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Title: Sectoral policies as drivers of forest management and ecosystems services: A case study in Bavaria, Germany

Year: 2023

Version: Published version

Please cite the original version:

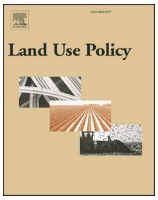
Toraño Caicoya, A., Poschenrieder, W., Blattert, C., Eyvindson, K., Hartikainen, M., Burgas, D., Mönkkönen, M., Uhl, E., Vergarechea, M., & Pretzsch, H. (2023). Sectoral policies as drivers of forest management and ecosystems services: A case study in Bavaria, Germany. Land Use Policy, 130, 106673. https://doi.org/10.1016/j.landusepol.2023.106673

Land Use Policy 130 (2023) 106673

Contents lists available at ScienceDirect

Land Use Policy

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



Sectoral policies as drivers of forest management and ecosystems services: A case study in Bavaria, Germany

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ARTICLE INFO

Keywords:
Biodiversity
Multi-objective optimization
Forest management
Climate change
Forest policy
Scenario analysis

ABSTRACT

European countries have national sectoral polices to regulate and promote the provision of a wide range of forest ecosystems services (FES). However, potential incoherencies among these policies can negatively affect the efficient provision of FES. In this work, we evaluated the coherence among three national policies from Germany and their ability to effectively provide FES in the future: the Forest Strategy 2020 (FS), the National Strategy on Biological Diversity (BDS), and the German National Policy Strategy on Bioeconomy (BES). Using forest inventory data from the Federal State of Bavaria, we simulated a range of forest management options under three climate trajectories for 100 years into the future (2012–2112). Then, with multi-objective optimization, we translated each policy into a specific scenario and identified the best combination of management regimes that maximizes the targets defined in each policy scenario. The three policies were vague in the definition of FES. The FS was the most comprehensive policy aiming for a higher degree of multifunctionality, whereas the BES and BDS focused on less FES. The FS and the BDS showed the highest coherence, while the BES showed a stronger focus on timber production. As a result, the optimal management programs of FS and BDS showed high integration, with a dominance of Continuous Cover Forestry (CCF), and certain shares of set asides. Climate change led to an increase of set aside areas due to increased productivity. In the BES, the share of land among management regimes was strongly segregated between CCF and rotation forestry. Our policy coherence analysis showed that achieving a multifunctional provision of FES requires policy coherence, fostering a diverse management of the landscape that mainly takes advantage of integrative management, like CCF, but also segregates important parts of the landscape for intensive use and set asides. Nevertheless, the current high standing volumes in Bavaria will pose an additional risk to implement such management.

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https://doi.org/10.1016/j.landusepol.2023.106673
Received 8 January 2022; Received in revised form 6 February 2023; Accepted 1 April 2023
Available online 7 April 2023

1. Introduction

Over the last few decades, the need for sustainable and multifunctional forest use has pushed European institutions to promote regulations concerning forest functions and services like timber provision, biodiversity and resilience (Courvoisier et al., 2017; Wolfslehner et al., 2020, p. 113). EU-policies have been adopted on the national level and translated into sectoral strategies following different goals impacting forest management. As a result of the varying objectives that govern the implementation of these policies, conflicting demands may occur, resulting in ineffectiveness or even putting pressure on the forest ecosystem and the provision of services (Aggestam and Pülzl, 2018).

At the European level, forest ecosystem services (FES) are most comprehensively addressed in the EU Forest Strategy (EC, 2013), but they are also represented in other sectoral policies like the EU Biodiversity Strategy (EC, 2011) and the EU Bioeconomy Strategy (EC, 2018). These policies may differ in terms of multifunctionality governance and policy implementation (Primmer et al., 2015; Winkel and Sotirov, 2016), and as there has been no coordination when defining these policies, it is assumed that there is only moderate coherence amongst them (Bouwma et al., 2018). This lack of policy coherence, defined as "the systematic promotion of mutually reinforcing policy actions across government departments and agencies creating synergies towards achieving the intended objectives" (OECD, 2001), is expected to create undesired trade-offs among various FES, which in turn may result in losses of sustainability (Nabuurs et al., 2019; Nilsson et al., 2012). Although it is clear that forest-related policies and governance mechanisms respond to well-known challenges in their socio-ecological and institutional setting, the understanding of how policies interact across scales and across policy sectors is limited (Primmer et al., 2021). Therefore, more coherent policy-making and more integrative strategies are needed, especially when it aims at strengthening interconnections among different economic, social and environmental policy areas (Nilsson et al., 2012).

A key aspect of multifunctionality is the sustainable maintenance of ecosystem functions and flow of FES over time (Hölting et al., 2019; Manning et al., 2018,). Moreover, due to the high demand for wood-based products in Europe, forest management should not overlook sustainable wood production when incorporating the provision of different FES. In Germany, the model of integrative, multifunctional forestry has been reinforced for decades, highlighting the provision of multiple FES across the landscape and safeguarding wood production at the same time (Borrass et al., 2017; Suda and Pukall, 2014). However, forest planning is still mainly focused on sustainable flow of timber and neglects other FES. As many scenario studies (Pohjanmies et al., 2021) indicate an accelerated future demand of wood products, a common expectation is the need for increased wood harvest in the future. Additionally, this sustainability of regional forest productivity may decline due to climate change induced higher vulnerability of forest ecosystems (Gutsch et al., 2018; Hanewinkel et al., 2013).

While accounting for provisioning of various FES, forest management should not disregard sustainable wood production due to high demand in wood-based products in Europe (Buongiorno et al., 2011; Hetemäki et al., 2017, p. 50). Due to the intrinsic inertia of forest ecosystems, forest management decisions may be effective on the provision of FES decades later (Nikinmaa et al., 2020). Biber et al. (2021) concluded that there is still potential to steer a balanced provision of biodiversity, sustainable wood production, and carbon sequestration from European forests. Thus, we need to know to what extent forests can maintain multifunctionality while being managed for timber production within different climate change pathways, and how policies can support long-term sustainability of forest multifunctionality. Moreover, it is necessary to analyze the potential long-term impacts of the forest sectoral policies following different societal demands, as well as their consequences for forest ecosystems and forest management. To facilitate the intersectoral, political discussion process, we need to understand how well current strategies are designed and implemented on the national level (Linkevičius et al., 2019; Wolfslehner et al., 2020, p. 51).

Previous studies have shown the trade-offs that due to forest management appear among FES (Vizzarri et al., 2015; Biber et al., 2015) and the impact of stakeholder demands (Corrigan and Nieuwenhuis, 2017) making recommendations for future policy integration (Sotirov and Arts, 2018). However, studies at landscape to national scale, that combine governmental research and long-term forest management for all European regions are lacking. Recently, Blattert et al. (2022) used a multi-objective optimization tool to analyze main forest sectoral polices in Finland, noting incoherence amongst them. In our study, we used a similar optimization approach to analyze the coherence and alignment of the national specifications of EU strategies in Germany, focusing on the FES response from a Central European forest management perspective. Particularly, we explored multifunctional forestry in Germany, and the degree to which the main forestry sectoral policies can be implemented and how coherent the policy objectives are. This is also important with regard to EU level policy since Bavarian conditions may serve as an example of policy implementation in high productive central European forest conditions, which is distinctive to the boreal forest conditions analyzed by Blattert et al. (2022). Finally, through this study, we introduce a multi-objective optimization methodology that expands the knowledge of other works that analyzed forest multifunctionality and its policy implications (Eyvindson et al., 2018, 2021) with state of the art management simulations from Central Europe. For our analysis, we considered the German Forest Strategy 2020 (BMELV, 2011), the National Strategy on Biological Diversity (BMU, 2007), and the German National Bioeconomy Strategy (BMEL, 2020). These strategies represent the current valid national consolidations of the EU level forest, biodiversity and bioeconomy strategies. Specifically, with this work we aim to answer the following questions:

Q1: Which is the optimum combination of management practices for each policy strategy at the landscape scale?

Q2. What are long-term effects of current national sectoral policies on the provision of forest ecosystem services?

Q3. What is the coherence among policy documents analyzed through policy scenarios?

