comprise financial return (representing financial benefits), volume increment (representing biomass production), in situ carbon storage (aboveground biomass, referring to climate regulation), herbivore species richness and deadwood quality (to address habitat services).

We address the following research questions:

Q1. Do close-to-nature forest stand types make a difference concerning future forest landscapes' optimal ecosystem service provision?

Q2. Which objectives require higher and lower shares of close-to-nature forest stand types?

Q3. How strong are the trade-offs when optimising various bundles of decision criteria?

Q4. How does in- or exclusion of close-to-nature forest stand types impact a forest landscape's potential to provide ecosystem services?

A key concept in our study is minimising the maximum regret under multiple possible future contributions of several stand types to several ecosystem services. The intuition behind this approach is to optimise with a focus on the worst possible contribution across future scenarios so that the regret of not having chosen the optimal decision, i.e. the one leading to the maximal outcome, is as small as possible (Groetzner and Werner, 2022). Decision-making under uncertainty implies that the exact contribution of a chosen decision alternative is unknown, so various potential contributions are possible and need to be considered simultaneously (Knoke et al., 2022; Knoke et al., 2023b). In an uncertain world, decision-makers cannot map probabilities to specific future contributions of the decision alternatives (Knight, 1921).

When no associated probabilities for the possible contributions exist, selecting the decision alternative with the best average future contribution is not feasible. In such an uncertain situation, minimising the maximum regret across multiple scenarios is a suitable decision rule (mainly when uncertainties are large), as typical in climate modelling or intergenerational discounting (DeCanio et al., 2022; Hof et al., 2010). Large uncertainties are also inherent in decision-making in forest management, such as planning the tree species and stand type composition for a future forest landscape. We have only limited and uncertain knowledge concerning future forest stand survival and tree species suitability, the actual future contributions of specific forest stand types to multiple ecosystem services, possible changes to the preferences and values of decision-makers and stakeholders, and new political norms and recommendations which may support or compromise specific forest stand types and their ecosystem services.

Our study contributes to the body of knowledge through an innovative land-use allocation model, which we used to assess specific stand types when embedded in forest landscapes. The model facilitates analysing the impact of future uncertainties on trade-offs between several bundles of ecosystem services. This allows for an evaluation of silvicultural alternatives compared to conventional even-aged practices. At the same time, our modelling method to assess nature-based forest management at the landscape scale may broaden the options to improve the provisioning of uncertain ecosystem services beyond considering close-to-nature forestry as a "one-size-fits-all" solution.

2. Methods

Our method accounts for uncertainty and multiple objectives when planning a forested landscape's optimal long-term stand-type composition. The resulting desirable landscape portfolios can serve as guidelines for practical forest management when regenerating the existing older forest stands by providing information on the desirable overall enterprise-level composition of stand types. We call uncertain outcomes "contributions" to decision criteria and use "uncertainty scenarios" to represent multiple possible future contributions for each stand type and all contribution combinations across the stand types. A decision criterion represents an objective of a decision-maker, such as financial return, which measures the financial benefits a forest ecosystem provides.

2.1. Constructing uncertainty spaces

We considered eight stand types in our analysis. We included the uncertain stand-type contributions to the five decision criteria i using various uncertainty scenarios u and call these contributions y_{siu}. For example, for the stand type $s = \mathit{Douglas\ fir}$ and the decision criterion $i = \mathit{financial\ return}$ we considered 195 $US\$\ ha^{-1}yr^{-1}$ as an optimistic scenario, which represents an upper bound and a pessimistic scenario of 9 $US\$\ ha^{-1}yr^{-1}$, which represents a lower bound of possible contributions in our optimisation. The pessimistic scenario was estimated by subtracting three standard deviations std_{si} from the optimistic contribution y_{si} of a stand type to a decision criterion, with $y_{siu} = y_{si} - 3 \bullet std_{si}$ (for example with $std_{si} = 62$ for Douglas fir, see Table 1). Accounting for such wide intervals represents a cautious decision-maker who considers large possible negative future deviations from the expected contribution and can be called an "uncertainty-averse" decision-maker. Under the optimistic assumption, we kept $y_{siu} = y_{si}$, thus adopting the expected contribution. We abstained from using more optimistic estimates than the expected contributions, such as the expected contribution plus 3 standard deviations. To explore the impact of choosing a smaller size of the uncertainty on the trade-offs between bundles of ecosystem services, we conducted optimisations using $y_{siu} = y_{si} - 2 \bullet std_{si}$ as the pessimistic contribution and the lower interval bound.

Our robust optimisation model provides solutions that are deterministically immune to realisations of the uncertain contributions in uncertainty sets or spaces (Bertsimas et al., 2011). We used our optimistic and pessimistic contributions as representations of upper and lower bounds of intervals, where the future contributions of our stand types are assumed to reside. These bounds were combined for all stand types to construct an uncertainty set. We obtained $2^8 = 256$ discrete uncertainty scenarios u for our decision criteria i, with each scenario representing a unique combination of optimistic and pessimistic contributions across the eight stand types. These uncertainty scenarios build the non-smooth surface of a multidimensional (box) uncertainty space. Optimisations referring to the surface of this space imply that the obtained solutions guarantee a specific performance over the whole uncertainty space, thus providing a feasible solution for far more future scenarios than considered in the optimisation (Bertsimas et al., 2011). One uncertainty space was constructed per decision criterion, which we used as a reference space for all optimisations conducted throughout the paper, for example, when considering only a single stand type or a smaller uncertainty of the contributions of the stand types than assumed for standard optimisations (i.e. when using $y_{siu} = y_{si} - 2 \bullet std_{si}$). A constant reference space is essential to ensure comparability across the results obtained in different optimisations.

