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Ecosystem Services

What Drives Forest Multifunctionality in Central and Northern Europe? Exploring the Interplay of Management, Climate, and Policies

--Manuscript Draft--

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Abstract:	Forests provide a range of vital services to society and are critical habitats for biodiversity, holding inherent multifunctionality. While traditionally viewed as a byproduct of production-focused forestry, today's forest ecosystem services and biodiversity (FESB) play an essential role in several sectoral policies' needs. Achieving policy objectives requires careful management considering the interplay of services, influenced by regional aspects and climate. Here, we examined the multifunctionality gap caused by these factors through simulation of forest management and multi-objective optimization methods across different regions - Finland, Norway, Sweden and Germany (Bavaria). To accomplish this, we tested diverse management regimes (productivity-oriented silviculture, several continuous cover forestry regimes and set asides), two climate scenarios (current and RCP 4.5) and three policy strategies (National Forest, Biodiversity and Bioeconomy Strategies). For each combination we calculated a multifunctionality metric at the landscape scale based on 5 FESB classes (biodiversity conservation, bioenergy, climate regulation, wood, water and recreation). In Germany and Norway, maximum multifunctionality was achieved by increasing the proportion of set-asides and proportionally decreasing the rest of management regimes. In Finland, maximum MF would instead require that policies address greater diversity in management, while in Sweden, the pattern was slightly different but similar to Finland. Regarding the climate scenarios, we observed that only for Sweden the difference in the provision of FESB was significant. Finally, the highest overall potential multifunctionality was observed for Sweden (National Forest scenario, with a value of 0.94 for the normalized multifunctionality metric), followed by Germany (National Forest

	scenario, 0.83), Finland (Bioeconomy scenario, 0.81) and Norway (National Forest scenario, 0.71). The results highlight the challenges of maximizing multifunctionality and underscore the significant influence of country-specific policies and climate change on forest management. To achieve the highest multifunctionality, strategies must be tailored to specific national landscapes, acknowledging both synergistic and conflicting FESB.
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Highlights

- Multi-objective optimization was used to estimate landscape’s maximum potential multifunctionality
- A combination of integrative management with segregation for set asides and intensive production is optimal
- Trade-offs between ecosystem services could impair the achievement of maximum multifunctionality
- Sectoral polices must address a high number of ecosystem services to foster multifunctionality

Abstract

Forests provide a range of vital services to society and are critical habitats for biodiversity, holding inherent multifunctionality. While traditionally viewed as a byproduct of production-focused forestry, today's forest ecosystem services and biodiversity (FESB) play an essential role in several sectoral policies’ needs. Achieving policy objectives requires careful management considering the interplay of services, influenced by regional aspects and climate. Here, we examined the multifunctionality gap caused by these factors through simulation of forest management and multi-objective optimization methods across different regions - Finland, Norway, Sweden and Germany (Bavaria). To accomplish this, we tested diverse management regimes (productivity-oriented silviculture, several continuous cover forestry regimes and set asides), two climate scenarios (current and RCP 4.5) and three policy strategies (National Forest, Biodiversity and Bioeconomy Strategies). For each combination we calculated a multifunctionality metric at the landscape scale based on 5 FESB classes (biodiversity conservation, bioenergy, climate regulation, wood, water and recreation). In Germany and Norway, maximum multifunctionality was achieved by increasing the proportion of set-asides and proportionally decreasing the rest of management regimes. In Finland, maximum MF would instead require that policies address greater diversity in management, while in Sweden, the pattern was slightly different but similar to Finland. Regarding the climate scenarios, we observed that only for Sweden the difference in the provision of FESB was significant. Finally, the highest overall potential multifunctionality was observed for Sweden (National Forest scenario, with a value of 0.94 for the normalized multifunctionality metric), followed by Germany (National Forest scenario, 0.83), Finland (Bioeconomy scenario, 0.81) and Norway (National Forest scenario, 0.71). The results highlight the challenges of maximizing multifunctionality and underscore the significant influence of country-specific policies and climate change on forest management. To achieve the highest multifunctionality, strategies must be tailored to specific national landscapes, acknowledging both synergistic and conflicting FESB.

Keywords: *multi-objective optimization, biodiversity, forestry, bioeconomy, forest policy, sustainability*

1 Introduction

Forest ecosystems provide multiple services simultaneously and possess intrinsic multifunctionality values (Winkel et al., 2022). The provision of forest ecosystem services and biodiversity (abbreviated to ecosystem services, for simplicity) has long been considered a side effect of traditional production-oriented forestry, but today ecosystem services play a crucial role in meeting the economic and population needs of modern societies (Teben'kova et al., 2020). For instance, climate mitigation demands such as storing carbon or temperature regulation have become increasingly relevant during the last decades (Benz et al., 2020), and recent forest-related policies particularly emphasize the importance of biodiversity conservation (EC, 2021a).

Forest multifunctionality is a complex issue which is difficult to quantify and achieve. Most forest management plans associate sustainable multifunctionality with supplying timber production over time as a primary objective, while providing additional ecosystem services such as non-timber products (e.g., berries, mushrooms, game) or recreational activities, as secondary objectives (Simons et al., 2021). As a result, the emphasis on timber production may not always lead to the most effective management for other essential ecosystem services (Peura et al., 2016). Further, several scenarios' studies report a future increase in wood demand, crucial for achieving the EU's climate mitigation goals (Grassi et al., 2017; Vizzarri et al., 2022). This trend is especially significant in the Nordic countries and is expected to result in increased wood harvest levels that may potentially intensify pressure on the provision of other ecosystem services and biodiversity (EC, 2018; FS, 2019). Nonetheless, the effects of climate change may hinder the expected higher wood provision when considering that, regionally, forest productivity could decrease and higher vulnerability against hazards is expected (Hanewinkel et al., 2013; Gutsch et al., 2018), even more prominently in southern regions of Europe (Gusti et al., 2020).

Multifunctionality, however, depends not only on the provision of multiple ecosystem functions and services simultaneously but also on interactions among them (Hölting et al., 2019). Some studies have noted that a higher forest landscape multifunctionality may require lower levels of individual ecosystem services (Vincent and Binkley, 1993; Jacobsen et al., 2013), whereas others showed that multifunctional landscapes might positively impact the conservation of biodiversity and the overall maintenance of ecosystem functions (Pasari et al., 2013). These findings illustrated that the provision of a specific ecosystem service is rarely independent of other services, and positive (synergies) and negative (trade-offs) relationships among forest services are common (Hölting et al., 2019; Pasari et al., 2013). For this reason, effective forest management strategies are essential for achieving multifunctionality in forested landscapes. Earlier studies applying simulation scenarios have examined how management impacts multifunctionality in European countries. Some of them are focused on specific management strategies, such as continuous cover forestry (Peura et al 2018; Eyvindson et al. 2021), while others analyze the best combination of a set of management strategies to enhance forest multifunctionality (Triviño et al., 2023). Similarly, a recent review by Felton et al. (2023) highlighted the complex interaction among alternatives management strategies and the complex array of outcomes for ecosystem services and biodiversity that may result from choosing among them, observing that each management strategies had its own suite of trade-offs, synergies and uncertainties.

A third factor in the achievement of landscape multifunctionality is the impact of policy implementation. Multifunctional and sustainable forest management has gained policy representation in Europe in the later years, integrating these principles into national forest policies (Sotirov and Arts, 2018). There is a growing recognition of the need for forest policies to not only prioritize timber production but also emphasize the vital role of forests in providing a wide range of ecosystem services (Keeble, 1988; Urquhart et al., 2012; Elomina and Pülzl, 2021). However, many of these forest-related policies outline their specific objectives and goals, often aiming at a specific ecosystem service, resulting in a variety of partly conflicting goals for forests (Pülzl and Hogl, 2013; Aggestam and Pülzl, 2018; Pülzl et al., 2018; Wolfslehner et al., 2020). Divergent interests and ideological differences across policy sectors result in divergent and sometimes ambiguous regulatory frameworks for ecosystem services within the EU. Consequently, the degree of implementation of multifunctional targets in sectoral policy strategies, like the New EU Forest Strategy for 2030 (EC, 2021b), the EU Biodiversity Strategy for 2030 (EC, 2021a), and the Bioeconomy Strategy (EC, 2018) will impact the continuous flow of the provision of forest ecosystem services as well as management of multifunctional forest landscapes.

To better understand the importance of the three multifunctionality drivers (region, climate and policy), we must evaluate and analyze the provisioning of multiple ecosystem services at a landscape level. This will clarify the challenges to enable multifunctional landscapes and guide future research. The main objective of this study is to examine the impact of forest management, depending on the region-specific climate, and corresponding national forest policies on the provision of different ecosystem services across different study areas – Finland, Norway, Sweden and Germany (Bavaria). This enables quantification of the area specific ecosystem service trade-offs, and the evaluation of sectoral policies to guide forest development towards the potential maximum multifunctionality. Specifically, we aim to answer the following questions:

- Q1: Under the maximum multifunctionality scenario, how do trade-offs and synergies between ecosystem services differ among the four studied areas?
- Q2: What is the proportional combination of management regimes that maximizes multifunctionality in each of the studied countries?
- Q3: How is the potential maximum multifunctionality promoted by different policy scenarios under climate pathways?

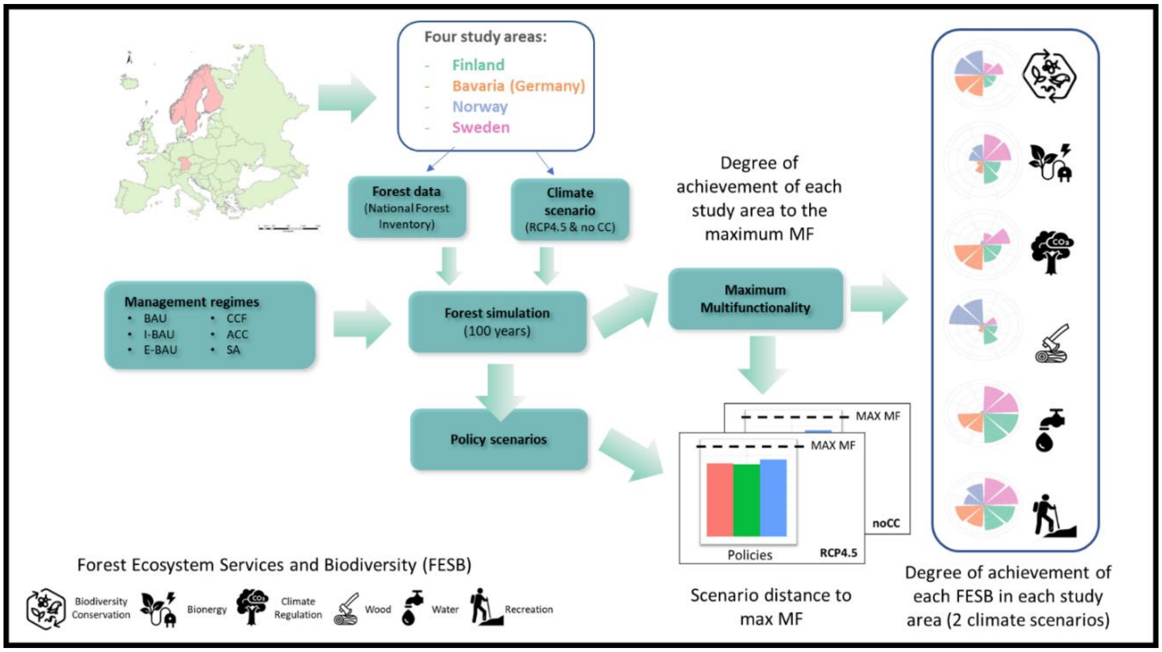

Figure 1: Illustration of the study approach. The study area comprises Finland, Sweden, Norway, and Germany represented by the state of Bavaria. Based on forest and climate data simulations scenarios are developed for 6 management regimes. Two optimization phases are performed, first for three sectoral policy scenarios and second for the maximum potential multifunctionality. By contrasting the outcomes of these two optimization processes, we can estimate the multifunctionality gaps between the policy scenarios and the maximum multifunctionality achievable. Finally, the provision of ecosystem services for the maximum multifunctionality is calculated. MF stands for multifunctionality. The six management regimes are: business as usual-rotation forestry (BAU), intensification of BAU (I-BAU), extensification of BAU (E-BA), continuous cover forestry (CCF), adaptation to climate change (ACC) and set-asides (SA).

2 Methods

2.1 Workflow and summary

To allow for regional comparisons of forest ecosystem services and therefore, forest multifunctionality, National Forest Inventories (NFIs) are, when available, among the best datasets to analyze forest wood availability at the national scale, since they usually cover the entire forest area of a country (Jandl et al., 2018; Blattert et al., 2020; Kovac et al., 2020). At the same time, advances to quantify the trade-offs and synergies between ecosystem services are gaining research attention. One approach to quantify the trade-off is multi-objective optimization, which formed part of the basis to solve land-use conflicts as well as assessing complex interactions between multiple ecosystem services (Chen et al., 2016; Eggers et al., 2020).

The combination of local level forest data and multi-objective optimization methodology has been used to compare the values of multifunctionality achieved in alternative scenarios (Pohjanmies et al., 2021) and to evaluate the impact of forest management alternatives in forest multifunctionality (Eyvindson et al., 2021). Figure 1 exemplifies our methodological approach. Four countries are assessed, Finland, Sweden, Norway, and the region of Bavaria in Germany (simplified to Germany).

Based on our findings, we assessed the reasons for variations between multifunctionality assessments and the implications for management and decision-making.

2.2 Forest data and simulation

This study was carried out in four European study regions (Figure 1) using a similar methodology across the regions. Data from the most recent National Forest Inventories were used in Sweden (2008-2012), Norway (NFI11, 2015-2019), and Bavaria representing Germany (NFI3, 2012) to simulate forest dynamics and management. In the case of Finland, the inventory scheme of the NFI11 was used to sample public forest data (2015/2016) and to represent the national forest area systematically. In total, 56221 plots were selected in Finland, 29892 in Sweden, 9371 in Norway, and 7456 in Germany (only in the state of Bavaria). For a more detailed description of the forest inventory data see supplementary material S1, Forest data management and simulations. National forest inventory data are a representative sample of the forest ecosystems of each region. Forests in the NFI datasets are mostly secondary managed forests, which is the most common in European forests, but they also include intensive plantations, and protected areas. Primary forests in the study regions are negligible.

For each NFI plot, forest dynamics development was simulated in five-year periods over 100 years using specific regional simulators. By using these tools, we were able to address the site-specific forest conditions and dynamics (tree growth, mortality, and regeneration), as well as to cope with the diversity of regional forest management practices. The forest simulators used were Heureka for Sweden

(Wikström et al., 2011), SiTree for Norway (Antón-Fernández and Astrup, 2022), SILVA for Germany (Pretzsch et al., 2002) and SIMO for Finland (Rasinmäki et al., 2009). These simulators use models built for the countries/regions they simulate. Additionally, we simulated forest dynamics and management under two climate trajectories: current climate (1.5 °C) and representative concentration pathways RCP 4.5. The so-called current scenario (1.5 °C) assumed net-zero GHG emission by the EU in 2050 since it counted on the EU and countries strongly contributing to the Paris Agreement's temperature objectives. The Nationally Determined Contribution (NDC, 2023) (NDC translated into the RCP 4.5) comprised a 40% reduction of greenhouse gas emissions by 2030 (from 1990 levels), as well as a 27% share for renewable energy, and a 27% increase in energy efficiency (For further details, see Supplementary S1 and S4).

Although simulated management regimes among study areas were heterogeneous due to different regional practices, they could be categorized into the following six common classes (Table 1 and Supplementary S1). The management regimes classified as business-as-usual represent even-aged forest management with intermediate thinnings and final clear-cut with planting after the final harvest. The intensified class (I-BAU) characterizes those regimes with shortened rotation times of forest stands. In Germany and Sweden these management regimes also included the promotion of productive foreign tree species while in the boreal study regions, it included the effects of fertilization. On the contrary, the extensify management class (E-BAU) includes regimes with prolonged rotation times and decreased thinning intensity (in all regions). In Finland and Sweden, this class allowed for a larger number of retention trees after the final cutting. A continuous cover forest class aims to maintain regular wood supply as well as forest stands permanently covered with complex tree structures and natural regeneration. In Finland and Germany, it also includes regimes that are production oriented for monospecific stands of Norway spruce or Scots pine. The adaptation to climate change class (ACC) promotes tree species diversity, aiming to increase resilience and stability to climate change and climate-induced disturbances. Finally, a set-aside regime was the alternative without any management activities (e.g., NFI plots falling into statutory protected areas were only simulated with set aside). Depending on the applied simulator and region (except for set aside) the total number of regimes representing each management class differed.

Table 1: Management regime classes applied in the forest growth simulations.

Management class	Description
Business-as-usual (BAU)	Management based on even-rotation forestry with intermediate thinning and final clear-cut with planting after the final harvest.
Intensified BAU (I-BAU)	Shortened rotation times of forest stands. It could include the effects of fertilization (boreal regions) or the promotion of productive foreign tree species (Germany and Sweden)
Extensified BAU (E-BAU)	Prolonged rotation times and decreased thinning intensity. Regimes that could leave a larger number of retention trees after final harvest (Finland and Sweden)
Continuous cover forestry (CCF)	Regimes based on continuous wood production and forest stands permanently covered with diverse structures and natural regeneration.
Adaptation to climate change (ACC)	Management aimed to promote species diversity to increase resilience and stability against climate change and disturbances.
Set-aside (SA)	Protecting forest, no thinning, no harvest.

2.3 Forest ecosystem service indicators

For each specific regional study area, management regime and climate scenario, the simulated forest characteristics (e.g., tree species, tree dimensions, deadwood amounts, harvest volumes) were used to estimate a set of ecosystem services indicators at each 5-years period. In total, we defined six common categories of forest ecosystem services according to international classification schemes (Haines-Young and Potschin-Young, 2018; M.E.A., 2005) and following an analysis framework for European policy documents (Primmer et al., 2021). The set of ecosystem services selected included wood production and bioenergy (provisioning services), water protection and climate regulation (regulating services), recreation (cultural services), and biodiversity conservation.

To ensure comparability across our study regions, in this work, we focus on the provision (supply) of ecosystem services, that are linked to the forest landscape structure and characteristics through indicators. In each study area there is at least one indicator corresponding to each ecosystem service and biodiversity. To select the ecosystem services indicators and include them in our analysis we applied two criteria: indicators should be addressed in the national policies and could be calculated from available data, in this case, data from National Forest Inventories (Blatter et al., 2022; Vergarechea et al., 2023; Toraño-Caicoya et al., 2023). In this way, we addressed a wide spectrum of ecosystem services instead of having only a common minimum set of indicators. Then, although indicators can differ among the four study regions, they represent a wide and common spectrum of ecosystem services, which can be used to develop comparisons among the four study regions. However, in this study, a comparison among study regions did not take place at the level of indicator but at the level of ecosystem services categories, as well as management classes. This approach allowed us to address the most significant societal preferences in each study region and to emphasize the multifaceted role of FES. For a more detailed description of the indicators used in each study region see Supplementary S2 and Table S6 – Table S9.

2.4 National policy scenarios.

We defined three policy scenarios for each study area (the Forest Scenario, Biodiversity Scenario, and Bioeconomy Scenario) based on the three main national policy documents which reflect the goals and governance mechanism for ecosystem services provision. The policy scenarios were represented by independent strategies (Finland and Germany) (Blattert et al. 2022, Toraño-Caicoya et al. 2023), a combination of policy strategies with an analysis of the parliament white paper on forest policy

(Norway) (Vergarechea et al. 2023), or specific reports advising policy implementation (Sweden) (Blattert, et al. 20023) conducted under the advice of key stakeholders. This variation in policy scenario definition among countries reflects the national differences in policy cultures and levels of national policy dissensus or consensus related to ecosystem services governances. Then, following the approach of Primmer et al. (2021), each of the major forest-related national policies was represented through a set of objective functions as described in Table S10 – Table S13. In the Supplementary material S3 we show how each study region has translated its national documents into an optimization problem and linked it to the simulated ecosystem services indicators.

Forest Strategy: In Finland, the Forest scenario provides wide coverage of ecosystem services and many quantitative targets (Blattert et al., 2022). The German scenario is characterized by a strong conception of multifunctionality, with minor emphasis on non-wood services. Contrarily, in Norway, the Forest scenario aimed at boosting the wood production and extraction of wood-based materials, bioenergy, and biofuels. Finally, Sweden replaces this scenario with the developing National Forest Program, which mainly aims to raise wood growth.

Biodiversity Scenario: For Finland, this scenario focuses on achieving a favorable status for biodiversity and ecosystem services by 2050. The German Biodiversity scenario followed the same logic, focusing on the provision of biodiversity conservation. In Norway, this scenario prioritizes preserving, and enhancing biological diversity as well as integrating the protection against erosion and the recreational value. In Sweden, the Biodiversity scenario also recognizes the multifunctional use of forest ecosystems on top of biodiversity conservation objectives. The Swedish Biodiversity scenario focused on the Swedish Environmental Objectives and the Swedish Achi Targets of the CBD.

Bioeconomy Scenario: The Finnish version of this scenario focuses on mobilizing forest resources to enhance the bioeconomy, while biodiversity should be simultaneously safeguarded at the current level.

The German case focuses on the provision of specific ecosystem services, in this case wood production. Contrary to other countries, the Bioeconomy scenario in Norway highlighted the value of the multifunctional use of forest ecosystems, recognizing the role of forests in climate regulation, wood production, bioenergy, biodiversity, and recreation. Finally, the Swedish scenario was replaced by inputs from specific studies on how to increase wood growth and enduring future harvest levels, while fulfilling conservation targets.

These scenarios were separately optimized for the ecosystem services demands stated by the national forest strategy, the biodiversity, and the bioeconomy strategy, (Blattert et al., 2022; Vergarechea et al., 2023, Toraño et al. 2023). The optimal solutions for these policy scenarios can be found in Supplementary Material S5. These scenarios were compared with an additional scenario that focused on maximizing multifunctionality, which will be defined in the following sections.

2.5 Measuring multifunctionality

The multifunctionality analysis was done in two steps. First, for each study area and climate scenario the maximum multifunctionality was calculated, using a multi-objective optimization framework like the one used by Eyvindson (2021) (section 2.5.1). Here, we understand maximum multifunctionality as the maximum provision of ecosystem services that a landscape can potentially achieve. Second, following the same procedure, a multifunctionality metric for each policy scenario and climate was calculated (section 2.5.2). In this way, the multifunctionality achieved by each policy scenario and climate could be compared with the potential maximum multifunctionality using the same scale.

2.5.1 Maximum multifunctionality: optimization

To explore potential national maximum multifunctionality we used a multi-objective optimization framework. The framework was used to identify optimal forest management programs that best fulfill the different demands for ecosystem services defined in the maximum multifunctionality scenario for each study area. Therefore, the optimization framework aimed to provide an efficient management solution for each forest entity. In this case, we used the future trajectories (5-year steps) of ecosystem services indicators on each NFI plot, as input.

The general frame for the optimization problem is one where we maximize multifunctionality (Eq. 1). This optimization can be seen as a goal programming formulation (such as in Eyvindson, 2012), where different ecosystem service classes can be treated with different distance measures.

$$\max \sum_{b \in B} \frac{MFd_b - MFd_{b^*}}{MFd_b^* - MFd_{b^*}} \tag{1}$$

where MFd_b, MFd_b^*, and MFd_{b^*} represent the measured, ideal, and anti-ideal multifunctional deviation for component b; B is the set of components. To calculate the ideal and anti-ideal values, a series of separate optimization problems were run both maximizing and minimizing the single indicator using all feasible management alternatives. For this problem formulation, the objective (Eq. 1) maximizes the summed normalized distance from each ecosystem service, while Eq. 2, measures the distance for wood production, bioenergy, water protection, and climate regulation and Eq. 3 for Biodiversity and Recreation:

$$MFd_b \ = \frac{1}{\#T_b} \sum_{t \in T_b} \frac{(f_t - f_{t^*})}{(f_t^* - f_{t^*})} \tag{2}$$

$$MFd_b = \ argmin_{t \in T_b} \frac{(f_t - f_{t^*})}{(f_t^* - f_{t^*})}, \forall\, b \ \in B \tag{3}$$

where f_{t^*} f_t^* and ft respectively represent the ideal, anti-ideal, and obtained values for indicator t. For the calculation of each value, a set of objective functions for each indicator were defined. All indicators (with their units) that were used to estimate each ecosystem service class, and the type of aggregation (averaging, Eq. 2, or minimizing, Eq. 3, when there is more than one) are summarized in Table 2 and the detailed in Supplementary material S6 (equations S1-S11) for all study regions. This set of indicators has defined the maximum multifunctionality scenarios for each region. To allow for replication we uploaded the code on an online repository together with a sample dataset (https://github.com/maeehart/MultiForestDemonstration).

2.5.2 Multifunctionality metric for each policy scenario and ecosystem services analyses

While a standardized method for evaluating multifunctionality is lacking, earlier research has commonly aggregated various ecosystem functions and services into a single metric, hereafter called the 'MF indicator', to estimate multifunctionality levels. In this study, we explored forest multifunctionality at the landscape scale, rather than at the stand scale. To achieve this, we initially assessed all indicators at the stand level and subsequently, these were aggregated across the respective country or region for each case study, resulting in a comprehensive landscape-level value.