2. Methods

2.1. Concept and workflow

The study work was divided in three phases: the preparation of the data (Fig. 1 – A), simulation of management (Fig. 1B – D) and multi-objective optimization (Fig. 1 E). During the first phase, we stratified the NFI data from Bavaria as case study (Section 2.2). Then, we defined set of plausible and commonly used management regimes (Section 2.3) which were simulated under three climate trajectories (Section 2.4). These simulations provided information on FES development that were characterized based on forest structural variables (dominant height, stand density, crown cover, etc.) and fuzzy indicators (indicators between 0 and 1 estimated from a combination of forest characteristics using fuzzy logic), estimated according to Biber et al. (2021) for each simulation pathway (Section 2.5).

Based on the evaluated policy objectives and constraints that target FES, each policy document was translated into a corresponding Policy Scenario developing objective functions and constraints for each targeted FES. For this, we evaluated the three main sectoral policy documents that target forests in Germany: the National Forest (FS), Biodiversity (BDS) and Bioeconomy (BES) strategies and developed three corresponding Policy Scenarios with three climate pathways (no Climate change, RCP2.6 and RCP4.5) (Section 2.6). Finally, through a multi-objective optimization framework, forest landscape management programs were calculated for the extent of the forest landscape of the Federal State of Bavaria (Section 2.7).

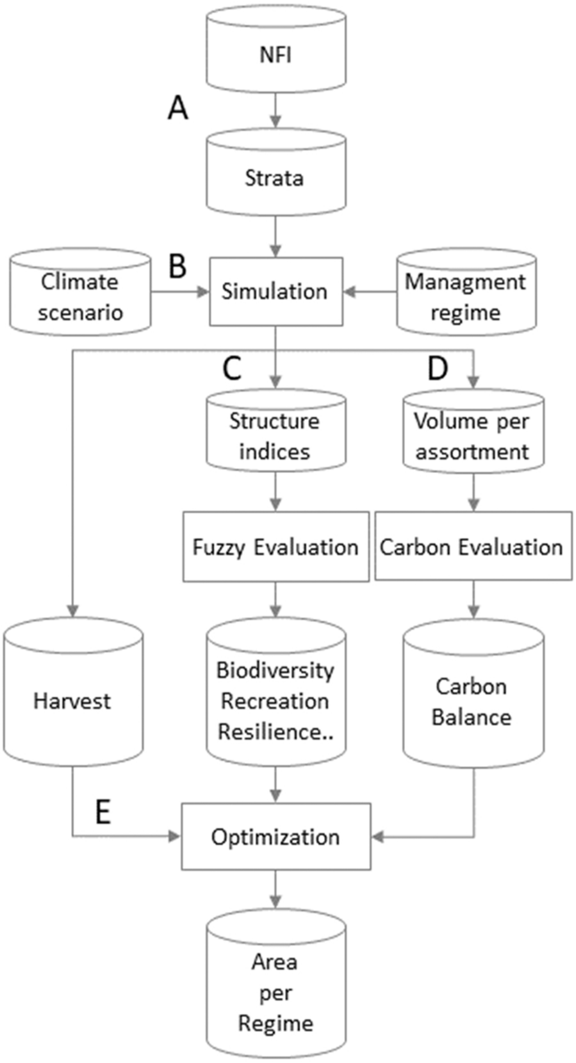

Fig. 1. Data flow of the study, including: (A) the stratification of NFI data to forest stand types, (B) climate-sensitive forest management simulations, (C) forest structure evaluation, (D) grading per sawn timber, pulpwood and residuals, and (E) multi-objective optimization that yields the area per management regime within the climate scenario being considered (see B).

2.2. Data set: NFI in Bavaria

This study focuses on the Federal State of Bavaria, which has heterogeneous site conditions and has a good representation of forest coverage and tenure types of Germany. The region is particularly suited to study the specific effect of each forest related policy on the optimum of forest management. Almost one quarter of German forests are located in Bavaria, as it is covered by 2.6 M ha of forests (31% of the territory, slightly above the national average). From this, 54.2% are private owned forests, 30.1% state owned forests, 13.5% communal forests and 2.2% federal forests. The main tree species by area are Norway spruce (*Picea abies (L.) H. Karst.*) (40.9%), Scots pine (*Pinus sylvestris L.*) (16.8%) and European beech (*Fagus sylvatica (L.)*) (13.6%) (StMELF, 2022). Bavarian forests present high standing volumes with 396 $m^3 ha^{-1}$ on average and a mean growth of 11.90 $m^3 ha^{-1} year^{-1}$ (BWI, 2012).

To define the forest initial conditions for the simulations we used data from the latest National Forest Inventory (BWI, 2012), with a total set of 7456 NFI plots situated in Bavaria. The NFI applies a permanent four-by-four-kilometer sampling grid, where each grid point is represented by a cluster of four inventory plots (BWI, 2021) (Fig. 2). The NFI data are publicly available including a database of tree height and diameter per species and inventory plot, where each tree size is linked to a representative factor for up-scaling.

2.3. Definition of management regimes

For the simulation of management-specific forest stand development, we defined six management types that reflect the currently broadly applied management approaches in Bavaria. For each type, one to several management regimes were formulated, in total 15 (Table 1). For further details, see Supplementary material (S2, Table A1 to A8). Type I to III cover management approaches that focus on timber production by applying systematic thinning and clear cuts for regeneration. This age class approach results in homogenized, mono-layered stands. Although other, later described types are also regularly implemented during the last decades, we name types I - III *Business as usual* (BAU) which allows comparisons with similar Scandinavian studies (Blattert et al., 2022; Hahn et al., 2021). We separate from the standard BAU (I) an *Intensified* BAU (II) where forests are managed by a shortening of the rotation period and promoting fast growing tree species. In addition, an *Extensified* BAU (III) is defined in which thinning from above is applied in early stages, followed by moderate thinning from above in older stages. For types I and II, two additional regimes reflect an initial harvest delay of 5 and 10 years, respectively to avoid heavy thinning in the very early simulation period due to the above mentioned currently high standing volumes.

In type IV *Continuous Cover Forestry* (CFF), we summarized silvicultural approaches where thinnings are less systematic and focus on target trees. Regeneration is initiated by shelter-wood femel coups (Pretzsch, 2019) instead of clear cuts. Stands managed according to type IV usually show a higher structural diversity compared to those managed under types I – III. Three variations were considered, varying in intensity and modifying the target diameter felling for conifer trees and number of competitors removed. Again, two regimes reflect a later start of thinning due to high stand densities.

Type V approach *Adaption to Climate Change* aims at creating and managing forest stands towards climate resilience. This regime promotes a broad diameter and tree height distribution as well as high tree species diversity with focus on broadleaved species. At the same time, it strives for a stable size class distribution and steady wood provision.

Each management regime is adjusted according to the dominating tree species (spruce, pine, beech) in terms of thinning intensity and frequency to address different growth dynamics.

Lastly, we defined a management regime where any management activity is abandoned (Type V, *Set Aside*).

2.4. Scenario simulation: management and climate

Simulations of management regime specific forest ecosystem development were performed using the forest simulator SILVA (Pretzsch et al., 2008, 2002), which has been parameterized on data from Bavaria, where the density of parameterization sites is particularly high, and has been developed to support practitioners in sustainable forest management. SILVA is based on a single-tree model that is spatially-dependent (tree positions matter) and age-independent. The simulation time horizon ranges from 5 years up to 110 years (2012–2122). SILVA has routinely been applied for landscape scale simulation of mixed and pure species stands comprising the most important tree species in central Europe (Biber et al., 2020). Further details about the simulator core function and functionality can be found in the supplementary material Appendix S1.

To maintain computational efficiency at the landscape scale, simulation with SILVA starts on a set of representative stands. Based on the forest structure retrieved from NFI, inventory plots were grouped into 3779 strata (Johansson et al., 1993, Pott et al., 2002). The stratification classifies NFI plots according to stand structure attributes, site quality and species composition, and management regime (see Section 2.2).

