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Sectoral policies cause incoherence in forest management and ecosystem service provisioning

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ABSTRACT

Various national policies guide forest use, but often with competing policy objectives leading to divergent management paradigms. Incoherent policies may negatively impact the sustainable provision of forest ecosystem services (FES), and forest multifunctionality. There is uncertainty among policymakers about the impacts of policies on the real world. We translated the policy documents of Finland into scenarios including the quantitative demands for FES, representing: the national forest strategy (NFS), the biodiversity strategy (BDS), and the bioeconomy strategy (BES). We simulated a Finland-wide systematic sample of forest stands with alternative management regimes and climate change. Finally, we used multi-objective optimization to identify the combination of management regimes matching best with each policy scenario and analysed their long-term effects on FES.

The NFS scenario proved to be the most multifunctional, targeting the highest number of FES, while the BES had the lowest FES targets. However, the NFS was strongly oriented towards the value chain of wood and bioenergy and had a dominating economic growth target, which caused strong within-policy conflicts and hindered reaching biodiversity targets. The BDS and BES scenarios were instead more consistent but showed either sustainability gaps in terms of providing timber resources (BDS) or no improvements in forest biodiversity (BES). All policy scenarios resulted in forest management programs dominated by continuous cover forestry, set-aside areas, and intensive management zones, with proportions depending on the policy focus. Our results highlight for the first time the conflicts among national sectoral policies in terms of management requirements and effects on forest multifunctionality. The outcomes provide leverage points for policymakers to increase coherence among future policies and improve implementation of multiple uses of forests.

1. Introduction

Forests provide a wide range of ecosystem services demanded by the society, like wood and non-wood forest goods as provisioning services, carbon storage, nutrient and water cycles as regulating services, as well as cultural services like recreation. Additionally, forests play a key role for biodiversity conservation (Forest Europe, 2020; MEA, 2005; Wolfslehner et al., 2019). These societal benefits, commonly referred to as forest ecosystem services (FES), have become the focus of a number of European policies (Bouwma et al., 2018; EASAC, 2017; Primmer et al., 2021).

The EU forest strategy (EC, 2013, 2021) recognizes FES more

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explicitly than any other policy and aims to balance the delivering of various FES and meeting the societal demands (Bouwma et al., 2018). In addition, forest issues are addressed by disparate sector policies. Even though these policies do not always directly refer to FES, they address the functions of forest ecosystems that benefit society (Primmer et al., 2021). The EU biodiversity strategy aims to halt the loss and restore biodiversity and ecosystem services (EC, 2011). The new EU biodiversity strategy promotes an increase in sustainable management and forest resilience against climate change. Further, it aims to protect 30% of the EU's land area, out of which 10% are strictly protected, including all remaining primary and old-growth forests (EC, 2020). At the same time, the bioeconomy strategy emphasizes a transition from a fossil-based to a bio-based economy, causing increased timber demands (EC, 2018). Overall, the coherence among existing EU-level sectoral policies is moderate, and the implementation of these policies is not coordinated (Bouwma et al., 2018; Wolfslehner et al., 2020). The lack of policy coherence is expected to create undesired trade-offs among FES, which in turn may decrease sustainability (Nabuurs et al., 2019; Nilsson et al., 2012; Winkel and Sotirov, 2015), particularly due to the uncertainty of climate change, which strongly affects European forests (Hanewinkel et al., 2013; Lindner et al., 2010; McDowell et al., 2020).

Unlike in agriculture, there is no common agreed EU forest policy among member states, due to factors like sectoral and institutional competition, and different economic interests. Instead, a collection of distinct and disintegrated policy initiatives exists at the member state level, guiding the management of FES and handling contradictions and conflicts (Pülzl et al., 2018; Winkel and Sotirov, 2015; Wolfslehner et al., 2020). In the case of Finland, the biodiversity strategy (FME, 2012), the bioeconomy strategy (FMME et al., 2014), and the national forest policy (FMAF, 2015, 2019), are the sectoral policies that handle resources for the provision of FES. National sectoral policies represent an operationalized version of the EU level counterparts, reflecting the demands Finnish policies place on FES (Primmer et al., 2021), and coordinating the diverse stakeholder interests (Harrinkari et al., 2016). The general pathway in the Finnish forest policy is to produce "more of everything", co-aligned with the global bioeconomy discourse to safeguard the use of forest resources, which contributes to the legitimisation of intensive management practices (Kröger and Raitio, 2017). In 2018, the total roundwood harvest in Finland was the highest ever with 78.2 million cubic meters (24% higher than the average over the preceding ten-year period). At the same time, around 11% of the forest is strictly protected. However, the majority of the protected forest (80%) is located in the low productive northern parts of Finland (Peltola et al., 2019). The prioritisation of production over ecological objectives is causing underlying conflicts within the Finnish forest policy pathway, which are not openly addressed (Kröger and Raitio, 2017).

To understand the conflicts among disintegrated sectoral policies and to identify synergies in ways forward, it is crucial to understand how the FES targets within the strategies plays out in the form of long-term levels and what management is needed to achieve the policy targets. Eyvindson et al. (2018) showed that increased timber harvests following the Finnish bioeconomy targets are causing trade-offs with the conservation capacity of the forest landscape and its ability to provide multiple FES.

The method of multi-objective optimization is widely used to alleviate conflicts between increasing harvest demands and sustaining non-woody FES (e.g. Chen et al. (2016); Eggers et al. (2020a); Knoke et al. (2016); Mazziotta et al. (2017)). It can be used to study how management targeting a focal objective affects another objective, and resolve conflicts by finding compromise solutions that balance among multiple FES objectives in the landscape (Mazziotta et al., 2017). For example, Pohjanmies et al. (2017) solved conflicts between provisioning and regulating services, and biodiversity conservation by identifying management solutions that minimized the losses of all objectives. Eyvindson et al. (2019) quantified the conflicts among different interest groups in forest resource management. Eggers et al. (2020b) revealed to stakeholders how their management preference plays out concerning economic and ecological indicators. Finally, the method was recently used to explore how the banning of clear-cutting management, advocated by Finnish citizen initiative to promote biodiversity, will reduce the future forest landscape multifunctionality (Eyvindson et al., 2021). Generally, there are large unrealized potentials for "win-win" management strategies that increase overall multifunctionality of landscapes (van der Plas et al., 2018), which are efficiently explored and revealed using this method.

Even though securing multiple FES has been identified as a key condition for overall sustainability of forest use (EASAC, 2017), the complex management drivers arising from the FES targets stated in sectoral policies are not well understood and have not gained much attention. Previous research tackled the question of conflicting forest sectoral policies only from the governance perspective (Bouwma et al., 2018; Primmer et al., 2021; Sotirov and Storch, 2018; Winkel and Sotirov, 2015), with limited focus on their long-term impact on actual FES levels in the forest. This is a serious drawback, because we do not know the potential inefficiencies resulting from policy incoherence at the level of forest landscapes. The scarce research on policy drivers for FES might depend on the different time perspectives between forest ecosystems (rather inert and long-term systems) and sectoral policy strategies (rather dynamic and short-term systems). Further, policies are based on specific sectoral interests and preparation processes, while their implementation is coordinated at the level of forest management. Additionally, policies and their objectives are quite often "fluffily" formulated, making it challenging to quantitatively assess and analyse the consequences of their implementation within forest management planning. This requires a framework that facilitates the holistic analysis of policy documents by standardising references to FES, as recently presented by Primmer et al. (2021), to gain information for strategic forest planning purposes.