We defined multifunctionality based on the aggregate six standardized ecosystem services classes. These classes were normalized using the theoretical maximum (ideal) and minimal (anti-ideal) values derived from the Tables S6-S9 and equation 1. Furthermore, we assigned equal priority to all components of multifunctionality, thereby giving each component an equal weight in our assessment.

Thus, we aggregated indicators within each ecosystem services class through two measures: the average value between all indicators (Eq. 2) and the minimum value across all indicators (Eq. 3). Wood production, bioenergy, water protection, and climate regulation were estimated as the average (of equal importance) of their indicators since our aim was to enhance the overall yield of these services. Conversely, biodiversity and recreation were estimated based on the minimum values across the indicators, as our objective is to maximize the benefits associated with the lowest scores.

Finally, a Pearson correlation analysis was used to assess the spatial correlation among the six common ecosystem services at the end of the simulation period. We calculated correlations to explore the interrelationships among the six ecosystem services within each NFI plot, resulting in a scatter plot matrix. This was done to identify synergies and trade-offs among the ecosystem services across the different study areas under the maximum multifunctionality scenario. The specific formula is as follows:

$$R = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 - (y_i - \bar{y})^2}} \tag{4}$$

Here, R denotes the relationship (either trade-of or synergist) between two ecosystem services. x_i and y_i represent individual values of the two services while $\bar{x}$ and $\bar{y}$ are their respective means. When the correlation coefficient was positive, it was assumed that there was a synergy between them; otherwise, a trade-off relationship was assumed. The strength of the correlation is determined by the absolute value of the correlation coefficient. In our case, a correlation coefficient in the range of (0, 0.2) indicates a weak correlation, that in the range of (0.2, 0.6) indicates a moderately strong correlation, and that in the range of (0.6, 1) indicates a strong correlation.

Table 2: Summary of indicators used to characterize each Forest Ecosystem Service and Biodiversity per country and the aggregation type. AVG stands for average and MIN for minimum measure used to aggregate the indicators in the multifunction optimization to ecosystem services classes.

Forest ecosystem services and Biodiversity	**Aggregation**	**Indicator (unit)**			
		Norway	**Germany**	**Finland**	**Sweden**
Wood production	**AVG (Eq.2)**	Harvest net value (NOK)	Annual Increment ($m^3ha^{-1}year^{-1}$)	Annual Increment ($m^3ha^{-1}year^{-1}$)	Net Present Value (SEK)
		Harvested volume (Mm^3)	Harvested volume ($m^3ha^{-1}year^{-1}$)	Harvested volume roundwood (m^3ha^{-1})	Annual Increment ($m^3ha^{-1}year^{-1}$)
					Harvested volume (m^3year^{-1})
Bioenergy	**AVG (Eq.2)**	Harvested residues (Kt)	Harvest residues (m^3)	Harvested biomass (m^3ha^{-1})	Harvested residues (m^3year^{-1})
Biodiversity	**MIN (Eq.3)**	MiS area[1] (ha)	Biodiversity fuzzy indicator (ND)	Conservation regimes (-)	Old Deciduous (ha)
		Deadwood volume (Mm^3)		Deadwood (m^3ha^{-1})	Deadwood volume (m^3ha^{-1})
		Bilberry (%)		Deciduous tree volume (%)	Share of regime SA (%)
				Large trees (DBH > 40cm) ($n\ ha^{-1}$)	
Water protection	**AVG (Eq.2)**	Harvest volume in steep terrain and mountain forests (Mm^3)	Crown coverage (%)	Regimes CCF/SA on peatland (%)	Share of regime CCF (%)
			Standing volume (m^3ha^{-1})		
Climate regulation	**AVG (Eq.2)**	CO_2 storage in harvested wood product (Kt)	Total Carbon Balance ($tC\ ha^{-1}$)	Carbon sink ($t\ CO_2\ ha^{-1}\ yr^{-1}$)	Carbon in wood and soil ($t\ CO_2\ ha^{-1}$)
		Flow of carbon sink in forest (MKt)			
Recreation	**MIN (Eq.3)**	Harvest in city plots forest (Mm^3)	Recreation and Esthetics fuzzy indicator (ND)	Recreation index (-)	Recreation index (-)
		Shannon index		Scenic index (-)	

MiS = Norwegian hot spot national inventory for biodiversity, the abundance of big and broadleaved trees.

3 Results

3.1 Consequences for the provision of ecosystem services

The results from the maximum multifunctionality scenario showed, as expected, the most balanced provision among the analyzed ecosystem services (Figure 2). This was more visible in the case of Finland and Germany. For this analysis we concentrate on a time snip after 100 years (Figures 2 and 3). The complete development in time (100 years) for each region can be seen in the Supplementary material, Figures S5-S8.

In Finland, the provision of water regulation services and recreation values did not differ much among policy scenarios, including the maximum multifunctionality scenario (Figure 2). Conversely, biodiversity remained consistently low across the three policy scenarios, and significantly lower than the levels observed in the maximum multifunctionality scenario. The Biodiversity scenario showed the lowest values for bioenergy and wood, while both the Bioeconomy and National Forest Strategy scenarios performed better than the maximum multifunctionality for wood and bioenergy.

In Germany, we observed that the Biodiversity scenario follows a very close and similar trend to the maximum multifunctionality, closely followed by the Forest Strategy. The latter slightly outperforms the other two scenarios in terms of recreation. The Bioeconomy scenario, in contrast, is more unbalanced, showing notably lower values for biodiversity and recreation. In general, all scenarios perform similarly in services such as wood, bioenergy, climate, and water, but they differ significantly when it comes to biodiversity.

In Norway, water regulation services consistently had the lowest values for all ecosystem services in all scenarios, closely followed by bioenergy (which approached zero for the Forest Strategy). The scenario that achieved the highest multifunctionality had the highest values for biodiversity, bioenergy, wood, and recreation benefits; however, the Biodiversity scenario had higher values for climate as shown in Figure 2. In the context of biodiversity conservation, the Biodiversity and Bioeconomy scenarios outperformed the National Forest Strategy but had, at the same time lower recreation values.

In Sweden, the provision of forest ecosystem services was particularly heterogeneous among scenarios (Figure 2). The Biodiversity Strategy led to the highest values for biodiversity and climate, closely followed by the maximum multifunctionality scenario. Moreover, these two scenarios provided the most favorable conditions for water resources and recreation. In contrast, both the National Forest Strategy and the maximum multifunctionality scenario outperformed the Bioeconomy scenario in terms of bioenergy levels. Finally, the highest levels of ecosystem services were observed in wood, particularly for the Bioeconomy scenario, followed by the Forest strategy, with the maximum multifunctional scenario showing the lowest levels in this regard.

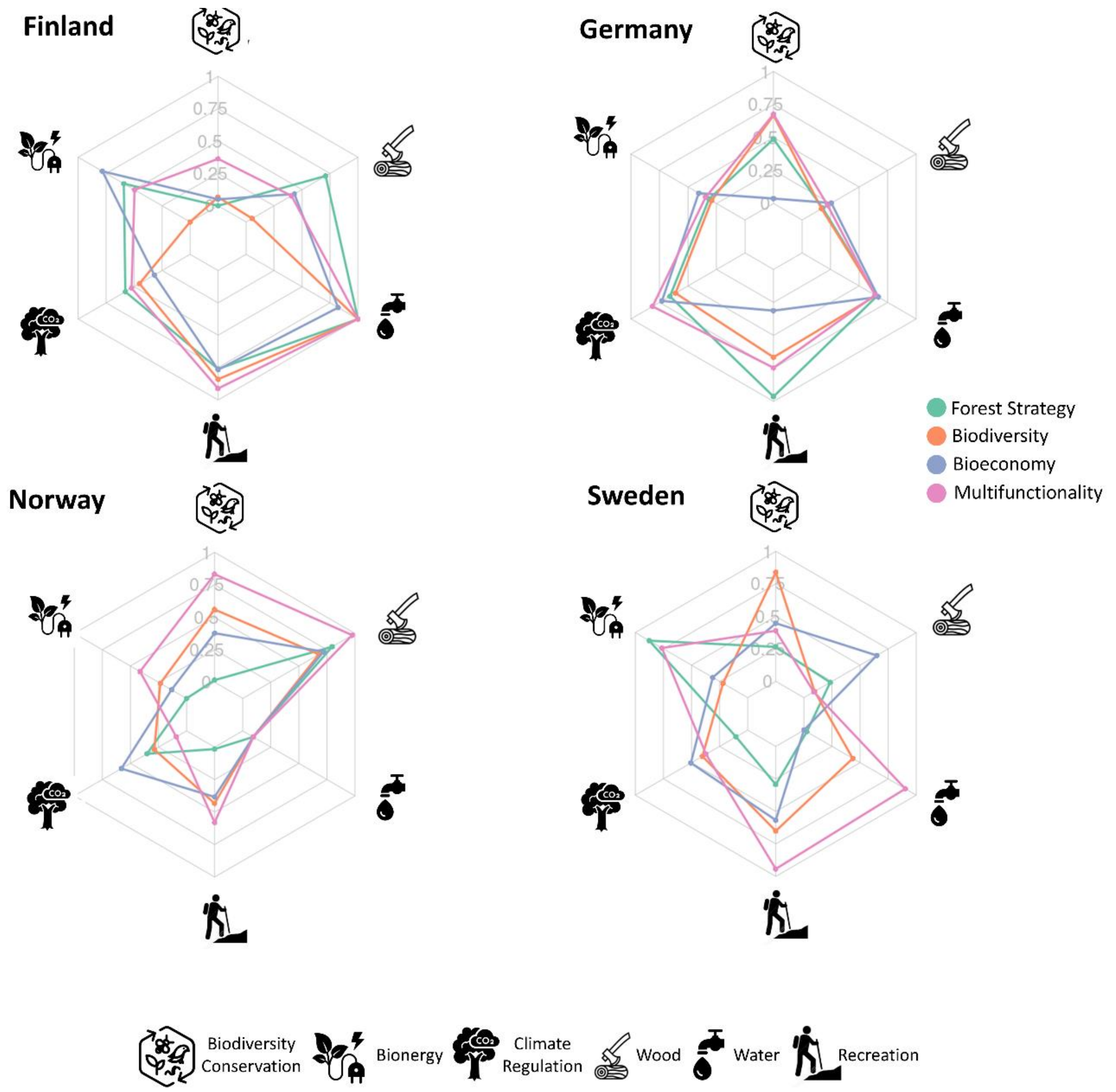

Figure 2: Comparison of the provision of Forest Ecosystem Services and Biodiversity for the national sectoral scenarios (National Forest, Biodiversity, and Bioeconomy strategies)) and the potential Maximum Multifunctionality scenario after 100 years for each of the study areas. The results are for the RCP4.5 climate scenario. To allow comparison between Ecosystem services and policy scenarios, values were normalized using the theoretical maximum (ideal) and minimal (anti-ideal) values derived from the Tables S6-S9 and equation 1. Results for noCC scenario are presented in Figure S8

Regarding the comparison between the two climate scenarios after 100 years (Figure 3), we observed that only in the case of Sweden the difference was dramatic, especially concerning wood- and climate-related services, which showed higher levels with RCP 4.5. In Germany, we observed changes in bioenergy and wood that decreased with RCP4.5. In Norway, however, there was only a slight decrease in wood. Whereas in Finland, RCP4.5 led to a higher wood supply (than in Sweden) and a higher value of bioenergy.

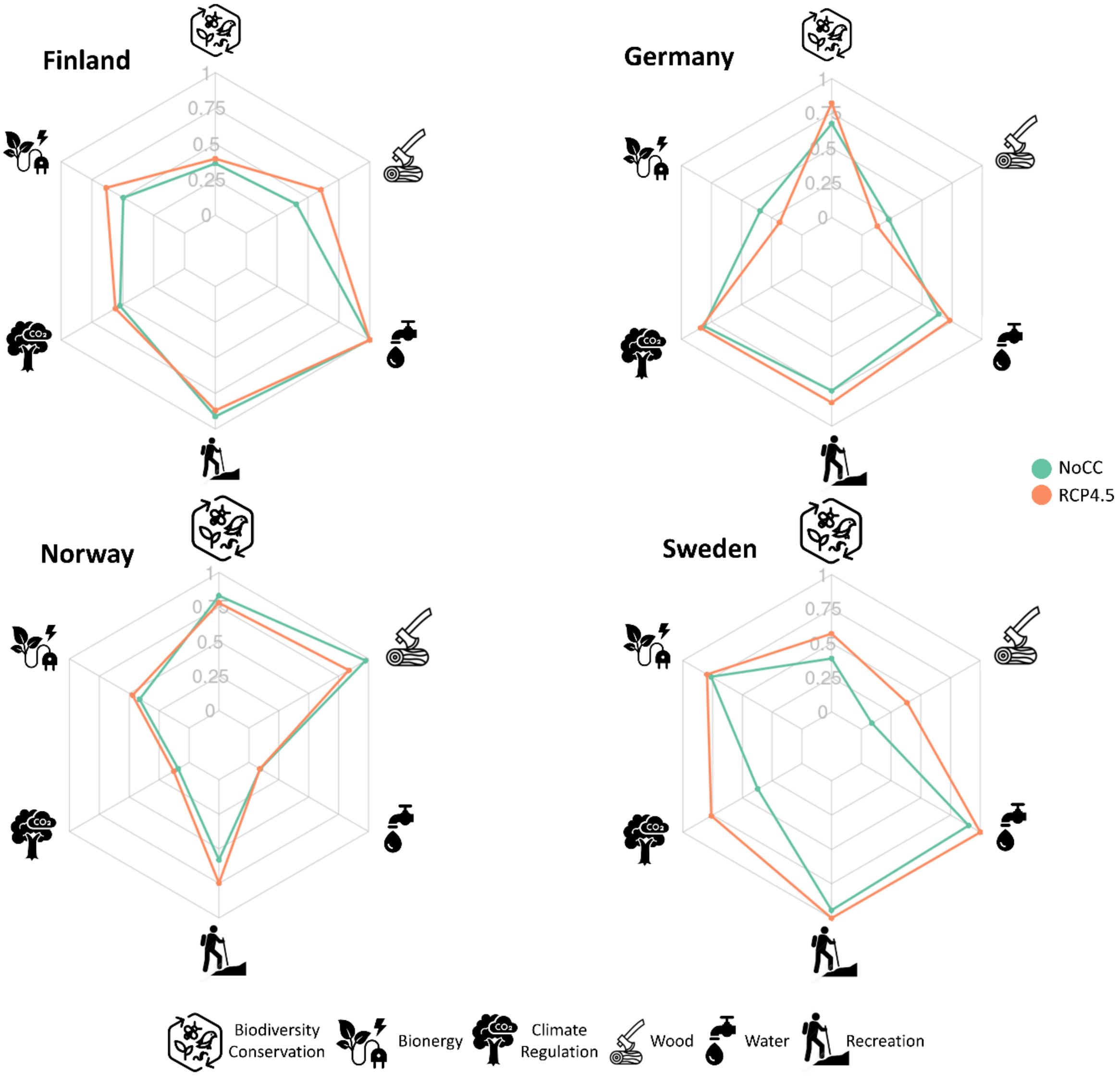

Figure 3: Comparison of the provision of Forest Ecosystem Services and Biodiversity for the two climate scenarios after 100 years of simulation, The green line: the so-called current scenario, 1.5 °C, (here noCC), and the orange line: RCP4.5 scenario for the max multifunctionality scenario. To allow comparison between Ecosystem services and climate scenarios, values were normalized using the theoretical maximum (ideal) and minimal (anti-ideal) values derived from the Tables S6-S9 and equation 1.

The potential maximum MF scenario revealed strong correlations, both positive and negative, between ecosystem services, but these differ amongst study regions (displayed for RCP4.5 in Figure 4 and for NoCC in Figure S9). Across all countries, a positive correlation was observed between wood and bioenergy, whereas negative correlations were found between recreation and climate, as well as wood and water. The ecosystem services wood and climate and the ecosystem services climate and bioenergy had a negative correlation for Finland and Norway but a positive correlation for Germany. Conversely, water and biodiversity displayed a positive correlation in Norway and Germany but neutral for Sweden and Finland. Other pairs of ecosystem services did not show significant correlations, suggesting a rather independent relationship. Notable examples include the lack of correlation between recreation and biodiversity in Norway and Germany, as well as between recreation and water in Norway, Germany, and Finland. Norway showed the lowest levels of correlation, indicating a higher degree of independence amongst ecosystems services compared to Germany and Finland. Finally, in Sweden positive correlations dominated and were particularly strong concerning climate regulation-recreation and wood-recreation. The negative correlations were generally weaker, tending towards zero.

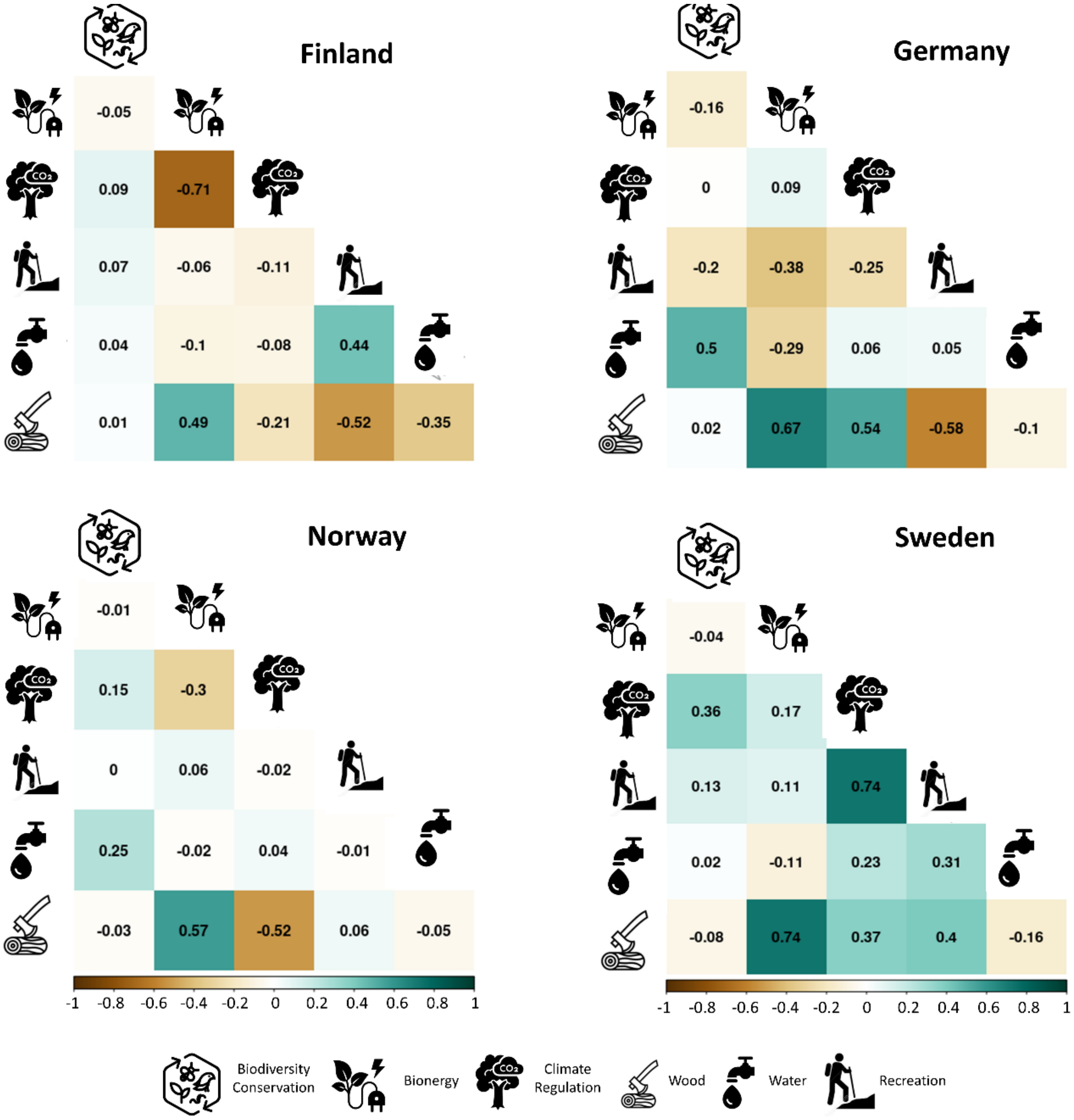

Figure 4: Synergies and trade-offs among the six ecosystem services selected for the potential maximum MF scenario and the RCP 4.5 climate scenario. Values correspond to pairwise Pearson's correlation coefficients between indicators (positive correlations = synergies and negative correlation = trade-offs). Results for noCC scenario are presented in Figure S9

3.2 Management prescription

The largest difference between the optimum proportion of each management regime necessary to achieve maximum multifunctionality and the corresponding proportions in each of the sectoral policy scenarios was found for Sweden (Figure 5). For each country, Figures S1-S4 in supplementary material show the proportion of optimal management regimens for the three policy and climate scenarios, which have been compared with the maximum multifunctionality scenario. In Germany and Norway maximum multifunctionality is, for all scenarios, mainly achieved by an increase in the proportion of set-aside, and a general decrease in a similar proportion of the rest of management regimes. This tendency was not observed in Finland, where almost the opposite trend was observed. Here, the proportion of set-asides is reduced compared with the Biodiversity strategy scenarios, with an increase in the diversity of management regimes applied. The effect of climate in the selection of optimal management regimes was small for Norway and Finland but larger in Germany and Sweden. In this regard, we could appreciate a stronger proportion of set-asides in Germany for RCP4.5 with the consequent stronger decrease for the rest of management regimes. In Sweden, the pattern was slightly different but closer to the Finnish case. The proportion of continuous forest cover was higher for both climates and policy scenarios in the maximum multifunctionality scenario compared with the sectoral policy scenarios while the set-aside area was lower instead. Additionally, the results showed that maximum multifunctionality could be achieved with a more intensive intensified business-as-usual (> 60%) under the Biodiversity scenario.

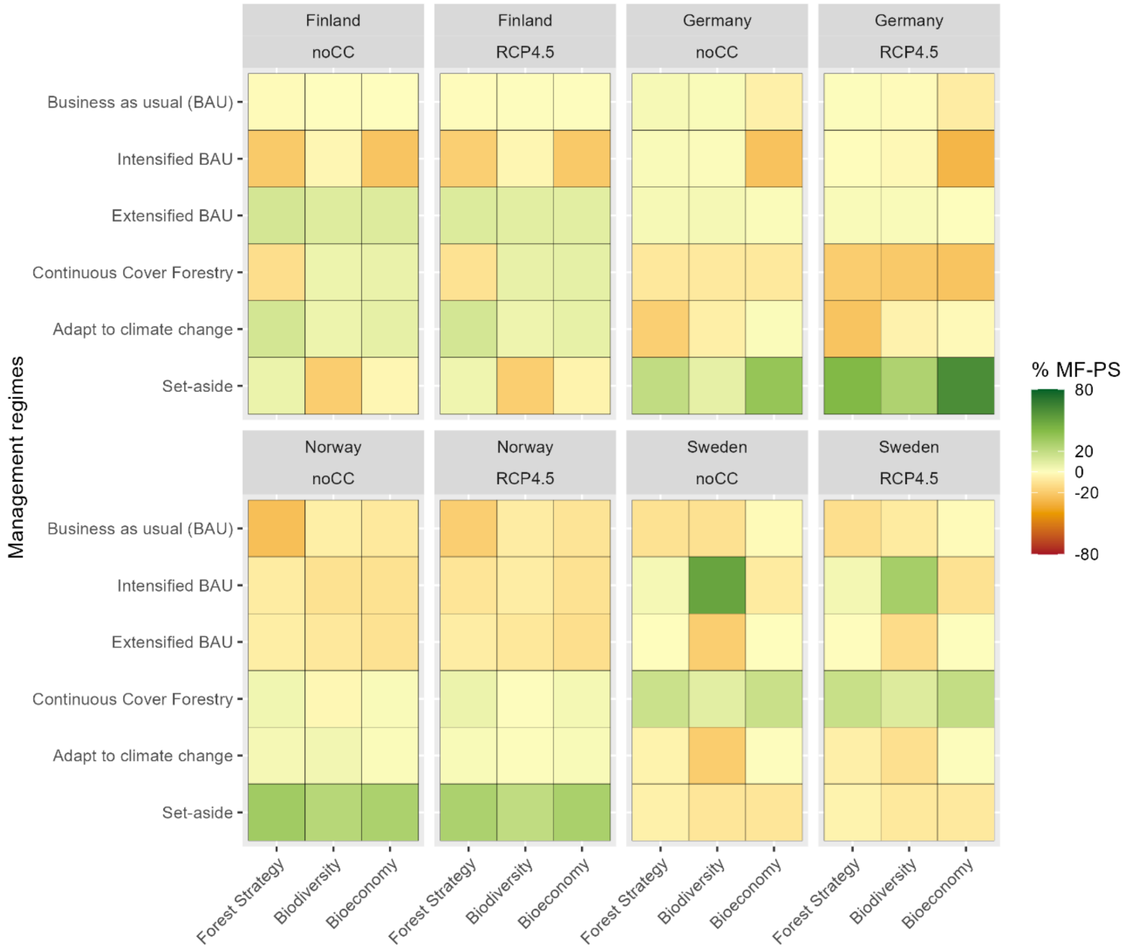

Figure 5: Difference in the share of management regimes between the maximum multifunctionality scenario (MF) and each of the policy scenarios (PS) for the study countries in the coming 100 years. noCC stands for the current climate scenario. The color ramp is centered around light yellow, when there are no differences, and then continuously scaled in 1% steps from -80% (dark red) to +80% (dark green). The proportion of management regime per policy and climate scenario of each of the studied areas are shown in supplementary material, S1-S4. The management categories are described in Table 1.