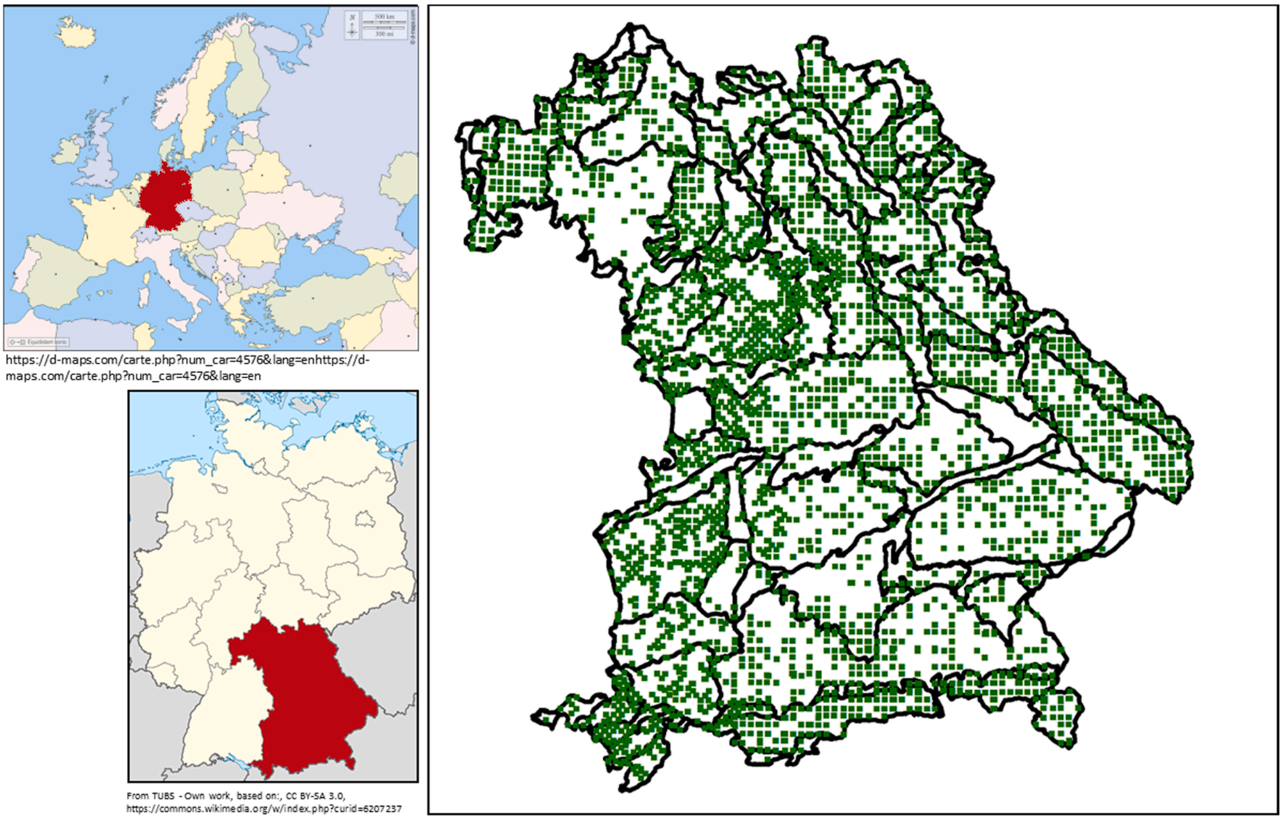

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Fig. 2. NFI points in Bavaria, Germany. The black lines represent the biogeoclimatic regions of potential vegetation growth (Arbeitsgemeinschaft Forsteinrichtung, 1985).

Table 1

Summary table of the simulated management regimes. Abbreviations stand for S (stands dominated by spruce), B (stands dominated by beech), P (stands dominated by pine); see Appendix S2, Tables A1 to A8 for more detail.

Management regime type	Focus	Abbreviation	Harvesting top height [m]			Management regime details
			S	B	P	
I - BAU	Wood production, age class	BAU_0	30	30	30	Standard BAU
		BAU_0_p1				Mature stands at simulation start not harvested before year 5
		BAU_0_p2				Mature stands at simulation start not harvested before year 10
II - Intensified BAU	Intensified wood production, age class	BAU_RR	25	30	25	Short rotation
		BAU_RR_p1				Mature stands at simulation start not harvested before year 5
		BAU_RR_p2				Mature stands at simulation start not harvested before year 10
		BAU_FS	33	30	30	Promoting fast growing (foreign) species
III - Extensified BAU	Extensified wood production, age class	Extensified BAU	33	33	33	Thinning from below in younger stages, delayed and less intense thinning from above in older stages
IV - CCF	Continuous wood production structure	CCF_P1	38	33	33	Standard CCF
		CCF_P2	38	33	33	Buffer temporal variation of supply. Reduction target diameter fellings for conifers
		CCF_P3	12 *	12 *	12 *	Thereby keep more straight and simple, harvest coniferous stand.
		CCF_P3_p1				Mature stands at simulation start not harvested before year 5
		CCF_P3_p2				Mature stands at simulation start not harvested before year 10
V - Adaptation to climate change	Multifunctionality	Adaptation to climate change	32	25	28	Promote diversity, stability, continuity, converts to broadleaved dominated stands
VI - Set Aside (SA)	Set aside	SA	NA	NA	NA	No thinning, no harvest

*selection cutting phase

Growth functions in SILVA consider climate and site conditions. Climate scenarios can be translated into site parameters for each ecoregion. Accordingly, management regimes were further simulated under three climate scenarios. One scenario represents the historical climate (i.e. no climate change), which is part of SILVA's default configuration. Two further scenarios represent future climate trajectories, based on Representative Concentration Pathways (RCPs): RCP2.6 and RCP4.5. These scenarios had been computed by HADGEM2-ES GCM (Jones et al., 2011), and were retrieved from ISIMIP (2020). Each climate scenario was translated into a site quality data set for SILVA (see section Supplementary material S1). This data set provided all climatic site quality indicators except CO_2 and NO_x for each of SILVA's five-year simulation time steps. The concentrations of CO_2 and NO_x where extrapolated in time based on their level in year 1800 (280.37 ppm resp. 287.6 ppb).

2.5. Forest ecosystem services and indicators

The policy analysis done by Primmer et al. (2021) was used as basis for the selection of FES object of study. This work defined ten FES that are in accordance with common international classification schemes (Haines-Young and Potschin-Young, 2018). The set of FES comprises wood production, bioenergy, non-wood forest products, biodiversity conservation, water protection, climate regulation, resilience (regulating services), and recreation (cultural services), assigning biodiversity conservation and resilience to the class of regulation services.

From the complete set of FES, we opted to exclude Game and Cultural heritage from this analysis. The investigated forest policies in Germany do not advocate the development of forests for the provision of ungulate game species, as browsing by those species is widely considered a threat to forestry. We did not have a model to represent Cultural Heritage within the forest; however, it can be linked to culturally reasoned attributes of naturalness in Germany. Thus, that service was not explicitly addressed but rather represented through the recreational value.

Based on the simulated forest stands, a set of FES indicators were estimated, at each 5-year period, and for each management regime and climate scenario. Wood production was 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). For bioenergy, marginal assortments are typically used for energy wood (harvest residues and stumps). Biodiversity conservation was represented by the Biodiversity fuzzy indicator from Biber et al. (2021). Additionally, it was also addressed based on tree species diversity, described by the Shannon index of tree species, and the species profile index developed by Pretzsch (2009). Erosion and water protection were evaluated through forest stability indicators, like the standing volume and the crown coverage. Resilience was represented by “storm & bark beetle risk” indicator from Biber et al. (2021) and by the natural potential vegetation (nPV). The latter was estimated as a distance metric between the species composition of the stand (as species number) and the natural potential vegetation defined by Bavarian Regional Office for the Environment (nPV, 2021). This metric was calculated as a simple Euclidian distance between the ideal species proportion of the nPV composition and the simulated one. The species composition was simplified to match SILVA’s simulated species and species groups (those broadleaf species that do not match SILVA’s seven main species are grouped as soft or hard broadleaves; all nPV conifers listed are represented by SILVA). Climate regulation was addressed through indicators of carbon storage on the one hand, and avoidance of carbon emission, on the other. We, therefore, applied a total carbon balance indicator, which accounts for carbon storage in standing stock and 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., 2020). Finally, recreation was also estimated from the “recreation & esthetics” fuzzy indicator reported by Biber et al. (2021).

2.6. Policy scenarios

In the following sections, we describe the rationale for the selection of the objective functions that described the FES. First, we identified the relevant mentioned FES in each of the three sectoral policies, to define the corresponding policy scenarios and then we described which indicators are going to be implemented. For each Policy Scenario we developed functions only for the FES that Primmer et al. (2021) identified for each case. The mathematical details and expressions can be found in Appendix S3 and summary of the indicators and corresponding equations in Table 2.

