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Future wood demands and ecosystem services trade-offs: A policy analysis in Norway

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ABSTRACT

To mitigate climate change, several European countries have launched policies to promote the development of a renewable resource-based bioeconomy. These bioeconomy strategies plan to use renewable biological resources, which will increase timber and biomass demands and will potentially conflict with multiple other ecosystem services provided by forests. In addition, these forest ecosystem services (FES) are also influenced by other, different, policy strategies, causing a potential mismatch in proposed management solutions for achieving the different policy goals. We evaluated how Norwegian forests can meet the projected wood and biomass demands from the international market for achieving mitigation targets and at the same time meet nationally determined targets for other FES. Using data from the Norwegian national forest inventory (NFI) we simulated the development of Norwegian forests under different management regimes and defined different forest policy scenarios, according to the most relevant forest policies in Norway: national forest policy (NFS), biodiversity policy (BIOS), and bioeconomy policy (BIES). Finally, through multi-objective optimization, we identified the combination of management regimes matching best with each policy scenario. The results for all scenarios indicated that Norway will be able to satisfy wood demands of up to 17 million m^3 in 2093. However, the policy objectives for FES under each scenario caused substantial differences in terms of the management regimes selected. We observed that BIES and NFS resulted in very similar forest management programs in Norway, with a dominance of extensive management regimes. In BIOS there was an increase of set aside areas and continuous cover forestry, which made it more compatible with biodiversity indicators. We also found multiple synergies and trade-offs between the FES, likely influenced by the definition of the policy targets at the national scale.

1. Introduction

In the context of the 2030 United Nations Sustainable Development Goals and the Paris Agreement climate change targets, several European countries have recently launched strategies aimed at promoting the development of a renewable resource-based bioeconomy (EU, 2018; Primmer et al., 2021). These bioeconomy strategies are based on promoting activities that use renewable biological resources to produce

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food, materials, and energy (Schulz et al., 2021). The transition to a circular bioeconomy does not constitute a predetermined path (Patermann and Aguilar, 2021); however, it is widely agreed that it will result in an increased wood demand (EU, 2012; Hetemäki et al., 2017; Primmer et al., 2021). As a result, some countries with large forest resources, like the Nordic European countries, have placed forestry at the core of their bioeconomy strategies (Patermann and Aguilar, 2021).

Increased wood and biomass demands may conflict with other ecosystem services provided by forests (Duncker et al., 2012; Blattert et al., 2020) including among others the provision of fresh water, recreation, maintenance of biodiversity, flood control, and climate regulation. Besides, in most countries, bioeconomy development is just one of several policy targets with implications for forest resources and management. For example, many countries have a biodiversity strategy, which focuses mostly on forest ecosystem services (FES) related to biodiversity (BMU, 2007; ME, 2012).

In Norway, the bioeconomy strategy [BIES] (Skog 22) (INNR, 2015), the biodiversity strategy [BIOS] (Natur for livet) (MCE, 2015), and the white paper on forest policy and the wood industry, here labeled the national forestry strategy [NFS] (Verdier i vekst) (NMAF, 2016), are the main policies that impact forest management. These strategies address and promote diverse functions of forest ecosystems, even though they do not always refer explicitly to them (Primmer et al., 2021). Due to the specific policy focus, the detail and number of addressed FES objectives varies significantly between policies. For instance, while BIOS recognizes the importance of biodiversity conservation and promotes resilience, NFS has more of a value chain perspective, and BIES aims to increase timber and biomass production (Nilsson et al., 2012; Nabuurs et al., 2019).

These strategies are often developed in non-coordinated processes, both in Norway and other countries, and there is therefore a risk of lack of coherence in terms of opposing targets. This lack of policy coherence can cause a mismatch, leading to suboptimal management and divergent flows of FES (Aggestam and Pülzl, 2018; Blattert et al., 2022), i.e. the provision of one ecosystem service can produce a simultaneous decrease in the provision of another service (win-lose), or can have a positive effect on the provision of the other service (win-win) (Howe et al., 2014; Mina et al., 2017). Which forest management regime – or combination of these - is "optimal" to satisfy FES demands will depend on the policy and its objectives for FES, as well as the existence of trade-offs between FES (Temperli et al., 2012; Schulz et al., 2021). In this context, there is increasing scientific evidence that more diversified forest management (allocating areas to different management objectives instead of promoting a unique management regime that tries to address all FES targets) could help to reconcile some trade-offs between FES (Eyvindson et al., 2021; Messier et al., 2021). This diversified approach could potentially help satisfy the demands for different FES in the same forest stand.

To assess complex interactions between multiple FES, multi-objective optimization is a popular choice which has been widely used to solve land-use conflicts (Myllyviita, 2011; Uhde et al., 2015; Eggers et al., 2020; Blattert et al., 2022). For instance, Eyvindson et al. (2018) used a multi-objective optimization approach to assess the impact of different harvesting intensities on biodiversity and non-wood ecosystem services and identified compromise solutions that minimized the conflict between these objectives. 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 whole forest area of a given country and are designed to assess the state and condition of the country's forest resources (Jandl et al., 2018; Kovac et al., 2020; Blattert et al., 2020). The combination of NFI data and multi-objective optimization methodology has been used to measure conflicts among different objectives at the national level and resolve them by finding management programs (optimal combinations of different regimes fulfilling best the FES demands), providing compromise solutions (Mazziotta et al., 2017; Pohjanmies et al., 2017a; Eyvindson et al., 2021). Recently, Blattert et al. (2022) applied multi-objective optimization to assess the incoherences among Finnish forest sectoral policies in terms of management requirements and effects on forest multifunctionality at the national scale. However, as an EU member state, Finland's national sectoral policies and strategies are strongly aligned with EU policy objectives, since these are operationalized versions of their EU counterparts. In our study, the three main strategies evaluated have different implementations, although the objectives of these policies usually follow similar guidelines. Hence, the Norwegian study presented here shows how policies are implemented in a non-EU context, with less productive forest conditions, and with different societal needs than those of Blattert et al. (2022).

In Norway, forest ecosystems and their services are of high economic, ecological, and social importance. Consequently, there is a broad range of research on the impact of forest management on the provision of FES and their valuation (Schröter et al., 2014; Brown et al., 2015; Dannevig et al., 2015; Hynes et al., 2021; Berglihn and Gómez-Baggethun, 2021). This research offers insight into how ecosystem services can be integrated into decision-making in the Norwegian context (Filyushkina et al., 2015). However, these findings remain patchy and confined to the boundaries of separate policy domains. In this study, we aim to evaluate how the three main policies governing Norwegian forests (Verdier i vekst, Natur for livet, and Skog 22) can simultaneously contribute to achieving wood and biomass demands and ensuring the sustainability of FES. Research on policy conflicts and their effect on the provision of FES could help to develop policy instruments that would contribute to maximizing the benefits that forest ecosystems provide to current and future generations. Specifically, we aim to answer the following questions: Q1) Can Norwegian forests satisfy the projected wood and biomass demand for achieving climate mitigation targets while simultaneously meeting FES demands under the three different national policies? Q2) What is the optimal combination of forest management regimes to achieve these demands? Q3) What is the effect on the provision of FES if wood demands that represents climate change mitigation targets need to be achieved? To answer these questions, we first simulated the provision of different FES by the Norwegian forests under alternative forest management regimes. Second, we elaborated demand for FES according to the three most relevant forest policies in Norway and defined representative forest policy scenarios. In addition, we modeled the expected future wood and biomass demands related to climate mitigation targets and finally, we used a multi-objective optimization framework to assess the optimal forest management for meeting FES demands (Fig. 1).