2.2. Distances to be minimised

Our optimisation defined the relative distances $D_{iu\%}$ (Eq. (1)) between the maximal achievable contribution in an uncertainty scenario and the achieved landscape level contribution as regret (Eq. (1)).

$$D_{iu\%} = \frac{\underset{s}{max}\{y_{siu}\} - Y_{iu}(a_s)}{\underset{s}{max}\{y_{siu}\} - \underset{s}{min}\{y_{siu}\}} \bullet 100 \tag{1}$$

with

$$Y_{iu}(a_s) = \sum_s a_s \bullet y_{siu} \tag{2}$$

Here, a_s is the land share allocated to stand type s, with $\sum_s a_s = 1$ and $Y_{iu}(a_s)$ is the contribution of the whole landscape portfolio. We can now minimise the maximum regret, i.e. the maximum relative distance, by seeking an optimal allocation of land shares to stand types (Eq. 3). To minimise the maximum relative distance β, the land cover shares a_s allocated to eight stand types are optimised using the following objective function and constraints:

$$\underset{a_s}{min}\, \beta \tag{3}$$

s.t.

$$\beta \geq D_{iu\%} \quad \forall i, u \tag{4}$$

$$a_s \geq 0 \tag{5}$$

$$\sum_s a_s = 1 \tag{6}$$

Eq. (4) assures the linearity of the optimisation problem. Eq. (3) can be minimised across all decision criteria and uncertainty scenarios, but it can also be minimised for single decision criteria only over their uncertainty space.

2.3. Robust Pareto frontiers

We complemented the above-described optimisation approach with analyses of robust Pareto frontiers to derive possible trade-offs between two bundles of decision criteria. Pareto frontiers are often used to study the trade-offs between conflicting management objectives in environmental science (e.g. Vasilakou et al., 2024 or Giagkiozis and Fleming, 2014). In our approach, a Pareto frontier represents the maximum guaranteed contribution of a specific landscape portfolio to one set of decision criteria f without compromising a pre-defined guaranteed contribution to another set of decision criteria z. Each element along a Pareto frontier thus represents an undominated landcover portfolio, for which no better alternative exists given that pre-defined provision level of z (e.g., Hayes et al., 2022). The minimum contributions are guaranteed for all possible future contributions y_{siu} included in the uncertainty spaces described above. Guaranteed contributions are thus immune to the uncertainty associated with variation of the contributions used as input data if the input data is included in the uncertainty space.

Pareto frontiers suggest not a single solution but a set of solutions called "efficient" because the achieved guaranteed contribution to one set of decision criteria cannot be improved without compromising the guaranteed contribution to the other set of decision criteria. All members of a Pareto frontier represent different preferences of decision-makers, with portfolios close to the left corner implying high weights of the decision criteria represented by the y-axis and portfolios close to the right corner of the frontier implying high weights of the decision criteria represented by the x-axis.

For our Pareto analysis, we first defined two maximum distances to be considered for two bundles of decision criteria, where subscripts f and z represent the different bundles of decision criteria. Minimising the maximum distance across decision criteria f is subject to respecting various tolerated maximum distances D_{zt} for decision criteria z (Eq. (9)).

$$\underset{a_s}{min}\, \beta_f \tag{7}$$

s.t.

$$\beta_f \geq D_{fu\%} \quad \forall f, u \tag{8}$$

$$D_{zt} \geq \beta_z \quad \forall z, u \tag{9}$$

Eqs. (5) to (6) apply here also.

The variable β_f is the maximum distance across the uncertainty scenarios for decision criteria f ($\beta_f = max\, D_{fu\%}$) and β_z for decision criteria z ($\beta_z = max\, D_{zu\%}$). We started with tolerating $D_{zt} = 100\%$, which means we only optimised considering decision criteria f. Subsequently, we reduced D_{zt} in Eq. (9) in steps of one to 5 % points as long the problem optimisation remained feasible.

For a convenient graphical representation, we translated the maximum distances into guaranteed contributions, which we call guaranteed performances p_f and p_z.

$$p_f = 100 - \beta_f \tag{10}$$

$$p_z = 100 - D_z \tag{11}$$

2.4. Implementation

We used open-access software to solve our robust multiple objective allocation problems ("OpenSolver", see Mason, 2012). The model results below are fully reproducible with the information provided in our paper, as shown by colleagues who have used Python or CPLEX for this. An "R"-based model code for single objective or multiple objective, robust optimisations, such as we used for obtaining the results shown in Figs. 1

and 2 (see below), has been published by Husmann et al. (2022). This code does not yet cover the Pareto-frontier optimisations we employed to produce Figs. 3 and 5. However, it provides a good insight into the robust multiple objective optimisation of land-use allocations based on open-access software. An example model implementation sheet built into “OpenSolver” (Mason, 2012) is available upon request from the authors.