Additionally, two hard constraints were implemented in all Policy Scenarios, as they are part of national and federal state law in Bavaria and will deliver more realistic scenarios. These constraints on management regimes comprise a prohibition of clear cuts on protected areas (Federal Nature Protection law- BNatSchG, 2009, §5 (A3)) and limit clear cut activity on state owned forests. Thus, we decided to exclude all management regimes that include clear cuts as final cutting from these lands (all regimes with acronym BAU) (eq. S4). We decided not to apply extra set aside restrictions on the strictly protected areas (1.7% of the forested area (BWI, 2012)) as they would complicate the optimization without significantly impacting the results.

2.6.1. Forest strategy 2020

Within the scope of the German Forest Strategy - FS (BMELV, 2011), the production of wood from sustainable forestry should be ensured. Moreover, the conditions for a sustainable supply of raw materials for the wood, paper and energy industries should be improved. To follow the objective of sustainability within that scenario, we defined an even-flow function that maintains the volume of harvested products to be as constant as possible (eq. S5d). At the same time, we also applied an even-flow function for the annual increment ensuring sustainable growth (eq. S5d).

In terms of bioenergy, the use of wood, in particular for heat and power generation, has increased significantly in recent years due to fluctuating and rising prices for fossil fuels. However, bioenergy is mentioned in the document without clear objectives. From this text, we assumed that the FS aims at fostering wood-based energy products. Therefore, we maximized the minimum annual increment of the energy-wood assortments (eq. S5a).

Forest biodiversity, should be further improved and incorporated into the decision-making and planning processes. To address this, we selected three indicators, i.e. the species profile index by Pretzsch (2009), the volume of large trees with a DBH $>$ 60 cm, and the volume of coarse deadwood. To combine the last two indicators into a scalar for optimization we used the biodiversity fuzzy indicator, developed by Biber et al. (2020). Thus, we implemented two objective functions, which maximize the average value of each indicator (eq. S5a), not allowing the biodiversity indicator to decrease (eq. S5c).

The FS puts an emphasis on the FES water protection. The strategy suggests that the forest and the forest floor should ensure an even discharge, mitigating flood peaks and protecting against erosion. Moreover, the strategy states that forests should provide high filtration capacity for drinking water. We selected crown cover as a comprehensive and straightforwardly quantifiable proxy for this FES (EEA, 2015). To maintain the crown cover on a constant level and avoid drastic changes, we implemented a function that minimizes its maximum yearly increase (eq. S5a). To emphasize the stability of forests we introduced an even-flow function for the standing volume (similar to growth) (eq. S2).

Forests and forestry are more linked to climate than any other sector. While forest preservation, sustainable forestry and timber use will mitigate climate change, forests may rapidly deteriorate through climate change impacts. Carbon storage in standing stock, soil and durable wood products, in addition to the substitution effects of fossil fuels and construction materials by wood may considerably reduce CO_2 emissions. Too cover the various factors that contribute to the mitigation effect of forest management, we used the Carbon Balance by Biber et al. (2020), and aimed at maximizing this indicator (eq. S5a).

The value of the forest for recreation and leisure and its special cultural functions and services should be maintained and negative impacts on nature, forest ownership and management should be avoided through appropriate measures. We used the recreational and esthetics fuzzy indicator from Biber et al. (2021) to track this FES. The FS does not mention it as a clear objective, but it does imply a maintenance of the recreation function of forests and its importance for the future. Thus, we decided to maximize the average of the indicator, to potentially increase the recreation benefits (eq. S5c).

In terms of resilience, the forest also fulfills essential functions for society, nature and the environment. It is a habitat for animals and plants, a climatic regulator, and contributes to protection against

Table 2
Sectoral policies optimization scenarios. Objectives are coloured in blue and constraints in red. CC stands for Clear-Cut and ND for non-dimensional.

Forest ecosystem services (FES)	Indicator (unit)	National forest strategy Objective / Constraint	Eq.	step	Biodiversity strategy Objective / Constraint	Eq.	step	Bioeconomy strategy Objective / Constraint	Eq.	step
Wood production	Increment (m^3 year^{-1} ha^{-1})	Maximise (even-flow)	**S5d**	**1**						
	Harvested volume (m^3 year^{-1} ha^{-1})	Maximise (even-flow)	**S5d**	**1**						
	Saw Timber (m^3 year^{-1} ha^{-1})							Maximise	**S5a**	**1**
	Pulp Wood (m^3 year^{-1} ha^{-1})							Maximise	**S5a**	**1**
Bioenergy	Energy Products (m^3 year^{-1} ha^{-1})	Maximise	**S5a**	**2**				Maximise	**S5a**	**1**
Biodiversity Conservation	Biodiversity indicator (ND) (Biber et al. 2021)	Maximise (change >0)	**S5c**	**1**	Maximise	**S5c**	**1**	Maximise (even-flow)	**S5d**	**3**
	Shannon index (ND) (Shannon, 1948)	Maximise	**S5a**	**3**	Maximise	**S5c**	**1**			
	Species profile index (ND) (Pretzsch 2009)	Maximise	**S5a**	**3**	Maximise	**S5c**	**1**			
	Share of regime SA (%)				Target of 5%	**S3a**	**1**			
Water protection	Crown coverage (m^2 ha^{-1})	Maximise	**S5a**	**1**				Maximise (even-flow)	**S5d**	**3**
	Standing volume (m^3)	Constant (change > 0)	**S2**	**1**						
Climate regulation	Total Carbon Balance (tC year^{-1}) (Biber et al. 2021)	Maximise	**S5a**	**3**				Maximise	**S5c**	**2**
	Relative Living Carbon (tC year^{-1}) (Biber et al. 2021)				Maximise target 2020 (+5%)	**S6a**	**1**			
	Natural pot. vegetation (nPV) (ND)				Minimise	S7	1			
Recreation	Recreation & aesthetics indicator (ND) (Biber et al. 2021)	Maximise	**S5c**	**1**						
Resilience	Storm & bark beetle risk (ND) (Biber et al. 2021)	Minimise	**S7**	**3**						
Legal constraints	CC on protected land	Enabled constraint	**S4**	**1**	Enabled constraint	**S4**	**1**	Enabled constraint	**S4**	**1**
	CC on state forests	Enabled constraint	**S4**	**1**	Enabled constraint	**S4**	**1**	Enabled constraint	**S4**	**1**

negative effects on steep slopes. Especially relevant in the FS is the statement that "The increasing proportion of mixed forest reduces existing risks compared to large-scale coniferous tree stands against climate and weather-related changes”. Here, we used the indicator for “storm and beetle risks” (Biber et al., 2021) at stand level, which serves very well to describe the resilience ecosystem service. As a higher relative value of the indicator (0−1) means higher risk, we implemented a minimization of the maximum value (eq. S7).

2.6.2. *National strategy on biological diversity*

Only two FES have been addressed in the National Strategy on Biological Diversity - BDS (BMU, 2007), Biodiversity and climate regulation.

Forest biodiversity conservation is clearly mentioned by the BDS: “The forests in Germany have a high natural diversity and dynamics in terms of their structure and species composition and fascinate people with their beauty”. Thus, we measured the service by the biodiversity indicator and two structural diversity indicators: the Shannon index and the species profile index (see Section 2.5) to ensure an enrichment of both the species composition and the structure of forests. Three objective functions were implemented with an even-flow maximization of the average indicator value to maintain average levels of biodiversity and increase them if possible (eq. S5c). Finally, the policy states that at least 5% of the forests should be set aside to evolve with natural processes. Thus, we implement a SA target of ≥ 5% of land share (eq. S3a).

In the vision about climate regulation, the strategy includes the following: "By 2020, natural storage capacity for CO_2 in rural habitats has increased by ten percent." Moreover, few but clear objectives were found concerned with the increase of natural forests, as they would lead to a higher carbon sequestration potential in the forest. To account for this we implemented, first, an even-flow function for the carbon balance (including sequestration and emissions) (eq. S5a); second a maximization with the constraint that there should be at least a 5% increase in the carbon stored in living biomass aboveground, as compared to the reference line of 2020 (eq. S6a). Third, to describe the natural forests, we decided to minimize the maximum distance between the current species structure and the natural potential vegetation (nPV) (see Section 2.5) (eq. S7).