2. Materials and methods

2.1. Forest data and simulation

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 m^2 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 (Fig. 2). The forests are of variable ages and are mostly dominated by Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), and birch (*Betula pendula* and *pubescens*), with other deciduous species interspersed at varying tree densities (for a more detailed description of the sampling design, see Breidenbach et al. (2020)). Plot-level forest inventory data were used as input data in a single-tree forest growth simulator implemented in the SiTree platform (Antón-Fernández and Astrup, 2022) to simulate the development of Norwegian forests under different management regimes. Climate change impacts on the Norwegian forests were modeled through an empirical climate-sensitive site index model (Antón-Fernández et al., 2016). The main climate variables

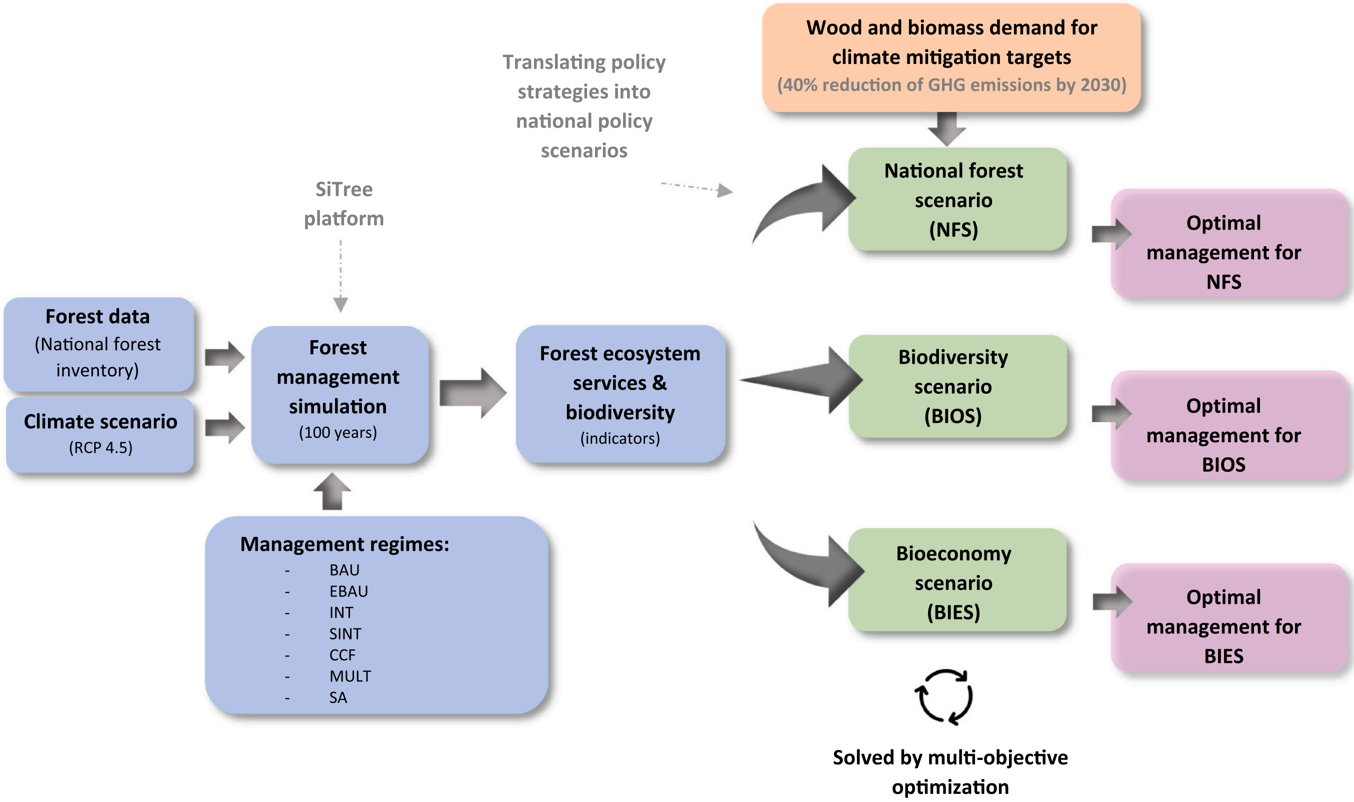

Fig. 1. Schematic diagram illustrating the workflow used in this study. First, forest inventory data were used to simulate the forest dynamics over 100 years. With the output of these simulations, we evaluated the provision of FES using a series of indicators. Based on national policy strategies (Verdier i vekst, Natur for livet, and Skog 22), we defined three policy scenarios (NFS, BIOS, BIES). We included the wood demands for achieving EU mitigation targets on top of these three scenarios and solved for each scenario using a multi-objective optimization tool.

driving the climate-sensitive site index model were 30-year average temperature (growing season temperature sum) and moisture (June monthly moisture surplus calculated as the difference between monthly mean precipitation and potential evapotranspiration). Temperature and moisture were represented as 30-year window means, covering the period 1971–2100, and were obtained from the Norwegian Meteorological Institute. The future climate followed the representative concentration pathway (RCP 4.5) and 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.

2.2. *Management regimes*

We simulated a large number of management alternatives, classified into seven management regimes (Table 1). These management regimes represent different levels of harvest intensities, rotation times, green tree retention levels, numbers of thinnings, and types of regeneration. Four of the management regimes were based on modifications of the most common management regime in Norway, business as usual regime (BAU) with an even-aged rotation forest management according to the Norwegian management guidelines, extensified BAU (EBAU), intensive (INT) and intensive-short (SINT). EBAU is similar to BAU but with longer rotation age. Intensive includes higher management intensity (e.g. higher planting density, fertilization), while Intensive-short further shortens the rotation age. The multispecies (MULT) regime aims at promoting mixtures of species of spruce/pine/birch in the stands. The regime continuous cover forestry (CCF) aims to diversify the forest structure and to convert the stands to permanently covered without having a final clear-cut. Finally, we defined the set aside (SA) regime as the alternative with no management activities.