2.5. Stand types

We used published data to inform the optimisation scenarios (Table 1). The close-to-nature forest stand types have been designed using a stand-level optimisation approach published by Knoke et al. (2020). In the stand-level optimisation one Silver fir and one Douglas fir dominated stand (both mixed with Norway spruce and European beech) maximised the worst relative financial return at stand level across $2^3 = 8$ uncertainty scenarios for the financial return (annuities computed using a discount rate of $r = 0.015$). The financial decision criterion was calculated as an annuity (called soil rent in forest economics). Annuities correspond to the commonly used soil expectation value. Using annuities instead of soil expectation values is sometimes better understood by practitioners. According to the stand-level optimisation, in the stand dominated by Silver fir (50 % Silver fir, 39 % Norway spruce, 11 % European beech), the first regeneration cohort was established (in a gap of circa 500 m^2) at the age of 30 years. Further regeneration cohorts were established during the simulation every ten years until all trees originally planted were replaced over 120 years. A maximum standing timber volume was achieved at age 60 (388 m^3 per hectare), which is later reduced but does not fall below 196 m^3 per hectare after that (no clear-cut). Optimisations considering Douglas fir led to a dominance of this tree species (55 % Douglas fir, 34 % Norway spruce, 11 % European beech). Here, the first regeneration cohort was established (in a gap of circa 500 m^2) at the age of 40 years. The maximum timber volume in this optimised stand was achieved with an age of 60 years (488 m^3 per hectare), which does not fall below 189 m^3 per hectare afterwards.

The financial and growth data for European beech was taken from Knoke et al. (2020), assuming a rotation of 120 years. The European Beech financial and growth data was also used for Oak. European beech and oak differed only in terms of biodiversity data. This is a simplifying assumption, which has only a moderate impact on the results (see Section 4). Data for Scots pine was adopted from Knoke et al. (2017), while the biodiversity data for all tree species was extracted from Gang et al. (2024) (see Table 1). As in other approaches (e.g. Neuner et al., 2013; Uhde et al., 2017; Gang et al., 2024), homogenous site conditions were assumed.

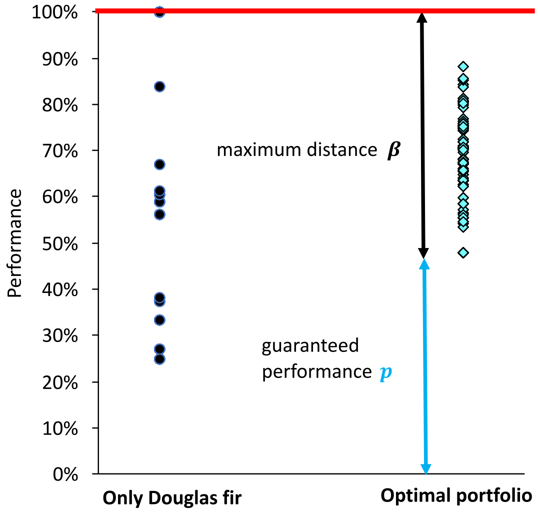

Fig. 1. Minimisation of the maximal distance β (or maximisation of the guaranteed performance p) for the criterion financial return. The figure shows the distances $D_{iu\%}$ to 100 % and the performances $p_{iu\%} = 100 - D_{iu\%}$ for 256 uncertainty scenarios computed for forest landscapes either consisting of Douglas fir only or consisting of a mixed landscape portfolio.

The standard deviations were computed based on eight uncertainty scenarios derived from the variances associated with the survival curves published by Brandl et al. (2020). These survival curves were considered in the optimisations by Knoke et al. (2020). Standard deviations for the biodiversity data were obtained from Gang et al. (2024). The financial return was computed using a discount rate of $d = 0.015$. Volume increment is the annual change of the cumulative total growth performance, and the carbon storage refers to the aboveground biomass averaged of time (see Knoke et al., 2020a for detailed explanations). Gang et al. (2024) described the two biodiversity indicators in detail.

Data for financial return (annuities computed for discount rate $d = 0.015$), volume increment, carbon storage derived from input data of an optimisation model (Knoke et al., 2020), were complemented with data for Douglas fir (adopted from Heidingsfelder and Knoke, 2004). Data for Scots pine was adopted from Knoke et al. (2017). The data for herbivores and deadwood was obtained from Gang et al. (2024) [who used unpublished data from Gossner and Brändle, Swiss Federal Institute for Forest, Snow and Landscape Research WSL for herbivore richness and data published by Kahl et al., 2017 for deadwood speed of decay]. Standard deviations were derived from expected survival probabilities (Knoke et al., 2020), Monte-Carlo simulations (Knoke et al., 2017), or adopted from Gang et al. (2024). Values for the mixed close-to-nature stand types represent tree-species-proportion weighted averages.

3. Results

3.1. Contribution to decision criteria

The optimisation (i.e., minimising the maximum distance or regret) of the financial return across the considered 256 uncertainty scenarios led to integrating both close-to-nature forest stand types (dominated either by Silver fir or Douglas fir) into the landscape portfolio. Fig. 1 shows how the resulting diversified landscape portfolio reduced the distance β between the maximum possible and the achieved contribution to the financial return compared to a landscape consisting only of Douglas fir (represented by diamonds). Note that the pure Douglas fir portfolio provided a variety of alternative contributions to the financial return, as its contributions were derived using the same uncertainty space as used for the more diversified forest landscape portfolios, referring to possible contributions of all stand types. Depending on the scenario, stand types other than Douglas fir may represent the maximum and minimum achievable financial contributions leading to the shown range of values for Douglas fir.