2.6.3. *German national policy strategy on bioeconomy*

In the National Policy Strategy on Bioeconomy - BES (BMEL, 2020), the sustainable wood supply is the basis and motor for the success of the "Cluster Forest" (Network of supply- and process-industry). Thus, wood production occupies a central role. This policy objective was translated by maximizing the minimum over the simulation period of the two main wood-products assortments (sawn timber (eq. S5a) and pulpwood (eq. S5a)).

The policy further mentioned that in 2030 biomaterials and bioenergy will account for one third of total industrial production and that the importance of such materials is expected to increase. Since no specific targets were set, we decided to maximize the minimum volume of saw logs, pulpwood and harvest residues that can go to energy production (eq. S5a).

Biodiversity is seen by the BES as a basis for a sustainable bioeconomy and at the same time, bioeconomy is seen as a possible protection strategy for biodiversity, although the strategy accepts that there may be conflicts among the two objectives. However, biodiversity was not mentioned as a direct objective, but at least to be preserved. Thus, we opted for an even-flow function using the biodiversity indicator, previously introduced (eq. S5d).

Soil erosion and water protection are not directly mentioned as an FES in BES. The focus lies on the intrinsic contribution of a sustainable bio-economy for the soil fertility and water protection. Since this FES is hard to quantify and suitable indicators were not available, we decided to use the crown cover as a proxy for forest protection, assuming that a stable crown cover ensures protection against erosion and generally improves infiltration and constant water storage (Zhou et al., 2008). For this, we used an even-flow function, to maintain and maximize the constant crown cover (eq. S5d). As erosion and water were not directly mentioned in the strategy, we addressed a minimum priority during the optimization.

Climate regulation is addressed by the reduction potential of carbon dioxide that forests have, because they can store CO_2 for a long time. In this policy, carbon does not play an important role, as it is not mentioned directly as an objective. However, if, as specified in BES, forests must ensure the storage of CO_2 over time, we decided to maximize the minimum of the total carbon balance over the simulation period (eq. S5c), while accounting also for the substitution effects of timber.

2.7. *Multi-objective optimization problem*

Landscape-scale forest management programs were obtained through the optimization of objective functions based on the societal demands highlighted in the national forest sectoral policies (Section 2.7). The multi-objective optimization sought the best management per stand and identified the optimal management combination over the forest landscape that best fulfills the policy demands. For each policy scenario (PS) a single solution can be found through the general formulation of the multi-objective optimization problems (Miettinen, 2012):

$$\underset{x}{\text{minimize}}\{f_1(x), \ldots, f_n(x)\}$$

$$\text{subject } x \in S$$

where $f_i(x)$ denotes the different objective functions (Appendix S3), x the vector of management regimes (Section 2.4), and S is the feasible set of management regimes determined by a set of constraints. We formulate the technically specific multi-objective optimization problem in the next paragraph.

Each objective can be interpreted as setting targets for the policy relevant FES indicators. Technically this was done by using a so-called achievement scalarizing function (ASF) of (Wierzbicki, 1982). Constructing the ASF requires preference information, from which the preferability of the solution can be measured in a theoretically justifiable fashion. The preference information obtained for the ASF can be seen as “aspiration targets” or so-called reference points that are aimed to be achieved (or exceeded), but that will be relaxed if targets cannot be reached. This interpretation guarantees the production of produce Pareto optimal solutions, which means solutions where none of the objectives can be improved without impairing one of the other solutions (Miettinen, 2012). To allow for the incorporation of strictly interpreted preference information we used the so called epsilon constraint method in multi-objective optimization to set strict upper/lower targets for specific objective values (Miettinen, 1999, pp 85–95, ε-Constraint Method). Epsilon-constraint method guarantees weakly Pareto optimal solutions, where all the objectives cannot be improved simultaneously. Solving the multi-objective optimization problem resulted from combining the two methods:

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

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

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

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

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 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 values of objective functions that should desirably be achieved. The objective vector z is the image space of the feasible set, with z^{ideal} being the ideal vector of the problem (maximum value of objective) 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 an augmentation term guaranteeing that the solutions are indeed Pareto optimal, with a small positive constant ρ, e.g. 0.0001. If the problem is feasible, i.e. no conflict among FES, the optimization process will find the optimal regional level solution for each FES, according to the specific objective function and constraints. However, the selected FES are usually conflicting and require some preferential information to find a specific solution. This preference information can be given as a reference point (a desired outcome), and provides context to the optimization problem (Wierzbicki, 1982). If the preferential information is very specific, it can be included as an epsilon constraint (Haimes et al., 1971).

Due to the unspecific orientation of the policies, we decided to prioritize the objective functions based on the FES priority classification defined in on the framework of Primmer et al. (2021). This used a coding scheme that ranks how each FES in the documents is addressed, with a range from zero to four (0 = no mention; 1 = mentioned indirectly; 2 = mentioned directly but not as an objective; 3 = stated as an objective but no stated targets or measures for implementation, 4 = central objective with clear targets and measures for implementation). Thus, for objectives that were classified with a rank of four the reference points were set to the maximum of the solution space. For those ranked at one, the reference point was set to the minimum and at 25% and 75% of the maximum, for objectives ranked two and three respectively.

The optimization process comprises three operational steps. First, the hard constraints that limit clear cuts in protected land and state forests were included (eq. S4). Second, each epsilon constraint was defined, and third each objective is provided a reference value according to the abovementioned scale. The multi-objective optimization resulted in management regime specific area shares reflecting the optimal, policy scenario specific requirements for ecosystem service provision.

Further details on the optimization process and mathematical formulation can be found in the supplementary material Appendix S3.

3. Results

3.1. *Optimal management programs*

The optimized set of management regimes used in each Policy Scenario highlight the differences among policies, showing the different shares of management regimes that optimized the objectives of each policy (Fig. 3).

The first common result among the three scenarios is that CCF remained the dominant class over all policies and across climates (Fig. 3 and in detail in Fig. 4). However, the other management classes showed higher variations among scenarios. The FS scenario has a focus on CCF, climate adaption and SA showing a nearly even distribution among management types that maintain canopy cover. BDS also showed a high share of the group, CCF, climate adaption and SA, whereas intensified BAU was enhanced compared to FS at the expense of climate adaption. Differently, BES revealed the highest proportion of BAU and intensified BAU of all three-policy scenarios. Interestingly, BES (Fig. 3 on the right) also shows the highest share of CCF. Yet, the diversity of management regimes were higher in FS and BDS than in BES.

Extensified management regimes play nearly no role in any of the policy scenarios. A clear difference between BES and the other policy scenarios is obvious in terms of SA. SA was almost not present in the BES scenario (Fig. 3, right) while in the FS scenario it ranged from 21% to 28% (Fig. 4, left), and in BDS (Fig. 3, middle) from 24% to 30%, respectively, meeting the 5% target in both scenarios.

Within the management types, we noted two peculiarities in the single management regimes distribution (Fig. 4). Due to the current generally high stocking volumes in the forests, a delayed harvest of mature stands is necessary to meet future FES requirements (Fig. S4).

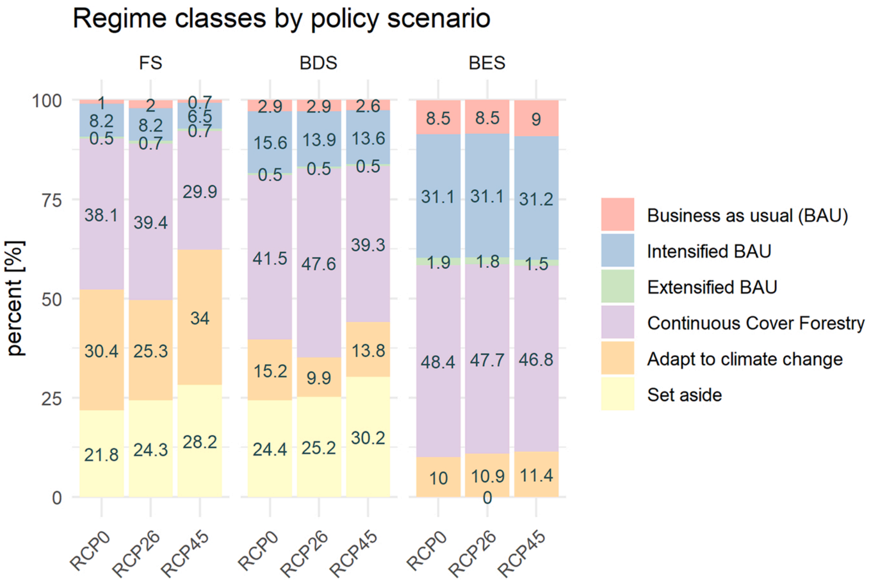

Fig. 3. Optimum area share of management regime class for the three policy scenarios representing the German national forest strategy (FS), the Biodiversity strategy (BDS) and the Bioeconomy strategy (BES). The optimization was repeated for three climate change scenarios: no Climate Change (RCP0), RCP2.6 and RCP4.5.