This paper aims to close the gap between governance research and long-term forest ecosystem management research to investigate the effects of sectoral policies on forest landscapes, and their ability to provide FES. Using Finland as a case study, we ask: I) How can national sectoral policies for forestry, biodiversity and bioeconomy translate into explicit scenarios that can be quantitatively evaluated? II) What is the required forest management program (a combination of management regimes) that best fulfil the FES demands given by different policies? III) What are the long-term effects of the policies and their associated, resulting management programs on FES? IV) Are such policies causing sustainability gaps in terms of FES? To answer these questions, we analysed three sectoral policies on societal demands for nine FES categories, adopting the policy analysis framework of Primmer et al. (2021). We used multi-objective optimization to identify management programs that achieved policy demands and analysed their impacts on FES. The basis for the optimization was simulations of long-term forest dynamics and management of a forest sample representing the national scale (Fig. 1).

2. Method

2.1. Study region and data

Finnish national forest sectoral policies are addressing the whole boreal forest land in Finland, which accounts for 86% of the land area (including 10% of unproductive forest area). According to the 12th national forest inventory (NFI), half of the growing stock in Finland is made up of pine (*Pinus sylvestris*), 30% is spruce (*Picea abies*), 17% is birch (*Betula pendula*, *B. pubescens*) and the remaining 3% are other broadleaved trees. The annual increment totalled 108 Mm^3, with a mean of 6.9 m^3ha^{-1} in southern and 3.2 m^3ha^{-1} in northern Finland. Approximately, two-thirds of the forest land is on mineral soil, with the remaining part on peatlands. Peatland areas have, however, decreased during the past several decades, due to ditching, resulting in the

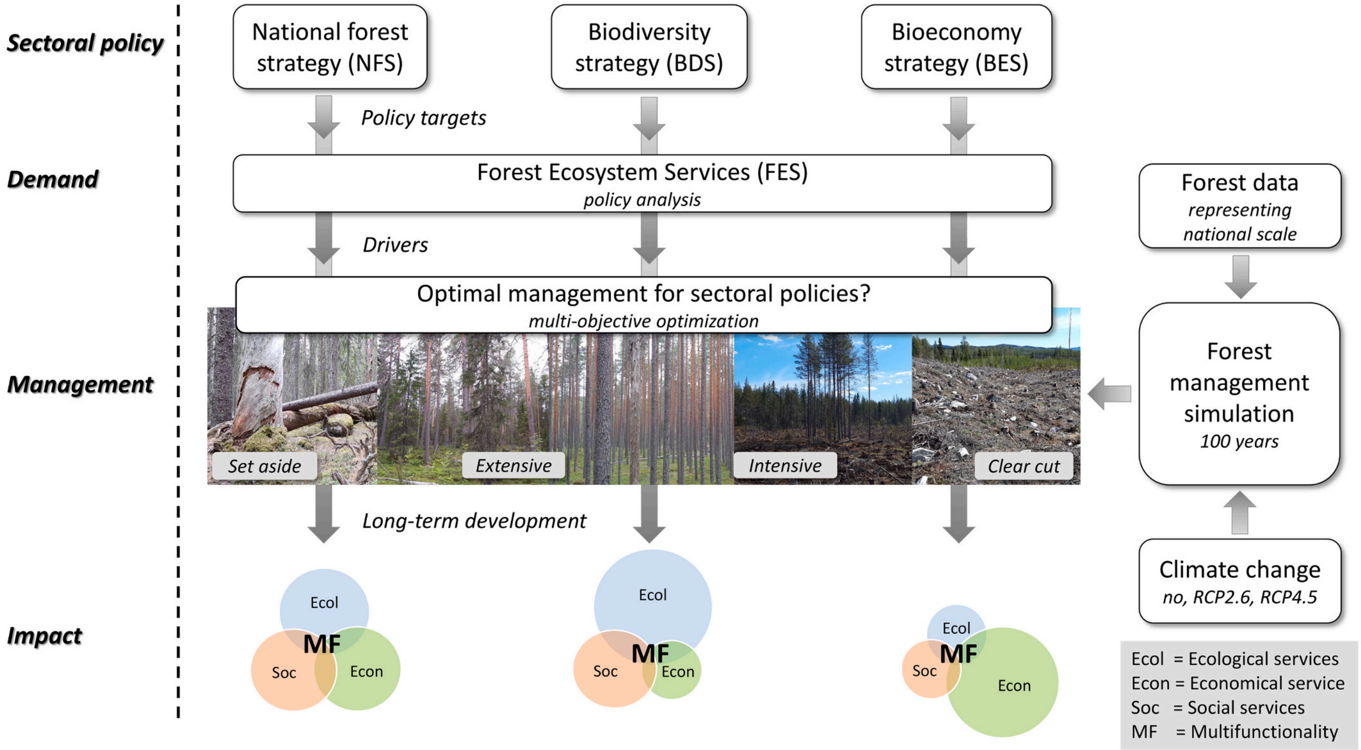

Fig. 1. Illustration of the study approach. Finnish sectoral policies were analysed regarding their demands for forest ecosystem service (FES). Multi-objective optimization was used to identify management programs that achieved policy demands and the long-term management impact on FES was analysed. The basis for the optimization was national simulations of forest dynamics and management.

vegetation and growth of trees typical of mineral soils. Around 11% of the forest land in Finland is under strict protection (Peltola et al., 2019).

To accurately represent the forest conditions across Finland and at the same time to allow reasonable computation time for data simulation and optimization, we created a sub-sample of the stands from the Finnish Forest Centre.[1] The publicly available data describe the forest situation at stand level over the whole of Finland, containing basic information about individual stands (e.g., location, soil type) and detailed information about their current structure (e.g., tree species distribution, tree density, tree size). Forest stands were selected along the regional and temporal specific NFI sampling grid; when a NFI plot centre falls into a stand this stand was noted (Fig. 2). In total, 39,445 stands were selected for our analysis showing an average age of 53.8 years (sd = 29.8). To account for the national scale, simulated stand outcomes (Section 2.2) were normalized to values per hectare and multiplied by the represented forest area of the NFI plot. We also recorded if a NFI plot centre was located in a statutory protected area, whereby management activities were not allowed. The data about the protected areas were freely available from the Finnish environmental Institute (SYKE).[2] For details about data generation, see the supplementary material Appendix S1.

2.2. Forest management simulation

The forest dynamics and management was simulated using the open source forest simulator SIMO (Rasinmäki et al., 2009). SIMO simulates tree growth, mortality and regeneration for even-aged (Hynynen et al., 2002) and uneven-aged boreal forests (Pukkala et al., 2013). For each forest stand, we simulated 29 management regimes in five-year periods from 2016 to 2116, with the exact number of management alternatives applied depending on the initial conditions of each individual stand (i.e. dominant stand height, basal area, site type, and stand age; Table 1). The regimes provided a diverse set of management alternatives for each stand out of which the optimization afterwards selected an ideal one based on the management effects on FES indicators.