Using a forest landscape consisting only of Douglas fir as a benchmark, the guaranteed performance ($p = 100 - \beta$) increased from 25 % to 48 % for the diversified landscape portfolio, where close-to-nature forests cover 43 % of the forestland. This means the optimisation reduced the maximum relative regret from 75 % (pure Douglas fir) to 52 % (diversified forest landscape composition). The optimisation of the future forest composition excluded even-aged broadleaved forests when financial return was the only objective (Fig. 2A). Still, European beech is part of the mixed close-to-nature stand types. Under the financial return objective, the proportion of close-to-nature forests was highest, but still, even-aged forest types covered more than 50 % of the forest land. Even considering only one decision criterion, the desirable future forest landscapes were diversified.

This is a consequence of the large uncertainty intervals that cause forest landscape diversification to buffer against this uncertainty.

Considering all decision criteria simultaneously resulted in a highly diversified landscape portfolio, where the guaranteed performance tended to be lower than for single-objective optimisation. Excluding close-to-nature forest stands from the optimisation reduced the

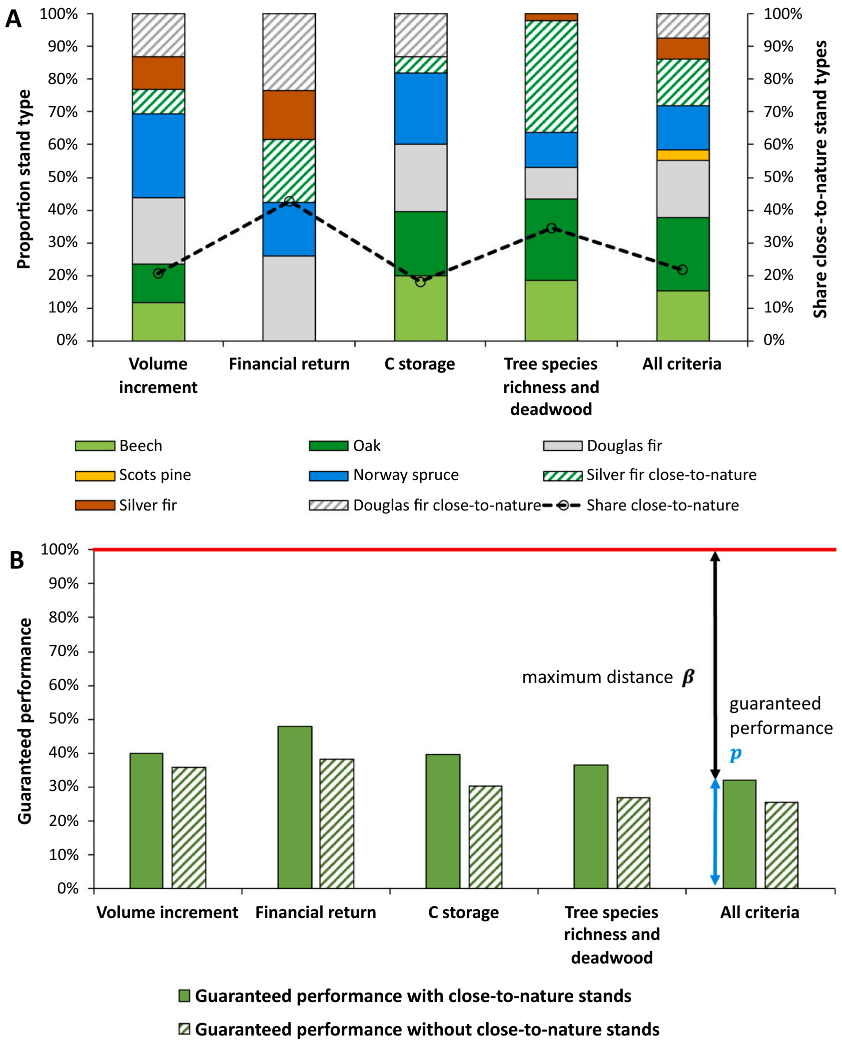

Fig. 2. A. Future forest landscape composition when optimised for single and for all criteria and share of close-to-nature forest stands. B. Guaranteed performance when optimised for single and for all criteria, either in- or excluding close-to-nature forest stands.

guaranteed performance by about 10 % points for almost all decision criteria. Only for the volume increment objective was the difference in guaranteed performance slight when excluding close-to-nature stand types (Fig. 2B).

A large proportion of oak (between 23 % and 25 %) supported biodiversity conservation and achieved the best compromise across all decision criteria. Under the biodiversity conservation scenario, the Silver fir close-to-nature forest stand held a high share (34 %).

The impact of considering multiple possible future uncertainty scenarios on the optimal landscape composition is large. Optimising only with the expected values (data not shown) led to landscapes covered by only one stand type (the one with the highest performance concerning the decision criterion under consideration). Only for the two biodiversity criteria (herbivore species richness and speed of deadwood decay), which we considered simultaneously, would the future landscape consist of European beech and oak stand types.

3.2. The trade-off between bundles of decision criteria

Here, we first show the impact of the size of the considered uncertainty on the level and shape of the resulting Pareto frontiers, using the trade-off between biodiversity and financial return indicators as an example (Fig. 3A). Given a moderate level of uncertainty (with optimistic values −2 standard deviations resulting in pessimistic values), generally higher performance levels than under higher levels of uncertainty (here represented by considering −3 standard deviations) can be achieved for both bundles of decision criteria. The whole Pareto frontier under moderate uncertainty was flatter than under higher uncertainty, so increasing financial return did not reduce the biodiversity indicators so strongly. Close-to-nature forests were integrated into all landscape portfolios of the Pareto frontier under moderate uncertainty, but their share was smaller than under higher uncertainty levels.