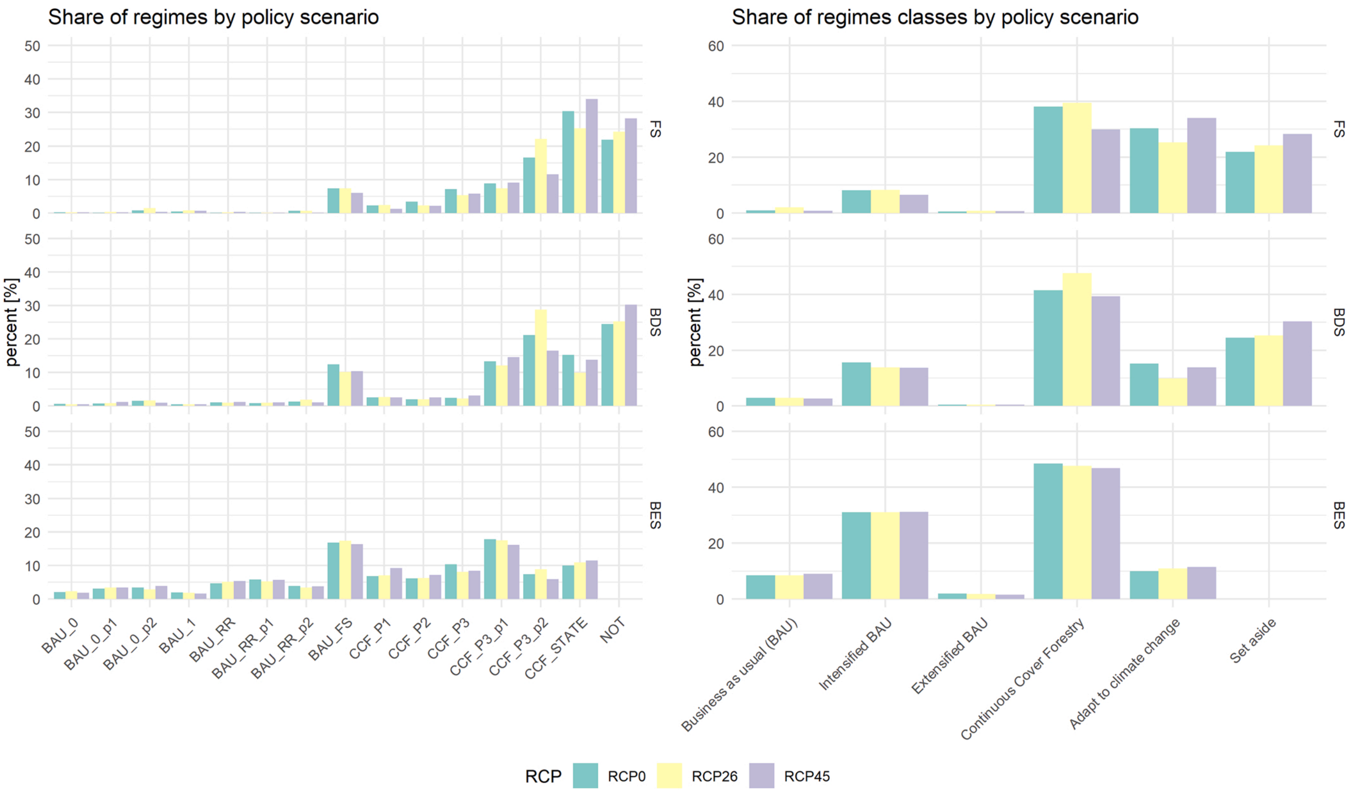

Fig. 4. Optimal management solution for the three policy scenarios representing the German national forest strategy (FS), the Biodiversity strategy (BDS) and the Bioeconomy strategy (BES). Presented are the shares for each of the 15 management regimes (see Table 1) on the left and the corresponding management classes on the right. The optimization was repeated for three climate change scenarios: no Climate Change (RCP0), RCP2.6 and RCP4.5.

This fact is indicated by the high share of management with delayed starting of harvest within the management types (Fig. 4 – left). While within the "Intensified BAU" class, BAU_FS (foreign species) had the largest representation in all three scenarios, followed by BAU_RR.

Finally, regarding the climate regulation FES, we observed that, while the distribution pattern of management regimes is hardly affected by climate scenarios in BES (Fig. 3 – right), differences in shares of management classes among climate scenarios occur in FS and BDS. Concerning RCP2.5, CCF is fostered under both policy scenarios on the expense of climate adaptation. However, this change is reversed under RCP 4.5 indicating the need for climate adaption in forests. Warmer climates lead to a higher share of SA in FS and BDS.

3.2. Long term provision of ecosystem services

In this section, we present the development of selected indicators for the FES that were most relevant for the sectoral policies. Development trends for all the indicators can be seen in the supplementary material Appendix S4.

Wood production showed distinct trends for the assortments, especially for saw logs and pulpwood (Fig. 5) and with slight modifications due to climate change for all scenarios. The first noticeable effect was the strong increase in harvesting of both saw logs and pulpwood for the BES scenario. In the case of saw logs, the harvested trend converged with the other scenarios after 20 years, but for pulpwood, it remained constant on a significantly higher level. In the BES scenario, harvested volume and energy products were prioritized. This, combined with the essential structure of forest stands in Bavaria (very high standing volumes, and ages close or beyond the rotation periods), favors a very strong harvest in the initial simulation periods, that later stabilizes due to production sustainability. This transition of old stands with high standing volume stabilized after 20 years, transforming the stands into highly productive forests with lower standing volumes and therefore higher proportion of assortments of smaller size that are suitable for the pulpwood industry. This effect is also visible in Fig. 6, where the standing volume was drastically reduced under BES scenario from current 450 m^3/ha to a steady state at about 200 m^3/ha.

The development for FS and BDS followed a similar trend. The indicator for wood production, harvested wood volume, was always slightly higher in FS than in BDS. However, the differences in potential production of wood products did not differ much among them.

In the case of the biodiversity indicator (Biber et al., 2021), BES

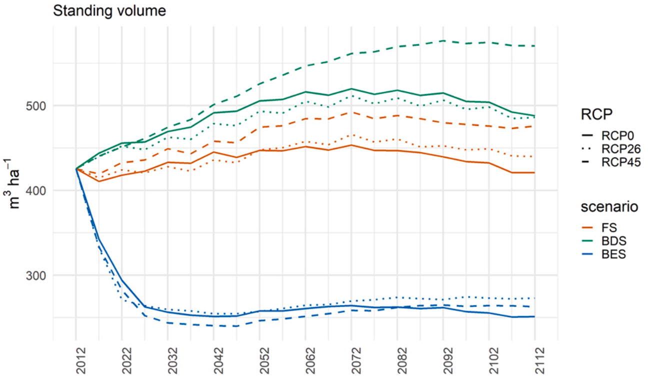

Fig. 6. Development of the standing volume during the simulation period for the three policy scenarios representing the German national forest strategy (FS), the Biodiversity strategy (BDS) and the Bioeconomy strategy (BES). The optimization was repeated for three climate change scenarios: no Climate Change (RCP0), RCP2.6 and RCP4.5.