The regimes can be categorized into six classes based on their defining features, like harvest intensity, rotation time, green tree retention, time and number of thinnings, stand regeneration, and fertilization. The six classes are (Table 1): business as usual (BAU) regimes with an even-aged rotation forest management according to the Finnish management guidelines (Äijälä et al., 2014); regimes with intensified (IBAU) and extensified (EBAU) versions of rotation forest management; regimes that increase the broadleave shares on medium fertile sites in southern and central Finland for better adaptation to climate change (ACC); continuous cover forestry (CCF) regimes that convert stands into permanently covered and diverse structured forests, and a setting aside (SA) regime with no management activities. Appendix S2 lists details of the management regimes.

Forest development and management were simulated under three climate change scenarios: current climate, representative concentration pathways RCP2.6 and RCP4.5 scenario. The regional climate variables driving stand growth and soil dynamics (mean and amplitude of temperature, CO_2, concentration, precipitation) were based on Lehtonen et al. (2016), and the climate data of the Canadian Earth system model CanESM (von Salzen et al., 2013). The impact of climate variables on forest growth dynamics in SIMO was included based on climate sensitive statistical growth and yield models (Matala et al., 2006; Matala et al., 2005). The simulations were conducted with high performance computational resources provided by CSC - IT Center for Science LTD (cPouta, https://research.csc.fi).

2.3. Forest ecosystem services and indicators

Simulated forest stand characteristics and harvested potential under

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[1] http://www.metsaan.fi (March 2021).

[2] https://www.syke.fi/en-US/Open_information (March 2021).

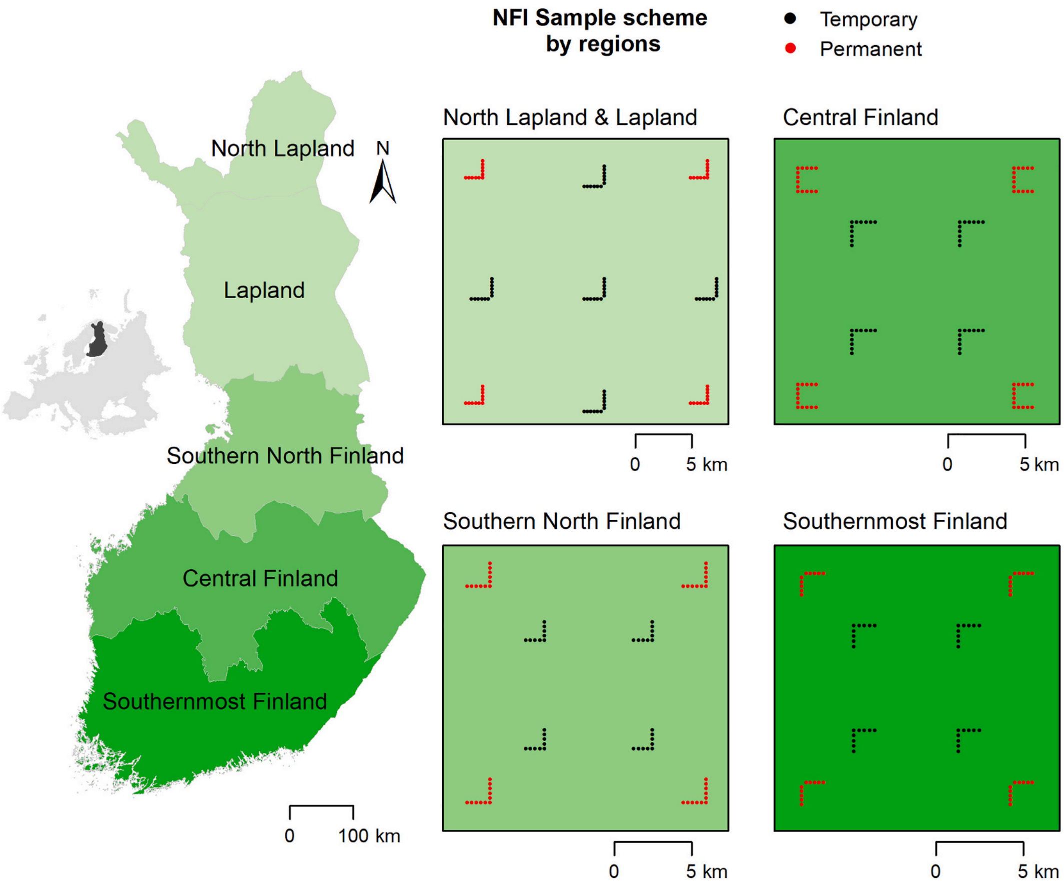

Fig. 2. The national scale of Finland was used as study area represented by a systematic sample of forest stands from the Finnish Forest Centre (www.metsaan.fi) along the National Forest Inventory (NFI11) sampling grid.

Table 1
The alternative management regimes applied in the forest growth simulations have been grouped into six categories. For details see Appendix S2.

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

the different management regimes and climate change scenarios were used to calculate indicators for FES assessments. The policy framework of Primmer et al. (2021) defines ten FES according to international classification schemes (Haines-Young and Potschin-Young, 2018; MEA, 2005), allocating biodiversity conservation and resilience as regulating services. The ten FES were: wood production, bioenergy, non-wood forest products, and game animals (provisioning services); biodiversity conservation, water protection, climate regulation, and resilience (regulating services); as well as recreation and cultural heritage (cultural service). Except for the cultural heritage service, we linked to each FES our simulated indicators to assess their long-term provisioning (Table 2). Cultural heritage was not considered as we currently do not have empirical information or models to link forest structural characteristics with the emotional and spiritual relationships of citizens with forests.

The FES wood production was measured by the simulated annual yearly increment (m^3 ha^{-1} yr^{-1}) and the periodically harvested timber volume (m^3 ha^{-1}). Bioenergy was assessed by the harvested biomass (m^3 ha^{-1}), which summarises the combined volume of harvest residues, uplifted tree stumps and roots. Uplifting stumps and roots were only simulated for spruce and pine stands under rotation forestry that are situated on fertile and medium fertile site types.

Non-wood FES were assessed by the yield of bilberry, cowberry and marketable mushrooms, which are important non-timber products in the boreal forest (Miina et al., 2020; Wolfslehner et al., 2019). The yield (kg ha^{-1}) for bilberry (*Vaccinium myrtillus L.*) (Miina et al., 2009) and cowberry (*Vaccinium vitis-idaea L.*) (Turtiainen et al., 2013) was predicted with models considering site and stand characteristics like basal area (BA) and the dominant tree species as independent variables. Marketed mushrooms yield (kg ha^{-1}) was estimated using the models of Tahvanainen et al. (2016). The mushroom models were developed for Norway spruce dominated stands in eastern Finland, and therefore can overestimate expected yields for less productive forests over all of Finland. Yet, we include this measure for sake of quantitative comparison on the suitability of alternative management regimes for this

Table 2

Three policy scenarios were optimized representing the Finnish national forest strategy, the biodiversity strategy and the bioeconomy strategy. Scenarios were described by the considered ecosystem service indicators, and the way indicators have been implemented in the multi-objective optimization: as objectives to be *maximized,* or as constraints. The optimal solution was approached stepwise in a lexicographic approach following the preferences set by the policies (indicated by column ‘step’).