2.3. *Ecosystem services provision and indicators*

We evaluated the provision of different ecosystem services under the management regimes defined previously. We considered six FES: (i) timber production, (ii) bioenergy, (iii) biodiversity conservation, (iv) erosion and water regulation, (v) climate regulation, (vi) and recreation. These FES were evaluated by a series of indicators (Table 2). The FES timber production (i) was assessed by two indicators: harvest net income in Norwegian kroner (NOK) and the total harvested volume of commercial timber (m^3). We calculated harvest net income 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., 2014). The FES bioenergy production (ii) was evaluated by the amount of harvested energy wood, i.e. tops and branches, known by their Norwegian acronym as GROT and here labeled as harvested residues. Biodiversity conservation (iii) was assessed by MiS area, bilberry (*Vaccinium myrtillus*) 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 by mapping fine-scale hotspots for 12 habitat types *(livsmiljø)*. These habitat types are grouped according to positions along main environmental gradients, productivity, and humidity. The information recorded by the MiS system is used as a basis for all forest management in Norway, such as where to leave trees and which kind of trees should be left in different forest stands (Gjerde et al., 2007; Timonen et al., 2010). Therefore, using data from NFI we classified the NFI plots as MiS (1) or not MiS (0) focusing on the abundance of big trees and broadleaved trees. Bilberries are the most common wild berries in Norway. Here, bilberry coverage (%) was calculated using a

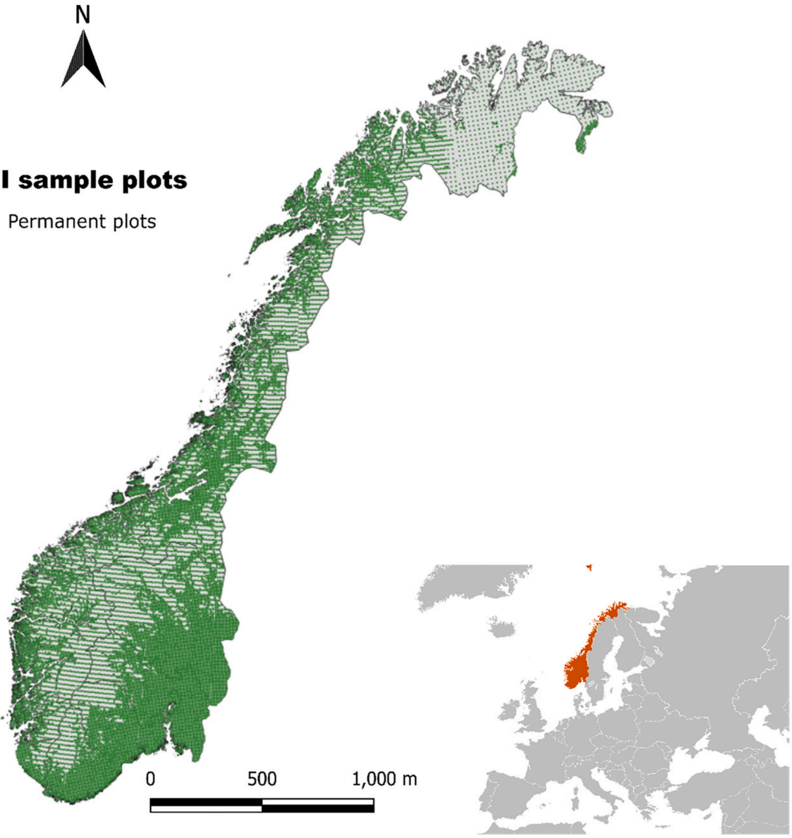

Fig. 2. Distribution of NFI sample plots comprising our dataset representing the forest situation in Norway.

Table 1
Management regimes applied in the forest growth simulations.

Management category	Description
Set aside (SA)	Protection forest, no management actions are taking place
Business as usual (BAU)	Business as usual, even-aged management, according to Norwegian recommendations (planting, final felling with clear cut)
Extensified BAU (EBAU)	Extensive even-aged management – longer rotation time (rotation age increase by 40%)
Intensive (INT)	Intensive even-aged management (planting, higher density, fertilization, thinning)
Intensive short (SINT)	Intensive even-aged management -shorter rotation age (rotation age decrease by 20%)
Continuous cover forestry (CCF)	Continuous cover forestry (every 15 years the periodic increment is harvested)
Multispecies (MULT)	Multispecies even-aged management (replanted with a mixture of spruce, pine and birch)

beta regression model fitted to the Norwegian NFI bilberry cover data, which predict the bilberry coverage of the forest floor based on stand characteristics (stand age, vegetation type, and stand basal area). We also included the volume of deadwood as a FES for biodiversity since it is an indicator of forest conservation value (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. To evaluate erosion and water regulation (iv), we calculated the clear-cut area (ha) in steep terrain and in mountain forests, assuming that forest areas that were recently clear-cut are lacking sufficient protection against erosion (Frehner et al., 2007). We included as climate mitigation indicators the sum of the predicted amount of carbon stored in living trees, deadwood, and soil (v). To calculate the 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 HWP carbon pool is assumed empty at the beginning of the simulations. Therefore, at the beginning of the simulations, the HWP pool will only increase since there won't be an outflow from the pool through oxidation of the carbon in HWP until later (25 years from the first harvest). Finally, we measured the recreational aspects of the forest by the Shannon index and the proportion of city forest (vi). The Shannon index (Jost, 2006) was used to calculate the tree species diversity for each NFI plot, assuming that 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. Further details are presented in the Supplementary material.

2.4. Scenario definition

We defined three policy scenarios based on the main national policy documents reflecting the goals and governance mechanisms for FES provision in Norway: The white paper on forest policy and wood industry, labeled here National Forest Strategy, NFS, (Verdier i vekst) (NMAF, 2016), the Biodiversity Strategy, BIOS, (MCE, 2015) (Natur for livet), and the Bioeconomic Strategy, BIES (INNR, 2015) (Skog 22). To evaluate the ability of the Norwegian forest to provide the FES demanded by the policies, we elaborated and translated the quantitative and qualitative FES demands of policy documents into scenarios that can be optimized based on our simulated indicators. Details of the policy scenarios are provided in Table 2 and Appendix S4.

Table 2

Set of indicators and constraints used in each of the policy scenarios, NFS, BIOS, and BIES. Scenarios are described by the considered ecosystem service indicators, the way indicators have been implemented as objectives (epsilon constraint = red, maximize the objective under the given constraints = blue). MiS area = set-aside areas of "Complementary Hotspot Inventory". The corresponding equations (Eq.) for the individual indicator objective function are presented in Supplementary material S5.

Forest ecosystem service (FES)	Indicator (unit)	National forest strategy		Biodiversity strategy		Bioeconomy strategy	
		objective / constraint	Eq.	objective / constraint	Eq.	objective / constraint	Eq.
Wood production	Harvest net value (NOK)	Maximize	**1a**			Maximize	**1a**
	Harvested volume (Mm^3)			Maximize (even-flow)	**1a**		
Bioenergy	Harvested residues (kt)	Maximize: plots with harvest costs <150 NOK)	**3**			Maximize: plots with harvest costs <200 NOK)	
Biodiversity	MiS* area (ha)	No decline allowed	**2**	No decline allowed	**2**	No decline allowed	
	Deadwood volume (Mm^3)			No decline allowed	**2**		
	Bilberry (%)			No decline allowed	**2**		
	MIS area (ha)			Maximize	**1a**		
	Deadwood volume (Mm^3)			Maximize	**1a**		
	Bilberry (%)			Maximize	**1a**		
Water protection	Harvest vol. in steep terrain and mountain forests (Mm^3)			No increase allowed	**4**		
Climate regulation	CO_2 storage in harvested wood product (kt)	Maximize	**1b**			Maximize	**1b**
	CO_2 storage in harvested wood product (kt)	No decline allowed					
	Flow of carbon sink in forests (Million kt)					Maximize	**1c**
Recreation	Harvest in city forest plots (Mm^3)			No decline allowed	**2**	No decline allowed	**2**
	Shannon index			No decline allowed	**2**	No decline allowed	**2**

2.4.1. National Forest scenario

The NFS aims to raise the forest and wood industry value, increasing the sustainable production and extraction of raw materials as well as the profitable production of bioenergy and biofuels. Therefore, the FES wood (harvest net value) and bioenergy (harvest residues, i.e. branches and tops) objectives were considered as objectives to be maximized. The latter was only considered available for the market if the harvest cost profitability of bioenergy production (extraction cost to roadside) was below 150 NOK. The NFS also set targets for biodiversity conservation. These targets were considered as constraints avoiding a decrease from the current state. Further, the policy includes strong ambitions to convert Norway into a low-emission society, while promoting the use of wood in construction. Thus, we addressed climate regulation both as an objective to maximize and as a constraint, avoiding a decrease from the current status.