3.3 Multifunctionality achieved per policy scenario.

Using the methods described in 2.5.1, we calculated for each country the potential maximum multifunctionality metric and compared this with the multifunctionality metric observed in each of the policy scenarios (section 2.5.2). Thus, we could compare the distance from each of the policy scenarios to the maximum multifunctionality that can be potentially achieved for each study region (Figure 6). We observed that Finland, Germany, and Sweden could all achieve similar levels of maximum multifunctionality, although these levels were slightly lower for Norway. Germany and Sweden, and Finland and Norway showed similar multifunctionality patterns, both in terms of their maximum multifunctionality across policy scenario and their impact in climate. In the former two countries, Sweden and Germany, the National Forest scenario gave the highest multifunctionality with a multifunctionality metric value of 0.94 and 0.83, respectively, closely followed by the Biodiversity scenario (0.70 and 0.73), while the Bioeconomy scenario (0.63 for both) resulted in the lowest multifunctionality. Under the RCP4.5, all scenarios deviated slightly from maximum multifunctionality, but the difference was negligible. In Norway, the influence of climate played a much smaller role, with almost no noticeable impact. The Biodiversity scenario showed slightly higher values for the current climate (noCC), even though it resulted in the lowest multifunctionality (0.49). Finally, in Finland, the trend was the opposite compared to Germany and Sweden, showing the maximum multifunctionality for the Bioeconomy scenario (0.61). The trend, however, was smoother than that in Sweden and Germany.

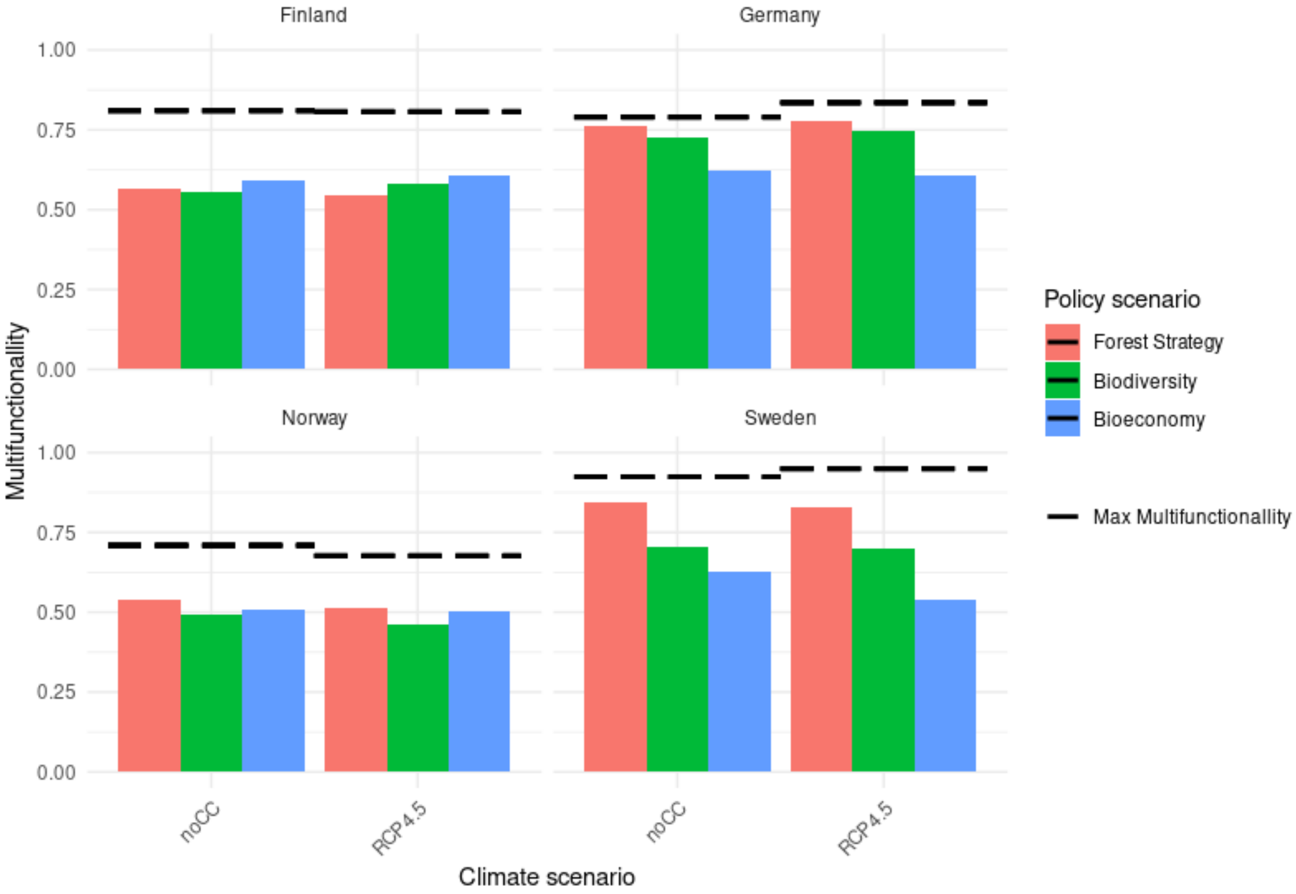

Figure 6: Potential maximum multifunctionality (dashed line) per case study plotted against the actual multifunctionality per policy scenario and climate. noCC stands for the current climate scenario.

4 Discussion

4.1 Role of ecosystem services for a multifunctional management

Our correlation analyses among ecosystem services showed strong synergies and trade-offs among some ecosystem services. These synergies can be used in multifunctionally oriented management (Felipe-Lucia et al., 2018). Specifically, those ecosystem services that have a strong negative correlation will impair the achievement of maximum multifunctionality, as an improvement of one will translate into a decline of the other. We could clearly observe this in wood and recreation. In this case, for all study regions higher procurement of wood would negatively impact the recreation potential of forests. We also found that wood and bioenergy are strongly correlated, as such, an improvement in the provision of wood would improve the provision of bioenergy as well. This was expected, as they are both closely related to forest harvest levels. However, other synergies or conflicts were not so evident, for example, water and biodiversity, which for Germany and Norway are positively correlated.

In some regions (especially Germand and Finland), we observed that correlations among ecosystem services were more pronounced than in others. In this case, the occurrence of large negative or positive correlations would cause high difficulties in obtaining high multifunctionality since some groups of ecosystem services will play against others. It should be noted that our results are influenced significantly by key choices made in the study design like simulation length, the choice of discount rate, or the indicators used, among others. Especially, in such cases of conflicting ecosystem services, segregating specialized forest management by forest ecosystem service at the landscape level might be appropriate (Duncker et al., 2012), as we discuss below.

These findings show that to maximize forest multifunctionality, management strategies and policies must account for these linkages and enhance the supply of several interrelated ecosystem services. Despite recent efforts to incorporate forest multifunctionality into policies and management objectives (Sotirov and Arts, 2018), the challenge remains with scarcity of knowledge on the consequences of specific environmental policies or management decisions for different ecosystem services and their relationship. Thus, our optimization analyzes like this can be used to support regionally relevant choices between optimizing the supply of multiple ecosystem services at a given location, easier when synergies exist, or segregating specialized forest management, which is more suitable when trade-offs among ecosystem services are dominant (Duncker et al., 2012).

Recent studies have shown that a key insight from the ecosystem services management framework, and therefore multifunctionality, is the unavoidable trade-offs in benefit supply (Mazziotta et al., 2022; Morán-Ordóñez et al., 2020; Turkelboom et al., 2018; Vergarechea et al., 2023). Assessing the synergies and trade-offs of ecosystem services could provide a baseline for comparing alternative future scenarios and insights into potential policy and management outcomes (Bryan, 2013; Mouchet et al., 2014). Even with ecosystem service like Recreation, which is yet a poorly developed economic sector on typical forest land in all studied areas, an expected increased influence on future forest management (Tudoran et al., 2022) will need to be considered in any implementation. Others more established, like wood production are balanced with recreation over time, but it is essential to develop site-specific management strategies. For example, those areas with high recreational demand may benefit from extending the rotation period (Eggers et al., 2018). Moreover, since wood and bioenergy are positively correlated, it would be expected that focusing on water protection (by protecting steep slopes) would result in better forest structures for biodiversity.

In our study we focused on the supply of ecosystem services. However, considering both supply and demand of ecosystem services, especially in the context of planning and decision-making, is important, as there are typically mismatches in the spatial distribution and routing of these services (Laterra et al., 2016). For instance, providing recreation opportunities in hard-to-reach areas may yield limited real benefits to society, since very few people would be able to enjoy it. Conversely, providing recreational options in peri-urban areas, where demand is high and accessibility is easy, can significantly enhance societal benefits.

The inclusion of simulated climate effects did not appear to change the distribution of ecosystem services for maximum multifunctionality. Only in Sweden, the provision of all ecosystem services increased in RCP4.5 compared with a no change scenario, confirming the findings of (Mazziotta et al., 2022) that higher GHG concentrations would enhance multifunctionality. In Nordic countries, RCP4.5 generally increases growth (D’Orangeville et al., 2018; Reyer et al., 2014), so it allows a higher provision of wood without hindering the provision of other ecosystem services. However, as Blattert et al. (2022) recently noted, we should not underestimate the effect of climate change on the provision of ecosystem services under different policy scenarios, since the low effect of climate on outcomes is partly caused by the defined optimization problem (objective functions & constraints) that balance out climate-induced gains and losses. For instance, studies have concluded that higher forest growth due to climate change might reduce wild berry production since forests will likely become too dense, reducing sunlight, and reaching understory vegetation (Mazziotta et al. 2022). Further, an increasing number of studies have shown that climate change will lead to higher disturbance rates in the future, influencing forest dynamics and therefore the capacity of forests to provide ecosystem services (Danneyrolles et al., 2019; Vanderwel and Purves, 2014). Consequently, climate change might offset productivity gains in the Nordic countries by increasing disturbances (insect pest outbreaks, extreme droughts, storms, and forest fires), making it harder to meet wood demands (D'Orangeville et al., 2018; Hanewinkel et al., 2013). There is therefore a risk that the increase in tree stocks in these studies is overestimated. However, these sources of uncertainty were not considered in the current study and might pose additional challenges to achieving multifunctionality in our study areas.

4.2 Management recommendations to improve multifunctionality.

Overall, to increase multifunctionality required an increase in the proportion of forests allocated to the set aside management regime. However, this conclusion should be taken with care, since climate change induced changes in disturbance regimes were not included in the management regimes, this scenario could be unrealistic, especially because wood production is still needed. To optimize management for multifunctionality, the regimes must be adapted to each country's landscape conditions and the impact of management differs among countries due to starting landscape conditions and specific policy targets.

In Germany, the proportion of continuous cover forestry and multifunctional regimes adapted to climate change would have to be decreased for all policy scenarios. This can be seen as an alternative to an increased proportion of set-asides. This compensates for the maintenance of regimes with intense harvesting strategies, that account for the loss of wood production coming from set-asides. In Norway, this is also apparent although in this case, continuous cover forestry and adaptation to climate change should be slightly increased as well. The main difference here may be a result of the already large proportion of continuous cover forestry in Germany. In both cases, there is also a decrease in the rest of the management regimes, especially the most intensive ones, suggesting that intensive regimes in these study areas might result in losses of multiple non-timber forest benefits. This has been observed by Jonsson et al., (2020) Nolet et al., (2018), and Pohjanmies et al. (2021), who found a reduction in forest multifunctionality due to intensive forestry. Pohjanmies et al. (2021) also found that, when maximizing multifunctionality, temporary set-asides (20 years at a time) was by far the most widely applied regime, ranging from 54% to 89% of total forest area, with the remaining area under rotation or continuous cover forestry. These are, however, levels for temporary set-asides, and in practice preserving such high levels of set-aside permanently, would become problematic at a certain point due to the narrow space remaining for intensifying/managing the rest of the forest.

In the Finnish and Swedish cases, the situation is reversed. Countries with highly intensive management, maximum multifunctionality can only be achieved by increasing the area with regimes that adapt forest against climate change, and, in turn, favors continuous cover forestry, combined with intense wood production regimes (intensive business as usual) in other parts of the territory. However, this also requires certain proportions of set-aside areas. The former two management regimes promote species diversity and structural heterogeneity, increasing multifunctionality and alleviating trade-offs more than other management alternatives (Huuskonen et al., 2021; Schwaiger et al., 2018). Interestingly, in Sweden, the area of intensified business as usual had to be increased to reach maximum multifunctionality for the Biodiversity scenario, in contrast to the other case areas, moving from a relatively even distribution of management regimes to a more segregated one.

This emphasizes the importance of careful planning, where a combination of management alternatives and their share of the landscape can fulfill specific management objectives. A recent study has demonstrated that the principles of Climate-Smart Forestry can reconcile biomass harvesting targets and a supply of forest ecosystem services (Verkerk et al., 2020). As they observed, through an optimal combination of forest management planning it is possible to differentiate between areas supplying timber at high rates, and areas devoted to climate change mitigation, non-wood ecosystem provisioning, and biodiversity conservation. However, restricting the range of management alternatives may lead to a decrease in the effectiveness of the overall management objectives (Eyvindson et al., 2021).

The degree of implementation of multifunctional forestry enabled the achievement of maximum multifunctionality. In Germany, traditional multifunctional management has eased the optimization for maximum multifunctionality. Since the starting point management is based on diverse forest landscapes - with mixed species and structures, combined with diverse management strategies - the goals were easier to achieve (Borrass et al., 2017). This means the landscape was already providing multiple ecosystem services, so it was not necessary to modify the current conditions drastically. Specifically, in German forests, there has been a notable shift in federal policy and federal state forest laws toward multifunctional management in the last few decades (Borrass et al., 2017). The opposite example can be represented by the Finnish or Swedish forest management plans, which should start going beyond an economic growth paradigm (e.g., high annual increment targets) to achieve higher multifunctionality (Blattert et al. 2022). Interestingly, we could observe how the different conceptions of the Forest Strategy affected multifunctionality, with contrasting results between Germany and Finland. While for the first it almost achieved maximum multifunctionality, for the latter, the high harvest targets of the Finnish forest strategy impede the achievement of non-timber services and biodiversity, which increases within policy conflicts and leads in turn to lower multifunctionality levels.

4.3 Impact of national strategies on potential maximum multifunctionality

According to our investigations, the potential level of maximum multifunctionality is similar for all countries, so we conclude that such levels are possible in all regions. Only Norway showed slightly lower maximum levels, pointing out lower potential due to distinctively lower forest productivity than the other study regions. While the other Fennoscandia countries, Finland, and Sweden, have high shares of productive forest land (~5.2 m^3 ha^{-1} $year^{-1}$, representing a 66%, and 56% of the total forest land respectively) (Blattert et al. 2023), in Norway the percentage is much lower 22.25% (Peltola et al., 2020; Rytter et al., 2016; SFA, 2022; SSB, 2022).

Strategies that resulted in a high diversity of forest management regimes, like the case of the German Forestry strategy, are the closest to the potential maximum multifunctionality. This was achieved by integrative management at the stand level (Continuous Cover Forestry and Adaption to climate change types of management) (Sotirov and Arts, 2018) and by adopting a broad range of silvicultural techniques across the territory that best adapt to the landscape conditions. However, those strategies that concentrate only on a reduced number of objectives are prone not to foster a wide range of management regimes and therefore will not achieve high levels of multifunctionality, the biodiversity strategy in Norway is one example. Likewise, Helseth et al. (2022) already illustrated that policy measures to increase biomass growth are not sufficient to safeguard multiple functions and services of forest ecosystem. This is exemplified by Bioeconomy in Germany and Sweden, the Biodiversity in Finland, and the National Forest strategy in Norway. It further means that the intensive timber production, which is prevailing particularly in Fennoscandian countries, hampers the achievement of full multifunctionality (Triviño et al., 2017), and it is especially evident in strategies that are more business as usual (Forest Strategy in Sweden and Finland, and climate oriented in Germany and Norway-Bioeconomy).

Lastly, it is noteworthy to mention that in this study we investigated the potential long-term supply of ecosystem services over large regions/nations according to national policy strategies. While empirical studies on preferences and spatial-specific demands of recreation (and other ecosystem services) are necessary in decision-making, it goes beyond the scope of the policy strategies included in this study, and hence this study. Not only because of the large scale of the policies/analyses, but also because we do not know how the societal preferences and infrastructures, and eventually demand, will develop in the future.

5 Conclusions

The development of a common understanding and measure of forest multifunctionality helps to balance the provision of different forest ecosystem services and offers better means for evaluating how far the estimated multifunctionality of current policies is from the potential maximum level of multifunctionality. Nevertheless, our work showed that different countries require different combinations of management regimes to achieve maximum multifunctionality. Thus, in those countries with the highest absolute levels of timber production, namely Sweden and Finland, the situation contrasted with Germany and Norway. Specially, this higher presence of intensive management regimes and homogenous landscape structure can affect the capacity of sectorial policies to increase or even achieve their potential maximum multifunctionality. The effects of the Policy strategies on the potential multifunctionality could be detected using multi-objective optimization. Our findings reveal that strategies with a specific focus tended to reduce multifunctionality, however, these outcomes differed among countries, as general forest productivity seems to improve maximum potential multifunctionality.

Across the studied European countries, multi-objective management, not only at the stand scale but also at the landscape scale, showed indeed the largest potential to achieve maximum multifunctionality.

This arises as management recommendation across the landscape, as we could see that next to management regimes like continuous cover forestry, which provides multiple forest ecosystems, other areas should be dedicated to production and others to conservation to maximize overall multifunctionality. Specially, set-asides (conservation) should increase under climate change scenarios.

Finally, future policies must not forget to account for feedback loops, as conflicts and synergies among forest ecosystems, are essential to improve efficiency when they are positively correlated and can pose a major obstacle when trade-offs exist among them.

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7 References

Aggestam, F., Pülzl, H., 2018. Coordinating the Uncoordinated: The EU Forest Strategy. Forests 9, 125. https://doi.org/10.3390/f9030125

Antón-Fernández, C., Astrup, R., 2022. SiTree: A framework to implement single-tree simulators. SoftwareX 18, 100925. https://doi.org/10.1016/j.softx.2021.100925

Benz, J.P., Chen, S., Dang, S., Dieter, M., Labelle, E.R., Liu, G., Hou, L., Mosandl, R.M., Pretzsch, H., Pukall, K., Richter, K., Ridder, R., Sun, S., Song, X., Wang, Y., Xian, H., Yan, L., Yuan, J., Zhang, S., Fischer, A., 2020. Multifunctionality of Forests: A White Paper on Challenges and Opportunities in China and Germany. Forests 11, 266. https://doi.org/10.3390/f11030266

Blattert, C., Mönkkönen, M., Burgas, D., Di Fulvio, F., Toraño Caicoya, A., Vergarechea, M., Klein, J., Hartikainen, M., Antón-Fernández, C., Astrup, R., Emmerich, M., Forsell, N., Lukkarinen, J., Lundström, J., Pitzén, S., Poschenrieder, W., Primmer, E., Snäll, T., Eyvindson, K., 2023. Climate targets in European timber-producing countries conflict with goals on forest ecosystem services and biodiversity. Commun Earth Environ 4, 1–12. https://doi.org/10.1038/s43247-023-00771-z

Blattert, C., Eyvindson, K., Hartikainen, M., Burgas, D., Potterf, M., Lukkarinen, J., Snäll, T., Toraño-Caicoya, A., Mönkkönen, M., 2022. Sectoral policies cause incoherence in forest management and ecosystem service provisioning. For. Policy Econ. 136, 102689. https://doi.org/10.1016/j.forpol.2022.102689

Blattert, C., Lemm, R., Thürig, E., Stadelmann, G., Brändli, U.-B., Temperli, C., 2020. Long-term impacts of increased timber harvests on ecosystem services and biodiversity: A scenario study based on national forest inventory data. Ecosyst. Serv. 45, 101150. https://doi.org/10.1016/j.ecoser.2020.101150

Borrass, L., Kleinschmit, D., Winkel, G., 2017. The "German model" of integrative multifunctional forest management—Analysing the emergence and political evolution of a forest management concept. For. Policy Econ., Alternative Pathways to Sustainability? Comparing Forest Governance Models 77, 16–23. https://doi.org/10.1016/j.forpol.2016.06.028

Bryan, B.A., 2013. Incentives, land use, and ecosystem services: Synthesizing complex linkages. Environ. Sci. Policy 27, 124–134. https://doi.org/10.1016/j.envsci.2012.12.010

Chen, S., Shahi, C., Chen, H.Y.H., 2016. Economic and ecological trade-off analysis of forest ecosystems: options for boreal forests. Environ. Rev. 24, 348–361. https://doi.org/10.1139/er-2015-0090

Danneyrolles, V., Dupuis, S., Fortin, G., Leroyer, M., de Römer, A., Terrail, R., Vellend, M., Boucher, Y., Laflamme, J., Bergeron, Y., Arseneault, D., 2019. Stronger influence of anthropogenic disturbance than climate change on century-scale compositional changes in northern forests. Nat. Commun. 10, 1265. https://doi.org/10.1038/s41467-019-09265-z

D'Orangeville, L., Houle, D., Duchesne, L., Phillips, R.P., Bergeron, Y., Kneeshaw, D., 2018. Beneficial effects of climate warming on boreal tree growth may be transitory. Nat. Commun. 9, 3213. https://doi.org/10.1038/s41467-018-05705-4

Duncker, P.S., Raulund-Rasmussen, K., Gundersen, P., Katzensteiner, K., De Jong, J., Ravn, H.P., Smith, M., Eckmüllner, O., Spiecker, H., 2012. How Forest Management affects Ecosystem Services, including Timber Production and Economic Return: Synergies and Trade-Offs. Ecol. Soc. 17.

EC, 2021a. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. EU Biodiversity Strategy for 2030. Bringing nature back into our lives, 380 final. COM(2020), Brussels.

EC, 2021b. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions - New EU Forest Strategy for 2030. Common Policy Cent. 2021/572.

EC, 2018. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. A sustainable Bioeconomy for Europe: Strengthening the connection between economy, society and the environment., 673 final. COM(2018), Brussels.

Eggers, J., Lindhagen, A., Lind, T., Lämås, T., Öhman, K., 2018. Balancing landscape-level forest management between recreation and wood production. Urban For. Urban Green., Cemeteries as green urban spaces 33, 1–11. https://doi.org/10.1016/j.ufug.2018.04.016

Eggers, J., Melin, Y., Lundström, J., Bergström, D., Öhman, K., 2020. Management Strategies for Wood Fuel Harvesting—Trade-Offs with Biodiversity and Forest Ecosystem Services. Sustainability 12, 4089. https://doi.org/10.3390/su12104089

Elomina, J., Pülzl, H., 2021. How are forests framed? An analysis of EU forest policy. For. Policy Econ. 127, 102448. https://doi.org/10.1016/j.forpol.2021.102448

Eyvindson, K., 2012. Balancing equity and efficiency of goal programming for use in forest management planning. Can. J. For. Res. 42, 1919–1925. https://doi.org/10.1139/x2012-135

Eyvindson, K., Duflot, R., Triviño, M., Blattert, C., Potterf, M., Mönkkönen, M., 2021. High boreal forest multifunctionality requires continuous cover forestry as a dominant management. Land Use Policy 100, 104918. https://doi.org/10.1016/j.landusepol.2020.104918

Felipe-Lucia, M.R., Soliveres, S., Penone, C., Manning, P., van der Plas, F., Boch, S., Prati, D., Ammer, C., Schall, P., Gossner, M.M., Bauhus, J., Buscot, F., Blaser, S., Blüthgen, N., de Frutos, A., Ehbrecht, M., Frank, K., Goldmann, K., Hänsel, F., Jung, K., Kahl, T., Nauss, T., Oelmann, Y., Pena, R., Polle, A., Renner, S., Schloter, M., Schöning, I., Schrumpf, M., Schulze, E.-D., Solly, E., Sorkau, E., Stempfhuber, B., Tschapka, M., Weisser, W.W., Wubet, T., Fischer, M., Allan, E., 2018. Multiple forest attributes underpin the supply of multiple ecosystem services. Nat. Commun. 9, 4839. https://doi.org/10.1038/s41467-018-07082-4

Felton, A., Belyazid, S., Eggers, J., Nordström, E.-M., Öhman, K., 2023. Climate change adaptation and mitigation strategies for production forests: Trade-offs, synergies, and uncertainties in biodiversity and ecosystem services delivery in Northern Europe. Ambio. https://doi.org/10.1007/s13280-023-01909-1

FS, 2019. The National Forest Strategy 2025 – an updated version Government Resolution of 21 February 2019, Publications of Ministry of Agriculture and Forestry in Finland 2019:7. Ministry of Agriculture and Forestry.