Forest ecosystem services (FES)	Indicator (unit)	National forest strategy (NFS)		Biodiversity strategy (BDS)		Bioeconomy strategy (BES)	
		Objective / constraint	step	Objective / constraint	step	Objective / constraint	step
Wood production	Increment (m^3 ha^{-1} yr^{-1})	Target in 2025: ≥ 115 Mm^3; in 2050: ≥ 125 Mm^3	1				
	Harvested roundwood (m^3 ha^{-1})	Target in 2025: ≥ 80 Mm^3	1	*Maximize* (even-flow)	1	*Maximize* even-flow under biodiversity constraints	2
Bioenergy	Harvested biomass (m^3 ha^{-1})	Target in 2025: ≥ 6.5 Mm^3	1			*Maximize* even-flow under biodiversity constraints	2
Non-wood	Bilberry (kg ha^{-1})	No decline, *maximize* it further	3				
	Cowberry (kg ha^{-1})	No decline, *maximize* it further	3				
	Mushrooms (kg ha^{-1})	No decline, *maximize* it further	3				
Game	HSI moose (−)	*Maximize*	4	*Maximize*	1		
	HSI capercaillie (−)	*Maximize*	4	*Maximize*	1		
	HSI hazel grouse (−)	*Maximize*	4	*Maximize*	1		
Biodiversity Conservation	Regime SA (−)			Target of 17%	1		
	Conservation regimes*** (−)	Target of ≥4.5%	2	Target of 4.5%	1		
	Deadwood (m^3 ha^{-1})	Target in 2025: avg. ≥ 8 m^3ha^{-1}	2	Target in 2050: increase by 60%	1	No decline allowed, but no target	1
	Deciduous tree volume (%)	*Maximize*	4	Target in 2050: increase by 10%	1	No decline allowed, but no target	1
	Large trees (DBH > 40 cm) (n ha^{-1})	*Maximize*	4	Target in 2050: increase by 10%	1	No decline allowed, but no target	1
Water protection	Only regimes CCF/SA on peatland (%)	Enabled constraint	1	Enabled constraint	1		
Climate regulation	Carbon sink (t CO_2 ha^{-1} yr^{-1})	Target in 2025: ≥ 27.88 $MtCO_2$ equivalent	2	*		**	
Recreation	Recreation index (−)	*Maximize*	4	*Maximize*	1	*Maximize*	2
	Scenic index (−)	*Maximize*	4	*Maximize*	1	*Maximize*	2
Resilience	CC adaption regimes (−)	*Maximize*	4	*		**	

* Indirectly addressed by importance of protected areas for carbon sinks; ** Indirectly addressed by exploiting timber resources; *** Conservation oriented regimes were represented by two CCF regimes with reduced thinning intensity (CCF_3, CCF_4), and an extensified BAU regime with retention tree (BAUwGTR, see Appendix S2 for details on regimes).

important non-timber product.

The FES game included three species: moose (*Alces alces*), western capercaillie (*Tetrao urogallus*), hazel grouse (*Bonasia bonasa*). We selected these species to represent a wide range of important game animals in Finland. The occurrence of moose was measured with a species-specific habitat suitability index (HSI) describing their winter-feeding habitats based on the stand characteristics tree species mixture, stand density and height of trees (Kurttila et al., 2002). The HSI models describing the stand characteristics for the occurrence of capercaillie and hazel grouse were taken from (Mönkkönen et al., 2014). The HSI vary between 0 (unsuitable habitat) and 1 (most suitable habitat).

According to the red list of habitat types in Finland (Kontula and Raunio, 2019), the most significant reasons for forest habitat types becoming red-listed are a reduction in deadwood, reduction in old-growth forests and individual old trees as well as changes in tree species composition by reducing the share of deciduous trees. The biodiversity conservation value of the forest was thus measured by five separate variables: deadwood volume (m^3 ha^{-1}); percentage of deciduous trees in the standing tree volume (%); the number of large trees (diameter at breast height DBH > 40 cm); the share of stands that are managed by SA, representing strict protected areas; the share of stands that are managed with CCF (two regimes with reduced thinning intensity, basal area threshold +3, +6 m^2 ha^{-1}) and an extensified BAU version with retention trees, representing biodiversity conservation oriented management in commercial forests.

The water quality of lakes and streams depends on the management activities on adjacent forests. Intensive management with clear-cutting combined with ditches increase nutrient and sediments discharges to the water bodies, particularly on peatland (Marttila et al., 2020; Nieminen et al., 2017; Tolkkinen et al., 2020). As indicator for the FES water quality, we used the share of CCF on peatlands, which is seen as an economically and environmentally feasible management option to decrease negative water quality impacts (Nieminen et al., 2018).

Climate regulation was measured by the carbon sink (t CO_2 ha^{-1} yr^{-1}), which represents the change in carbon storage between two simulation time steps. Carbon storage was the sum of the total carbon held within standing timber, deadwood, and soil, converted in its corresponding CO_2 content. The carbon of standing timber and deadwood was evaluated as 50% of the dry biomass. Deadwood decomposition was simulated using the models from Mäkinen et al. (2006). Soil carbon was quantified using two models; for mineral soil the Yasso07 model was used (Liski et al., 2005; Tuomi et al., 2011; Tuomi et al., 2009), and for peatland soils the carbon flux models by Ojanen et al. (2014), accounting also for the initial carbon pool of peat soils. The carbon storage in wood products was not included since we consider the forest landscape as our system boundary.

FES recreation was calculated using two indices (Pukkala et al., 1988; Pukkala et al., 1995), which estimate people’s average opinion about the recreational value (recreation index) and beauty of forests (scenic index) of managed forest stands. The indices assume that the recreational values of forests increases with the age and size of trees, as well as increasing the shares of pines and birches.

The aspect of resilience was quantified by the share of forest stands managed with the adaption regimes (ACC, see Table 2), applied in

Southern and Central Finland on medium fertile sites. It is widely acknowledged that minimizing the future effects of climate induced disturbances require an increase of broadleaves in the forest stands and landscape (Venäläinen et al., 2020).

2.4. Policy analysis

The three Finnish sectoral policies analysed were: National Forest Strategy (NFS) (FMAF, 2015, 2019), Biodiversity Strategy (BDS) (FME, 2012), and Bioeconomy Strategy (BES) (FMME et al., 2014). Therefore, we followed the recent work of Primmer et al. (2021), and their methodological framework for categorizing and assessing how FES are mentioned in policy documents. Translating policy documents into a multi-objective optimization problem requires a detailed information on which FES are addressed, and what is the stated demand for FES in each policy.

The framework used a coding scheme that weights 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 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). For each policy document, Primmer et al. (2021) summarised how the FES are mentioned and extracted the corresponding text parts (qualitative FES demands), which were filled into a template and stored in a database. We further elaborated this approach and particularly focused on quantitative demands and indicators for FES explicitly indicated in each policy document. Stated policy demands and indicators for FES were then related to our simulated FES indicators and used to define a multi-objective optimization problem to be solved for each policy. A detailed overview of the policy analysis and the collected data is given in Appendix S3.