2.4.2. Biodiversity scenario

This scenario (BIOS) prioritizes the multifunctionality of forests, recognizing that forests host biodiversity and do not only serve wood-based industries and rural development. Therefore, biodiversity indicators (MiS area, bilberry yield, and deadwood volume) were implemented as constraints avoiding a decrease from the initial state and as objectives to maximize. Additionally, the policy recognizes the role of forests in regulating services such as natural flood control and protection against erosion. To achieve the targets related to water regulation, we avoided the increase of final cuttings in areas with steep terrain and mountain forests. Since the policy aims to increase the recreational value of forests, the FES recreation (city forest and Shannon index) was also included as a constraint, avoiding a decrease. Here, we used the number of plots with high values of the Shannon index (> 3) and the number of city forest plots.

2.4.3. Bioeconomy scenario

Under the BIES there is a focus to increase the sustainable extraction of timber resources from the Norwegian forests. Using a similar approach to the NFS, FES wood (harvest net value) and bioenergy (harvested residues) objectives were maximized considering the profitability of harvests, with a threshold for production cost <200 NOK. MiS area, which represented the biodiversity targets, was also included as a constraint, avoiding a decrease from the current situation. Similar to NFS, we here promoted the use of wood in construction, maximizing the CO_2 storage in HWP. However, this scenario also stated targets for maximizing the flow of carbon sinks in forests. Finally, this policy also aims to increase the recreational value of forests; following the same approach as in BIOS, recreation indicators were included as a constraint, avoiding a decrease from the initial state.

2.5. Demands for wood and biomass

Wood and biomass demand targets for Norway were expressed as timber demands and modeled using the GLOBIOM-forest model (IIASA's Global Biosphere Management Model, (Lauri et al., 2021)). GLOBIOM is an economic model that jointly covers the forest, agricultural, livestock, and bioenergy sectors, allowing it to consider a range of direct and indirect origins of biomass used. In the version used in this study, GLOBIOM-forest, the forest industry and forest bioenergy sectors are modeled in more detail while the representation of the agricultural sector is simplified. Then, based on increment data from the Global Forest Model (G4M) (Kindermann et al., 2008; Gusti and Kindermann, 2011), forest biomass supply is described by spatially explicit harvest potentials, taking into account the transportation costs and forest management type-specific land-use change costs. Using NFI data, GLOBIOM calibrates the total forest area in the EU countries and divides this area into three forest types (primary forests, secondary forests, and managed forests), and different management classes (no management, low intensity, multifunctional, high intensity).

In this study, we used the Nationally Determined Contribution (NDC) scenario to reflect future wood demands for the energy, transport, and building sectors under a climate change mitigation ambition. As a baseline for projecting future wood demands, the scenario was developed utilizing the SSP2 (Socio- Economic Pathway "Middle of the Road") assumptions for global socio-economic developments (e.g., GDP and population growth). Then, the demands for wood and biomass in GLOBIOM were further detailed according to the RCP-related mitigation demand projections of the MESSAGE energy system model (Fricko et al., 2017). Specifically, this scenario included a 40% reduction of GHG emissions by 2030 as compared to 1990 levels (translated into the RCP4.5) and accounted for the targets as set out in the 2016 Nationally Determined Contribution (NDC) by the European Commission. Even though GLOBIOM provides data for different scenarios, we decided not to include any climate scenario comparisons in this manuscript, since after a preliminary analysis we did not observe significant differences between climate scenarios in our results. Therefore, wood demands for material and bioenergy resources were projected at the national level until 2100 in 10-year time steps, under the NDC scenario. These GLOBIOM demands comprise five marketable timber products: sawlogs, pulpwood, other industrial roundwood, fuelwood, and logging residues. We used only the first two timber products, and we grouped the sawlogs and pulpwood products into a "total wood demand". By using multi-objective optimization, we matched the projected wood and biomass demand with the simulated timber harvest to determine whether Norway is capable of meeting climate mitigation targets. Therefore, the future expected wood demands representing the climate change targets were included as additional constraints in each policy scenario described above (section 2.4).

2.6. Optimization methods

We addressed the FES demands of the national strategies as well as the wood demands (GLOBIOM) using a multi-objective framework. We designed policy-specific multi-objective optimization problem formulations to find a specific solution for each policy scenario (Miettinen, 1999a) based on the preferences defined previously (section 2.4 and Table 2) while meeting the wood demand constraints from GLOBIOM (section 2.5):

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

$$subject\ x \in S$$

Here, $f_1(x)$ defines the different objective functions, x is the vector of management regimes used in the optimization, and S is the potential set of management regimes determined by a set of constraints. Inside the optimization software, maximization objectives are reformulated as minimization objectives by convention. Through specifying constraints and objectives, which represents the policy targets in Norway, the optimization aimed to seek an efficient solution for individual forests defined from NFI plots. Therefore, by using achievement scaling functions (ASFs) (Wierzbicki, 1986) or an epsilon constraint method (Miettinen, 1999b), it is possible to address the stated requirements from the strategy (Wierzbicki, 1986). Here, "soft targets" or reference points can be used to describe ASF functions, which are aimed to be achieved and relaxed if not feasible, while epsilon constraints define instead strict upper/lower targets that need to be achieved. This resulted in a set of different objective functions that were used to define the national policy scenarios in Norway. Through the use of these approaches, we achieved Pareto optimal solutions (i.e., a solution where no objective can be improved without impairing another (Miettinen, 1999a)).

In this way, according to the specific objective functions and constraints defined in each policy scenario, the optimization process will find the optimal solution for each plot FES if the problem is feasible while minimizing conflicts between FES. However, finding this optimal solution is challenging, since most of the FES are conflicting. To do so, we followed a step-wise approach: 1) the hard targets or epsilon constraints were included, so we constrained timber harvest to match GLOBIOM demands (supported by the graphical user interphase of the optimization tool – see Supplementary Fig. S1); 2) the national policy targets for FES were then optimized (as a reference point), considering the objectives and constraints defined in Table 2.