Grassi, G. et al. The key role of forests in meeting climate targets requires science for credible mitigation. Nat. Clim. Chang. 7, 220–226 (2017).

Gusti, M., Di Fulvio, F., Biber, P., Korosuo, A., Forsell, N., 2020. The Effect of Alternative Forest Management Models on the Forest Harvest and Emissions as Compared to the Forest Reference Level. Forests 11, 794. https://doi.org/10.3390/f11080794

Gutsch, M., Lasch-Born, P., Kollas, C., Suckow, F., Reyer, C.P.O., 2018. Balancing trade-offs between ecosystem services in Germany's forests under climate change. Environ. Res. Lett. 13, 045012. https://doi.org/10.1088/1748-9326/aab4e5

Haines-Young, R., Potschin-Young, M., 2018. Revision of the Common International Classification for Ecosystem Services (CICES V5.1): A Policy Brief. One Ecosyst. 3, e27108. https://doi.org/10.3897/oneeco.3.e27108

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, 203. https://doi.org/10.1038/nclimate1687

Helseth, E.V., Vedeld, P., Framstad, E., Gómez-Baggethun, E., 2022. Forest ecosystem services in Norway: Trends, condition, and drivers of change (1950–2020). Ecosyst. Serv. 58, 101491. https://doi.org/10.1016/j.ecoser.2022.101491

Hölting, L., Beckmann, M., Volk, M., Cord, A.F., 2019. Multifunctionality assessments – More than assessing multiple ecosystem functions and services? A quantitative literature review. Ecol. Indic. 103, 226–235. https://doi.org/10.1016/j.ecolind.2019.04.009

Huuskonen, S., Domisch, T., Finér, L., Hantula, J., Hynynen, J., Matala, J., Miina, J., Neuvonen, S., Nevalainen, S., Niemistö, P., Nikula, A., Piri, T., Siitonen, J., Smolander, A., Tonteri, T., Uotila, K., Viiri, H., 2021. What is the potential for replacing monocultures with mixed-species stands to enhance ecosystem services in boreal forests in Fennoscandia? For. Ecol. Manag. 479, 118558. https://doi.org/10.1016/j.foreco.2020.118558

Jacobsen, J.B., Vedel, S.E., Thorsen, B.J., 2013. Assessing costs of multifunctional NATURA 2000 management restrictions in continuous cover beech forest management. Forestry 86, 575–582. https://doi.org/10.1093/forestry/cpt023

Jandl, R., Ledermann, T., Kindermann, G., Freudenschuss, A., Gschwantner, T., Weiss, P., 2018. Strategies for Climate-Smart Forest Management in Austria. Forests 9, 592. https://doi.org/10.3390/f9100592

Jonsson, M., Bengtsson, J., Moen, J., Gamfeldt, L., Snäll, T., 2020. Stand age and climate influence forest ecosystem service delivery and multifunctionality. Environ. Res. Lett. 15, 0940a8. https://doi.org/10.1088/1748-9326/abaf1c

Keeble, B.R., 1988. The Brundtland report: 'Our common future.' Med. War 4, 17–25. https://doi.org/10.1080/07488008808408783

Kovac, M., Gasparini, P., Notarangelo, M., Rizzo, M., Cañellas, I., Fernández-de-Uña, L., Alberdi, I., 2020. Towards a set of national forest inventory indicators to be used for assessing the conservation status of the habitats directive forest habitat types. J. Nat. Conserv. 53, 125747. https://doi.org/10.1016/j.jnc.2019.125747

Laterra, P., Barral, P., Carmona, A., Nahuelhual, L., 2016. Focusing Conservation Efforts on Ecosystem Service Supply May Increase Vulnerability of Socio-Ecological Systems. PLOS ONE 11, e0155019. https://doi.org/10.1371/journal.pone.0155019

Mazziotta, A., Lundström, J., Forsell, N., Moor, H., Eggers, J., Subramanian, N., Aquilué, N., Morán-Ordóñez, A., Brotons, L., Snäll, T., 2022. More future synergies and less trade-offs between forest ecosystem services with natural climate solutions instead of bioeconomy solutions. Glob. Change Biol. 28, 6333–6348. https://doi.org/10.1111/gcb.16364

M.E.A., 2005. Millenium Ecosystem Assessment- Ecosystems and Human Well-Being: Our Human Planet: Summary for Decision Makers. Island Press.

Mendoza, G.A., Prabhu, R., 2000. Development of a Methodology for Selecting Criteria and Indicators of Sustainable Forest Management: A Case Study on Participatory Assessment. Environ. Manage. 26, 659–673. https://doi.org/10.1007/s002670010123

Morán-Ordóñez, A., Ameztegui, A., De Cáceres, M., de-Miguel, S., Lefèvre, F., Brotons, L., Coll, L., 2020. Future trade-offs and synergies among ecosystem services in Mediterranean forests under global change scenarios. Ecosyst. Serv. 45, 101174. https://doi.org/10.1016/j.ecoser.2020.101174

Mouchet, M.A., Lamarque, P., Martín-López, B., Crouzat, E., Gos, P., Byczek, C., Lavorel, S., 2014. An interdisciplinary methodological guide for quantifying associations between ecosystem services. Glob. Environ. Change 28, 298–308. https://doi.org/10.1016/j.gloenvcha.2014.07.012

NDC, 2023. Nationally Determined Contributions Registry | UNFCCC [WWW Document]. URL https://unfccc.int/NDCREG (accessed 3.14.23).

Nolet, P., Kneeshaw, D., Messier, C., Béland, M., 2018. Comparing the effects of even- and uneven-aged silviculture on ecological diversity and processes: A review. Ecol. Evol. 8, 1217–1226. https://doi.org/10.1002/ece3.3737

Pasari, J.R., Levi, T., Zavaleta, E.S., Tilman, D., 2013. Several scales of biodiversity affect ecosystem multifunctionality. Proc. Natl. Acad. Sci. 110, 10219–10222. https://doi.org/10.1073/pnas.1220333110

Peltola, A., Räty, M., Sauvula-Seppälä, T., Torvelainen, J., Uotila, E., Vaahtera, E., Ylitalo, E., 2020. Suomen metsätilastot : Finnish forest statistics 2020. Luonnonvarakeskus (Luke).

Peura, M., Silveyra Gonzalez, R., Müller, J., Heurich, M., Vierling, L.A., Mönkkönen, M., Bässler, C., 2016. Mapping a 'cryptic kingdom': Performance of lidar derived environmental variables in modelling the occurrence of forest fungi. Remote Sens. Environ. 186, 428–438. https://doi.org/10.1016/j.rse.2016.09.003

Peura, M., Burgas, D., Eyvindson, K., Repo, A., Mönkkönen, M., 2018. Continuous cover forestry is a cost-efficient tool to increase multifunctionality of boreal production forests in Fennoscandia. Biological Conservation 217, 104–112. https://doi.org/10.1016/j.biocon.2017.10.018

Pohjanmies, T., Eyvindson, K., Triviño, M., Bengtsson, J., Mönkkönen, M., 2021. Forest multifunctionality is not resilient to intensive forestry. Eur. J. For. Res. 140, 537–549. https://doi.org/10.1007/s10342-020-01348-7

Pohjanmies, T., Triviño, M., Le Tortorec, E., Mazziotta, A., Snäll, T., Mönkkönen, M., 2017. Impacts of forestry on boreal forests: An ecosystem services perspective. Ambio 46, 743–755. https://doi.org/10.1007/s13280-017-0919-5

Pretzsch, H., Biber, P., Ďurský, J., 2002. The single tree-based stand simulator SILVA: construction, application and evaluation. For. Ecol. Manag., National and Regional Climate Change Impact Assessments in the Forestry Sector 162, 3–21. https://doi.org/10.1016/S0378-1127(02)00047-6

Primmer, E., Varumo, L., Krause, T., Orsi, F., Geneletti, D., Brogaard, S., Aukes, E., Ciolli, M., Grossmann, C., Hernández-Morcillo, M., Kister, J., Kluvánková, T., Loft, L., Maier, C., Meyer, C., Schleyer, C., Spacek, M., Mann, C., 2021. Mapping Europe's institutional landscape for forest ecosystem service provision, innovations and governance. Ecosystem Services 47, 101225. https://doi.org/10.1016/j.ecoser.2020.101225

Pülzl, H., Hogl, K., 2013. European forest governance: issues at stake and the way forward, What science can tell us. European Forest Inst, Joensuu.

Pülzl, H., Wydra, D., Hogl, K., 2018. Piecemeal Integration: Explaining and Understanding 60 Years of European Union Forest Policy-Making. Forests 9, 719. https://doi.org/10.3390/f9110719

Rasinmäki, J., Mäkinen, A., Kalliovirta, J., 2009. SIMO: An adaptable simulation framework for multiscale forest resource data. Comput. Electron. Agric. 66, 76–84. https://doi.org/10.1016/j.compag.2008.12.007

Reyer, C., Lasch-Born, P., Suckow, F., Gutsch, M., Murawski, A., Pilz, T., 2014. Projections of regional changes in forest net primary productivity for different tree species in Europe driven by climate change and carbon dioxide. Ann. For. Sci. 71, 211–225. https://doi.org/10.1007/s13595-013-0306-8

Rytter, L., Ingerslev, M., Kilpeläinen, A., Torssonen, P., Lazdina, D., Löf, M., Madsen, P., Muiste, P., Stener, L.-G., 2016. Increased forest biomass production in the Nordic and Baltic countries – a review on current and future opportunities. Silva Fenn. 50. https://doi.org/10.14214/sf.1660

Schwaiger, F., Poschenrieder, W., Biber, P., Pretzsch, H., 2018. Species Mixing Regulation with Respect to Forest Ecosystem Service Provision. Forests 9, 632. https://doi.org/10.3390/f9100632

SFA, 2022. Statistics [WWW Document]. URL https://www.skogsstyrelsen.se/en/statistics/ (accessed 8.10.22).

Simons, N.K., Felipe-Lucia, M.R., Schall, P., Ammer, C., Bauhus, J., Blüthgen, N., Boch, S., Buscot, F., Fischer, M., Goldmann, K., Gossner, M.M., Hänsel, F., Jung, K., Manning, P., Nauss, T., Oelmann, Y., Pena, R., Polle, A., Renner, S.C., Schloter, M., Schöning, I., Schulze, E.-D., Solly, E.F., Sorkau, E., Stempfhuber, B., Wubet, T., Müller, J., Seibold, S., Weisser, W.W., 2021. National Forest Inventories capture the multifunctionality of managed forests in Germany. For. Ecosyst. 8, 5. https://doi.org/10.1186/s40663-021-00280-5

Sotirov, M., Arts, B., 2018. Integrated Forest Governance in Europe: An introduction to the special issue on forest policy integration and integrated forest management. Land Use Policy 79, 960–967. https://doi.org/10.1016/j.landusepol.2018.03.042

SSB, 2022. The National Forest Inventory [WWW Document]. SSB. URL https://www.ssb.no/en/jord-skog-jakt-og-fiskeri/skogbruk/statistikk/landsskogtakseringen (accessed 8.10.22).

Teben'kova, D.N., Lukina, N.V., Chumachenko, S.I., Danilova, M.A., Kuznetsova, A.I., Gornov, A.V., Shevchenko, N.E., Kataev, A.D., Gagarin, Yu.N., 2020. Multifunctionality and Biodiversity of Forest Ecosystems. Contemp. Probl. Ecol. 13, 709–719. https://doi.org/10.1134/S1995425520070136.

Torano, A.C., Poschenrieder, W., Blattert, C., Eyvindson, K., Hartikainen, M., Burgas, D., Mönkkönen, M., Uhl, E., Vergarechea, M., Pretzsch, H., 2023. Sectoral policies as drivers of forest management and ecosystems services: A case study in Bavaria, Germany. Land Use Policy 130, 106673. https://doi.org/10.1016/j.landusepol.2023.106673

Triviño, M., Morán-Ordoñez, A., Eyvindson, K., Blattert, C., Burgas, D., Repo, A., Pohjanmies, T., Brotons, L., Snäll, T., Mönkkönen, M., 2023. Future supply of boreal forest ecosystem services is driven by management rather than by climate change. Glob. Change Biol. 29, 1484–1500. https://doi.org/10.1111/gcb.16566

Triviño, M., Pohjanmies, T., Mazziotta, A., Juutinen, A., Podkopaev, D., Le Tortorec, E., Mönkkönen, M., 2017. Optimizing management to enhance multifunctionality in a boreal forest landscape. J. Appl. Ecol. 54, 61–70. https://doi.org/10.1111/1365-2664.12790

Tudoran, G.-M., Cicșa, A., Cicșa (Boroeanu), M., Dobre, A.-C., 2022. Management of Recreational Forests in the Romanian Carpathians. Forests 13, 1369. https://doi.org/10.3390/f13091369

Turkelboom, F., Leone, M., Jacobs, S., Kelemen, E., García-Llorente, M., Baró, F., Termansen, M., Barton, D.N., Berry, P., Stange, E., Thoonen, M., Kalóczkai, Á., Vadineanu, A., Castro, A.J., Czúcz, B., Röckmann, C., Wurbs, D., Odee, D., Preda, E., Gómez-Baggethun, E., Rusch, G.M., Pastur, G.M., Palomo, I., Dick, J., Casaer, J., van Dijk, J., Priess, J.A., Langemeyer, J., Mustajoki, J., Kopperoinen, L., Baptist, M.J., Peri, P.L., Mukhopadhyay, R., Aszalós, R., Roy, S.B., Luque, S., Rusch, V., 2018. When we cannot have it all: Ecosystem services trade-offs in the context of spatial planning. Ecosyst. Serv. 29, 566–578. https://doi.org/10.1016/j.ecoser.2017.10.011

Urquhart, J., Courtney, P., Slee, B., 2012. Private woodland owners' perspectives on multifunctionality in English woodlands. J. Rural Stud. 28, 95–106. https://doi.org/10.1016/j.jrurstud.2011.08.006

Vanderwel, M.C., Purves, D.W., 2014. How do disturbances and environmental heterogeneity affect the pace of forest distribution shifts under climate change? Ecography 37, 10–20. https://doi.org/10.1111/j.1600-0587.2013.00345.x

Vergarechea, M., Astrup, R., Fischer, C., Øistad, K., Blattert, C., Hartikainen, M., Eyvindson, K., Di Fulvio, F., Forsell, N., Burgas, D., Toraño-Caicoya, A., Mönkkönen, M., Antón-Fernández, C., 2023. Future wood demands and ecosystem services trade-offs: A policy analysis in Norway. For. Policy Econ. 147, 102899. https://doi.org/10.1016/j.forpol.2022.102899

Verkerk, P.J., Costanza, R., Hetemäki, L., Kubiszewski, I., Leskinen, P., Nabuurs, G.J., Potočnik, J., Palahí, M., 2020. Climate-Smart Forestry: the missing link. For. Policy Econ. 115, 102164. https://doi.org/10.1016/j.forpol.2020.102164

Vincent, J.R., Binkley, C.S., 1993. Efficient multiple-use forestry may require land-use specialization. Land Econ. 69.

Vizzarri, M., Pilli, R., Korosuo, A., Frate, L. & Grassi, G. in Climate-Smart Forestry in Mountain Regions (eds Tognetti, R., Smith, M. & Panzacchi, P.) 507–520 (Springer International Publishing, 2022).

Wikström, P., Edenius, L., Elfving, B., Eriksson, L.O., Lämås, T., Sonesson, J., Öhman, K., Wallerman, J., Waller, C., Klintebäck, F., 2011. The Heureka forestry decision support system : an overview [WWW Document]. URL http://mcfns.com/index.php/Journal/article/view/MCFNS.3-87 (accessed 8.10.22).

Winkel, G., Lovrić, M., Muys, B., Katila, P., Lundhede, T., Pecurul, M., Pettenella, D., Pipart, N., Plieninger, T., Prokofieva, I., Parra, C., Pülzl, H., Roitsch, D., Roux, J.-L., Thorsen, B.J., Tyrväinen, L., Torralba, M., Vacik, H., Weiss, G., Wunder, S., 2022. Governing Europe's forests for multiple ecosystem services: Opportunities, challenges, and policy options. For. Policy Econ. 145, 102849. https://doi.org/10.1016/j.forpol.2022.102849

Wolfslehner, B., Pülzl, H., Kleinschmit, D., Aggestam, F., Winkel, G., Candel, J., Eckerberg, K., Feindt, P., McDermott, C., Secco, L., Sotirov, M., Lackner, M., Roux, J.-L., 2020. European forest governance post-2020. European Forest Institute.

Supplementary material

Supplementary 1: Forest data, management, and simulations

Finland - SIMO

Germany (Bavaria) - SILVA

Norway - SiTree

Sweden – Heureka

Supplementary 2: Forest Ecosystem Services and Indicators

Supplementary 3: National policy scenarios

Supplementary 4: Climate scenarios

Supplementary 5: Outcomes of Optimal National Management Strategies

Supplementary 6: Multi-objective optimization

Supplementary 7: Complete timely development of each FESB class for each climate, policy scenario and country

Supplementary 8: Radar plot comparing each policy scenario and Max MF scenario for no CC

Supplementary 9: Synergies and trade-offs among the six FESB selected for the potential maximum MF scenario and the no CC climate scenario

1. Forest data management and simulations

1.1. Finland

In Finland, the data used provides detailed forest stand information and represents a sub-sample of the public data from the Finnish Forest center from 2016 (www.metsaan.fi). In addition, we used data form the Multi-source National Forest Inventory from 2015 to complement the information, since this Multi-source provides information on the total forest land in raster format (http://kartta.luke.fi/index-en.html) (Mäkisara et al. 2019). Then, following the design of the 11th Finnish National Forest Inventory (FNFI), both data sources were sampled along the regional and temporal systematic clusters, defining four regions:

- Lapland and North Lapland (the design from Lapland was extended to North Lapland)
- Southern North Finland
- Central Finland
- Southernmost Finland.

In this case, forest simulations were carried out with the open source forest simulator SIMO (Rasinmäki et al. 2009). SIMO simulates individual tree growth, mortality and regeneration for even-aged (Hynynen et al. 2002) and uneven-aged boreal forests (Pukkala et al. 2013). Climate variables driving stand growth and soil dynamics (mean and amplitude of temperature, CO_2 concentration, precipitation) were based on Lehtonen et al. (2016), and the climate data of the Canadian Earth system model CanESM (von Salzen et al. 2013). Based on the models of Matala et al. (2006), the impacts of climate on tree growth were introduced into the calculation of volume growth and further allocated between diameter and height growth. Simulations for Finland were then conducted with high performance computational resources provided by CSC – IT Center for Science LTD (cPouta, https://research.csc.fi).

Using SIMO, we simulated forest Management in five-year periods over 100 years for each NFI plot. Table S1 describes the basics concepts of the six management classes defined, which are based on the work of Eyvindson et al. (2018). Therefore, the maximum number of management regimes simulated by stand was 29 depending on the initial stand characteristics (i.e., dominant height, basal area, site type, and age). 24 regimes were modifications of even-aged rotation forestry, which is the business-as-usual regime (BAU). The implementation of BAU followed the “best practices guide” for managing forests in Finland (Äijälä et al. 2014). Four regimes represented a continuous cover forestry management, and one regime represents setting aside, where no management takes place. (Table S2).

Table S1: Basic concepts of the six regime classes simulated in Finland.

Management class	**Description**
Business-as-usual (BAU)	Even-aged rotation forestry, according to Finnish recommendations (Äijälä et al. 2014); rotation length between 70-90 years; final felling is determined by site type, dominant stand height, and age; 5 retention trees ha^{-1}; replanting after final felling; 1-3 thinnings during rotation
Intensified BAU (I-BAU)	Modifications of BAU, regimes with shortened rotation length (-5 to -20 year); regimes with shortened rotation and additional fertilization (300kg N ha^{-1}) at basal area (BA) threshold of 14-20 m^2 ha^{-1} (Kukkola and Saramäki 1983, Pukkala 2017)
Extensified BAU (E-BAU)	Modifications of BAU, with either postponed final fellings (5, 15, 30 years) or with retention trees left after final felling (30 trees ha^{-1} or 30 m^3 ha^{-1})
Continuous Cover Forestry (CCF)	Large trees are periodically removed (thinning from above) down to BA threshold (16 - 22 m^2 ha^{-1} depending on site fertility); four different predefined BA thresholds; natural regeneration of stands
Adaption to climate change (ACC)	Modification of BAU, aims to increase resilience against climate change on the most prone medium fertile sites (Herb rich heath, Mesic heath) in Southern and Central Finland; replanted with broadleaves trees (*Betula pendula*) after final felling
Set aside (SA)	No management activities, only tree growth, mortality and natural regeneration are simulated

Table S2: Summary table of the simulated management regimes for Finland and their allocation to the six management classes.

Management class	**Management regime**	
	Abbreviation	**Description**
Set aside (SA)	*SA*	No management, only growth and mortality
Business-as-usual (BAU)	*BAU*	Rotation forestry, no thinnigs prior clearfelling
	BAU w thin	Rotation forestry, with thinnings prior clearfelling
	BAU w/o thin	Rotation forestry, no thinnings prior or after clearfelling
Extensified BAU (E-BAU)	*BAU w GTR*	= *BAU*, with 30 retention trees or 30m^2 per ha left
	BAU w thin GTR	= *BAU w thin*, with 30 retention trees or 30m^2 per ha left
	BAU + 5	= *BAU*, with 5 year extended rotation age
	BAU + 15	= *BAU*, with 15 years extended rotation age
	BAU +30	= *BAU*, with 30 years extended rotation age
	BAU w thin +5	= *BAU w thin*, with 5 year extended rotation age
	BAU w thin +15	= *BAU w thin*, with 15 years extended rotation age
	BAU w thin +30	= *BAU w thin*, with 30 years extended rotation age
Intensified BAU (I-BAU)	*BAU -5,*	= *BAU*, with 5 years shorter rotation age
	BAU w thin -5	= *BAU w thin*, with 5 years shorter rotation age
	BAU w/o thin -20	= *BAU w/o thin*, with 20 years shorter rotation age
	BAU F	= *BAU*, with fertilization
	BAU w thin F	= *BAU w thin*, with fertilization
	BAU -5 F	= *BAU -5*, with fertilization
	BAU w thin -5 F	= *BAU w thin -5*, with fertilization
	BAU w/o thin -20 F	= *BAU w/o thin -20*, with fertilization
Adaptation to climate Change (ACC)	*BAU w thin B*	= *BAU w thin*, with increased broadleave planting
	BAU w thin GTR B	= *BAU w thin GTR*, with increased broadleave planting
	BAU w thin +5 B	= *BAU w thin +5*, with increased broadleave planting
	BAU w thin +15 B	= *BAU w thin +15*, with increased broadleave planting
	BAU w thin +30 B	= *BAU w thin +30*, with increased broadleave planting
Continuous Cover	*CCF 1*	Thinning from above, basal area threshold -3 m^2/ha

Forestry (CCF)	*CCF 2*	Thinning from above, basal area threshold +/-0 m^2/ha
	CCF 3	Thinning from above, basal area threshold + 3 m^2/ha
	CCF 4	Thinning from above, basal area threshold + 6 m^2/ha

1.2. Germany

In Germany we used the latest NFI (2012) to define the initial forest state for the simulation. In this case we had a total of 7456 NFI plots throughout Bavaria. A permanent four-by-four-kilometer sampling grid (locally even denser) is applied over the entire country and each grid point is represented by a cluster of four inventory plots (BMLE 2016). Data from the NFI are available upon request.

By using the forest simulator SILVA (Pretzsch et al. 2002, Pretzsch 2009) we simulated forest management and dynamics in Germany. SILVA is a single-tree-based model that is distance-dependent (tree positions matter) and age-independent. Under a broad range of silvicultural concepts, SILVA simulates the development of even-aged or uneven-aged mixed and monospecific forests. The simulator estimates potential height growth based on site quality, which is estimated from soil moisture and nutrient stage, length of the vegetation period and by a set of further climatic variables. Temperature, precipitation, temperature amplitude, and the atmospheric concentrations of CO_2 and NO_x are the climatic driving forces. Except the latter two, these climate variables were computed from HADGEM2- ES GCM model (Jones et al. 2011), and were retrieved from Inter-Sectoral Impact Model Intercomparison Project (https://esg.pik-potsdam.de/search/isimip/).

In total, we simulated 15 management regimes in five-year periods over 100 years that can be grouped into six management classes. These classes represent the most relevant silvicultural practices (**Table S3**): i) the business-as-usual classes (BAU), ii) intensified BAU, and iii) extensified BAU generally apply traditional silvicultural practices with thinning from below and final clearfelling. These three classes, however, differ in their degree of forest productivity stimulation. iv) The continuous cover forestry (CCF) regimes commonly aim at creating and maintaining a stable size class distribution with emphasis on steady wood provision. Regimes within this lass have thus been tailored to suit intervention frequency and intensity as typical for small private forest managers, who consider forestry rather as an additional source of income. v) To account for the state forestry's aim of establishing climate resilient forests, a further regime was simulated that aims at continuous cover with high structure and species diversity (adaptation to climate change). vi) The class of set aside (SA) strictly inhibits any intervention.