2.5. Sectoral policies optimization

The analysed FES demands of the sectoral policies were used to define individual objectives for each policy scenario, which were then jointly addressed within a unique multi-objective optimization problem (section 2.5.4). The aim of the optimization was to select an ideal management regime per stand and identify the optimal management combination best fulfilling the policy demands for FES. Therefore, the optimization alleviated conflicts among multiple FES by finding a compromise solution that minimizes the maximum deterioration among objectives. Sections 2.5.1 to 2.5.3 describe how the FES indicators were addressed in each policy optimization scenarios, further summarised in Table 2. Details are provided in Appendix S4.

2.5.1. National forest strategy scenario

The NFS defined clear quantitative yearly targets at the national scale for the increment (2025: 115 Mm^3; 2050: on avg. 125 Mm^3), harvested roundwood (80 Mm^3), and biomass (6.5 Mm^3). Monetary targets were not specified by the policy. Similarly, the policy stated targets for deadwood (2025: on avg. 8 m^3 ha^{-1}, south 5m^3 ha^{-1}, north 10–11 m^3 ha^{-1}) and yearly carbon sinks in forests (2025: 27.88 $MtCO_2$ equivalent). These targets were considered as constraints that aimed to reach the demands until the defined years and maintain such demand levels for all years afterwards (Appendix S4, Eq. S1). Non-wood objectives (bilberry, cowberry, mushrooms) were considered as constraints avoiding a decrease from the current state and aiming to maximize it simultaneously (Eq. S2). The NFS described them as by-products with an important and growing demand. The share of strictly protected forest areas in Finland (currently 10.6% of forestry land) was, according to the NFS, considered as large in international terms. To improve biodiversity protection, this scenario aims at increasing the proportion of biodiversity conservation sites in managed forests. This was implemented through constraining the share of conservation regimes (see Table 2) to at least 4.5% from the beginning of the 100-year planning horizon (Eq. S3). This target represents three times the current situation of conservation sites in commercial forests. The policy target for water regulation suggests the use of the best available management practice for its protection. This was implemented through constraining peatland management to the use of CCF or SA regimes (Eq. S4).

The FES representing recreation and the biodiversity goals for deciduous and large trees were addressed as objectives to be maximized, with (Eq. S5): the recreation and scenic indices maximized for the worst case over all simulated years (minimum value); the deciduous and large trees (biodiversity) optimized towards the best case at the end of the planning horizon (last year). Similarly, the FES game was addressed, where we maximized for the average value over time to overcome zero HSI values that can arise under those “fuzzy” assessment for species habitat characteristics. The FES game was considered by the policy as an “important by-product”, but with decreasing game populations (particularly moose), because of the expected future decrease of habitats (spruce forests). To meet the resilience targets of the policy, we aimed to maximize the share of ACC regimes (Eq. S3).

The overall complexity of the optimization problem and the preferences set by the policy on certain FES required using a lexicographic approach (Miettinen, 1999c), where objectives are optimized groupwise. The first group of objectives optimized for was wood production and bioenergy under the constraints for water regulation. The optimal solution for this group then entered the following optimization step as constraints. For the second group, the target values of biodiversity and climate regulation were optimized. Third, the group of non-wood was optimized, and finally all remaining objectives. The rationale for the ordering of these groups was the emphasis found in the written policy documents (Table 2, Appendix S3).

2.5.2. Biodiversity strategy scenario

The BDS aims to ensure a favourable status of biodiversity and ecosystem services by 2050, for which Finland will urgently undertake effective actions designed to halt the loss of biodiversity. Therefore, the biodiversity indicators for deadwood, deciduous and large trees were implemented as constraints avoiding a decrease from the current state and aiming for a favourable status by 2050. Since the policy lacks clear numerical values, we defined numerical targets that should represent the urgent and effective actions demanded by the policy: deadwood should increase by 60%, deciduous and large trees by 10% (Appendix S4, Eq. S6). A target value of 17% for protected areas (SA) was set to follow the Convention on Biological Diversity, and a target value of 4.5% for biodiversity conservation regimes in production forests was set, similar to NFS (Eq. S3). To achieve the stated water regulation targets, the constraint requiring that only CCF and SA were allowed on peatland was implemented (Eq. S4). The remaining services wood production, game, and recreation were implemented as objectives to be maximized, whereby the HSI for game, the recreation and scenic indices were addressed like in the NFS. Wood production was maximized for a continuous supply of harvested roundwood (even-flow) next to biodiversity constraints, as the policy aims to utilise the resources sustainably (Eq. S5). Climate regulation and resilience targets were indirectly addressed in the policy by increased shares of protected areas for carbon sinks, why no additional objectives were implemented.

2.5.3. Bioeconomy strategy scenario

Under the BES, Finland was considered to have high growth potential for roundwood and biomass for energy purpose, which are expected to increase further under climate change. The policy aims to simultaneously mobilize the resources for bioeconomy purposes and safeguard biodiversity. Therefore, the first lexicographic group aimed to maximize the even-flow of harvested roundwood and biomass (Appendix S4, Eq. S5), under the constraint that biodiversity does not decline (Eq. S6). In the second lexicographic group, the FES recreation was maximized under the constraints of maximum possible harvests and no decline in biodiversity (Eq. S5). Climate regulation and resilience were also addressed by the policy, but with the logic that exploiting the forest resources will directly contribute to them. Thus, no additional objectives were considered.

2.5.4. *Multi-objective optimization implementation*

From a technical perspective, a single solution for each policy scenario can be found through the formulation of unique multi-objective optimization problems (Miettinen, 1999a):

$$\underset{x}{\mathit{minimize}}\ \{f_1(x),\ldots,f_n(x)\}\qquad\qquad \mathit{subject}\ x\in S \tag{1}$$

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

The aim of the optimization is to seek out an efficient management solution for each stand, which is achieved through specifying constraints and objectives that are logically consistent. The stated requirements from the strategy can therefore be addressed by using Achievement scalarizing functions (ASF) (Wierzbicki, 1986) or by the epsilon-constraint method (Miettinen, 1999b). ASF functions can be seen as “soft targets” or reference points that are aimed to be achieved and relaxed if not feasible. Epsilon-constraints define instead strict upper/lower targets that need to be achieved. The use of these approaches is to guarantee Pareto optimal solutions (i.e., a solution where none of the objectives can be improved without impairing one of the other solutions (Miettinen, 1999a)). For each scenario, we have developed a unique multi-objective optimization formulation meeting the stated and perceived objectives of each strategy (section 2.5.1 to 2.5.3).

Individual objectives were normalized by using a pay-off table, were the evaluation of objective ranges (ideal and anti-ideal value) was conducted using single-objective problems that were maximized or minimized (based on the preferences for each objective). This allowed to jointly address the individual objectives when solving the problem and make them comparable. The final values for each individual objective were stored after the optimization procedure, including; the ideal, the anti-ideal, and the optimal solution.

These values were further used for a graphical interpretation of the optimization outcomes in terms of provided FES demands and constraint achievement levels (section 3.1.2). Therefore, the individual optimal solutions were normalized in relation to the ideal and anti-ideal values of objective ranges:

$$u(a)=\frac{a-a_*}{a^*-a_*} \tag{2}$$

where $u(a)$ is the normalized optimal solution a related to the anti-ideal a_* and ideal a^* solution of the objective ranges. If objectives were addressing a clear target value (implemented as constraint), optimal solutions were further normalized in relation to the target value (Table 2, except enabled constraints).

$$u(a)=\frac{a-a_*}{t_a-a_*}, \mathit{if}\ a<t_a \tag{3}$$

and

$$u(a)=\frac{a}{t_a}, \mathit{if}\ a\geq t_a \tag{4}$$

where t_a is the target value for a. These normalizations allowed a graphical interpretation on how good the optimal landscape management fulfilled the societal demands stated by the policies. (section 3.1.2).