Therefore, the optimization approach can allocate different management regimes to a plot, but the largest proportion of plots were assigned to a unique management regime. When more than one management regime is selected for a plot, the optimization algorithm assigns percentages of the area represented by the plot to each of the selected management regimes, and each of these areas follows its own management regime, including harvesting schedule and regeneration. This approach allowed us to evaluate whether Norway might achieve future wood demands for reaching EU mitigation targets (Q1) and how different management alternatives could contribute to accomplishing those targets (Q2). The detailed equations are provided in Appendix S5. The framework used to solve the optimization problem was implemented in Python. We uploaded the Python code of the optimization together with a sample dataset on an online repository to allow for demonstration (https://github.com/maeehart/MultiForestDemonstration).

2.7. Trade-offs and synergies on the provision of ecosystem services

The optimization outcomes for each scenario were evaluated regarding the occurrence of trade-offs and synergies among FES. Then, by comparing their accumulated value over the simulated period in each NFI plot, we analyzed the spatial correlation (Pearson) between pairs of indicators (Q3) for each policy scenario. In this case, "trade-off" applies when two FES show opposing trends, while "synergy" defines when the supplies of two FES co-vary positively.

3. Results

3.1. Optimal combination of forest management for policy scenarios

Results from the optimization showed that Norway will be able to satisfy GLOBIOM biomass demands for wood and bioenergy, regardless of the policy scenario (Q1). In all three scenarios, NFS, BIOS, and BIES, the volume harvested matches GLOBIOM demands (Fig. 3). This trend shows a significant and linear increase during the first 50 years of the simulations, where the harvest volume increases from 11 million m^3 in 2018 to 16.8 million m^3 in 2073. After this year, the harvest volume displays a smoother growth until it reaches 17 million m^3 at the end of the simulation, 2093.

The management regime class distribution of the optimal solution for each policy scenario (Fig. 4) shows differences between the policy scenarios in terms of optimal management. The extensive regime class (BAU), which is the traditional regime applied in Norway, was the optimal management in the NFS scenario for almost 40% of the area, but only for 20% under BIOS. Under BIOS there is a decrease of around 2 million ha in the area assigned to BAU (Fig. S2a), while the area assigned to set-aside and continuous cover forest increases by 1.2 million ha (from 15% up to 25.5%) and 0.5 million ha, respectively.

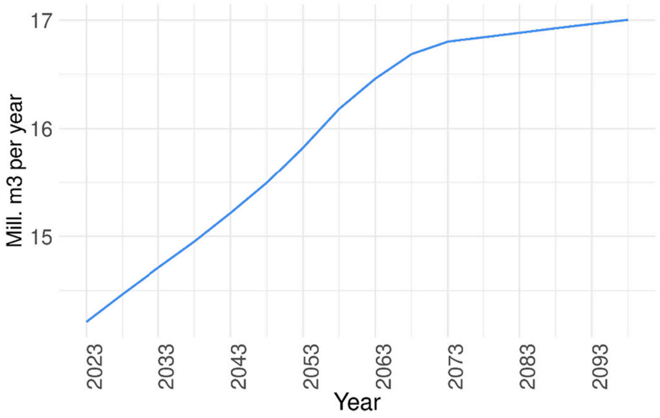

Fig. 3. GLOBIOM wood and biomass demands for the NDC scenario, and provision of harvested volume under the three policy scenarios: NFS, BIOS and BIES. Here, the attained harvest volumes and GLOBIOM wood and biomass demands for the NDC scenario completely match all 3 scenarios.

The BIES resulted in almost equal shares for BAU, the traditional extensive regime (28.1%), and EBAU (30.7%), followed by set-aside (15.3%) and intensive (11.8%). Compared with the NFS, BIES has less area (1 million ha) allocated to BAU, while the management intensive (INT), extensified BAU (EBAU), set-aside (SA),and continuous cover forestry (CCF) increase (Fig. S2b).

3.2. *Future provision of forest ecosystem services under different policies*

Overall, the three policy scenarios provided an increase in the harvest annual net value over the value at the beginning of the period. Differences between policy scenarios were especially marked towards the end of the simulation when the NFS predicted the largest harvest annual net values (Fig. 5a). Harvested residues showed a decreasing trend with relatively high interannual variability during all the simulations.

Biodiversity indicators for MiS area, bilberry, and deadwood showed the effect of the constraints on the optimization problem (Fig. 5 c, d, f). The MiS area increased with time under BIOS and BIES. Initially, the strongest increase was under BIOS where the indicator was introduced as an objective to maximize as well as a constraint (avoid a decline from the current state, 2018) (Fig. 5c). However, after 2042, a strong increasing trend in BIES is observed, leading to values above BIOS by the end of the simulation. The scenario BIOS showed an even-flow bilberry yield, showing the effect of the constraints avoiding a decrease from the current state. The opposite is the case in the other two scenarios, where the area of bilberry decreases during the first years (especially in NFS). After this decline, the BIES showed a growing trend in bilberry cover that was flattening out towards 2073. Conversely, until almost the end of the simulations, the NFS does not start showing a growing trend for this indicator. All three scenarios resulted in an increase of deadwood throughout the simulation (Fig. 5e), although only in BIOS was it included as an objective to maximize.

Carbon storage in harvested wood products showed a significant increase during the first periods, reaching a maximum of 82 million kt CO_2 in 2038 in NFS. This is followed by a decrease reaching around 25 million tons at the end of the simulations. Overall, trends are very similar among all three scenarios, with BIOS showing slightly lower values during the first half of the simulations (Fig. 5f). The flow of carbon sink in the forest showed an increasing trend through the simulations, mostly in the BIES scenario, where the indicator flow of the carbon sink in forests was introduced as an objective to maximize (Fig. 5g).

The pattern of the Shannon index differed among scenarios. The BIOS provided the highest values for this indicator, but a slightly decreasing trend during the simulations. After declining, the BIES also showed a strong increase in the development of this indicator, and almost reached a similar level to BIOS by the end of the simulation. Finally, results for harvest in areas defined as city forest plots as well as for harvest in steep terrain are shown in the supplementary material. These indicators showed marked fluctuations (peaks) but no trend throughout the simulations (Figs. S8 and S9).

3.3. *Trade-offs and synergies on the provision of ecosystem services*

Although we found that the intensity of the correlations varied among the policy scenarios, the strongest correlation among indicators (positive and negative) was found in BIES. For instance, we observed that BIES, and to a slightly smaller degree BIOS, had significant trade-offs (negative correlation) between harvest residues and biodiversity indicators, especially with MiS area and deadwood. Nonetheless, both in BIOS and BIES, these results were the opposite for net harvest value and biodiversity indicators. Overall, across all policy scenarios, net harvest value and harvest residues showed negative trade-offs, but the strength of the correlations increased in BIES. As we expected, MiS area, bilberry, and deadwood indicators (Biodiversity FES) were positively correlated in BIOS and BIES, but in NFS, bilberry and deadwood had a negative correlation. This opposite trend in NFS is also observed in the relationship between these two indicators, bilberry and deadwood, with the Shannon index, where deadwood correlated negatively and bilberry positively, with Pearson's coefficients of −0.93 and 0.96 respectively. In BIES, the inclusion of an objective related to the flow of carbon sink in forests in the optimization problem leads to strong synergies (positive correlation) between this indicator and the three biodiversity indicators, especially the MiS area, with correlation coefficients of 0.9. These synergies were not observed in either NFS or BIOS.