Considering −3 standard deviations as the size of the uncertainty intervals and starting from the optimal landscape composition to conserve biodiversity (with a proportion of even-aged broadleaved stands of 44 %), improving financial return strongly compromised biodiversity conservation (Fig. 3A). This indicates a substantial trade-off between biodiversity conservation and financial return. The maximum guaranteed performance for financial return only allowed a maximum guaranteed performance for the bundle of biodiversity indicators of 10 %.

The trade-off between biodiversity indicators and carbon storage plus volume increment was still substantial but not as strong as the trade-off between biodiversity and financial return (Fig. 3B). When carbon storage plus volume increment was one bundle of ecosystem services, the maximum guaranteed biodiversity still allowed a guaranteed performance level for carbon storage and a volume increment of more than 25 %.

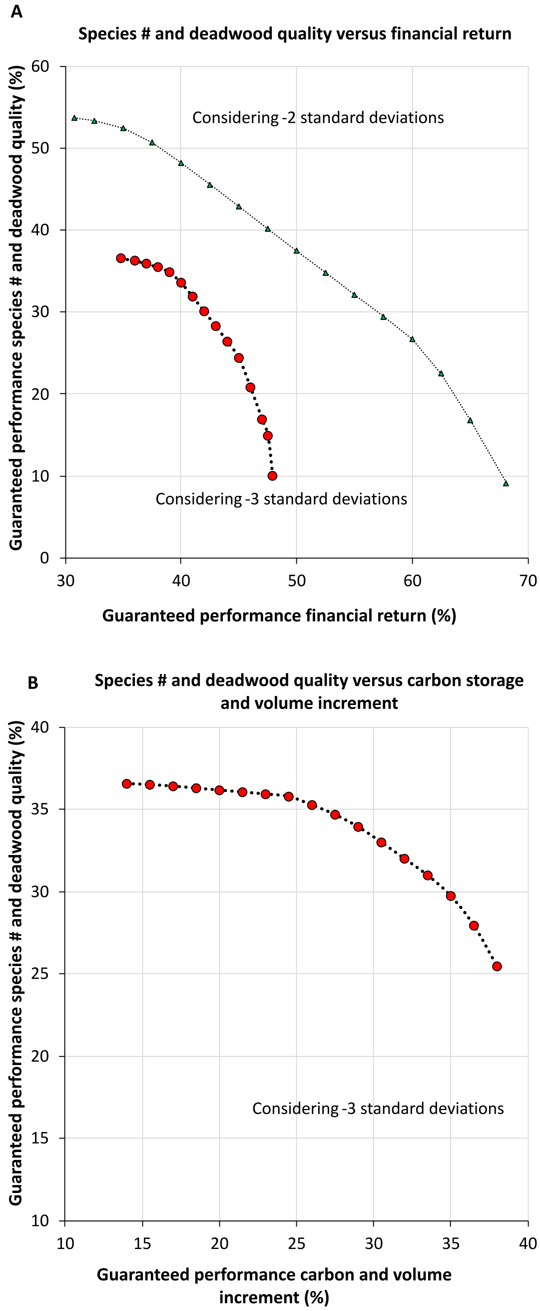

Fig. 3. A. Maximum guaranteed performance for biodiversity indicators without violating required performance levels for financial return, shown for two alternative levels of uncertainty considered. B. Maximum guaranteed performance for biodiversity indicators without breaking required carbon storage and volume increment performance levels.

3.3. Robustness of the Pareto frontiers

The Pareto-efficient forest landscape portfolios contributed robustly to the decision criteria (Fig. 4).

We can show the robustness using a simulation experiment, where we randomly selected the individual contributions of the stand types to the decision criteria from the uncertainty intervals using the pessimistic and optimistic contributions as bounds (assuming a uniform distribution within the intervals). The optimised landscape portfolios representing the Pareto frontier can then be confronted with these random contributions. Such a simulation experiment resulted in most cases in better performance of future landscape contributions than the robust Pareto frontiers suggested. Across numerous iterations, we did not identify any portfolio performance level lower than the guaranteed performance level of the Pareto frontier and even only rare cases of performances close to the frontier (Fig. 4). This shows that the Pareto frontier reflects the maximum relative regret, which will never be exceeded, provided the considered random contributions reside in the before-defined uncertainty spaces. Conversely, the robust Pareto frontier represents guaranteed performance levels immune to the uncertainty we have considered.

3.4. Impact of close-to-nature forests on Pareto frontiers

Including close-to-nature forests in the landscape portfolios generally enhanced the robust performance levels of all Pareto-efficient portfolios. This can be shown by excluding the close-to-nature forest stand types from the optimisation, which moved the whole frontier of guaranteed performances downwards (Fig. 5). The improvement by including close-to-nature forests appears particularly strong when considering trade-offs with financial return (Fig. 5A).

4. Discussion

Our study presents a new method to assess the uncertain contributions of alternative silvicultural regimes (i.e. alternatives to conventional even-aged forest management) to multiple ecosystem services at the landscape scale. The assessment goes beyond comparing mutually exclusive silvicultural options, thus offering the opportunity for trade-off analyses between managing different bundles of ecosystem services at landscape scales. A central finding is that providing multiple ecosystem services requires different stand types and silvicultural systems associated with a high compositional diversity of the resulting future landscape portfolios. Close-to-nature forest stand types provided essential contributions to all considered decision criteria, while close-to-nature forest stand types did not dominate the obtained desirable forest landscape portfolios.