The multi-objective optimization framework was implemented in python and solved with CPLEX and conducted with high performance computational resources provided by CSC - IT Center for Science LTD (cPouta). To allow for demonstration we uploaded the Jupyter notebook on an online repository together with a sample dataset (https://github.com/maeehart/MultiForestDemonstration).

3. Results

3.1. *Optimal management for policy scenarios*

3.1.1. *Management programs*

The optimized forest stand management program was aggregated and illustrated as the percentage area assigned to each regime class (Fig. 3) and individual regimes (Appendix S4). There were clear differences between the policy scenarios in terms of optimal management programs. The traditional BAU regimes were rarely the optimal management across all scenarios. NFS received the maximum proportion of BAU (3.4%), which slightly decreased with increasing climate change. Overall, climate change showed only minor effects on the optimal management combination. SA, CCF, and IBAU was assigned the highest area shares across all optimized scenarios, which means a segregation in forest management across the forest landscapes.

Under NFS, management class CCF received the highest share (up to 41.2%), followed by IBAU and SA, and small amounts of EBAU. ACC was not part of the optimal solution. Under BDS, almost half of the forest was assigned to SA and the remaining half was split among the other management classes (except BAU). The BES scenario resulted in almost equal shares of IBAU (up to 33.1%) and SA (35.7%), followed by CCF (19.3%) and some shares for EBAU and ACC.

3.1.2. *Objective ranges and constraints*

Because of multiple, and often conflicting FES objectives within individual policy scenarios, the maximum level of the objectives for FES was not reached in any of the optimized scenarios (Fig. 4a, Fig. 5a, Fig. 6a). Thus, policies are not only compromises when developed by politics but also in practice in the forest – the maximum of all objectives cannot be reached. Moreover, the degree to which the maximum potential level could be achieved strongly varied between optimized scenarios. The NFS scenario, for example, received relatively high levels of timber production and carbon sink objectives, but reached low levels in relation to the maximum particularly for biodiversity objectives (Fig. 4a). Under the BDS scenario, relatively high levels of recreation and some biodiversity related objectives (e.g., deadwood and share of deciduous trees) were reached, but timber production remained at a low level compared with potential maximum (Fig. 5a). The BES scenario performed well with respect to objectives related to bioenergy and timber production, but less well with respect to biodiversity (Fig. 6a).

The policy scenarios can also be compared concerning whether their main objectives (constraints) as specified in the associated policy document can be reached or not. From this perspective, the scenario BDS is the most coherent as all its constraints can be achieved (Fig. 5b). Under the BES scenario, it was not possible to achieve bioenergy or timber production related objectives (only 75% of the maximum possible harvest) when simultaneously fulfilling biodiversity constraints (Fig. 6b). The NFS scenario showed a strong within-policy incoherence as in the optimal solution most objectives remained under the targeted levels (Fig. 4b). Notable is the discrepancy between objective and constraint achievement. Whereas targeted conservation regimes preformed poor in terms of achieved objective levels (Fig. 4a), constraints were instead over exceeded (Fig. 4b). Vice versa it was the case for the increment objectives under the NFS scenario – high levels for objectives, whereas constraints were not achieved under current climate. Thus, climate change will likely change the situation increasing the possibility to achieve the alternative targeted levels in FES (red points, blue triangles). However, the biodiversity objective of deadwood remained very far from the targeted level irrespective of the climate change scenario.

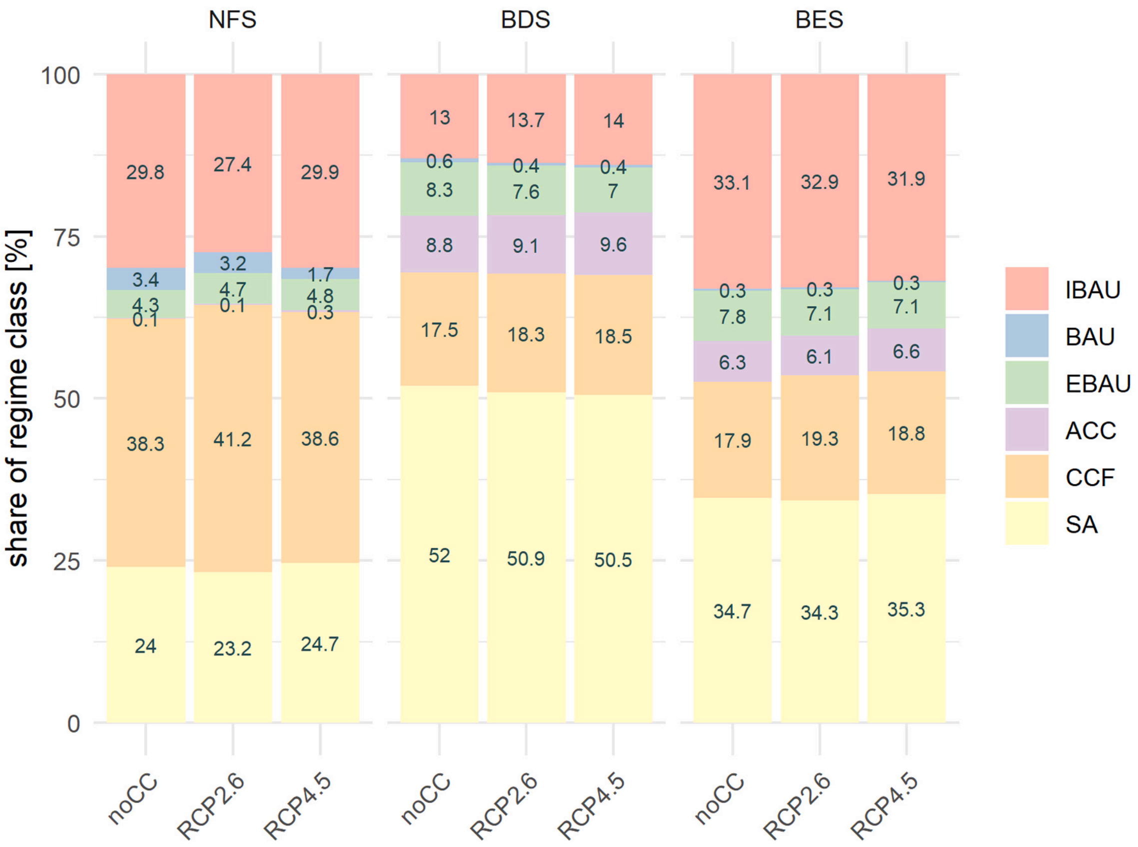

Fig. 3. Optimal management solution for the three policy scenarios representing the Finnish national forest strategy (NFS), the biodiversity strategy (BDS) and the bioeconomy strategy (BES). The management categories considered were business as usual (BAU), intensified (IBAU) and extensified BAU (EBAU), continuous cover forestry (CCF), adaption to climate change regimes (ACC) and setting aside (SA). The optimization was repeated for three climate change scenarios: current climate (noCC), RCP2.6 and RCP4.5.