4. Discussion

In this study, we evaluate if and how the Norwegian forest can satisfy future wood and biomass demands, and simultaneously achieve the FES demands of national policies. Further, the FES synergies and trade-offs from the different demand levels were analyzed. Our results revealed that Norway will be able to achieve demands for wood and biomass (GLOBIOM) in all policy scenarios, but that the future provision of ecosystem services by Norwegian forests will be strongly determined by policy targets at the national scale.

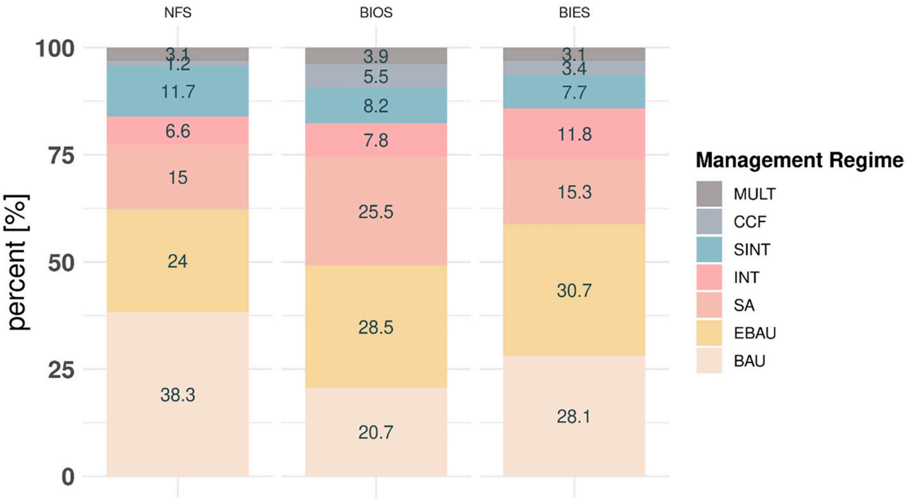

Fig. 4. Optimal management solution for the three policy scenarios representing the Norwegian national forest strategy (NFS), the biodiversity strategy (BIOS), and the bioeconomy strategy (BIES). The management categories are described in Table 1.

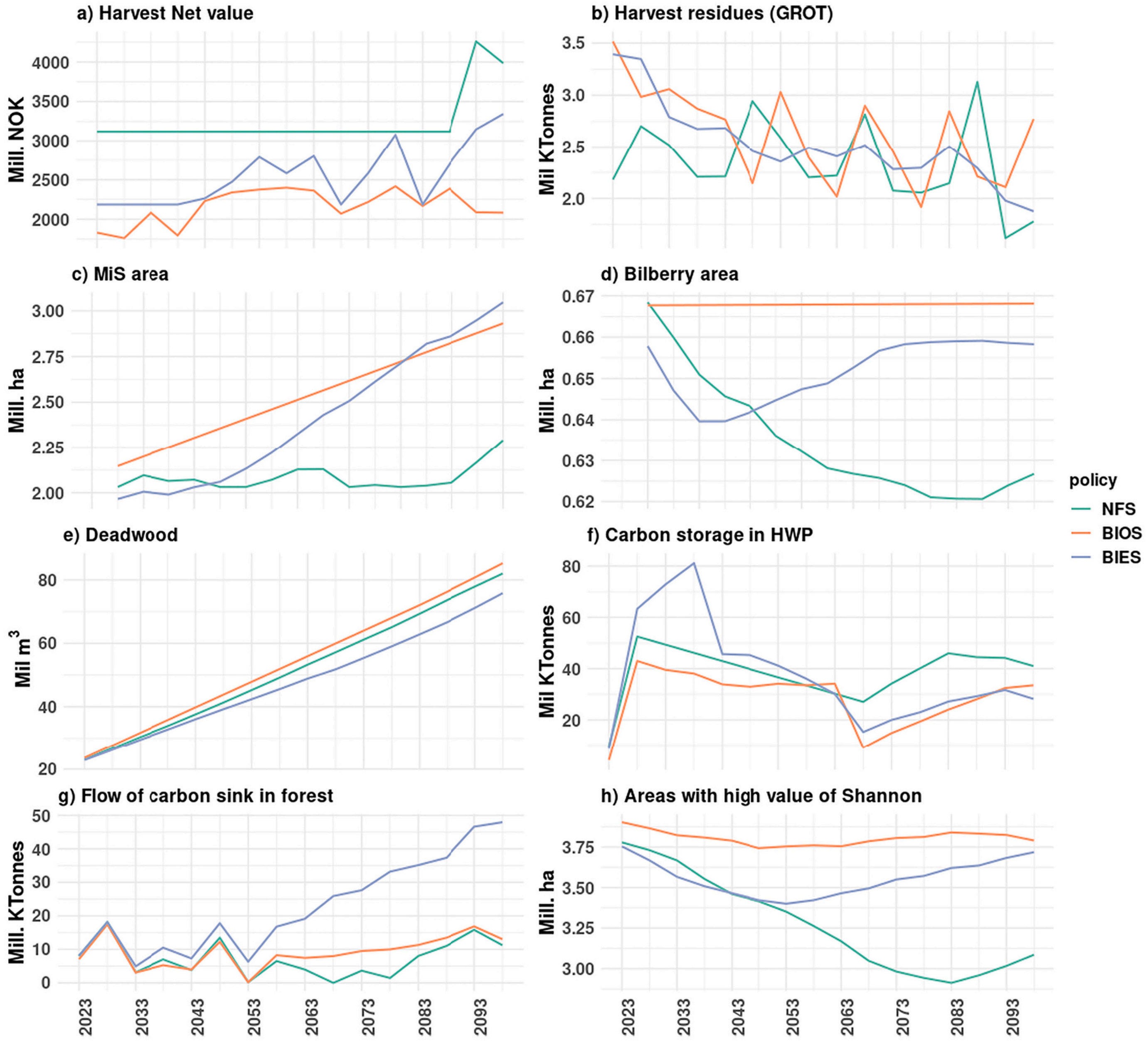

Fig. 5. Effect of optimal solution on the future development of FES indicators. These indicators represent total values for Norway under the different policy scenarios (NFS = national forest scenario, BIOS = biodiversity scenario, and BIES = bioeconomy scenario). *MiS area = set-asides areas of "Complementary Hotspot Inventory".*

4.1. National targets under different policy scenarios

Wood and biomass demand representing climate mitigation targets and expressed as GLOBIOM demands were easily reached for all policy scenarios. These GLOBIOM demands reach almost 17 million m^3 in 2093 (64% more than at the starting point in 2018) and are in line with those shown by Solberg et al. (2021), who projected a rather high harvest growth from 10 million m^3 in 2010 to 15.6 million m^3 in 2050 for Norway. Historically, harvest levels have remained relatively stable around 10–13 million m^3 per year, while the annual increment net growth has increased from 20 million m^3 in 1990 to 24 million m^3 in 2020 (SSB, 2020). These values show that the growth rates currently achieved in Norwegian forests are well below their production potential. Besides, it has been predicted that the increases in temperature and atmospheric CO_2 concentration will promote growth and thus increase biomass production in most tree species in boreal forests (Solberg et al., 2003; Andreassen et al., 2006; Brecka et al., 2018; Subramanian et al., 2019). We can then expect biomass production to rise even more in Norway as growing stock accumulates in forest landscapes. However, as we point out below (section 4.4), there are several other factors (disturbances) whose influence on the growth and development of forest landscapes could increase because of climate change. Therefore, although wood stocks are forecast or expected to increase in our scenarios, all these uncertainties could affect the growth and development of forests to a greater extent than at present.