Table S3: Summary table of the simulated management regimes for Germany and their allocation to the six management classes (S = stands dominated by spruce, B = stands dominated by beech, and P = stands dominated by pine).

Management classes	Management focus	Abbreviation	Harvesting top height [m]			Description
			S	B	P	
Business-as-usual (BAU)	Wood production clearfelling	BAU_0	30	30	30	Standard BAU
		BAU_0_p1				Initially mature stands not harvested before year 5
		BAU_0_p2				Initially mature stands not harvested before year 10
Extensified BAU (E-BAU)	Wood production with harvest delay	Extensified BAU	33	33	33	Lower intensity, later harvest
Intensified BAU (I-BAU)	Intensification of wood production	BAU_RR	25	30	25	Short rotation
		BAU_RR_p1				Initially mature stands not harvested before year 5
		BAU_RR_p2				Initially mature stands not harvested before year 10
		BAU_FS	33	30	30	Promote foreign species
Continues Cover Forestry (CCF)	Regular harvest structure mixture	CCF_P1	38	33	33	Standard CCF
		CCF_P2	38	33	33	Buffer temporal variation of supply
		CCF_P3	12	12	12	Thereby keep straighter and simpler, harvest coniferous stand
		CCF_P3_p1				Initially mature stands not harvested before year 5
		CCF_P3_p2				Initially mature stands not harvested before year 10
Adaptation to Climate Change (ACC)	Multifunctionality	Adaptation to Climate Change	32	25	28	Promote diversity, stability, continuity, converts to broadleaved dominated stands
Set aside (SA)	Set aside	SA	-	-	-	No thinning, no harvest

1.3.Norway

In Norway, we used the current Norwegian national forest inventory (NFI), carried out during 2015–2019, as the starting point of our 100 years simulations. That NFI is based on a five-year cycle, so each plot is resampled every 5th year with 1/5 of all NFI plots visited annually. These NFI plots are 250 m2 in size and were established at each intersection of a 3 × 3 km (easting x northing) grid in the lowlands, a 3 × 9 km grid in the mountains excluding Finnmark, and a 9 × 9 km grid in Finnmark. In total 9371 plots were selected over whole Norway and divides Norway into 4 strata:

- Lowland (below coniferous limit) except Finmark (94%)
- Mountain areas (above conif. Limit) except Finnmark (3.75)
- Lowland in Finnmark (1.6%)
- Mountain areas in Finnmark (0.4%)

For a more detailed description of the data sampling and design see (Breidenbach et al. 2020) or see https://www.ssb.no/en/jord-skog-jakt-og-fiskeri/skogbruk/statistikk/landsskogtakseringen.

Forest dynamics and management for Norway have been simulated using the open source simulator SiTree (Antón-Fernández and Astrup 2022), with imputation models (1 nearest neighbor) to estimate individual tree growth, mortality, and ingrowth. The imputation models used here were fitted to the Norwegian NFI. In this case, we used the forest inventory data from the last five-year cycles (2015 -2019), as input data in the SiTree platform. The effect of climate change was included by modifying the site index of the plots using empirical Norwegian climate data (Antón-Fernández et al. 2016). The climatic variables needed to run the climate-sensitive site index functions were obtained from the Norwegian Meteorological Institute (MET). The climatic data for the RCP 4.5 scenario were originated from a combination of ten regional climate model simulations from the EURO-CORDEX archive (Wong et al. 2016), which were downscaled to a 1 × 1 km grid and bias corrected.

Then, for each NFI plot, forest management was simulated in five-year periods over 100 years. In this case, depending on the initial stand characteristics, the total number of management regimes simulated by stand was up to 99. These regimes, however, can be allocated into the six common defined regimes classes (**Table S4**), of which four classes allow for a shift in the timing of the initial harvests in plots that were already in the mature age (to avoid a harvest peak in the first period). The shift allowed the already mature stands to be harvested at any time during the simulation for the regime class business-as-usual (BAU), as well as for the extensified (E-BAU) and intensified (I-BAU) subcategories of the class. For continuous cover forestry (CCF) the displacement was performed along 3 periods, since in CCF harvest activities are simulated every 15 years.

Table S4: Summary table of the simulated management regimes for Norway and their allocation to the six management classes.

Management class	**Management regime**	
	Abbreviation	**Description**
Set aside (SA)	*SA*	Protection forest
Business-as-usual (BAU)	*BAU + 5* *BAU + 10* *BAU + 15* *….* *BAU + 90*	Even-aged management (thinning, clearfelling, planting)
Extensified BAU (E-BAU)	*E-BAU + 5* *E-BAU + 10* *E-BAU + 15* *….* *E-BAU + 90*	Extensive even-aged management – longer rotation age (rotation increase to 140% of rotation age)

Intensified BAU (I-BAU)	*I-BAU + 5* *I-BAU + 10* *I-BAU + 15* *….* *I-BAU + 90*	Intensive even-aged management (planting, higher density, fertilization, thinnings, clearfelling)
	I-short-BAU + 5 *I-short-BAU + 10* *I-short-BAU + 15* *….* *I-short-BAU + 90*	Intensive even-aged management -shorter rotation age (rotation decrease to 80% of rotation age)
Continues Cover Forestry (CCF)	*CCF + 5* *CCF + 10* *CCF + 15*	Continuous cover forestry with harvest every 15 years (take out the 15-year growth)
Adaptation to climate Change (ACC)	*ACC + 5* *ACC + 10* *ACC + 15* *….* *ACC + 90*	Multispecies even-aged management (regeneration with a mixture of species of spruce / pine / birch)

1.4.Sweden

In Sweden, data from the Swedish NFI (2008-2012) was used to define the initial state of the forest. The SNFI is distributed over the country in a systematic cluster design comprising of squared tracts. In this case, every fifth year, two thirds of the tracts are revisited, which conform the permanent inventory. In addition, one third of these tracts are temporary and only visited once. Circular plots with a radius between 7 and 10 meters are placed alongside the borders of the tracts, whose lengths range between 300 and 800 meters. Plot and tract sizes differ depending on where in the country it is located and if it is a temporary or permanent plot (Fridman et al. 2014). In total 29 892 plots were used, representing the productive forest area of Sweden. Forestry is only allowed on productive forest land in Sweden, i.e., forest land with a potential yield capacity of 1 $m^3ha^{-1}year^{-1}$.

In Sweden, we used the Heureka system to perform the forest projections for the management regimes (Wikström et al. 2011). Based on empirical growth models (Fahlvik et al. 2014), mortality models (Fridman and Ståhl 2001) and models for in-growth (Wikberg 2004) the system projects individual tree development. In addition, the system has a built-in model modifying wood growth to the climate scenario RCP4.5, based on the process-based model BIOMASS (McMurtrie et al. 1990) adapted to Swedish conditions (e.g. Bergh et al. (2003)). Then, we used the Heureka application PlanWise to simulate the different management regimes in Sweden, were many different alternatives (so called treatment schedules) are projected for each treatment unit (here NFI plot) with different timings of forest management actions (cleaning, thinning, clear-felling).

In Heureka, management regimes can be defined with relatively high level of detail (**Table S5**). Several treatment schedules are generated in five-year periods over 100 years, for each treatment unit and their assigned management regimes. Each treatment schedule differs in the timing of management actions and covers the entire planning horizon.

Table S51: Summary table of the simulated management regimes for Sweden and their allocation to the six management classes. Regimes indicated with "" were only used in the bioeconomy scenario (BES).*

Management class	**Management regime**	
	Abbreviation	**Description**
Set aside (SA)	Unmanaged	Set aside; The forest grows from the initial state, no timber extraction
Business-as-usual (BAU)	BAU	Even-aged forestry; Biofuel extraction at final felling on dry and mesic soils, retaining 10 trees and 3 high stumps/ha at final felling (retention). Max 30 years delay in final felling after reaching minimum final felling age (according to the Swedish Forestry Act). Regeneration: planting
Extensified BAU (E-BAU)	BAU – No thinning	Even-aged forestry with no thinnings; BAU with no thinnings.
	BAU_ProlongedRotation	Even-aged forestry with prolonged rotations; BAU with final felling only allowed from 30 years to 50 years after reaching minimum final felling age
Intensified BAU (I-BAU)	BAU_FocusBioenergy_StumpHarvest	Even-aged forestry with bioenergy focus and stump harvest; BAU with biofuel extraction including stump removal (pine and spruce) and no retaining trees
	BAU FocusBioenergy	Even-aged forestry with bioenergy focus; BAU with biofuel extraction at final felling in all stands except on wet soils, bioenergy thinning is allowed.
	Int_prod*	BAU allowing breeding of plant material, short rotations, no thinnings and fertilization
	Int_HybridExotic*	BAU allowing planting hybrid/exotic-like species and managed accordingly (including no thinnings and short rotations)
	Int_Contorta*	BAU allowing planting Contorta and following adapted management (including shorter rotations and adapted thinnings)
Adaptation to climate change (ACC)	Even-aged forestry promoting broadleaves	BAU that aims at increasing the proportion of broadleaves in the landscape by increasing the share of retained broadleaves in cleaning and thinning operations and allowing for longer rotation periods. Natural regeneration (seed trees).
Continuous Cover Forestry (CCF)	CCF	Reoccurring selection fellings, minimum 10 years in-between 2 fellings. Only possible in spruce dominated stands. Natural regeneration.

2. Forest Ecosystem Services and Indicators

2.1. Finland

Wood production – The ecosystem service was measured by the simulated annual yearly increment (m3 ha-1 yr-1) and the periodically harvested timber volume (m3 ha-1).

Bioenergy – It assessed the harvested biomass (m3 ha-1), which summarizes the combined volume of harvest residues, uplifted tree stumps and roots (only for spruce and pine stands under rotation forestry on fertile and medium fertile site types).

Biodiversity conservation – According to the red list of habitat types in Finland (Kontula and Raunio 2019), the reasons for forest habitat types becoming red-listed are reduction in deadwood, reduction in old-growth forests and individual old trees as well as changes in tree species composition by reducing the share of deciduous trees. Thus, we measured biodiversity by five separate variables: deadwood volume (m3 ha-1); percentage of deciduous trees; the number of large trees (diameter at breast height DBH > 40 cm); the share of stands managed by set aside (representing strict protected areas), as well as the share of stands managed with CCF (two regimes with reduced thinning intensity) and rotation forestry with green tree retention (representing conservation oriented management in commercial forests (see Supplementary Note 4, Simulator and regimes of Finland).

Water protection – We used the share of CCF on peatlands as a management option to decrease negative water quality impacts to lakes and streams (Nieminen et al. 2018), which are caused by intensive management options (clearfelling combined with ditching) (Nieminen et al. 2017, Marttila et al. 2020, Tolkkinen et al. 2020).

Climate regulation – We measured by the carbon sink (t CO_2 ha^{-1} yr^{-1}), which represents the change in carbon storage between two simulation time steps. Carbon storage was the sum of the total carbon held within standing timber, deadwood, and soil, converted in its corresponding CO_2 content. The carbon of standing timber and deadwood was evaluated as 50% of the dry biomass (see Eyvindson et al. (2021)). The carbon storage in wood products was not included since national policies mainly defined the forest landscape as system boundary when setting targets.

Recreation – The ecosystem service was calculated using two indices developed by (Pukkala et al. 1988, Pukkala et al. 1995), which estimates people’s average opinion about the recreational value (recreation index) and beauty of forests (scenic index) of managed forest stands, assuming that their values increases with the age and size of trees, as well as increasing the shares of pines and birches.

Table S62: Summary of the indicators used in Finland. The summaries are based on the Maximum Multifunctionality scenario (MF).

FES	Indicators	Scenario	max	min	sd
Wood	Annual Increment (m^{3}ha^{-1}year^{-1})	noCC	49.6	0	3.56
	Annual Increment (m^{3}ha^{-1}year^{-1})	RCP4.5	35.90	0	4.162
	Harvested Volume (m^{3}ha^{-1})	noCC	126.51	0	10.466
	Harvested Volume (m^{3}ha^{-1})	RCP4.5	156.200	0	11.118
Bioenergy	Biomass (m^{3}ha^{-1})	noCC	23.18	0	1.834
	Biomass (m^{3}ha^{-1})	RCP4.5	26.190	0	1.986
Biodiversity	Conservation_regime	noCC	1	0	0.499
	Conservation_regime	RCP4.5	1	0	0.500
	Deadwood(m^{3}ha^{-1})	noCC	669.26	0.01	16.20
	Deadwood(m^{3}ha^{-1})	RCP4.5	650.520	0.01	16.181
	Deciduous tree volume (%)	noCC	100	0.000	39.376
	Deciduous tree volume (%)	RCP4.5	100	0	39.469
	Large trees (DBH > 40cm) (n ha^{-1})	noCC	381.85	0	22.083
	Large trees (DBH > 40cm) (n ha^{-1})	RCP4.5	420.760	0	20.643
Water protection	Regimes CCF/SA on peatland (%)	noCC	1	0	0.440
	Regimes CCF/SA on peatland (%)	RCP4.5	1	0	0.440
Climate regulation	Carbon sink (t CO2 ha-1 yr-1)	noCC	50.28	-132.7	13.152
	Carbon sink (t CO2 ha-1 yr-1)	RCP4.5	43.160	-152.2749	14.029
Recreation	Recreation index (-)	noCC	7.879	0	0.572
	Recreation index (-)	RCP4.5	8.197	0	0.613
	Scenic index (-)	noCC	14.751	0	1.78
	Scenic index (-)	RCP4.5	14.876	0	1.751

2.2.Germany

Wood production – We addressed by the indicators annual increment and harvested timber amount per simulation period. Both, harvested timber and bioenergy were calculated for individual tree dimensions based on the wood assortment program BDATPro (Kublin 2003).

Bioenergy – We used marginal assortments that are typically used for energy wood products (harvest residues and stumps).

Biodiversity conservation – We used the biodiversity fuzzy indicator from Biber et al. (2021). Additionally, it was also addressed based on tree species diversity, like the Shannon index of tree species (Jost 2006), and the species profile index developed by Pretzsch (2009). Further, the share of stands managed by set aside was considered representing strict protected areas.

Water protection – It was evaluated through forest stability indicators: the standing volume and the crown coverage.

Climate regulation – We addressed it through indicators of carbon storage on the one hand and avoidance of carbon emission on the other. We therefore applied a total carbon balance that accounts for carbon storages in standing volume and, in wood products, as well as the avoidance of CO_2 emission through substitutional use of construction wood instead of other construction materials (Biber et al. 2021).

Recreation – We used the "recreation & aesthetics" fuzzy indicator reported by Biber et al. (2021).

Table S73: Summary of the indicators used in Germany. The summaries are based on the Maximum Multifunctionality scenario (MF).

FES	Indicators	scenario	max	min	sd
Wood	Annual Increment ($m^3ha^{-1}year^{-1}$)	noCC	2.212E-07	-2.45E-07	6.038E-08
	Annual Increment ($m^3ha^{-1}year^{-1}$)	RCP45	2.775E-07	-2.35E-07	6.992E-08
	Harvested volume ($m^3ha^{-1}year^{-1}$)	noCC	615.003	0.000	69.241
	Harvested volume ($m^3ha^{-1}year^{-1}$)	RCP45	708.259	0.000	60.107
Bioenergy	Harvest residues (m^3)	noCC	8.924	0	0.997
	Harvest residues (m^3)	RCP45	1.051	0	0.089
Biodiversity	Biodiversity fuzzy indicator (ND)	noCC	0.910	0.090	0.195
	Biodiversity fuzzy indicator (ND)	RCP45	0.910	0.090	0.192
	DeadWood (m^3)	noCC	235.283	0.000	26.969
	DeadWood (m^3)	RCP45	172.366	0.000	28.826
Water protection	Crown coverage (%)	noCC	18.882	-18.546	3.982
	Crown coverage (%)	RCP45	19.590	-19.096	3.681
	Standing volume (m^3ha^{-1})	noCC	1.546E-06	6.464E-10	2.492E-07
	Standing volume (m^3ha^{-1})	RCP45	1.768E-06	3.15E-09	3.006E-07
Climate regulation	Carbon Balance (tC ha^{-1})	noCC	18.622	-20.234	2.211
	Carbon Balance (tC ha^{-1})	RCP45	10.521	-11.139	1.660

Recreation	Recreation and Esthetics fuzzy indicator (ND)	noCC	0.838	0.131	0.124
	Recreation and Esthetics fuzzy indicator (ND)	RCP45	0.831	0.081	0.121

2.3.Norway

Wood production – We used two indicators: discounted harvest net income (NOK) and total amount of harvested volume commercial timber (m3). Discounted harvest net income was calculated based on the revenues for harvested timber minus the cost of silvicultural operations and transportation. Timber prices and harvest costs were kept constant over the simulation horizon (Vennesland et al. 2013)

Bioenergy – We assessed bioenergy production by the amount of harvested energy wood, i.e. tops and branches, known in the Norwegian acronym as GROT and here labelled as harvested residues.

Biodiversity – Biodiversity conservation was assessed by MiS area, bilberry coverage, and deadwood volume. MiS (Miljøregistrering i skog in Norwegian) is a habitat inventory approach, called “Complementary Hotspot Inventory” (CHI). This habitat inventory approach is currently used in forestry planning in Norway and is based on identifying areas that are particularly important for red-listed species (Gjerde et al. 2007, Timonen et al. 2010). Therefore, the NFI plots were classified as MiS plot (1) or not (0) focusing on the abundance of big trees and broadleaved trees. Bilberries are the most common wild berries in Norway. The bilberry coverage (%) was calculated using a beta regression model fitted to the Norwegian NFI bilberry cover data, which predicts the bilberry coverage of the forest ground based on stand characteristics (stand age, vegetation type, and stand basal area). We also included volume of deadwood as an indicator since it is important for forest biodiversity conservation (Müller and Bütler 2010, Gao et al. 2015). The deadwood volume was estimated using a species and diameter class specific, climate adjusted decomposition function based on the mortality of stands from the NFI.

Water protection – We calculated the clear-cut area (ha) in steep terrain and in mountain forests, assuming that forest areas that were recently clear-felled are lacking a sufficient protection effect against erosion (Brang et al. 2006).

Climate regulation – We calculated the sum of the predicted amount of carbon stored in living trees, deadwood, and soil. To calculate the flow of carbon sink in living trees, the estimated biomass of individual trees was converted to its carbon equivalent using a factor of 0.5 (IPCC 2006). Soil carbon was estimated using the Yasso07 model (Liski et al. 2005). We also assessed the carbon storage in harvested wood products (HWP) considering two products, saw timber and wood-based panels with half-lives of 35 and 25 years, respectively. The current HWP pool is assumed to be zero. Thus, the carbon storage in HWP pool only increases at the beginning of the simulations since there is no release of carbon from the current HWP pool (until 25 years from the first harvest).

Recreation – We measured the recreational aspects of forests by the Shannon index and proportion of City Forest. The Shannon index (Jost 2006) was used to calculate the tree species diversity for each NFI plot, assuming that a higher diversity is more attractive for people seeking recreation. City forest is defined as a 30 km buffer zone around cities with a population greater or equal to 40.000 inhabitants, which was based on the urban area layer from Statistics Norway.

Table S84: Summary of the indicators used in Norway. The summaries are based on the Maximum Multifunctionality scenario (MF).

FES	Indicators	Scenario	max	min	sd
Wood	Harvested Volume (Mm3)	noCC	190.194	0	13.287
	Harvested Volume (Mm3)	RCP 4.5	186.848	0	13.127
	Net Value (NOK)	noCC	40803	-14818	2776
	Net Value (NOK)	RCP 4.5	42240	-18316	2782
Bioenergy	Harvested residues (Mm3)	noCC	72635.279	0	2372.018
	Harvested residues (Mm3)	RCP 4.5	113952	0	2759
Biodiversity	MIS_area (ha)	noCC	13.467	0	0.512
	MIS_area (ha)	RCP 4.5	13.467	0	0.606
	Bilberry (%)	noCC	0.985	0.002	0.064
	Bilberry (%)	RCP 4.5	1.000	0	0.064
	Deadwood (Mm3)	noCC	718.982	0	19.525
	Deadwood (Mm3)	RCP 4.5	536.655	0	18.734
Climate regulation	CO_2 in HWP (Kt)	noCC	109866	0	7762
	CO_2 in HWP (Kt)	RCP 4.5	1108026	0	16107
	CO2_forest (MKt)	noCC	418.532	-275.176	22.419
	CO2_forest (MKt)	RCP 4.5	1066.727	-249.512	27.433
Water protection	Harvest in steep terrain and mountain forests (Mm3)	noCC	8205.826	0	525.695
	Harvest in steep terrain and mountain forests (Mm3)	RCP 4.5	8205.826	0	530.895
Recreation	Harvest in city plots forest (Mm^3)	noCC	153.423	0	5.646
	Harvest in city plots forest (Mm^3)	RCP 4.5	186.848	0	5.627
	Shannon index	noCC	0.428	0	0.087
	Shannon index	RCP 4.5	0.441	0	0.087

2.4.Sweden

Wood production – We used the net present value (NPV in SEK), wood increment (m^3 ha^{-1} yr^{-1}), and the average (m^3 ha^{-1} yr^{-1}) and total annual harvest (m^3 yr^{-1}). The NPV is the discounted revenue minus the expenses for growing and extracting timber, calculated for the first year of the simulation. Wood increment is the net increase in biomass of the living trees. The average and total yearly harvest is the harvested forest biomass extracted and left in the forest.

Bioenergy – We used the harvested residues ($m^3 yr^{-1}$) as an indicator for bioenergy. In Heureka branches, foliage, roots > 5mm, and treetops can be extracted as residues depending on the management regime, e.g. stump harvesting is only allowed under *BAU_FocusBioenergy_StumpHarvest* (see **Supplementary Note 4,** Simulator and regimes of Sweden).

Biodiversity conservation – Biodiversity was measured by the share of set asides (%), deadwood volume (m^3 ha^{-1}), and the area of old (>80 years) deciduous-rich (>30 %) forest. The set aside area is a good biodiversity metric, since a large share of the threatened and rare species in Nordic forests depend on unmanaged forest where only natural disturbances are taking place, which are typical of set asides. The dead wood volume and the area of old deciduous-rich forests are two of the official environmental quality objectives indicators used to measure the state of Swedish forests from the perspective of biodiversity (see Swedish EPA 2022).

Water protection – For Sweden, we used the share of continuous cover forestry (% CCF) for the same reason as described in the case of Finland above, although CCF can be applied only where Norway spruce is the dominating species. Heureka does not allow CCF on forest land dominated by Scots pine. In Finland CCF is frequently applied on ditched mires dominated by pine, but mires are not managed in Sweden.

Climate regulation – We used the carbon stock in wood and soil (t CO2 ha-1) as an indicator for the role of the forest in the global carbon balance. The indicator is the sum of the carbon stock in the soil, deadwood, and the living biomass above ground.

Recreation – The recreation index ranges between 0 and 1 and is calculated from forest stand variables changing through time in the projections (Lind 2007). The index increases with stand age, tree size diversity, deadwood volume, and share of deciduous trees, and decreases with the number of downed logs, harvest residues, number of stems, and soil damage.

Table S95: Summary of the indicators used in Sweden. The summaries are based on the Maximum Multifunctionality scenario (MF).

FES	Indicators	Scenario	max	min	sd
Wood	Net Present Value (SEK)	noCC	521362100	0	9112034

	Net Present Value (SEK)	RCP4.5	565517700	0	10151240
	Annual Increment ($m^3ha^{-1}year^{-1}$)	noCC	29220.23	-1466.55	2721.04
	Annual Increment ($m^3ha^{-1}year^{-1}$)	RCP4.5	36502.24	-1711.42	3040.29
	Harvested volume ($m^3ha^{-1}year^{-1}$)	noCC	135429	0	10078.272
	Harvested volume ($m^3ha^{-1}year^{-1}$)	RCP4.5	163007	0	11932.239
Bionergy	Harvested residues (m^3year^{-1})	noCC	40136.6	0	2829.34
	Harvested residues (m^3year^{-1})	RCP4.5	56348.33	0	3187.23
Biodiversity	Old Deciduous (ha)	noCC	2356.05	0	196.09
	Old Deciduous (ha)	RCP4.5	2356.05	0	219.43
	Deadwood volume (m^3ha^{-1})	noCC	344034	0	17044
	Deadwood volume (m^3ha^{-1})	RCP4.5	378670.1	0	21414.168
Water protection	Share of regime CCF (%)	noCC	1870.45	0	346.66
	Share of regime CCF (%)	RCP4.5	2356.05	0	353.15
Climate regulation	Carbon in wood and soil (t CO_2 ha^{-1})	noCC	615251.1	649.0294	56764.89
	Carbon in wood and soil (t CO_2 ha^{-1})	RCP4.5	669246.8	649.0294	64288.31
Recreation	Recreation index (-)	noCC	1694	0	240
	Recreation index (-)	RCP4.5	1720.41	0	255.913

3. National policy scenarios

For each study region, we used national level policy documents to define the policy scenarios. This policy scenarios represent different demands of forest ecosystem services and biodiversity (FESB). Following the policy analysis framework of Primmer et al. (2021), we then categorized and assessed the stated FESB targets. To do it, the documents were mapped along nine FESB classes: wood, bioenergy, non-wood products, game, water protection, climate regulation, resilience, recreation, and biodiversity conservation. Six of these classes were common over all national policy documents. In a second step, the demands were evaluated for the addressed FESB in each policy. Finally, using the outcomes of the policy analyses we defined multi-objective optimization problems separately for each policy scenario. Therefore, the stated demands for FESB were related to our simulated FESB indicators by individual objective functions (e.g., Blattert et al. (2022)).