We did not focus on a real-world forest landscape but used a generic example based on a set of general indicators we collected from existing studies. Given that studies dealing with uncertainty in forest management planning are rare, we think this is appropriate for demonstrating a new method to integrate uncertainty into forest management planning and to assess different stand types at a general level. We used five indicators: financial, timber, carbon, species diversity, and deadwood contributions of the stand types. This set represents a reasonable number of indicators, covering important ecosystem services. For example, Knoke et al. (2016) have shown that using numerous indicators will not necessarily change land-use allocation results much. However, more specific and other indicators can be used for explicit applications to specific real-world forest enterprises. Site heterogeneity may be considered by conducting such portfolio analyses for smaller spatial units with comparable site conditions (see, for example, Clasen and Knoke, 2013 or Friedrich et al., 2021). An alternative would be to express site variability by enhancing the uncertainty intervals where the assumed contributions of the stand types reside. When tailored to specific real-world forest enterprises, our landscape portfolios may provide some guidelines for practical forest management for regenerating existing older forest stands, providing information on the desirable overall enterprise-level mix of stand types. An example study providing optimisations for a real-world forest enterprise is Neuner et al. (2013). However, the latter study used a more classical, purely financial Markowitz portfolio approach to optimise financial return as the only objective, considering risk (using probability distributions for financial return) instead of uncertainty (when no probabilities can be used).

Silvicultural alternatives' impact on landscape-scale trade-offs has yet to be studied more intensively. Among the existing optimisation studies analysing the contribution of continuous-cover-forest stands to multiple ecosystem services at the landscape level is Eyvindson et al.

Table 1

Expected contributions $\boldsymbol{y_{si}}$ of the considered single stand types to the decision criteria used for the optimisations and their standard deviations $\boldsymbol{std_{si}}$. *Close-to-nature stand types in italics and bold.*

	Decision criterion *i* (± standard deviation std_{si})				
Stand type *s*	Financial return	Volume increment	Carbon storage (aboveground biomass)	Herbivores	Deadwood speed of decay
	[€ per year per hectare]	[m^3 per year per hectare]	[tons C per hectare]	[Frequency]	[g per cm^3 per year]
Beech	17 (3.9)	8.8 (2.0)	108 (25)	333 (53)	0.069 (0.043)
Oak				913 (227)	0.021 (0.021)
Douglas fir	195 (62)	11.9 (3.8)	84 (27)	33 (1)	0.002 (0.027)
Scots pine	−38 (45)	7.0 (2.0)	47 (13)	410 (75)	0.015 (0.023)
Norway spruce	136 (66)	8.5 (4.1)	53 (26)	353 (58)	0.035 (0.034)
Silver fir mixed	***128 (28)***	***8.0 (1.7)***	***76 (15)***	***278 (26)***	***0.031 (0.017)***
Silver fir	124 (32)	8.7 (2.2)	63 (16)	207 (22)	0.02 (0.02)
Douglas fir mixed	***151 (39)***	***9.3 (2.3)***	***94 (24)***	***148 (17)***	***0.017 (0.02)***

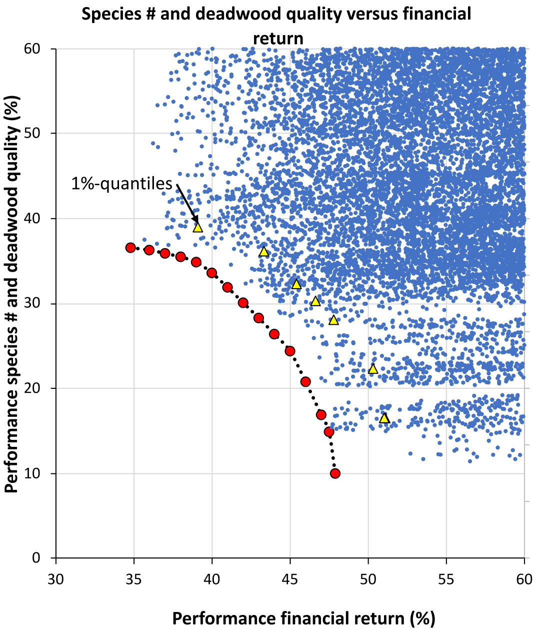

Fig. 4. Simulated performances of the Pareto-efficient landscape portfolios using random contributions of the single stand types drawn from the uncertainty intervals. As we truncated the axes at a performance level of 60 %, we integrated 1 % stochastic quantiles as yellow triangles for comparison. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(2021). This study obtained results similar to ours and highlighted the importance of allowing for diverse silvicultural systems. However, Eyvindson et al. (2021) conclude that high "… boreal forest multi-functionality requires continuous cover forestry as a dominant management". Our study does not fully confirm their conclusion for central European forest ecosystems. Unlike the mentioned study, we have included a method to consider the uncertainty around the actual (yet unknown) future contribution of the stand types to the decision criteria. Considering this uncertainty supports further diversification at the landscape scale and limits the dominance of either silvicultural system and, thus, the dominance of close-to-nature stand types.