Following the trends for the biodiversity FES observed in Fig. 5 (c,d, e), we observe that BIOS and partially BIES were the most consistent in the development of these indicators. The decline of the bilberry cover area under the NFS and BIES scenarios could be explained by the lack of constraints related to this indicator and reveals the well-known trade-off between timber production and the maintenance of other ecosystem services (Gamborg and Larsen, 2003; Duncker et al., 2012). Differences in MiS area between scenarios could be explained by the fact that in NFS and BIES the indicator was included in the optimization framework as a constraint and not as an objective to maximize, as in BIOS. For both BIOS and BIES, the MiS area (Fig. 5c) has a non-decreasing pattern, consistent with the policy targets related to this indicator, while for NFS, MiS area follows a different pattern, resulting in significantly lower levels of MiS area for this scenario. Interestingly, despite deadwood being only included in BIOS, the trends among policy scenarios were very similar, and in all scenarios, the deadwood constraints (not decreased from the current state) and objectives were achieved. However, characteristics such as qualities (development stages of deadwood and dimensions) and connectivity of patches with high deadwood volumes are essential to evaluate the role of deadwood in forest biodiversity and focusing only on the total volume increase could be not enough (Heilmann-Clausen and Christensen, 2004; Müller and Bütler, 2010; Andringa et al., 2019; Bujoczek et al., 2021).

In terms of carbon balance, the initial increase of carbon storage in HWP under the three scenarios is explained by the increasing trend in harvest levels during the first years of simulation (Fig. 5f). The growing stock in Norway has increased by approximately 30% since 1990 and almost 43% of the productive forest area consists of mature forests (KLD, 2020). Achieving a reduction in climate gas emissions is an overarching objective under three national policies, therefore, the harvested wood products will act as an important carbon sink and help to achieve climate neutrality by storing carbon and substituting fossil-based material. On the other hand, results related to the carbon sink strength in forests revealed that forests under BIES would be able to increase the carbon sink strength sequestration while meeting wood and biomass demand (Fig. 5g). Similar results were presented by Søgaard et al. (2020) who showed that managed forests in Norway will continue to be a significant carbon sink in the future, even under a higher harvest level.

4.2. *Trade-offs and synergies among forest ecosystem services*

Our results confirmed that the provision of a specific FES is rarely independent of other services, and positive (synergies) and negative (trade-offs) relationships among FES are common. For example, we found positive correlations between biodiversity indicators in those policy scenarios which prioritize the multifunctionality of forests, BIOS and BIES. These synergies between biodiversity indicators are common and have also been reported by several studies (Mina et al., 2017; Vauhkonen and Ruotsalainen, 2017; Albrich et al., 2018). For instance, Eldegard et al. (2019) found that bilberry cover increased with stand age, directly related to MiS area classification here. Lõhmus and Remm (2017) demonstrated the influence of stand density on bilberry habitat, modified by stand age and tree species composition, variables that simultaneously influence the availability of dead wood volumes and the definition of the MiS areas. They also found that the intensification of forestry brings reductions in bilberry cover, which agrees with the trade-offs observed between harvest residues and biodiversity indicators (Fig. 6) and with the decline of the bilberry cover area under NFS and BIES (Fig. 5d). An intensification of forest management to increase timber production can therefore result in a decrease in bilberry cover because of increased tree density (Barbier et al., 2008). Nonetheless, as Pohjanmies et al. (2017b) noted, under certain conditions, non-timber forest products like bilberry can benefit from stand management activities (Nybakken et al., 2012; de-Miguel et al., 2014).

On the other hand, our results did not show strong trade-offs between carbon stored in HWP and carbon sink in forests (that is, the relationship is negative but, in our case, the result was not significant). So, the maximization of the carbon sink in forests would not be strongly competing with the increased use of wood, as has been reported by other studies (Soimakallio et al., 2021). According to Pilli et al. (2017), increasing the harvest by 20% by 2030 would increase the net carbon storage in HWP by 8%, but the forest carbon sink in managed European forests would decrease by 37% compared to the average period in 2000–2012. However, as Blattert et al. noted (2022), it will be possible to minimize these conflicts by allocating the land to areas with different management purposes.

Finally, we observed that recreational values, such as the Shannon index, conflict with the maximization of harvest net value in BIOS, but not in NFS and BIES. From a recreational perspective, the main conflict in the Nordic countries is with timber production (Bell and Carrillo, 2007), and this conflict is likely to remain strong because of the expected increases in biomass demand. However, recreation is an economic sector in development that probably will have an increasing influence on future forest management (Holgén et al., 2000; Sherrouse et al., 2017). Consequently, it is important to find site-specific management strategies that balance wood production with recreational value over time. As an example, Eggers et al. (2018) suggested that extending rotation periods in areas with high recreational demand could be a beneficial strategy, as this practice increases recreational value without limiting wood production in the prioritized areas.

4.3. *Implications for forest management*

The definition of the targets at the national scale had a clear effect on the optimal solution (Fig. 4) for the three policy scenarios, which led to different management alternatives. In the optimal management solution for NFS, BIOS, and BIES, the extensive regimes (BAU and EBAU)

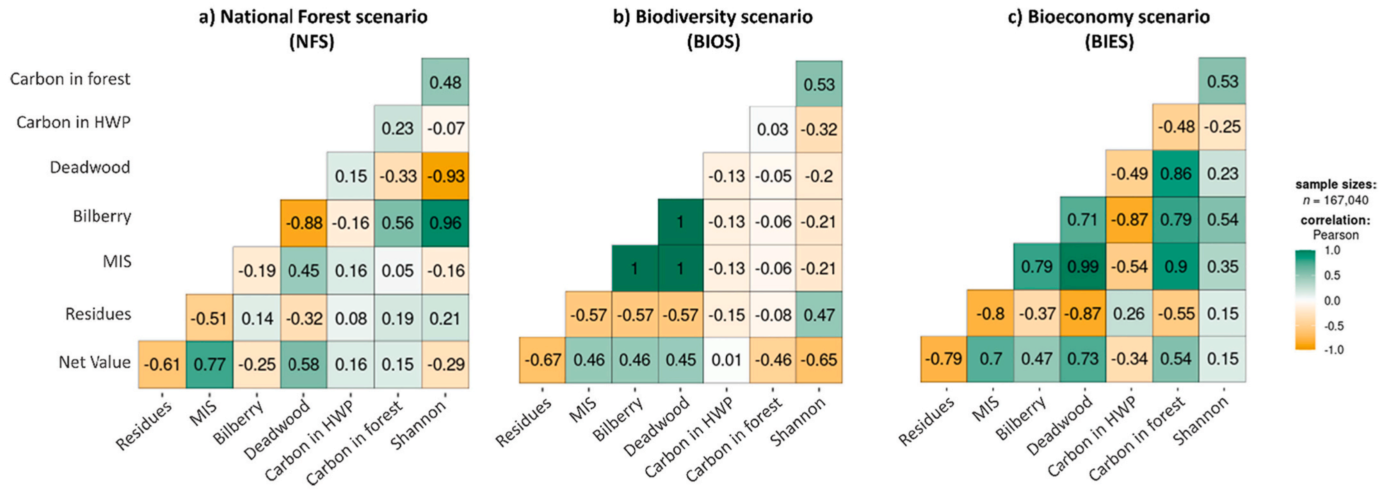

Fig. 6. Synergies and trade-offs among forest ecosystem service indicators for the three policy scenarios. Values correspond to pairwise Pearson's correlation coefficients (R^2) between indicators (positive correlations = synergies and negative correlation = trade-offs).