3.2. Forest ecosystem service flows under policies

The optimal management solutions under the three policy scenarios resulted in drastic among-policy differences in the flow of FES (Fig. 7 and Fig. 8).

Harvested roundwood, biomass and increment (Fig. 7a-c), showed the effects of the constraints. NFS followed the 80 Mm^3 roundwood and 6.5 Mm^3 biomass target from 2025 onwards. The increment showed a stepwise increase to meet the target values in 2025 (115 Mm^3) and 2050 (125 Mm^3), which were finally only reached under RCP 4.5. BES maximized the constant flow of timber resources but mobilized less roundwood and more biomass in comparison to NFS. BDS showed the lowest harvests, with peaking values during the last third of the simulation. This resulted from setting aside a large share of the area for conservation (mainly old stands with high ecological value), and as such causing a gap in harvested timber amounts.

The biodiversity indicators deadwood and deciduous trees were the highest under BDS at the end of simulations (Fig. 7d,f), while the amount of large trees increased under all scenarios. The strongest effect was under NFS due to the promoted individual tree growth under the large share of CCF (Fig. 7e). For deadwood and deciduous trees, the NFS scenario resulted in a decline until the end of the simulation. A notable result is that the deadwood decline was reversed when targeted increment constraints under the FES were ignored, while the required harvests of this scenario could still be achieved, see Appendix S8. The scenario BES again showed the effect of the constraints, which allowed no decline.

The non-wood indicator bilberry increased under all policy and climate change scenarios, except under BES and RCP 4.5 (Fig. 8a). It increased the most under BDS, but with climate change having a dampening effect. The temporary decline in NFS at 2021 explained that the constraint for this objective was not fulfilled (maximize the minimum value over the time, see Fig. 4b). The same effect caused the unfulfilled constraint for cowberry under NFS, which decreased also below the initial value from 2096 onwards (Fig. 8b). However, cowberry showed a strong increase for NFS at the beginning, peaking at 2036, before it collapsed. Similarly, cowberry did develop under BES, but the collapse was less distinct. BDS showed a fluctuated development for cowberry peaking at 2101 parallel with harvests, (Fig. 7a), but resulting overall in a decline. Mushrooms overall declined under all policy scenarios, strongest under BDS. Climate change had a positive effect, leading even to a stable development under NFS and RCP 4.5 (Fig. 8c).

The carbon sink was highest under NFS during the end, with up to 80 Mt. CO_2 per year stored in the forest to the end of the simulation (Fig. 8d). BDS resulted in the highest values at the beginning. Yet, the carbon sink collapsed during the second half of the simulation and became even negative, which correlated with the harvest peak. The BES led to a slight decrease in the carbon sink, with 28 $MtCO_2$ per year stored in the forest at the end. Climate change increased the sink capacity due to increased growth.

The game animals benefited most from the BDS scenario, but showed a decline under all three policy scenarios, with climate change having a minor effect (presented as the average for three HSI indices). The steep decline was influenced mostly by the HSI of capercaillie and hazel grouse, with the latter even close to extinction, whereas HSI for moose showed a slight increase to the end (see Appendix S4). The average of recreation and scenic index strongly increased under all policy scenarios, but with slightly higher values in the BDS. Both indices benefited from the larger proportion of areas with SA and CCF and the resulting old forest structural attributes (see Appendix S5).

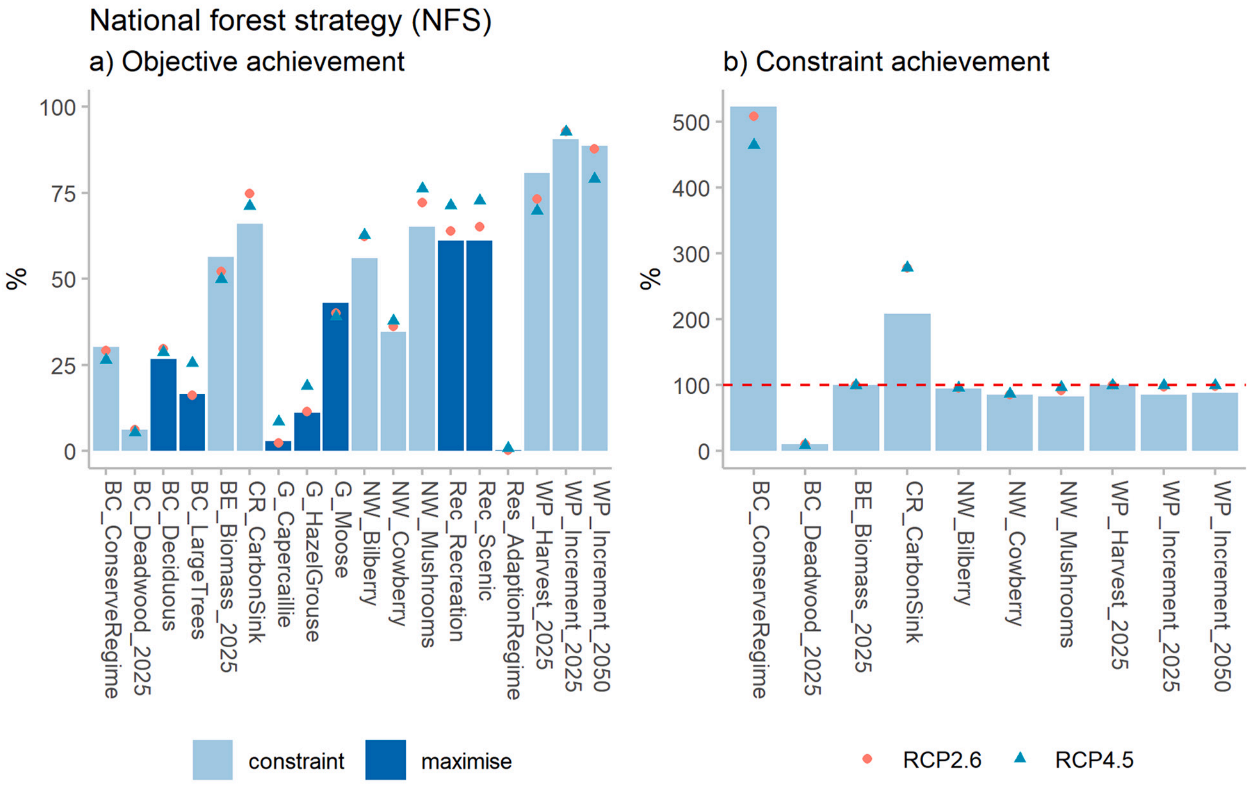

Fig. 4. Achievement of individual objectives (a) and constraints (b) under the national forest strategy (cf. Table 2). a) Normalized optimal solution in relation to the possible objective ranges (ideal and anti-ideal solution, Eq. 2). b) Normalized optimal solution in relation to the targeted values illustrated as red dashed line (if solution lies below the target = Eq. 3, if solution matches or lies above = Eq. 4). Bars represent the outcomes for current climate, circle and triangle represent the solutions under RCP2.6 and RCP4.5, respectively. The first letters of the x-axis label indicate the ecosystem service category: BC = biodiversity conservation, BE = Bioenergy, CR = climate regulation, G = game, NW = non-wood, Rec = recreation, Res = Resilience, WP = wood production. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