Fig. 5. Harvested volume for saw logs and pulpwood for the three policy scenarios representing the German national forest strategy (FS), the Biodiversity strategy (BDS) and the Bioeconomy strategy (BES). The optimization was repeated for three climate change scenarios: no Climate Change (RCP0), RCP2.6 and RCP4.5.

followed a different trajectory than FS and BDS (Fig. 7). For the FS and BDS scenarios Biodiversity values rise constantly with time, while the values decrease in the BES scenario, achieving a low but stable state. Climate change decreased the biodiversity values for all scenarios, in general. The maximum Biodiversity was achieved with FS under current climate conditions and the minimum with BES with RCP4.5. A comparison among these tendencies with those in Fig. 6 suggested a correlation of Biodiversity indicator and high standing volumes. However, the BDS achieved slightly higher standing volumes than FS, even if FS showed a better performance in terms of biodiversity. The climate scenarios showed distinct developments of standing volumes, with the best performing scenario being RCP 0 (no climate change) for all policy scenarios.

In the case of the “Recreation and Esthetics”, FS showed the highest values again, followed by BDS and BES. After an initial rapid phase of decrease, FS and BDS recovered steadily, while BES remains relatively low.

The development of the total carbon balance showed, for all scenarios, similar levels at the end of the simulation period (Fig. 8). However, BES showed a sharp decrease during the first periods, but recovered rapidly and achieved the highest values at the end. On the contrary, both FS and BDS constantly decreased over time. These trends manifest the substitution effects due to higher harvest levels (Fig. 5). The carbon balance initially decreases for BES due to harvest, followed by the stabilization of standing volume (Fig. 6). This effect, combined with the carbon substitution in saw logs, increased the carbon balance. We could not observe strong differences among climate scenarios. However, RCP 4.5 showed the highest values, due to even higher productivity and growth.

4. Discussion

4.1. Policy coherence

The three sectoral policy documents lacked, in general, of a quantitative formulation of targets or objectives. For this reason, for most FES, translation of the policy documents into scenarios was accomplished through defining objective functions without clear numerical targets; and, as a consequence, solving for each of the three scenarios objective functions provided a relatively large range in the outcomes of the set of FES.

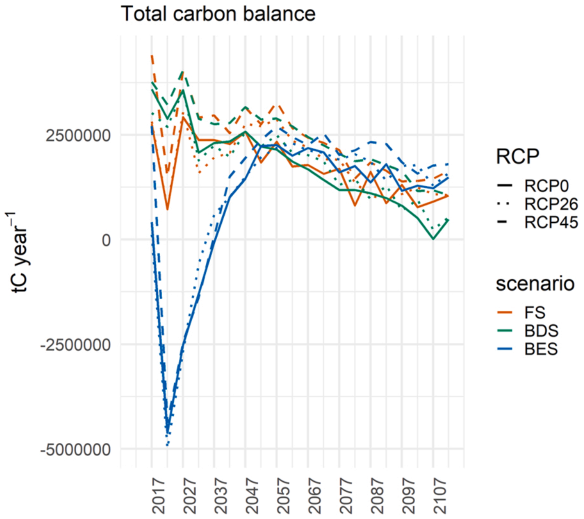

Fig. 8. Development of the total carbon balance for the three policy scenarios representing the German national forest strategy (FS), the Biodiversity strategy (BDS) and the Bioeconomy strategy (BES). The optimization was repeated for three climate change scenarios: no Climate Change (RCP0), RCP2.6 and RCP4.5.

Among the analyzed strategies, the FS addressed the highest number of FES among all analyzed policies, characterized by a strong multifunctionality conceptualization (Borrass et al., 2017). On the one hand, the number of indicators and objective functions was the highest for FS followed by BES and BDS. This indicates, that BDS and BES are policy documents focused on the provision of specific ecosystem services or functions, i.e. biodiversity and wood production, respectively. Specifically, the highest degree of coherence was observed between FS and BDS for the biodiversity indicators, i.e., biodiversity indicator and Shannon index. Structural indicators like the crown cover followed very similar trends for both scenarios and all climates (Fig. 7-left and Fig. S2). For these indicators, BES always followed a distinctive trend, separating and indicating incoherence between the latter and the former two (Fig. S2).

The evaluation of coherence showed how the FS and the BDS appear to have also coherent results in the distribution of management regimes. Even, if to promote biodiversity, we expected BDS to favor set-aside areas, the strategy led to a slightly stronger share of production oriented forestry with a larger total area covered by BAU regimes. This effect can be explained due to the strategy’s particular emphasis on the

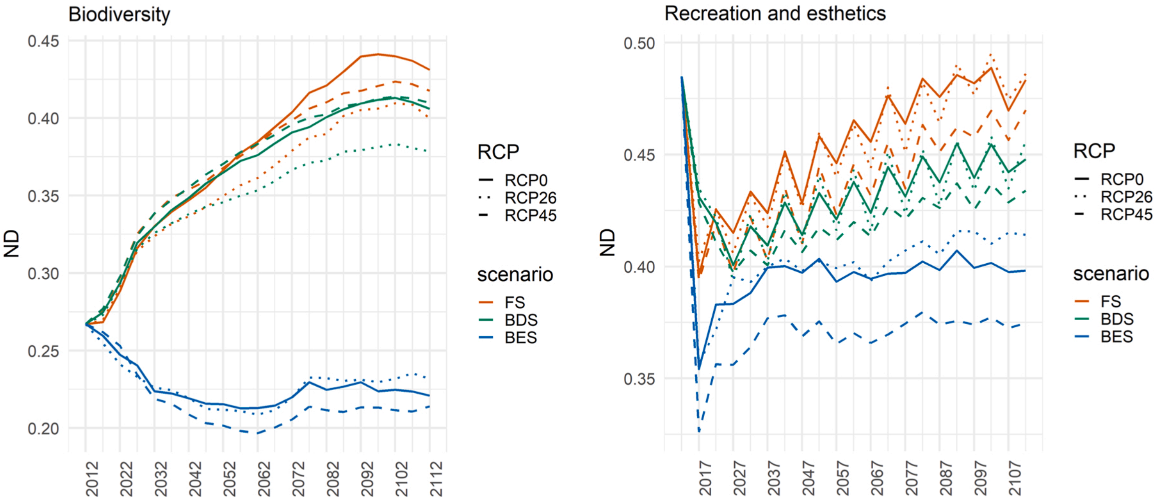

Fig. 7. Development of the fuzzy indicators for Biodiversity (on the left) and “Recreation and Esthetics” (on the right) for the three policy scenarios representing the German national forest strategy (FS), the Biodiversity strategy (BDS) and the Bioeconomy strategy (BES). The optimization was repeated for three climate change scenarios: no Climate Change (RCP0), RCP2.6 and RCP4.5.

targets biodiversity and carbon allocation to standing stock, while neglecting other FES. Moreover, the focus of BDS on the increase of living carbon, further promotes the share of SA and a markedly strong proportion of productive continuous cover forestry at the same time. Thus, meeting the 5% target of SA share is easily achieved for all climate scenarios. In contrast, BES emphasized wood production and the maintenance of biodiversity (but not its promotion), avoiding set aside areas, as these are not legally enforced. This strategy implies a high proportion of production oriented regimes and in our scenarios, we observed that it neglects high protection areas like the mentioned set-asides. Nevertheless, due to the implemented legal constraints (limitation of clear cutting in all the BAU regimes on protected and state forests), CCF forestry occupied the largest share not only in FS and BDS, but also in BES. Without these constraints, we would expect the share of intensification to significantly grow for all scenarios. Here, it is necessary to note that we have not included the currently strictly protected areas as a constraint in the optimization, due to the low representation in Bavaria. For this reason, a share of 1.7% (BWI, 2012) would have been expected in the BES if this constraint had been implemented, although not modifying the overall conclusions.

4.2. Forest management recommendations in Bavaria

In all three scenarios, the resulting management programs were dominated by multifunctional integrative management regimes. This means that management strategies, like CCF or other close to nature regimes (adapt to climate change), had the highest potential to deliver multiple ecosystem services, minimizing trade-offs coming from political incoherencies (Eyvindson et al., 2021).

Specifically, our quantitative policy analysis showed that the FS advocates for a strong proportion of multifunctional forestry and productive CCF rather than classical mono-specific management regimes that imply clear cuts. At the same time, the FS aimed to achieve multifunctionality at the landscape scale through the combination of a balanced set of management regimes, based on productive CCF and climate adaptation (Blattert et al., 2018; Eyvindson et al., 2021; Royer-Tardif et al., 2021), and meeting demands of FES by intensifying some portions (BAU) of the land, while sparing others (SA) (Augustynczik et al., 2018). In contrast, BES has a clear emphasis on wood production, segregating the landscape between BAU and CCF, and completely ignoring the use of setting aside forest areas. Therefore, those policies that were more coherent complemented the high diversity of management strategies at the stand scale that integrative regimes comprise, with shares of the landscape that fulfill specific objectives. These are intensification, focused on timber production or bioenergy, and set asides, more focused on biodiversity and protection. In conclusion, high diversity at the stand scale is as needed as diversity at the landscape scale, to improve multifunctionality and facilitate policy coherence.