The three scenarios and background documents used in each study area:

Study area – Finland

- **National Forest Strategy, NFS:** National Forest Strategy 2025 (FMAF 2015, 2019)
- **Biodiversity Strategy, BDS:** Saving Nature for People - National action plan for the conservation and sustainable use of biodiversity in Finland (FME 2012)
- **Bioeconomy Strategy, BES:** Finnish Bioeconomy Strategy (FMME et al. 2014)

Study area – Germany

- **National Forest Strategy, NFS:** Forest Strategy 2020 (BMELV 2011)
- **Biodiversity Strategy, BDS:** National Strategy on Biological Diversity (BMU 2007)
- **Bioeconomy Strategy, BES:** National Bioeconomy Strategy (BMBF and BMEL 2020)

Study area – Norway

- **National Forest Strategy, NFS:** The white paper on forest policy and wood industry (NMAF 2016)
- **Biodiversity Strategy, BDS:** The White paper Nature for life – Norway's national biodiversity action plan (MCE 2015)
- **Bioeconomy Strategy, BES** SKOG22 Norwegian Bioeconomy Strategy (INNRC 2015)

Study area – Sweden

- **National Forest Strategy, NFS:** National forest program 2018, National Forest Impact Analysis - SKA 15 (SFA 2015), Swedish Forestry Act, The Swedish Environmental Code
- **Biodiversity Strategy, BDS:** CBD Aichi Target 11, Swedish Environmental Objectives
- **Bioeconomy Strategy, BES:** National Forest Impact Analysis - SKA 15 (SFA 2015), Forest management with new possibilities - Report 24 (SFA 2019), Possibilities for intensive growth of forest (MINT) (Larsson et al. 2009), CBD Aichi Target 11

How each study region has translated their national policy documents into an optimization problem and linked it to the simulated FESB indicators is presented in **Table S6 – Table S9**.

In Finland, there was a wide variation in the number and detail of FESB addressed in Finland's policies. While acknowledging the multifunctional use of forest ecosystems with clear numerical targets that address wood production, bioenergy and biodiversity, the NFS is still centered around the value chain of wood and bioenergy. As part of the BDS, effective actions were aimed at halting biodiversity loss and achieving a favorable status by 2050. The Finnish BES follows the logic of mobilizing forest resources for bioeconomy while simultaneously preserving biodiversity. However, we should point out that in the individual policies, ecosystem services other than wood and biodiversity received little. Resilience and climate regulation were indirectly addressed by two contradictory mechanisms: forest area under protection (BDS), or sustainable use of timber resources (BES).

The federal republic policy documents in **Bavaria** were analyzed to represent state-level developments but generally lack quantitative objectives. In Germany, forest ecosystems have long been used in a variety of multifunctional ways, which was explicitly acknowledged in the NFS. The BDS and BES, on the other hand, were more narrowly focused on specific FESB, namely biodiversity and wood production. Finally, as they are not considered matters of forest policies In Bavaria, the provisioning ecosystem services beyond wood and bioenergy (e.g., berries, mushrooms, game) gain little focus.

In Norway, the detail in which these FESB were addressed also varied significantly between policies, since the policies were more specialized to specific FESB. By increasing the production and extraction of wood-based materials, bioenergy, and biofuels, the forest policy aimed to boost the wood industry. In contrast, the BDS focused on preserving and enhancing biological diversity, protecting against erosion, and promoting recreational activities. Contrary to other countries, the BES highlighted the value of the multifunctional use of forest ecosystems, recognizing the role of forests in climate regulation, wood production, bioenergy, biodiversity, and recreation. However, like the other countries, the policies generally lack quantitative objectives.

In Sweden, dedicated documents fully corresponding to the focal policy strategies are not yet available, but partly developing. Instead, available public documents and reports were grouped to represent the three strategies. NFS was replaced by the developing National Forest Program with recommendations to increase wood growth, national forest use scenarios and main legislation. Similarly, the BDS was replaced by the Swedish Environmental Objectives and the Swedish Achi Targets of the CBD and recognized the multifunctional use of forest ecosystems. Finally, BES was replaced by inputs from specific studies on how to increase wood growth and enduring future harvest levels, in combination with fulfilling conservation targets. The selection of documents was further based on consultation of stakeholder in the sector and represents a more bottom-up understanding of the future development of the sector than the other study regions.

Table S10 Optimization scenarios of ***FINLAND*** *describing the applied indicators and optimization rules to address the forest ecosystem service demands of the three national policy scenarios; with step = order of optimization steps following the priority assigned to objectives, red = epsilon constraint, blue = maximize objective. The corresponding equation types (Eq.) for the individual objective functions are explained in supplementary section S5*

Ecosystem services & biodiversity	**Indicator (unit)**	**National forest strategy**			**Biodiversity strategy**			**Bioeconomy strategy**		
		Objective / Constraint	**Eq.**	**step**	**Objective / Constraint**	**Eq.**	**step**	**Objective / Constraint**		**step**
Wood production	Increment (m^3 ha^{-1} yr^{-1})	Target 2025: ≥ 115 Mm^3; target 2050: ≥ 125 Mm^3	**S1**	**1**						
	Harvested roundwood (m^3 ha^{-1})	Target 2025: ≥ 80 Mm^3	**S1**	**1**	Maximize (even flow)	**S5a**	**1**	Maximum even flow	**S5a**	**2**
Bioenergy	Harvested residues (m^3 ha^{-1})	Target 2025: ≥ 6.5 Mm^3	**S1**	**1**				Maximum even flow	**S5a**	**2**
Non-wood	Bilberry (kg ha^{-1}) *(Miina et al. 2009)*	No decline, maximize further	**S2**	**3**						
	Cowberry (kg ha^{-1}) *(Turtiainen et al. 2013)*	No decline, maximize further	**S2**	**3**						
	Mushrooms (kg ha^{-1}) *(Tahvanainen et al. 2016)*	No decline, maximize further	**S2**	**3**						
Game	HSI moose (-) *(Kurttila et al. 2002)*	Maximize	**S5c**	**4**	Maximize	**S5c**	**1**			
	HSI capercaillie (-) *(Mönkkönen et al. 2014)*	Maximize	**S5c**	**4**	Maximize	**S5c**	**1**			
	HSI hazel grouse (-) *(Mönkkönen et al. 2014)*	Maximize	**S5c**	**4**	Maximize	**S5c**	**1**			
Biodiversity	Share of regime SA (%)				Target of 17%	**S3a**	**1**			
Conservation	Conservation regimes (-) [a)]	Target of ≥ 4.5 %	**S3a**	**2**	Target of 4.5%	**S3a**	**1**			
	Deadwood (m^3 ha^{-1})	Target 2025: avg. ≥ 8 m^{3}ha^{-1}	**S1**	**2**	Target 2050: increase by 60%	**S6**	**1**	No decline & no target	**S6**	**1**
	Deciduous tree volume (%)	Maximize	**S5b**	**4**	Target 2050: increase by 10%	**S6**	**1**	No decline & no target	**S6**	**1**
	Large trees (DBH > 40cm) (n ha^{-1})	Maximize	**S5b**	**4**	Target 2050: increase by 10%	**S6**	**1**	No decline & no target	**S6**	**1**
Water protection	Regimes CCF/SA on peatland (%)	Enabled constraint	**S4a**	**1**	Enabled constraint	**S4a**	**1**			
Climate regulation	CO_2 sink in forest (t CO_2 ha^{-1} yr^{-1}): including deadwood decomposition *(Mäkinen et al. 2006)* and soil, mineral *(Liski et al. 2005, Tuomi et al. 2009, Tuomi et al. 2011)* and peatland *(Ojanen et al. 2014)*	Target 2025: ≥ 27.88 MtCO_2 equivalent	**S1**	**2**						
Recreation	Recreation index (-) *(Pukkala et al. 1995)*	Maximize	**S5a**	**4**	Maximize	**S5a**	**1**	Maximize	**S5a**	**2**
	Scenic index (-) *(Pukkala et al. 1995)*	Maximize	**S5a**	**4**	Maximize	**S5a**	**1**	Maximize	**S5a**	**2**
Resilience	Share of regime ACC (%)	Maximize	**S3b**	**4**						

a) Conservation oriented regimes were represented by two CCF regimes with reduced thinning intensity (CCF_3, CCF_4), and an extensified BAU regime with retention tree ((BAUwGTR, see Simulator and regimes of Finland, Table S2)

*Table S11: Optimization scenarios of **GERMANY** describing the applied indicators and optimization rules to address the FESB demands of the three national policy scenarios; with step = order of optimization steps following the priority assigned to objectives, red = epsilon constraint, blue = maximize/minimize objective. The corresponding equation types (Eq.) for the individual objective functions are explained in supplementary section S5*

Ecosystem services & biodiversity	**Indicator (unit)**	**National forest strategy**			**Biodiversity strategy**			**Bioeconomy strategy**		
		Objective / Constraint	**Eq.**	**step**	**Objective / Constraint**	**Eq.**	**step**	**Objective / Constraint**	**Eq.**	**step**
Wood production	Increment (m^3 ha^{-1} yr^{-1})	Maximize (even-flow)	**S5a**	**1**						
	Harvested volume (m^3 ha^{-1} yr^{-1})	Maximize (even-flow)	**S5a**	**1**						
	Sawlogs (m^3 ha^{-1} yr^{-1})							Maximize (even-flow)	**S5a**	**1**
	Pulpwood (m^3 ha^{-1} yr^{-1})							Maximize (even-flow)	**S5a**	**1**
Bioenergy	Energy Products (m^3 ha^{-1} yr^{-1})	Maximize	**S5a**	**2**				Maximize	**S5a**	**1**
Non-wood $^{a)}$										
Game $^{a)}$										
Biodiversity	Biodiversity indicator (-) *(Biber et al. 2021)*	Maximize (change >0)	**S5c**	**1**	Maximize	**S5c**	**1**	Maximize	**S5a**	**3**
Conservation	Shannon index (-) *(Shannon and Weaver 1949)*	Maximize	**S5c**	**3**	Maximize	**S5c**	**1**			
	Species profile index (-) *(Pretzsch 2009)*	Maximize	**S5c**	**3**	Maximize	**S5c**	**1**			
	Share of regime SA (%)				Target of 5%	**S3a**	**1**			
Water protection	Crown coverage (m^2 ha^{-1})	Maximize	**S5a**	**1**				Maximize	**S5a**	**3**
	Standing volume (m^3)	Constant (change > 0)	**S2**	**1**						
Climate regulation	Total Carbon Balance (tC year^{-1}) *(Biber et al. 2021)*	Maximize	**S5a**	**3**				Maximize	**S5c**	**2**
	Relative Living Carbon (tC year^{-1}) *(Biber et al. 2021)*				Maximize target 2020 (+5%)	**S6a**	**1**			
Recreation	Recreation & aesthetics indicator (-) *(Biber et al. 2021)*	Maximize	**S5c**	**1**						
Resilience	Storm & bark beetle risk (-) *(Biber et al. 2021)*	Minimize	**S7**	**3**						
	Pot. natural vegetation (pnV) (-)				Minimize	**S7**	**1**			
Legal constraints	CC on protected land	Enabled constraint	**S4a**	**1**	Enabled constraint	**S4a**	**1**	Enabled constraint	**S4a**	**1**
	CC on state forests	Enabled constraint	**S4a**	**1**	Enabled constraint	**S4a**	**1**	Enabled constraint	**S4a**	**1**

a) No targets or objectives mentioned in national policies.

Table S12: Optimization scenarios of ***NORWAY*** *describing the applied indicators and optimization rules to address the FESB demands of the three national policy scenarios; with step = order of optimization steps following the priority assigned to objectives, red = epsilon constraint, blue = maximize objective. The corresponding equation types (Eq.) for the individual objective functions are explained in supplementary section S5*

Ecosystem services & biodiversity	**Indicator (unit)**	**National forest strategy**			**Biodiversity strategy**			**Bioeconomy strategy**		
		Objective / Constraint	**Eq.**	**step**	**Objective / Constraint**	**Eq.**	**step**	**Objective / Constraint**	**Eq,**	**step**
Wood production	Harvest net value (NOK)	Maximize	**5a**	**1**				Maximize	**5a**	**1**
	Harvested volume (Mm^{3})				Maximize (even-flow)	**5a**	**1**			
Bioenergy	Harvested residues (Kt)	Maximize: plots with harvest costs < 150 NOK)	**S8**	**2**				Maximize: plots with harvest costs < 200 NOK)	**S8**	**2**
Non-wood a)										
Game b)										
Biodiversity	MIS c) area (ha) *(Gjerde et al. 2007)*	No decline allowed	**2**	**3**	No decline allowed	**2**	**1**	No decline allowed	**2**	**3**
	Deadwood volume (Mm^{3})				No decline allowed	**2**	**1**			
	Bilberry d) cover (%)				No decline allowed	**2**	**1**			
	MIS c) area (ha) *(Gjerde et al. 2007)*				Maximize	**5a**	**1**			
	Dead wood volume (Mm3)				Maximize	**5a**	**1**			
	Bilberry d) cover (%) **d)**				Maximize	**5a**	**1**			
Water protection	Harvest vol. in protect areas (Mm^{3})				No increase allowed	**S7**	**1**			
Climate regulation	Natl. CO_2 in harvested wood product (Kt)	Maximize	**5c**	**2**				Maximize	**5c**	**2**
	Natl. CO_2 in forest (MKt): including CO_2 in living biomass, and mineral soils *(Liski et al. 2005)*							Maximize	**5d**	**2**
Recreation	Harvest vol. in city forest (Mm^{3})				No decline allowed	**2**	**2**	No decline allowed	**2**	**3**
	Shannon index (-) *(Frank et al. 2013)*				No decline allowed	**2**	**2**	No decline allowed	**2**	**3**
Resilience a)										

a) No targets or objectives mentioned in national policies.

b) No indicator models were available for assessing the game in Norway at the time of this study.

c) MIS = Norwegian hot spot national inventory for biodiversity, the abundance of big and broadleaved trees.

d) Bilberry was allocated to biodiversity since the Biodiversity strategy mentioned it more explicitly under this service.

Table S13: Optimization scenarios of ***SWEDEN*** *describing the applied indicators and optimization rules to address the FESB demands of the three national policy scenarios; with step = order of optimization steps following the priority assigned to objectives, red = epsilon constraint, blue = maximize objective. The corresponding equations types (Eq.) for the individual objective functions are explained in supplementary section S5*

Ecosystem services & biodiversity	**Indicator (unit)**	**National forest strategy Objective / Constraint**	**Eq.**	**step**	**Biodiversity strategy Objective / Constraint**	**Eq.**	**step**	**Bioeconomy strategy Objective / Constraint**	**Eq.**	**step**
Wood production	Net Present Value (SEK)	Maximize	**S5a**	**2**	Maximize	**S5a**	**3**	Maximize	**S5a**	**6**
	Wood increment (m^3 ha^{-1} yr^{-1})				Maximize	**S5a**	**2**	Target 2050: 5.5 m^3 ha^{-1} yr^{-1}	**S1b**	**1**
	Average harvest volume (m^3 ha^{-1} yr^{-1})	Maximize (even-flow)	**S5a**	**2**	Maximize (even-flow)	**S5a**	**3**	Maximize (even-flow)	**S5a**	**4**
	Total harvest volume (m^3 yr^{-1})	Enabled constraint: Harvest ± 10% of increment	**S4b**	**1**				Target 2080: 141 Mm^3	**S1b**	**1**
Bioenergy	Harvested residues (m^3 yr^{-1})							Target 2030: 14 Mm^3	**S1a**	**2**
Non-wood a)										
Game a)										
Biodiversity	Share of regime SA (%)	12.8%	**S3a**	**1**	17%	**S3a**	**1**	17%	**S3a**	**3**
	Deadwood volume (m^3 ha^{-1})	No decrease	**S2**	**1**	Target 2050: increase by 60% on managed land	**S6a**	**1**	No decrease	**S2**	**5**
	Old, deciduous-rich forest area (ha)	No decrease	**S2**	**1**	Target 2050: increase by 60% on managed land	**S6a**	**1**	No decrease	**S2**	**5**
Climate	Carbon in wood and soil (t CO_2 ha^{-1})	No decrease	**S2**	**1**	No decrease	**S2**	**1**	No decrease	**S2**	**5**
Recreation	Recreation index (-)	No decrease	**S2**	**1**	No decrease	**S2**	**1**	No decrease	**S2**	**5**
Water	Share of regime CCF (%)				10%	**S3a**	**1**			
Resilience	Deciduous volume (m^3 ha^{-1})	No decrease	**S2**	**1**	Target 2050: increase by 60% on managed land	**S6a**	**1**	No decrease	**S2**	**5**

a) No up-to-date indicator models were available for assessing the non-wood and game in Sweden at the time of this study.

4. Climate scenarios

4.1. Nationally Determined Contribution (NDC) scenario

This scenario included the 2030 target for the EU as communicated in the Nationally Determined Contribution (NDC) documentation submitted by the EU to the UNFCCC. The scenario as such included a 40% reduction of greenhouse gas emissions by 2030 (from 1990 levels), a 27% share for renewable energy, and a 27% increase in energy efficiency.

This scenario built to a large extent on the achievement of the energy and climate 2030 targets as adopted by the EU leaders in October 2014, further refined on May 2018 with the agreement on the Effort Sharing Regulation and enhanced in June 2018 with the agreement on the recast of Renewable Energy Directive and the revised Energy Efficiency Directive. The scenario thereby built on the 2020 climate and energy package and incorporates several major recently agreed pieces of legislation, as well as recent Commission proposals:

- The revised EU ETS Directive (Directive (EU) 2018/410) which entered into force on 8 April 2018;
- The LULUCF Regulation (Regulation (EU) 2018/841) which entered into force on 9 July 2018;
- The Effort Sharing Regulation (Regulation (EU) 2018/842) which entered into force on 9 July 2018;
- The Energy Performance of Buildings Directive (Directive (EU) 2018/844) which entered into force on 9 July 2018, according to which new buildings are assumed to be nearly zero-energy buildings as of 2020;
- The Commission proposal for the recast of the Renewable Energy Directive. In its agreed version by the European Parliament and the Council on June 14th, 2018 it features a 32% overall RES EU target;
- The Commission proposal for the revision of the Energy Efficiency Directive. In its agreed version by the European Parliament and the Council on June 20th, 2018 it features 32.5% overall Primary Energy Consumption and Final Energy Consumption target (compared to 2007 Baseline), as well as a continuation of Art 7 of EED post-2020 without a sunset clause;
- The Commission proposal for the revision of the Eurovignette Directive;
- The Commission proposal for the revision of Combined Transport Directive;
- The Commission proposal for the revision of Clean Vehicles Directive;
- Regulation on electronic freight transport information;
- The Commission proposal for new CO2 standards for LDVs and HDVs.

It should be noted that it was assumed that the recent EU LULUCF Regulation is included in the EU target but the harvest level for the individual member states and its forest reference level (FRL) estimates was not constrained, as stated in the countries NFAP's (National Forestry Accounting Plan). The reason is that the FRL is only for accounting, and it is not sure yet how member states will implement policies to influence the forest harvest levels as defined in the countries final FRL.

The scenario does not include any target after 2030 as this was neither included in the original EU NDC specifications. Thus, no long-term policy targets (i.e., 2040, 2050, 2100) were included and accounted for in this scenario as set by individual EU member states. Furthermore, it should be noted that these scenarios do not account for the Agriculture, Forestry and Other land use (AFOLU) specific targets and accounting rules put forward in the EU ‘Fit for 55’ proposal (EC 2021), such as the target of the AFOLU sector to become climate neutral by 2035.

4.2.1.5 °C scenario

The overall aim of this scenario was that the EU and the countries commit and actively contribute to the Paris Agreement's temperature objectives of pursuing efforts to limit the global rise in temperature to 1.5℃ by the end of the century (year 2100).

This scenario built up on the NDC scenario for reaching policy targets of 2030 (see section above). At the EU level, it is compatible with the European Commission’s proposal for a climate-neutral Europe by 2030. The scenario thus assumed that EU overall would achieve net-zero greenhouse gas emissions by 2050. It should be noted that net-zero greenhouse gas emissions were here interpreted as the reduction of all greenhouse gases to net zero. However, greenhouse gas emissions neutrality does not imply full decarbonization, as the remaining emissions of CO_2 in the transport, industry and building sectors, and of non-CO_2 greenhouse gases, mostly in agriculture, may be compensated by negative emissions from LULUCF sink (mainly forests) and using Biomass for Energy production coupled with Carbon Capture and Storage (BECCS). At the national level, it was intended to include policies as legislated and currently proposed for the period of 2030 to 2050 (e.g., legislation that Sweden would reach net-zero emissions by the year 2045).

5. Outcomes of Optimal National Management Strategies

Finland

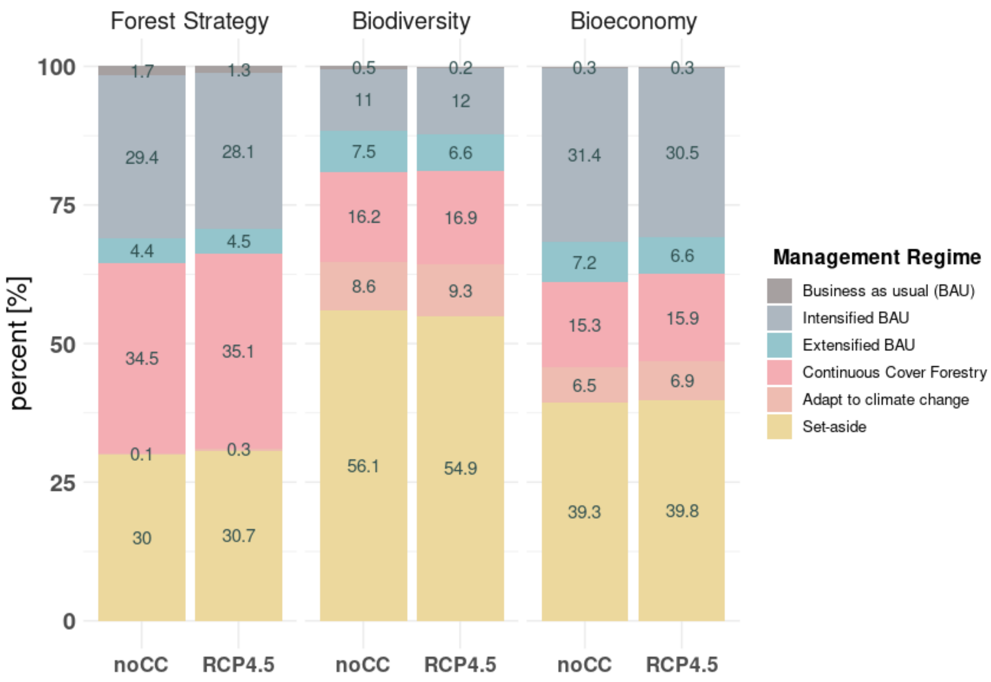

Figure S1. Optimal management solution for the three policy scenarios representing the national forest strategy (NFS), the biodiversity strategy (BDS), and the bioeconomy strategy (BES) in Finland.