Other landscape-level optimisation studies include optimising forest landscapes for multiple objectives using Pareto frontiers (Pohjanmies et al., 2017; Triviño et al., 2017). Pohjanmies et al. (2017) found that optimising over larger planning regions supports minimising trade-offs between timber production and carbon storage. Triviño et al. (2017) showed that no single forest management regime can simultaneously maximise individual or multiple objectives. Instead, combining different management regimes was necessary to achieve a good compromise because the numerous considered stands of various ages and tree species

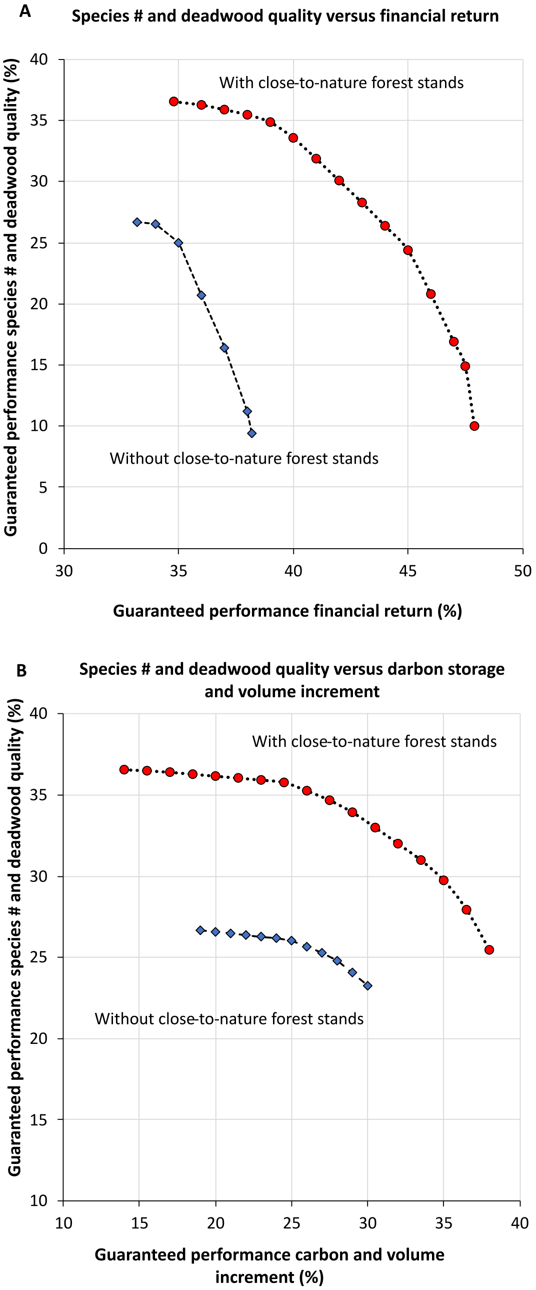

Fig. 5. Maximum guaranteed performance for biodiversity indicators without violating required performance levels for (A) financial return or (B) carbon storage and volume increment: with and without close-to-nature forest stands.

under different conditions required different management strategies. A further example focused on soil protection and considering other objectives through constraints. Rodrigues et al. (2021) showed that past levels of timber production can be reached in the future while reducing soil erosion using linear programming.

Most landscape-level optimisation studies ignore the possible impact of uncertainty on the optimal solution. An exception is Mazziotta et al. (2023), who simulated a stochastic sampling procedure for several variables to create a possible range for their Pareto frontiers. Their simulation procedure nicely showed how the Pareto frontier might change substantially under random variations of the input information, implying a range of optimal solutions (land allocation to different management alternatives) depending on the random data used for the optimisation. Their valuable stochastic approach to consider risks was based on Gaussian or log-normal probability distributions, while our approach differed. Instead, we adopted a non-stochastic ex-ante representation of possible future variability of our input information that did not require any probability distributions. Then, we searched for one robust solution for each member of our Pareto frontier. Implementing such a robust solution guarantees the minimum performance level for all perturbations of the input information in our uncertainty spaces (see Fig. 4). The robust solutions that determine our Pareto frontier represent all possible weightings of two bundles of decision criteria. These solutions can be recommended to decision-makers whose preferences correspond to these weightings. In the future, it would be interesting to test if the lower range of stochastic Pareto frontiers would roughly correspond with our robust Pareto frontiers. At the same time, Fig. 4 suggests that the robust frontier may even be more conservative. A significant advantage of our non-stochastic robust approach is its relatively low data demand.

The assumptions we made to represent uncertainty are essential. For example, we abstained from using positive uncertainty by adding some standard deviations to the expected value, which would create even more optimistic contributions than we have used. With optimistic contributions being the expected ones plus some standard deviation, we would obtain a vast uncertainty space, thus obtaining relatively low guaranteed performances for diversified portfolios. The expected contributions would not impact the solutions in such a case, as these would be included in the then very large uncertainty spaces. With test simulations, we found that Scots pine obtained much higher shares under these large and, in part, extremely optimistic uncertainty spaces than otherwise, as its high uncertainty leads us to assume high optimistic values. Such a result appears counterintuitive and supports speculative decision-making, at least for Germany, where Scots pine shows poor financial performance. We would thus recommend considering only the downside uncertainty, but that depends, of course, on the purpose of the study. In addition, the size of the considered downside uncertainty impacts the results. Assessing the impact of the considered uncertainty on the Pareto frontier, we found that reducing the size of the uncertainty intervals from 3 to 2 standard deviations allowed for higher performance levels, leading to flatter Pareto frontiers. The close-to-nature forest stand types were still included with substantial shares under lower uncertainty but not as much as under higher uncertainty. This highlights the attractiveness of close-to-nature stand types, particularly under higher uncertainties. Methodologically, the flatter frontiers under lower uncertainty suggest less severe trade-offs. Conversely, ignoring the high uncertainties in reality means underestimating the trade-offs. One could use ellipses as an alternative to the box-uncertainty spaces, assuming a random behaviour of the considered contributions of the stand types. An example of using ellipses as uncertainty spaces is Knoke et al. (2020). However, assuming a random behaviour of the considered variables under severe uncertainties could mean a too-optimistic assumption.