together with the set-aside contributed 2/3 of the area. The remaining 1/3 was almost covered by intensive regimes (INT and SINT) with small areas assigned to multispecies and continuous cover regimes. In BIOS there is a significant increase in proportions of set-aside (SA) as well as forest area under continuous cover forestry (CCF) (Figs. 4 and S2a), and a decrease in the business-as-usual regime (BAU). These management practices positively influence forest structure and biodiversity in many ways, e.g., canopy structure, amount of deadwood left in the forest, rotation length, the number of old trees, and tree mixture (Castro et al., 2015; Bernes et al., 2015; Eyvindson et al., 2018). Those forest structural features are important to ensure the long-term environmental and socio-economic viability of forests (European Commission, 2021). However, to achieve this, and meet demands for bioenergy and wood at the same time, a compensatory increase in timber harvest elsewhere might be required (Duncker et al., 2012). Therefore, the reduction in timber harvest caused by larger set-aside areas could be replaced by increased harvests from forest areas dedicated to intensive production (Fig. S2a). As a result, there is a possibility that the forest may degrade to some extent in some specific areas, especially in NFS and BIES where the biodiversity targets were more challenging to achieve. To minimize this, policies should establish instruments to motivate forest owners to adapt their management practices so that they can use forest more effectively to reduce forest degradation. Corresponding programs already exist in Norway (Norwegian Ministry of Agriculture and Food, 2005, MCE, 2015), a central regulation under the act is the obligation for forest owners to regenerate areas within three years after harvesting. In addition, economic support is provided for sustainable forestry activities. A recent priority has been to support forest roads and timber terminals in areas where forestry infrastructure is sparse, causing forest resources to be underutilized. In addition to grant support, the Norwegian forestry act mandates each forest property to set aside a certain share of the timber sales for reinvestment in forest management (Forest Trust Fund). Typical activities would be reforestation, silviculture, forest management planning, and infrastructure development (NMAF, 2016). As part of the national policy, it has also been decided that the proportion of protected forests will increase from 5 to 10%. However, it has not been decided which forest types will be protected and how the effect of different protection strategies will affect both the economy and biodiversity. Depending on which forest types are protected, the effect on degradation (and the economy) could vary greatly.

In short, by comparing the three policy scenarios, it is evident that no single management strategy would be able to maximize the provision of multiple FES at the same time. In this sense, a mixture of these scenarios might be most desirable as it would include different preferences. However, the analysis shows the conflicts of policies in terms of management (a new dimension compared to previous studies that have analyzed incoherences) and the need that future policies should be more aligned.

4.4. *Limitations and methodological aspects*

When defining the optimization problems through the national policies, we opted for including only the FES that are mentioned in the policy documents. Additionally, our analysis was limited to using variables that are available from the Norwegian NFI and we did not include the impacts of other sources of uncertainty, such as natural disturbances. However, it is expected that Norwegian forests will be greatly affected by climate change, causing natural disturbances (extreme droughts, storm events, insect pest outbreaks, and forest fires) to increase in frequency and severity (Machado Nunes Romeiro et al., 2022). Therefore, including disturbances might affect the management of these policy scenarios. Especially in the Nordic regions, increased disturbances might cancel out climate change-induced productivity gains (Reyer et al., 2017; Brecka et al., 2018; D'Orangeville et al., 2018). Therefore, climate mitigation targets would face additional challenges to achieve the required wood demands (Hanewinkel et al., 2012). This will likely exacerbate existing synergies and trade-offs between FES and further increase the incoherence in policy objectives at the national level (Mina et al., 2017; Albrich et al., 2018). On the other hand, we have identified a range of indicators useful for quantifying and valuing important national ecosystem services in Norwegian forests. However, this required inherent simplifications and should be interpreted with care, since for example concepts such as biodiversity and the related FES are very broad and can differ widely among countries and different types of actors (e.g., researchers, foresters, conservationists, etc.) (Juerges et al., 2021). In this respect, some authors have noted the need to develop common indicators to allow international comparisons and thus enable international reporting (Hansen and Malmaeus, 2016), as well as to reduce different interpretations.

5. Conclusions

In this study, we focused on how Norwegian forests can meet the projected wood demands for achieving climate mitigation targets (GLOBIOM demands for wood and biomass) while simultaneously meeting FES demands targeted under three national policies, Verdier i vekst (NFS), Natur for livet (BIOS) and Skog 22 (BIES). We provide an example of how policies are implemented in a non-EU context, with less productive forest conditions, and with different societal needs than, for instance, those presented by Blattert et al. (2022), whose national sectoral policies represent an operationalized version of the EU-level counterparts. Here, the BIES scenario was the most detailed, since it was defined by a greater number of indicators (eight) and was the scenario that showed the strongest relationships (trade-offs and synergies) among indicators. Although this scenario was the most ambitious in the multiplicity of its objectives, it shows incoherencies with recreation indicators (Shannon index), especially during the first years of the simulations. In addition, we observed that BIES and NFS resulted in very similar forest management programs at the landscape level in Norway. On the other hand, BIOS resulted in an increase of set-aside areas, continuous cover forestry, and multispecies management, which made it more compatible with biodiversity indicators: bilberry cover, MiS area (set-aside areas of "Complementary Hotspot Inventory"), and volume of deadwood. However, the increase in set-aside areas in BIOS could be offset by higher harvests elsewhere. This will concentrate forest management on specific land areas, increasing the impact on them. To reduce forest degradation, policy makers should develop incentives to motivate forest owners to adapt their management practices. Finally, our study also highlights that there are multiple trade-offs and synergies between ecosystem service provision that are probably determined by the definition of policy targets at the national scale. Policy impacts can vary and identifying winners and losers when evaluating the impacts of national policies (NFS, BIOS, and BIES) on alternative FES will improve the transparency of political decision-making.

Author contributions

MV, CA, KØ, RA: conceptualization of the study. MV, CA, CF: data curation. RA, MM: Funding acquisition. MH, KE, MV, CA, CB, AT: Optimization and software. MV, CA, FD, NF: Simulation and optimization. RA, CA, DB: Project admin and supervision. MV: Data analysis and writing of original draft. All authors: review & editing.

Declaration of Competing Interest

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

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2022.102899.

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