Germany

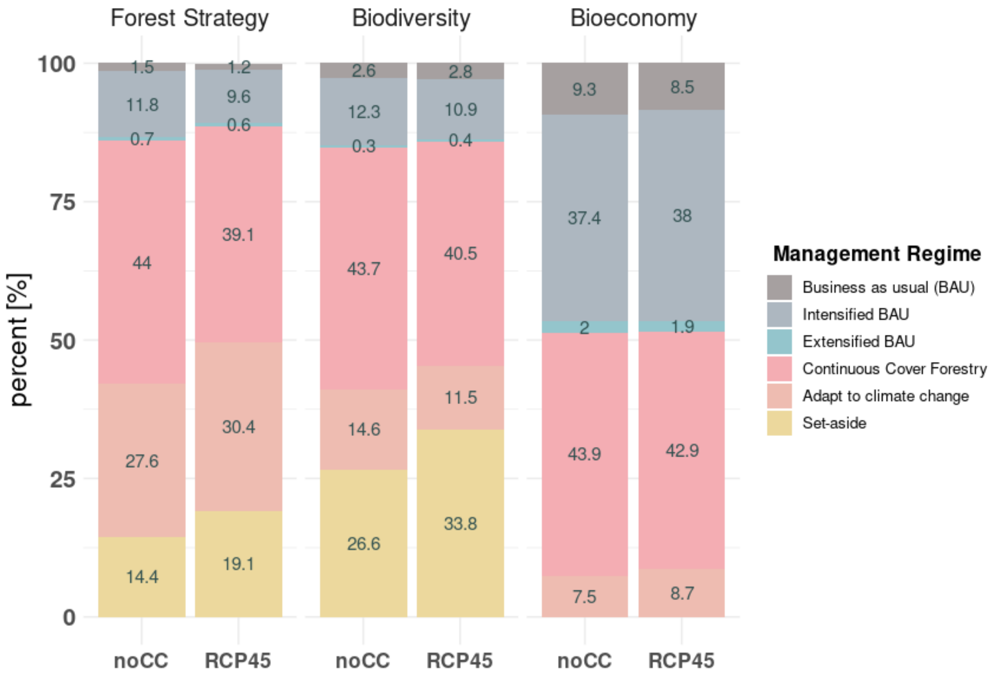

Figure S2. Optimal management solution for the three policy scenarios representing the national forest strategy (NFS), the biodiversity strategy (BDS), and the bioeconomy strategy (BES) in Germany

Norway

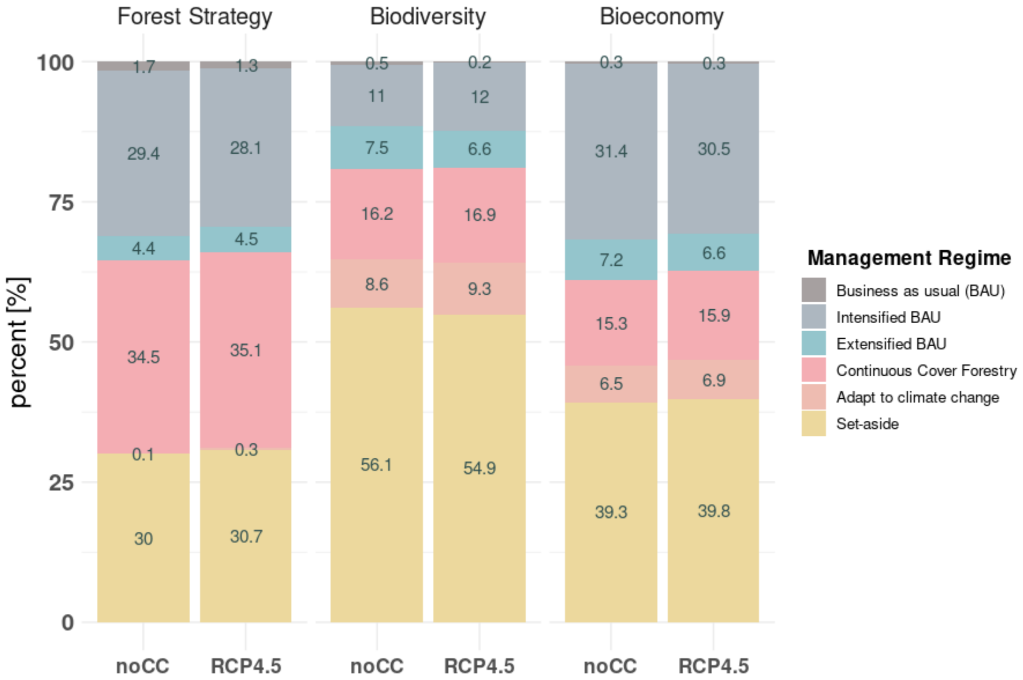

Figure S3. Optimal management solution for the three policy scenarios representing the national forest strategy (NFS), the biodiversity strategy (BDS), and the bioeconomy strategy (BES) in Norway.

Sweden

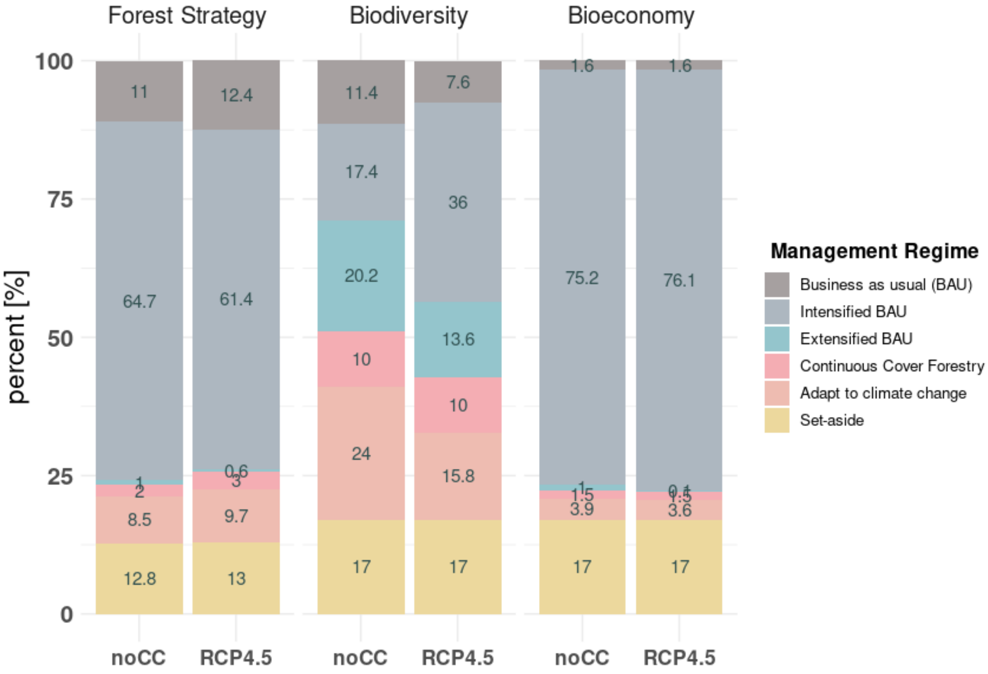

Figure S4. Optimal management solution for the three policy scenarios representing the national forest strategy (NFS), the biodiversity strategy (BDS), and the bioeconomy strategy (BES) in Sweden

6. Muti-objective optimization

For each study area, we used different types of objective functions and constraints to represent the different demands for FESB in our three policy scenarios. These functions are shown in the Supplementary equation S1-S11. Those individual functions and constraints were combined into a logically consistent multi-objective optimization problem, depending on the scenario definitions. See the scenario definition in section 3, the indicators used, and the allocation of the equation types to the different scenarios. The notations of below equations are:

$f_n(x)$	the objective function addressing a FESB indicator
$f_{n,0}$	the objective function addressing a FESB indicator in starting year t_0
P_{target}	the target value for an objective function (FESB indicator)
x_{kj}	the decision for stand k to conduct management regime j
c_{kjt}	the indicator value from stand k according management regime j at the simulation period t (in total 5-year steps over 100years); values of c_{kjt} were normalized in the way that the ideal point becomes *1* and the nadir point becomes *0* by using a pay-off table
K	the total number of stands
J_k	the set of all management regimes for stand *j*
$J_{LandType}$	the smaller set of management regimes on certain land type (e.g., peat, state forest)
T	the total number of simulated periods (t) under consideration. Each forest simulator projected the indicator development in 5-year steps over 100 years.
$Y_{\geq target\ year}$	the set of years equal to and greater than a target year t
a_j	the area of a stand under management *j*
u	positive and negative deviations allowed for a specific target.

Supplementary Equation 1: a) Reach a stated indicator level P_{target} until a target year t and maintain indicator levels for all years afterward; ***b)*** optionally, there is a linear increase required from the current levels to the target level on target year.

a) $f(x) \leq \sum_{k \in K} \sum_{j=1}^{J_k} x_{kj} c_{kjt} - P_{target}\,,\ \forall\ t \in Y_{\geq target\ year}$

b) $f(x) \leq \sum_{k \in K} \sum_{j=1}^{J_k} x_{kj} c_{kjt} - \left(\frac{target\ year - t}{target\ year - t_0} f_0 + \frac{t - t_0}{target\ year - t_0} P_{target}\right),\ \forall\ t \in T \setminus Y_{\geq target\ year}$

Supplementary Equation 2*:* avoid a decrease in indicator level compared to the current state ($t = t_0$) and aim to maximise it further (relative values, maximise the minimum).

$$f(x) \leq \frac{\sum_{k \in K} \sum_{j=1}^{J_k} x_{kj} c_{kjt}}{\sum_{k \in K} \sum_{j=1}^{J_k} x_{kj} c_{kjt_0}},\forall\ t \in T$$

Supplementary Equation 3: a) target a certain percentage share P_{target} of a management regime from the start of the planning horizon or ***b)*** maximize it without a target.

a) $f(x) \leq \frac{\sum_{k \in K} \sum_{j=1}^{J_k} x_{kj}}{\#K} - P_{target}\,,\forall\ t \in T$

b) $f(x) \leq \frac{\sum_{k \in K} \sum_{j=1}^{J_k} x_{kj}}{\#K},\forall\ t \in T$

Supplementary Equation 4: enabled constraint that **a)** restricts management regimes on specific land types (e.g., peatland, state forest) to a smaller set of allowed regimes, and **b)** makes sure the aggregated value of an indicator is u *%* larger/lower than the aggregated value of another indicator.

a) $if\ k = LandType,\ j \in J_{LandType}$

b)

$$\sum_{k \in K} \sum_{j=1}^{J_k} x_{kj} c_{kjt} \geq (1-u) \sum_{k \in K} \sum_{j=1}^{J_k} x_{kj} c_{kjt}^{*}\ ,\forall t \in T$$

$$\sum_{k \in K} \sum_{j=1}^{J_k} x_{kj} c_{kjt} \leq (1+u) \sum_{k \in K} \sum_{j=1}^{J_k} x_{kj} c_{kjt}^{*}\ ,\forall t \in T$$

$c_{kjt}^{*} \setminus c_{kjt}$

Supplementary Equation 5: maximize an ecosystem service indicator, with different planning horizons: ***a)*** minimum value over years that leads to the even-flow solution, ***b)*** last year value, ***c)*** average value over years, and ***d)*** for the sum over years.

a) $f(x) = min_{t\in T}\left(\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}\right)$

b) $f(x) = \sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kj\#T}$

c) $f(x) = \sum_{t\in T}\frac{\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}}{\#T}$

d) $f(x) = \sum_{t\in T}\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}$

Supplementary Equation 6: a) increase the indicator by a certain percentage (P_{target}) until a target year in comparison to the initial situation, ***b)*** optionally, there is a linear increase required from the current levels to the target level on target year.

a) $f(x) \le \frac{\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}}{\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt_0}} - P_{target}\ ,\forall t \in Y_{\ge target\ year}$

b) $f(x) \le \frac{\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}}{\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt_0}} - (\frac{target\ year - t}{target\ year - t_0} f_0 + \frac{t - t_0}{target\ year - t_0} P_{target})\ ,\forall t \in T \setminus Y_{\ge target\ year}$

Supplementary Equation 7: minimize an ecosystem service indicator (maximum value over years).

$$f(x) = max_{t\in T}\left(\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}\right)$$

Supplementary Equation S8: maximize an ecosystem service indicator (minimum value over years) in **a subgroup** of plots (e.g., maximize harvests of stands with harvest costs < 150/200 *Norwegian krone).*

$$f(x) = min_{t\in T}\left(\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}^{*}\right)$$

$$c_{kjt}^{*} = c_{kjt}\ if\ c_{kjt}^{*} < 150/200\ NOK\ , \qquad and\ zero\ otherwise$$

Targeting the GLOBIOM timber demands (P_{target}) and considering an assortment transfer to meet the demands was represented by the following equation.

Supplementary Equation S9: minimize the maximum difference between possible harvest and targeted timber demands: **a)** where harvests can still exceed demands, and **b)** with aiming for "exact" matching of demands as a constraint. The combination of assortments for demand matching (transfer of higher-class assortment to lower classes) classes can be defined by the decision maker

a) $f(x) = max_{t\in T}\left(max\left(\sum_{j=1}^{J_k} x_{kj}c_{kjt} - P_{target,t}\right),\ max\left(P_{target,t}\ -\ \sum_{j=1}^{J_k} x_{kj}c_{kjt}\right)\right)$

b) $f(x) = max_{t\in T}\left(max\left(\sum_{j=1}^{J_k} x_{kj}c_{kjt} - P_{target,t}\right),\ max\left(P_{target,t}\ -\ \sum_{j=1}^{J_k} x_{kj}c_{kjt}\right)\right) =\ 0$

Supplementary Equation S10: All objective functions are subject to the ***area constraint*** that each stand needs to be completely assigned to some management regime j:

$$\sum_{j=1}^{J_k} x_{kj} = a_j\ , \forall\ k \in K$$

Supplementary Equation S11: All functions are subject to an augmentation term that makes the optimization efficient, i.e. forcing secondarily the other objective function(s) within the multi-objective problem to be optimal:

$$\rho \sum\nolimits_{t\in T} \sum\nolimits_{k\in K} \sum_{j=1}^{J_k} x_{kj}c_{kjt}$$

Supplementary Equation S12: The individual objective functions were optimized by formulation of unique multi-objective optimization problems, each representing one optimization scenario (Miettinen 1999a):

$$\min_{x}\ \{f_1(x), \dots,\ f_n(x)\}$$

$$subject\ to\ \ x \in S$$

Here $f_n(x)$ denotes the individual objective functions, x the vector of management regimes that are to be chosen in the optimization, and S is the feasible set of management regimes determined by a set of constraints.

Each objective function can be interpreted as setting targets for the relevant demands (FESB indicators, timber demands for climate mitigation). Technically this was done by implementing two approaches: 1) so-called achievement scalarizing function (ASF) of Wierzbicki (1986), which can be seen as "soft targets" or so-called reference points that are aimed to be achieved, but that will be relaxed if targets cannot be reached; 2) so called epsilon constraint method (Miettinen 1999b), which can be interpreted as set strict maximal (or minimal) levels for minimization (or maximization) objectives. Solving the multi-objective optimization problem resulted from combining the two methods.

Supplementary Equation S13: The first component of the objective is an ASF function to be optimized (Hartikainen et al. 2016), incorporating the ε-constraint method:

$$s^{asf}: f(Q) \times R^{\tau} \rightarrow R,$$

$$\left(z, z^{ref}\right) \mapsto max_{i \in \tau}\left(z_i - z_i^{ref}\right)/\left(z_i^{ideal} - z_i^{nadir}\right)$$

$$+\rho \sum_{i \in \tau} z_i/\left(z_i^{ideal} - z_i^{nadir}\right)$$

subject to:

$$f_l(x) \leq \varepsilon_l \ \forall \ l \in \tau$$

$$x \in S$$

where τ is the set of objectives assigned to the ASF function, with $f(Q)$ being the feasible objective set, i.e. the set of all objective vectors that can be obtained from feasible solutions, and the elements of it being the objective vectors z. The reference points $z^{ref} \in R^{\tau}$ are provided as the aspiration levels, which are the desired values of objective functions that should be achieved. The objective vector z is in the image space of the feasible set, with z^{ideal} being the ideal vector of the problem (maximum values of objectives) and z^{nadir} being the nadir vector (minimum of individual objective) within the set of Pareto optimal solutions. The summation term at the end is a so-called augmentation term guaranteeing that the solutions are indeed Pareto optimal and not just weakly Pareto optimal, with ρ denoting an arbitrary small positive constant, e.g., the machine epsilon.

The overall complexity of multi-functional optimization scenarios required using a lexicographic approach (Miettinen 1999c) to balance among different demands and solve the optimization problem. Therefore, optimizations were done groupwise in sequential steps. The objective functions are numbered according to the order of optimization steps (**Table S6 – Table S9**), i.e., $g_1(x)$ is the first function(s) group by the priority of policy demands, second is the objective $g_r(x)$, and finally $g_{\#G}(x)$.

Supplementary Equation S14: The optimization consists in solving the problem according to its lexicographic ordering.

$$Lex(\min x) = \; g_1(x), g_r(x), g_{\#G}(x), r \in \{2, \dots, \#G - 1\}$$

The optimal solution of the lexicographic optimization problem is the solution of the last problem in the sequence $g_{\#G}(x)$. The optimization framework comes with a graphical user interface. This allowed setting flexibly and iteratively (sequential optimization steps) both options for the objective functions: soft reference points and hard upper/lower targets as epsilon constraints.

The newly developed multi-objective optimization framework was implemented in python and defines the common optimization rules. Each country applied the same python class, which was called in study regions specific Jupyter notebooks. Within the notebooks, the optimization problems were tailored to represent the specific national scenarios. For demonstration, we uploaded the Jupyter notebook for Finland on an online repository together with a sample dataset:

(https://github.com/maeehart/MultiForestDemonstration/tree/master/EUclimate_vs_natPolicy)

7. Complete timely development of each Forest ecosystem class for each climate, policy scenario and country.

A comparison of the time series of the six FESB, wood, bioenergy, biodiversity, climate, water and recreation, over the simulation period.

Finland

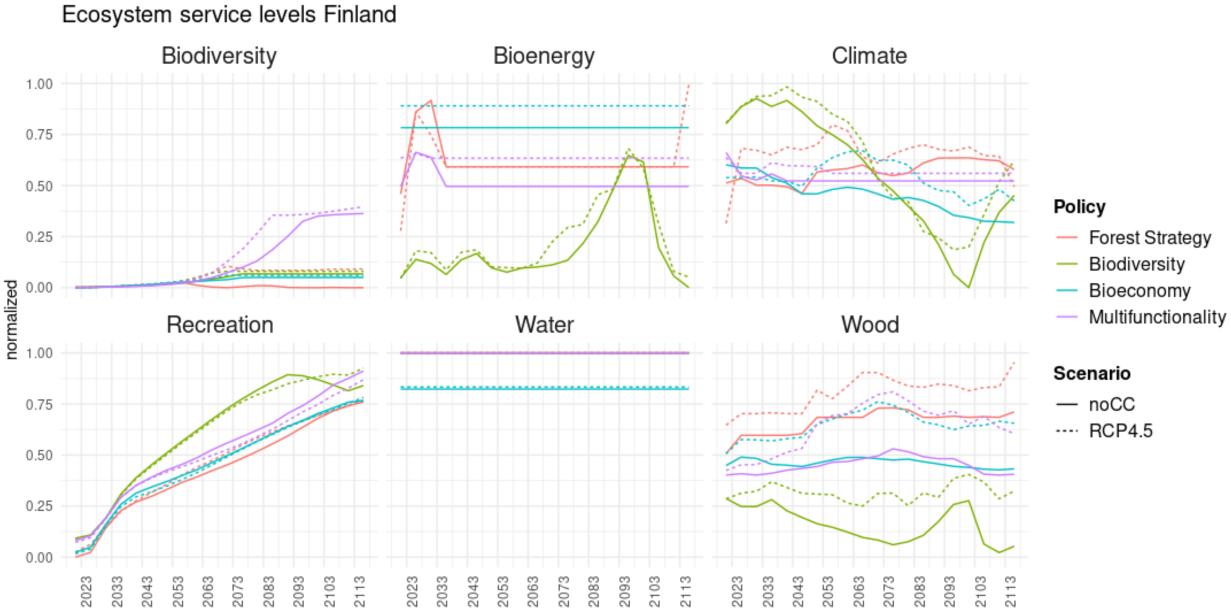

Figure S5. Effect of the optimal solution on the future development of forest ecosystem services indicators in Finland. NFS = national forest scenario, BIOS = biodiversity scenario, and BIES = bioeconomy scenario

Germany

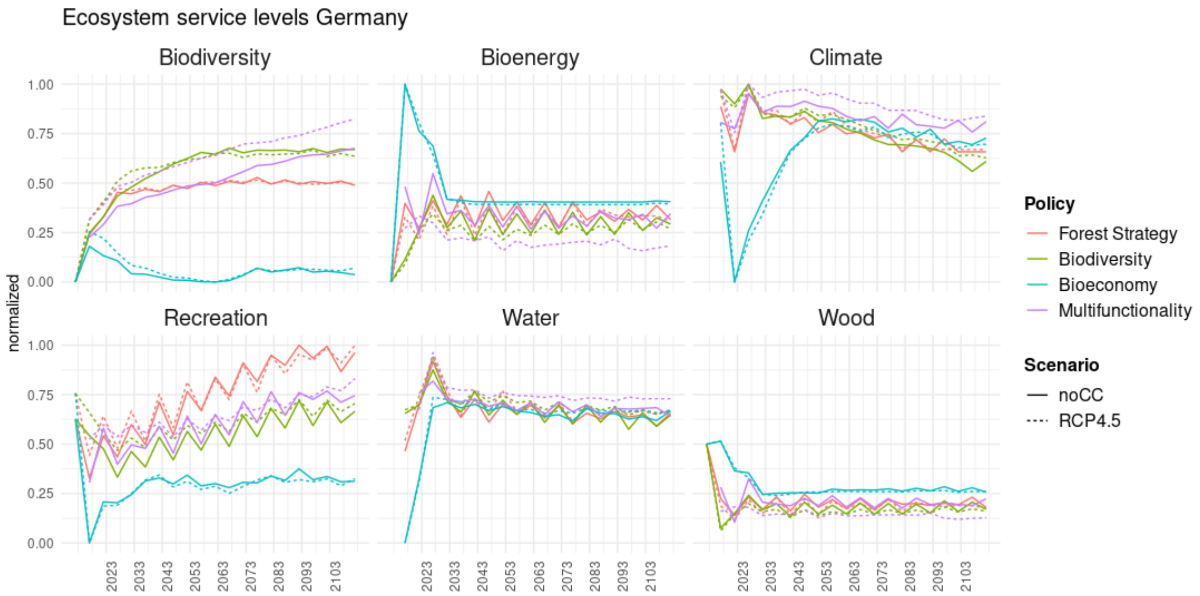

Figure S6. Effect of the optimal solution on the future development of forest ecosystem services indicators in Germany. NFS = national forest scenario, BIOS = biodiversity scenario, and BIES = bioeconomy scenario

Norway

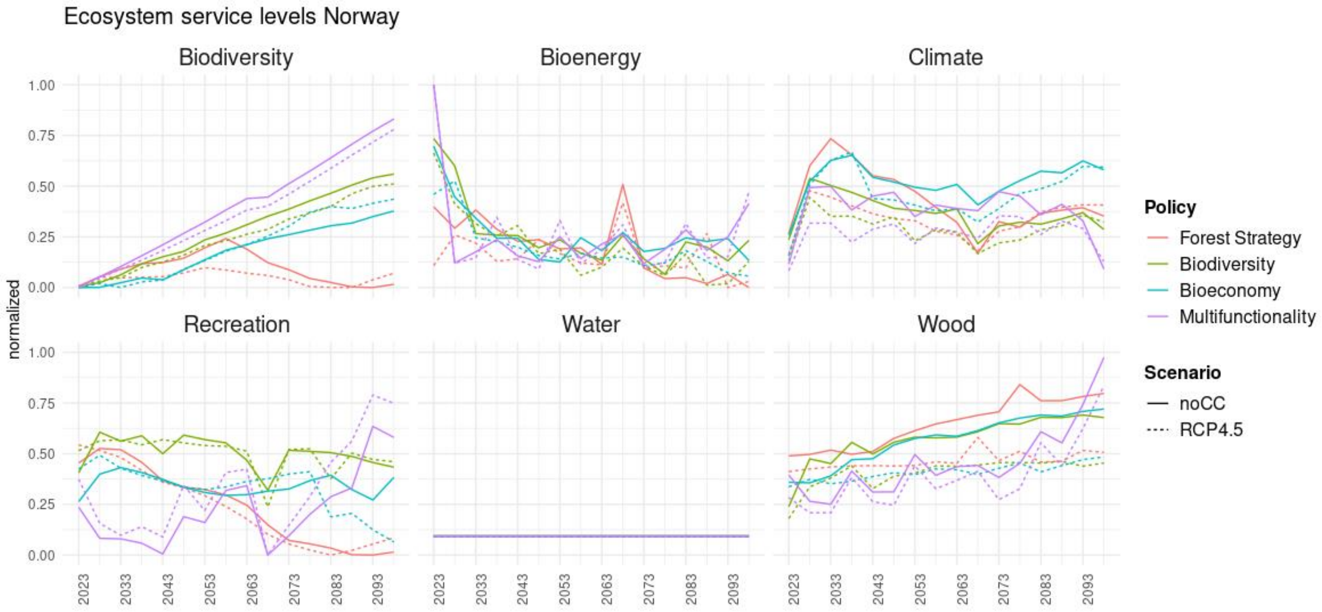

Figure S7. Effect of the optimal solution on the future development of forest ecosystem services indicators in Norway. NFS = national forest scenario, BIOS = biodiversity scenario, and BIES = bioeconomy scenario