Numerically, our study shows that close-to-nature stand types contribute to each single and to multiple considered decision criteria simultaneously. At the same time, they would not dominate the desirable future forest landscapes. Similar to other studies, this result emphasises that landscape-level diversification of tree species and silvicultural systems, and not constraining the choices for silvicultural systems too much, is essential to support single and multiple objectives. When multiple decision criteria are involved, the required landscape diversification increases compared to considering only one decision criterion. High landscape-level diversification was also suggested empirically to support biodiversity conservation (Schall et al., 2018) and by relationships between landscape heterogeneity and multifunctionality (Plas et al., 2019; van der Plas et al., 2016). Consequently, the finding about diversifying tree species and silvicultural systems to support multiple ecosystem services (measured by five decision criteria in our study) is robust. Too strong limitations on the size of allowable canopy openings in new forest laws would thus constitute an inappropriate constraint for multifunctional forest management.

Regarding the input information, we also used Beech data for Oak, differentiating only concerning the biodiversity data between both species. This might have biased the performance of Oak, for example, for carbon storage. But even when reducing the assumed carbon storage for Oak from 108 tons to 70 tons per hectare, their area share was reduced only by 1 % point in the multi-objective landscape portfolio. Considering only carbon storage as a decision criterion, the assumed reduction of the input information for Oak reduced the area share of Oak by 10 % points. However, our general results are not compromised by such alterations.

Summing up, we obtained the following results concerning our specific research questions:

Q1. Do close-to-nature forest stand types make a difference concerning future forest landscapes' optimal ecosystem service provision? Including close-to-nature forest stand types supported minimising the maximum regret for each decision criterion and under consideration of multiple decision criteria. This finding underlines that close-to-nature forests may stabilise the contributions of forest landscape portfolios to the considered decision criteria, making these stand types attractive portfolio components, particularly for risk-averse decision makers (Messerer et al., 2017).

Q2. Which objectives require higher and lower shares of close-to-nature forest stand types? Our close-to-nature-forest types had been optimised at stand level in another study to provide a favourable relation between their expected financial return and the variability of financial return (Knoke et al., 2020; Roessiger et al., 2013; Roessiger et al., 2011) before considering them as portfolio components at landscape scale. Their favourable reward-to-variability ratio made them attractive to support the minimum-regret portfolio, particularly with financial return as a single objective. With 43 %, the share of close-to-nature forests was thus the highest in the financial return portfolio. Interestingly, the close-to-nature forest stand dominated by Silver fir covered 34 % of the forest land when biodiversity conservation was the single objective. At the same time, the Douglas fir uneven-aged stand type was completely excluded when biodiversity conservation was maximised. For volume increment, carbon storage and multiple objectives, the share of close-to-nature forest stand types was lower than for financial return (18 % to 22 %). Close-to-nature forest stand types are thus no panacea, and their importance depends on the specific objectives of forest management. In addition, the potential for contributing to ecosystem services of close-to-nature stand types depends on the actual tree species considered, the site conditions, disturbance regimes and their management. The stand types considered in our study were optimised at stand level using financial objectives, which may differ from other studies.

Q3. How strong are the trade-offs and potential synergies when optimising various bundles of decision criteria? Our study found that trade-offs between biodiversity and the conservation of carbon storage (plus volume increment) and financial return were severe. In contrast, we found only moderate trade-offs between biodiversity conservation and improving carbon storage (plus volume increment) at the landscape scale. Sabatini et al. (2019) obtained similar empirical results and recommended separating the evaluation of management strategies between stand and landscape scales. They conclude that co-benefits between biodiversity and carbon should be considered at broader scales, not at stand level. According to Sabatini et al. (2019), stand-level co-benefits between biodiversity and carbon are likely in the tropics but less in European temperate forests.

Q4. How does in- or exclusion of close-to-nature forest stand types impact a forest landscape's potential to provide ecosystem services? Our results showed that including close-to-nature forest stand types would elevate the whole Pareto frontier, underlining that these stand types are innovative portfolio components that forest managers should consider enhancing the forest's capacity to provide ecosystem services under uncertainty.

Future studies may include spatial optimisation for real ecoregions or forest enterprises, where the considered stand types can coexist, including substitution effects of wood products, alternative optimisation approaches, stand types and set aside areas. For example, future studies could be inspired by Biber et al. (2020), who used a non-spatial scenario approach to consider real ecoregions and substitution effects.

5. Conclusions

- Close-to-nature forest stands help minimising the maximum regret of future forest landscapes
- Even-aged stand types are equally important at landscape scales, which include stand types with light-demanding and climate change-adapted tree species, such as Oak
- Multiple objectives and the minimisation of maximum regret under uncertainty both require increasingly diversified future forest landscapes, consisting of various stand types
- Forest regulations which limit canopy openings and the admissible reductions of standing timber stocks too firmly will exclude biodiversity-friendly and climate change-adapted stand types. This will compromise the management for multiple objectives and the climate change adaptation of forest landscapes

CRediT authorship contribution statement

Thomas Knoke: Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Peter Biber:** Writing – review & editing, Methodology, Formal analysis. **Tobias Schula:** Writing – review & editing, Project administration. **Jonathan Fibich:** Writing – review & editing, Validation. **Benjamin Gang:** Writing – review & editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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