Nevertheless, existing landscape structure and degree of implementation of close to nature regimes (CFF, adaptation to climate change) will affect the current optimum management programs. In this case, the very large proportion of forests with high standing volumes was a specific challenge to achieve the policy objectives in Bavaria. Due to historical reasons, a very high proportion of the lowlands is occupied by spruce stands that were massively planted after WWII. These helped to increase the productivity, particularly noted after 1960 (Pretzsch et al., 2014), and have achieved large standing volumes that are ready to be harvested. This disproportionality in the age classes across the landscape causes a challenge for future management, especially when aiming for a constant (and higher) supply of wood products.

During the optimization, we could observe that without allowing some of the management regimes to delay some harvesting volume at the beginning of the simulation, it would be very difficult to achieve the desired targets in the future and to ensure their sustainability. As a result, the selected types of management regimes were not realistic and had to be improved with harvest delays. This problem was even more challenging for the different wood assortments. That is, wood products originating from large trees, like sawn timber for veneer and construction, will suffer from a lack of provision in the future if high volumes are all harvested, to some extent, at the same level. Products of smaller dimensions, like chips and pulp, however may not be affected in the same level. Moreover, a transformation of some degree of the current forest stands into intensive plantations (with fast growing forest species) may help to compensate for the discontinuity in sustainable harvest volumes, produced by the intense harvest. This constitutes additional challenges to sustainable future provision of forest ecosystem services and instabilities that can put at risk the objectives of the sectoral policies and must be therefore taken into account in the future (Carpentier et al., 2017; Clark et al., 2018). Nevertheless, considering uncertainty would have an impact on the distribution of timber harvests over time, as shown for example by Härtl et al. (2013), Härtl and Knoke (2014) and Hahn et al. (2014) where the effects of financial risks, like oil prices or demand of timber products, were included in the optimization analyses. In this case, these works suggest that the strong harvest caused by the demand for timber, especially in the bioeconomy scenario, would be realistically distributed and balanced in time to adjust to the market conditions, resulting in a more sustainable distribution of management regimes.

4.3. Policy specifics and long-term provision of forest ecosystem services

Each of the policy documents recognized various FES, with varying degrees of detail. As it was expected, FS represented the most challenging optimization problem, due to the largest amount of objective functions, i.e. of addressed FES. Following the trends from the FES observed in Fig. 7 and S4, we could observe that FS and BDS are consistent in the development of FES, while BES follows different trends, resulting in a general conflict in the indicators that are related to diversity, e.g. Shannon Index, Biodiversity indicator or Species profile index. However, an additional conflict could be observed by having a better performance in terms of carbon sequestration by the BES in contrast to FS and BDS, which use objectives that tend to store carbon in living biomass, and therefore not promoting substitution effects (Lundmark et al., 2018). Nevertheless, these substitution effects may be overestimated since it is assumed that no efficiency gains will be done when national supply is reduced and imports increase, due to, especially the increase of natural damages (Hagemann et al., 2016). However, while the carbon trends are similar at the end, the dramatic decrease at the start likely has a large impact on the overall carbon stored in the forest. Moreover, if there was a temporal preference for carbon sequestration, BES would be infeasible.

Due to frequent use of qualitative targets per each sectoral strategy, the approach used to quantify the strategy objectives leaves room for varying interpretation. This was in some part expected, as each strategy implements the objectives of sometimes specific competing interest groups within the democratic process of policy implementation (Primmer et al., 2021). The interpretation of the sectoral documents as policy scenarios is also constrained by the availably and selection of indicators. Nevertheless, the optimized management programs showed a trend in long-term provision of FES that is plausible against the background of its underlying strategy, and enabled an assessment of each strategy's expected future trends.

As already mentioned, one critical aspect that differentiates German forest policy from other European countries' forest policies is the specific consideration of forest multifunctionality. In German forests, there has been a notable shift in federal policy and federal state forest laws towards multifunctional management in the last few decades (Borrass et al., 2017). The implementation of multifunctional management is compulsory for federal states, and therefore for Bavaria, and must be implemented by the state's forest management units in an exemplary manner. In private forests, multifunctional management is encouraged through consulting and even financial incentives. Thus, there is a far-reaching coherence between existing laws and regulations with current forest and environmental policies, thanks to a higher collaborative participation (Johansson, 2018). Notwithstanding, the set of requirements that define multifunctional forestry within legislation might have become outdated due to a change of paradigms within future oriented policies. For example, the FS does not exclude sustainable exploitation of the (non-native) conifers for wood production. Therefore, it might conflict with federal state forest laws, which typically support a diverse mixture of native tree species (Knoke et al., 2008). The BDS in turn recommends the reduction of foreign species in favor of native ones. Thus, it might contradict the objective of supporting forest resilience under extreme conditions of climate change, and a negative trade-off may arise (Cosyns et al., 2020). Typically, such national polices in European countries have been focused to a particular group of FES and trade-offs between different groups have not been fully analyzed (Makkonen et al., 2015).

Finally, climate had a reduced impact in the scenarios in comparison with management. However, there were some trends, especially for FS and BDS. In general, warmer climates represented by RCP 2.6 and 4.5 showed an increase in the potential share of the land that can be left as set aside, and at the same time, CCF, which already shows a land share dominance in all scenarios, tends to increase its land share for RCP 2.6 and 4.5. However, the increase in productivity predicted by the growth module in SILVA does not account for risks, like water stress, that could potentially attenuate or even reverse such gains. Nowadays, it is recognized, that in absence of counteracting measurements, future global changes will have a negative impact in the provision of FES, such as timber resources (Hanewinkel et al., 2013), biodiversity conservation or recreation. The integration of mechanistic models that can account for such changes could help to predict with higher accuracy the effects of climate change on the provision of FES (Seidl et al., 2011).

5. Conclusions

The multidisciplinary approach we used in this work revealed the potential impact of forestry policy on the management of German forested landscapes, using Bavaria, the largest of the German federal state as example. At the same time, we presented insights about the coherence and incoherence between the three main sectoral policies that target same resource, forests. This served as basis for a political discussion process, which requires knowledge-based arguments and to increase the efficiency of the multifunctional management of this common resource. This would not have been possible without a broad range of realistic forest management simulations that allowed characterizing slow changing systems, such as forests, into the future.

The Forest Strategy was the most detailed document we evaluated, addressing the largest number of Forest Ecosystem Services. Although this strategy has been ambitious in the multiplicity of its objectives, it has a strong inner coherence that is likely due to the yet strong emphasis on multifunctional management inside Bavarian and German forests and sustainable provision of multiple ecosystem services. The Biodiversity Strategy and Forest Strategy resulted in very similar landscape management programs across Bavaria. This indicated that, multifunctionality, as expressed in the Forest Strategy is compatible with biodiversity approaches. The Bioeconomy Strategy followed a notably distinct path, with a stronger segregation of uses concentrated in production-oriented regimes, and production oriented continuous cover forestry. Due to the strong emphasis on intensification inside the Bioeconomy Strategy, however, the resulting landscape segregation delayed its objectives and led to a notable conflict with the remaining two strategies. In summary, policies that promote a multifunctional integrative management regimes, but also allow for some shares of segregation with set asides and intensification will be most efficient in reduction of trade-offs among ecosystem services. However, current landscape structures, namely homogenous high standing volumes, will pose a risk to achieve policy objectives, and compromises must be considered.

Data Availability

Data will be made available on request.

Acknowledgements

This work has been conducted in the frame of the MultiForest project. Project MultiForest is supported under the umbrella of ERA-NET Cofund ForestValue by Academy of Finland, Business Finland, Federal Ministry of Agriculture, Forestry, Environment & Water Management (Austria), Agency for Renewable Resources (Germany), Research Council of Norway, Vinnova/Formas/SWEA (Sweden). ForestValue has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement N° 773324.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2023.106673.

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