Sweden

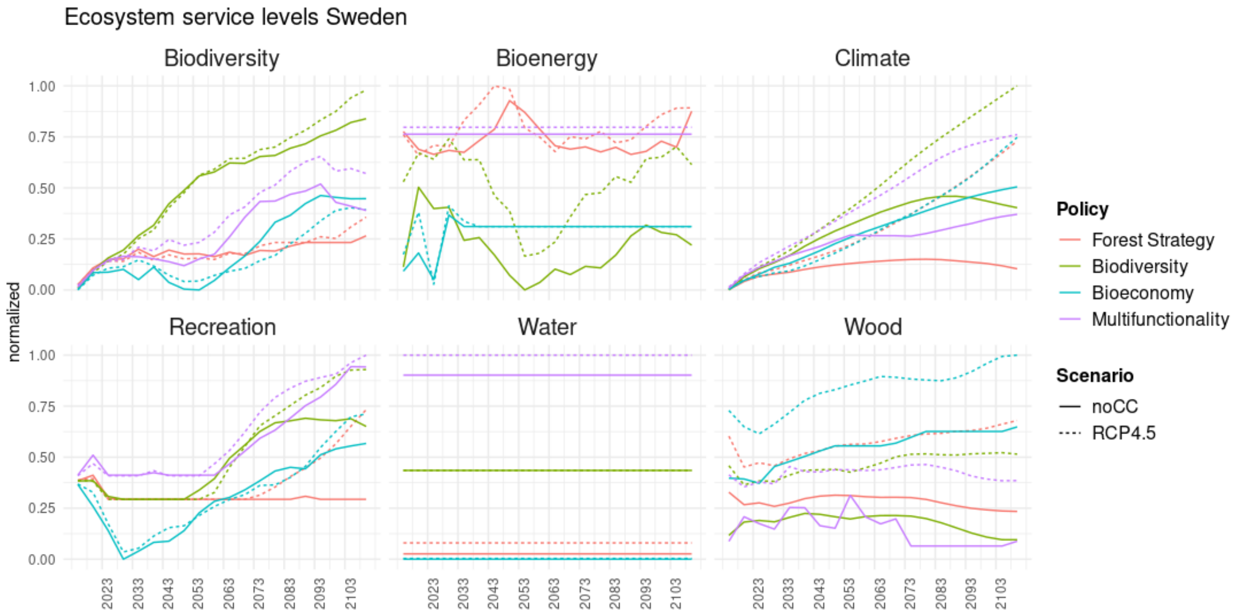

Figure S8. Effect of the optimal solution on the future development of forest ecosystem services indicators in Sweden. NFS = national forest scenario, BIOS = biodiversity scenario, and BIES = bioeconomy scenario

8. Radar plot comparing each policy scenario and Max MF scenario for no CC

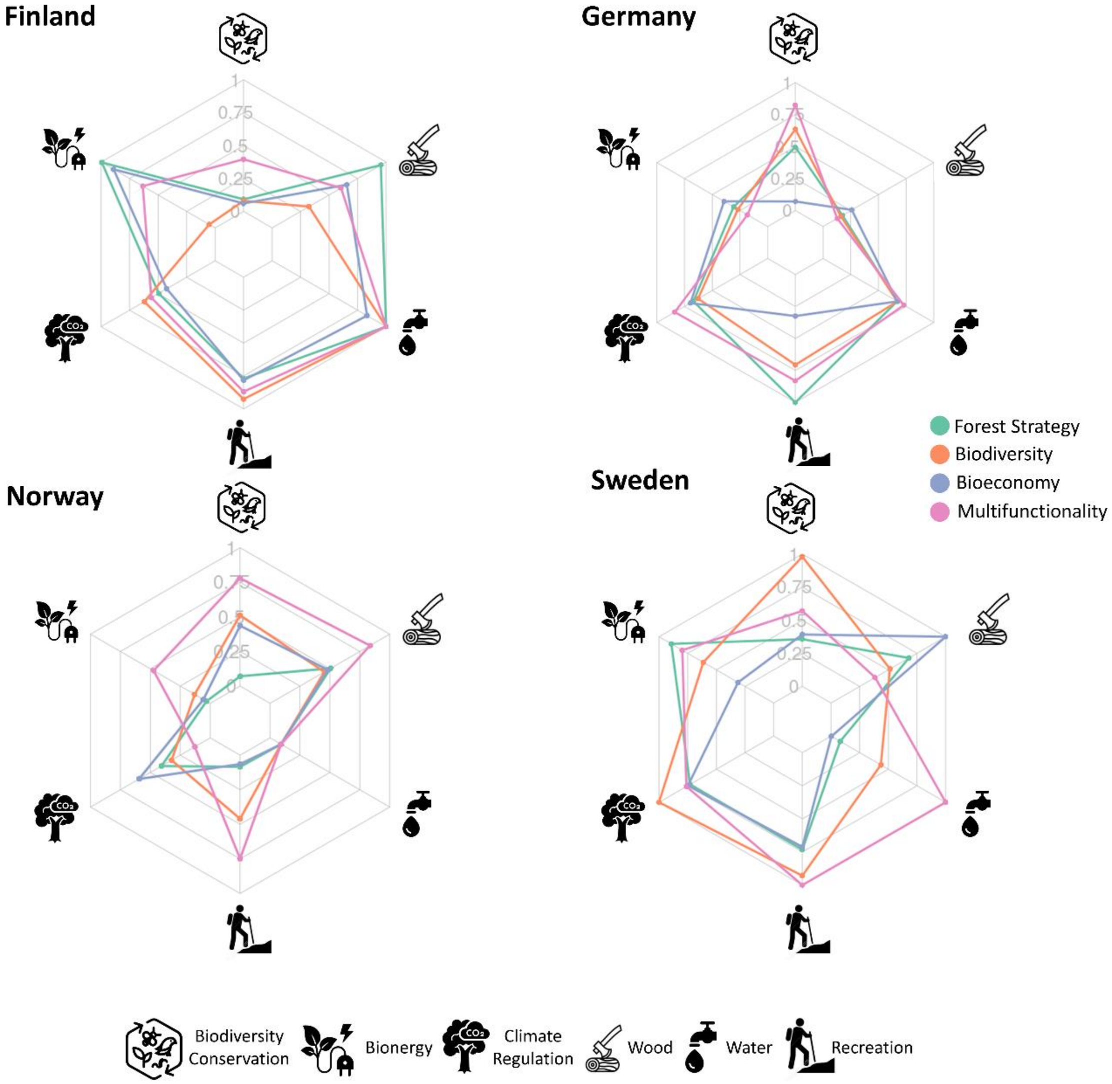

Figure S9: Comparison of the provision of Forest Ecosystem Services and Biodiversity for the national sectoral scenarios (National Forest, Biodiversity and Bioeconomy strategies)) and the potential Maximum Multifunctionality scenario during 100 years for each of the study areas. Results are for the noCC climate scenario.

9. FESB for a multifunctional management

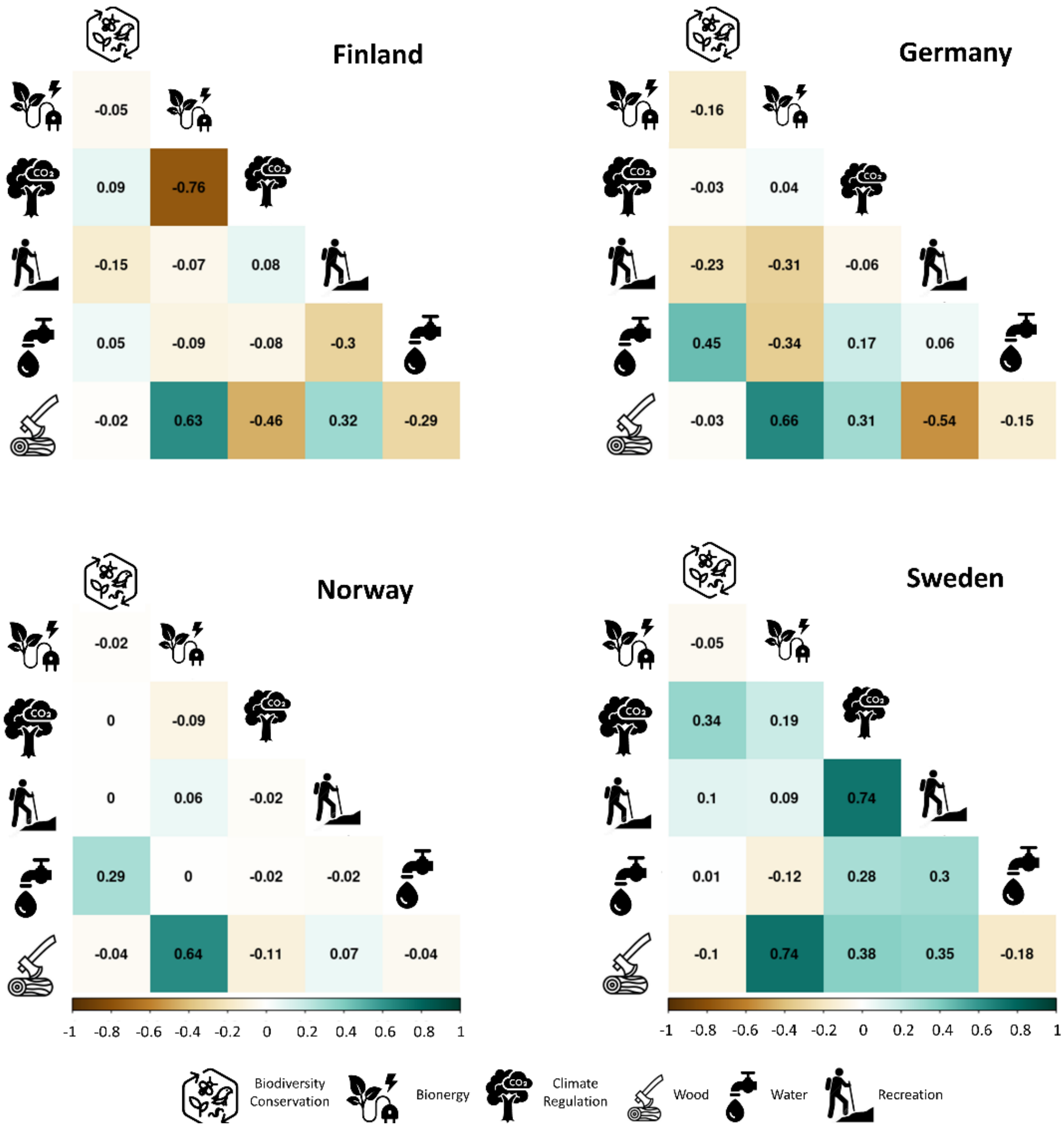

Figure S10. Synergies and trade-offs among the six FESB selected for the potential maximum MF scenario and the no CC climate scenario. Values correspond to pairwise Pearson's correlation coefficients between indicators (positive correlations = synergies and negative correlation = trade-offs).

References

Äijälä, O., A. Koistinen, J. Sved, K. Vanhatalo, and P. Väisänen. 2014. Hyvän metsänhoidon suositukset [Good forest management recommendations]. Forestry Development Center Tapio [In Finnish].

Antón-Fernández, C., and R. Astrup. 2022. SiTree: A framework to implement single-tree simulators. SoftwareX **18**:100925.

Antón-Fernández, C., B. Mola-Yudego, L. Dalsgaard, and R. Astrup. 2016. Climate-sensitive site index models for Norway. Canadian Journal of Forest Research **46**:794-803.

Bergh, J., M. Freeman, B. Sigurdsson, S. Kellomäki, K. Laitinen, S. Niinistö, H. Peltola, and S. Linder. 2003. Modelling the short-term effects of climate change on the productivity of selected tree species in Nordic countries. Forest Ecology and Management **183**:327-340.

Biber, P., F. Schwaiger, W. Poschenrieder, and H. Pretzsch. 2021. A fuzzy logic-based approach for evaluating forest ecosystem service provision and biodiversity applied to a case study landscape in Southern Germany. European Journal of Forest Research **140**:1559-1586.

BMBF, and BMEL. 2020. National Bioeconomy Strategy. Federal Ministry of Education and Research (BMBF) and Federal Ministry of Food and Agriculture (BMEL). Berlin.

BMELV. 2011. Forest Strategy 2020. Sustainable Forest Management - An Opportunity and a Challenge for Society. Federal Ministry of Food, Agriculture and Consumer Protection (Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz, BMELV). Bonn.

BMU. 2007. National Strategy on Biological Diversity. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). Berlin.

Brang, P., W. Schönenberger, M. Frehner, R. Schwitter, J. J. Thormann, and B. Wasser. 2006. Management of protection forests in the European Alps: An overview. Forest Snow and Landscape Research **80**:23-44.

Breidenbach, J., A. Granhus, G. Hylen, R. Eriksen, and R. Astrup. 2020. A century of National Forest Inventory in Norway – informing past, present, and future decisions. Forest Ecosystems **7**.

EC. 2021. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee for the Regions. 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality. COM(2021) 550 final. Brussels.

Eyvindson, K., R. Duflot, M. Triviño, C. Blattert, M. Potterf, and M. Mönkkönen. 2021. High boreal forest multifunctionality requires continuous cover forestry as a dominant management. Land Use Policy **100**:104918.

Fahlvik, N., B. Elfving, and P. Wikström. 2014. Evaluation of growth functions used in the Swedish Forest Planning System Heureka.

FMAF. 2015. National Forest Strategy 2025 – Government Resolution of 12 February 2015. Publications of the Finnish Ministry of Agriculture and Forestry (FMAF) 6b/2015. Helsinki.

FMAF. 2019. The National Forest Strategy 2025 – an updated version Government Resolution of 21 February 2019. Publications of the Finnish Ministry of Agriculture and Forestry (FMAF) 2019:17. Helsinki.

FME. 2012. Saving Nature for People - National action plan for the conservation and sustainable use of biodiversity in Finland 2013–2020, Publikation of the Finnish Ministry of the Environment (FME). Finland.

FMME, FMAF, and FME. 2014. Finnish Bioeconomy Strategy - Sustainable growth from bioeconomy. Publication of the Finnish Ministry of Employment and Economy (FMEE), Ministry of Agriculture and Forestry (FMAF), Ministry of the Environment (FME). Finland.

Frank, S., C. Fürst, L. Koschke, A. Witt, and F. Makeschin. 2013. Assessment of landscape aesthetics - Validation of a landscape metrics-based assessment by visual estimation of the scenic beauty. Ecological Indicators **32**:222-231.

Fridman, J., S. Holm, M. Nilsson, P. Nilsson, A. Ringvall, and G. Ståhl. 2014. Adapting National Forest Inventories to changing requirements – the case of the Swedish National Forest Inventory at the turn of the 20th century.

Fridman, J., and G. Ståhl. 2001. A Three-step Approach for Modelling Tree Mortality in Swedish Forests. Scandinavian Journal of Forest Research **16**:455-466.

Gao, T., A. B. Nielsen, and M. Hedblom. 2015. Reviewing the strength of evidence of biodiversity indicators for forest ecosystems in Europe. Ecological Indicators **57**:420-434.

Gjerde, I., M. Sætersdal, and H. H. Blom. 2007. Complementary Hotspot Inventory – A method for identification of important areas for biodiversity at the forest stand level. Biological Conservation **137**:549-557.

Hartikainen, M., K. Eyvindson, K. Miettinen, and A. Kangas. 2016. Data-Based Forest Management with Uncertainties and Multiple Objectives. Pages 16-29. Springer International Publishing, Cham.

INNRC. 2015. SKOG22 Nasjonal Strategi for Skog- og Trenaeringen. Innovation Norway and Norway Research Council (INNRC). Oslo.

IPCC. 2006. Guidlines for National Greenhouse Gas Inventories. Volume 4. Agriculutre, Forestry and Other Land Use. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.

Jones, C. D., J. K. Hughes, N. Bellouin, S. C. Hardiman, G. S. Jones, J. Knight, S. Liddicoat, F. M. O'Connor, R. J. Andres, C. Bell, K. O. Boo, A. Bozzo, N. Butchart, P. Cadule, K. D. Corbin, M. Doutriaux-Boucher, P. Friedlingstein, J. Gornall, L. Gray, P. R. Halloran, G. Hurtt, W. J. Ingram, J. F. Lamarque, R. M. Law, M. Meinshausen, S. Osprey, E. J. Palin, L. Parsons Chini, T. Raddatz, M. G. Sanderson, A. A. Sellar, A. Schurer, P. Valdes, N. Wood, S. Woodward, M. Yoshioka, and M. Zerroukat. 2011. The HadGEM2-ES implementation of CMIP5 centennial simulations. Geosci. Model Dev. **4**:543-570.

Jost, L. 2006. Entropy and diversity. Oikos **113**:363-375.

Kontula, T., and A. Raunio. 2019. Threatened Habitat Types in Finland 2018. Red List of Habitats – Results and Basis for Assessment. Finnish Environment Institute and Ministry of the Environment, Helsinki.

Kublin, E. 2003. Einheitliche Beschreibung der Schaftform – Methoden und Programme –BDATPro. Forstwissenschaftliches Centralblatt **122**:183-200.

Kukkola, M., and J. Saramäki. 1983. Growth response in repeatedly fertilized pine and spruce stands on mineral soils. Commun. Inst. For. Fenn. **114**:1-55.

Kurttila, M., T. Pukkala, and J. Loikkanen. 2002. The performance of alternative spatial objective types in forest planning calculations: A case for flying squirrel and moose. Forest Ecology and Management **166**:245-260.

Larsson, S., T. Lundmark, and G. Ståhl. 2009. Possibilities for intensive growth of forest (MINT), Governmental task Jo 2008/1885.

Lehtonen, I., A. Venäläinen, M. Kämäräinen, H. Peltola, and H. Gregow. 2016. Risk of large-scale fires in boreal forests of Finland under changing climate. Nat. Hazards Earth Syst. Sci. **16**:239-253.

Lind, T. 2007. Rekreationsindex-bestånd, Projekt: 2.3 Rekreation SLU, Umeå.

Liski, J., T. Palosuo, M. Peltoniemi, and R. Sievänen. 2005. Carbon and decomposition model Yasso for forest soils. Ecological Modelling **189**:168-182.

Mäkinen, H., J. Hynynen, J. Siitonen, and R. Sievänen. 2006. Predicting the decomposition of Scots pine, Norway spruce, and birch stems in Finland. Ecol Appl **16**:1865-1879.

Mäkisara, K., M. Katila, and J. Peräsaari. 2019. The Multi-Source National Forest Inventory of Finland – methods and results 2015. Natural resources and bioeconomy studies 8/2019. Natural Resources Institute Finland, Helsinki.

Marttila, H., A. Lepistö, A. Tolvanen, M. Bechmann, K. Kyllmar, A. Juutinen, H. Wenng, E. Skarbøvik, M. Futter, P. Kortelainen, K. Rankinen, S. Hellsten, B. Kløve, B. Kronvang, Ø. Kaste, A. L. Solheim, J.

Bhattacharjee, J. Rakovic, and H. de Wit. 2020. Potential impacts of a future Nordic bioeconomy on surface water quality. Ambio **49**:1722-1735.

MCE. 2015. Natur for livet. Norsk handlingsplan for naturmangfold. Ministry of Climate and Environment (MCE). Oslo.

McMurtrie, R. E., D. A. Rook, and F. M. Kelliher. 1990. Modelling the yield of Pinus radiata on a site limited by water and nitrogen. Forest Ecology and Management **30**:381-413.

Miettinen, K. 1999a. Nonlinear Multiobjective Optimization. Springer, Boston, MA.

Miettinen, K. 1999b. A Posteriori Methods. Pages 77-113 Nonlinear Multiobjective Optimization. Springer US, Boston, MA.

Miettinen, K. 1999c. A Priori Methods. Pages 115-129 Nonlinear Multiobjective Optimization. Springer US, Boston, MA.

Miina, J., J.-P. Hotanen, and K. Salo. 2009. Modelling the abundance and temporal variation in the production of bilberry (Vaccinium myrtillus L.) in Finnish mineral soil forests.

Miina, J., M. Kurttila, R. Calama, S. de-Miguel, and T. Pukkala. 2020. Modelling Non-timber Forest Products for Forest Management Planning in Europe. Current Forestry Reports **6**:309-322.

Mönkkönen, M., A. Juutinen, A. Mazziotta, K. Miettinen, D. Podkopaev, P. Reunanen, H. Salminen, and O.-P. Tikkanen. 2014. Spatially dynamic forest management to sustain biodiversity and economic returns. Journal of Environmental Management **134**:80-89.

Müller, J., and R. Bütler. 2010. A review of habitat thresholds for dead wood: A baseline for management recommendations in European forests. European Journal of Forest Research **129**:981-992.

Nieminen, M., H. Hökkä, R. Laiho, A. Juutinen, A. Ahtikoski, M. Pearson, S. Kojola, S. Sarkkola, S. Launiainen, S. Valkonen, T. Penttilä, A. Lohila, M. Saarinen, K. Haahti, R. Mäkipää, J. Miettinen, and M. Ollikainen. 2018. Could continuous cover forestry be an economically and environmentally feasible management option on drained boreal peatlands? Forest Ecology and Management **424**:78-84.

Nieminen, M., T. Sallantaus, L. Ukonmaanaho, T. M. Nieminen, and S. Sarkkola. 2017. Nitrogen and phosphorus concentrations in discharge from drained peatland forests are increasing. Science of The Total Environment **609**:974-981.

NMAF. 2016. Verdier i vekst. Konkurransedyktig skog- og trenæring. Meld. St. 6 (2016 – 2017). Norwegian Ministry of Agriculture and Food (NMAF). Oslo.

Ojanen, P., A. Lehtonen, J. Heikkinen, T. Penttilä, and K. Minkkinen. 2014. Soil CO2 balance and its uncertainty in forestry-drained peatlands in Finland. Forest Ecology and Management **325**:60-73.

Pretzsch, H. 2009. Forest dynamics, growth and yield: from measurement to model. Berlin: Springer-Verlag.

Pretzsch, H., P. Biber, and J. Ďurský. 2002. The single tree-based stand simulator SILVA: construction, application and evaluation. Forest Ecology and Management **162**:3-21.

Pukkala, T. 2017. Optimal nitrogen fertilization of boreal conifer forest. Forest Ecosystems **4**:3.

Pukkala, T., S. Kellomaki, and E. Mustonen. 1988. Prediction of the amenity of a tree stand. Scandinavian Journal of Forest Research - SCAND J FOREST RES **3**:533-544.

Pukkala, T., T. Nuutinen, and J. Kangas. 1995. Integrating scenic and recreational amenities into numerical forest planning. Landscape and Urban Planning **32**:185-195.

Rasinmäki, J., A. Mäkinen, and J. Kalliovirta. 2009. SIMO: An adaptable simulation framework for multiscale forest resource data. Computers and Electronics in Agriculture **66**:76-84.

SFA. 2015. National Forest Impact Analysis. SKA 15. Report 10. Swedish Forest Agency.

SFA. 2019. Forest management with new possibilities. Report 24. Swedish Forest Agency.

Shannon, C. E., and W. Weaver. 1949. The mathematical theory of communication. Urbana, Ill. : University of Illinois Press.

Tahvanainen, V., J. Miina, M. Kurttila, and K. Salo. 2016. Modelling the yields of marketed mushrooms in Picea abies stands in eastern Finland. Forest Ecology and Management **362**:79-88.

Timonen, J., J. Siitonen, L. Gustafsson, J. S. Kotiaho, J. N. Stokland, A. Sverdrup-Thygeson, and M. Mönkkönen. 2010. Woodland key habitats in northern Europe: concepts, inventory and protection. Scandinavian Journal of Forest Research **25**:309-324.

Tolkkinen, M. J., J. Heino, S. H. K. Ahonen, K. Lehosmaa, and H. Mykrä. 2020. Streams and riparian forests depend on each other: A review with a special focus on microbes. Forest Ecology and Management **462**:117962.

Tuomi, M., R. Laiho, A. Repo, and J. Liski. 2011. Wood decomposition model for boreal forests. Ecological Modelling **222**:709-718.

Tuomi, M., T. Thum, H. Järvinen, S. Fronzek, B. Berg, M. Harmon, J. A. Trofymow, S. Sevanto, and J. Liski. 2009. Leaf litter decomposition—Estimates of global variability based on Yasso07 model. Ecological Modelling **220**:3362-3371.

Turtiainen, M., J. Miina, K. Salo, and J.-P. Hotanen. 2013. Empirical prediction models for the coverage and yields of cowberry in Finland.

Venäläinen, A., I. Lehtonen, M. Laapas, K. Ruosteenoja, O.-P. Tikkanen, H. Viiri, V.-P. Ikonen, and H. Peltola. 2020. Climate change induces multiple risks to boreal forests and forestry in Finland: A literature review. Global Change Biology **26**:4178-4196.

Vennesland, B., A. Eid Hohle, L. Kjøstelsen, and L. Gobakken. 2013. Prosjektrapport Klimatre. Energiforbruk og kostnader - Skog og bioenergi. Ås.

von Salzen, K., J. F. Scinocca, N. A. McFarlane, J. Li, J. N. S. Cole, D. Plummer, D. Verseghy, M. C. Reader, X. Ma, M. Lazare, and L. Solheim. 2013. The Canadian Fourth Generation Atmospheric Global Climate Model (CanAM4). Part I: Representation of Physical Processes. Atmosphere-Ocean **51**:104-125.

Wierzbicki, A. P. 1986. On the completeness and constructiveness of parametric characterizations to vector optimization problems. Operations-Research-Spektrum **8**:73-87.

Wikberg, P.-E. 2004. Occurrence, morphology and growth of understory saplings in Swedish forests. Swedish University of Agricultural Sciences, Umeå, Sweden.

Wikström, P., L. Edenius, B. Elfving, L. Eriksson, T. Lämås, J. Sonesson, K. Öhman, J. Wallerman, C. Waller, and F. Klintebäck. 2011. The Heureka Forestry Decision Support System: An Overview. MCFNS **3**:87-95.

Wolfslehner, B., I. Prokofieva, and R. Mavsar, editors. 2019. Non-wood forest products in Europe: Seeing the forest around the trees. What Science Can Tell Us 10. European Forest Institute.

Wong, W. K., I. Haddeland, D. Lawrence, and S. Beldring. 2016. Gridded 1 x 1 km climate and hydrological projections for Norway.