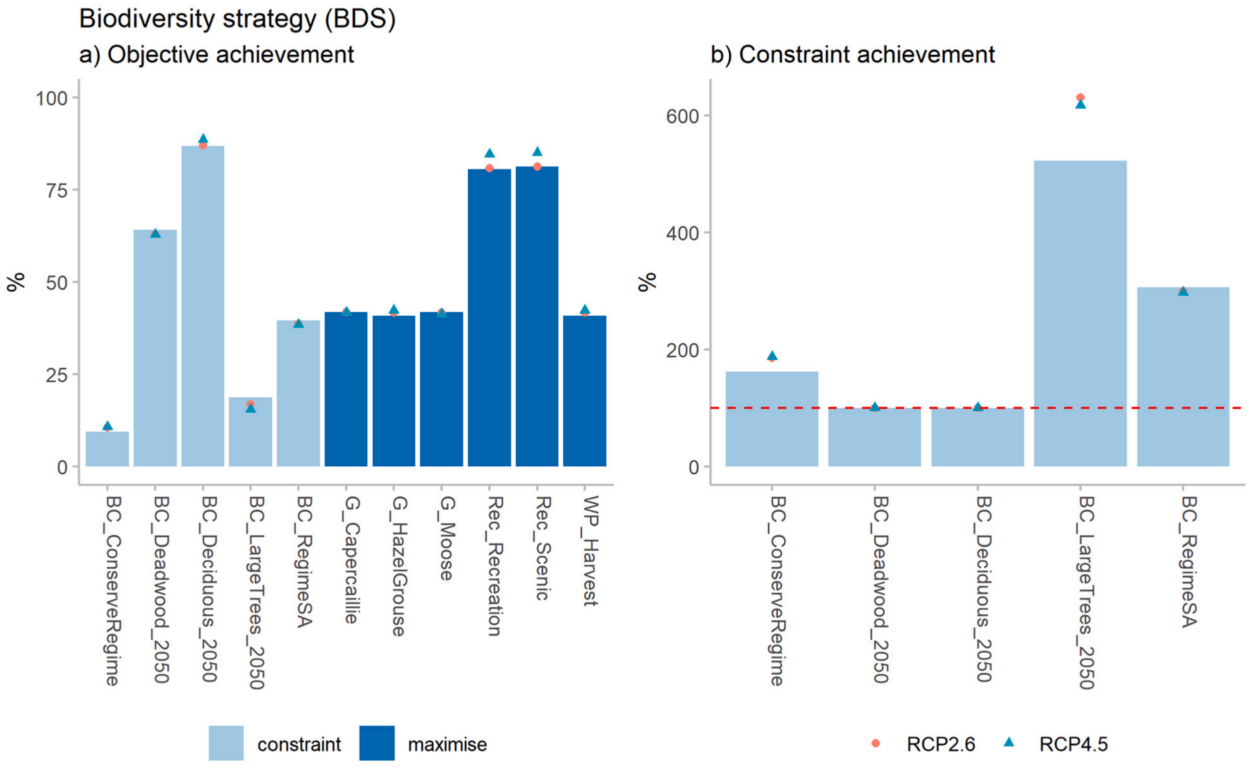

Fig. 5. Achievement of individual objectives (a) and constraints (b) under the biodiversity strategy (cf. Table 2). See Fig. 4 for explanation.

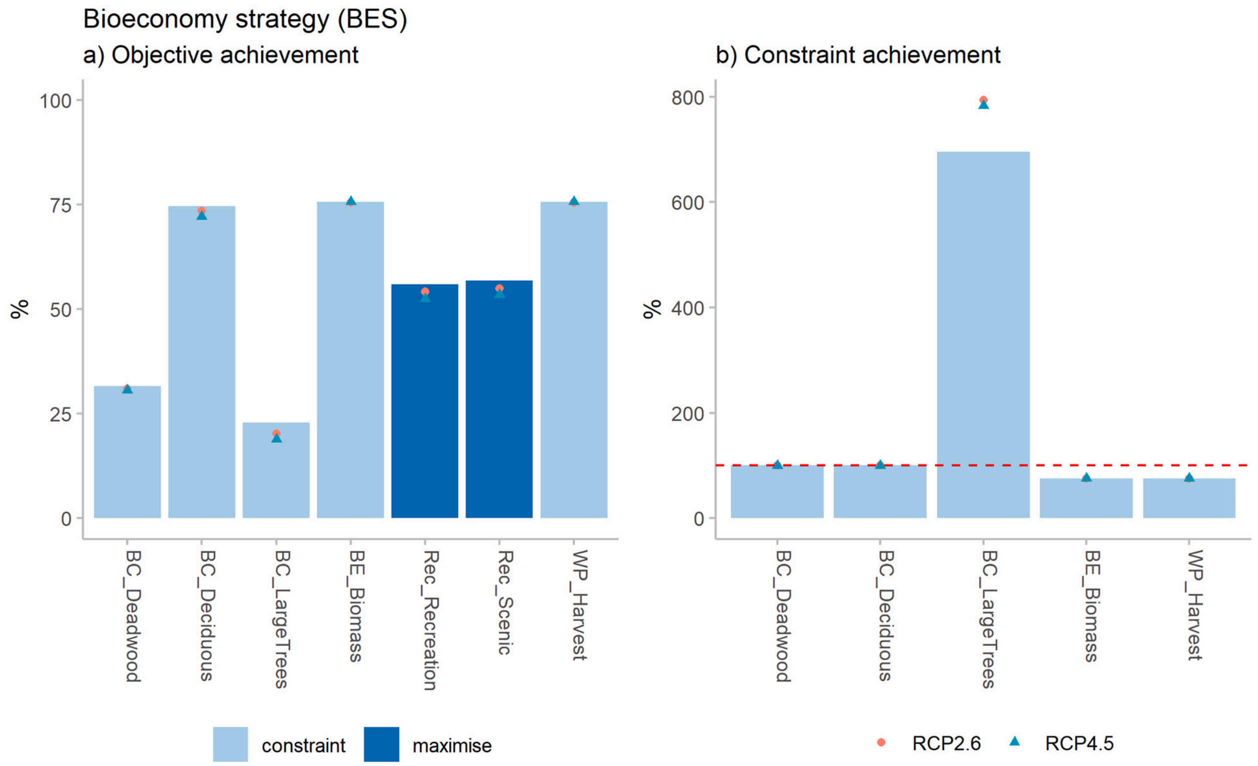

Fig. 6. Achievement of individual objectives (a) and constraints (b) under the bioeconomy strategy (BES, cf. Table 2). See Fig. 4 for explanation.

4. Discussion

Analyses of policy documents have shown that they are incoherent and that their ecosystem services concept is rather weak (Bouwma et al., 2018; Winkel and Sotirov, 2015). We show the long-term FES deficiencies in the forests resulting from these incoherencies, and present the forest management needed to meet the societal demands of the policies. We further highlight the incoherencies within the Finnish national forest strategy as not all stated policy demands for FES can be jointly met. For better policy integration and implementation, it is important to understand these incoherencies, because they provide leverage points to balance the conflicting societal demands of current policies. There are apparent opportunities for strengthening the coherence among policies at both national and regional levels (Bouwma et al., 2018).

4.1. Policy scenarios

The translation of the policy demands into a multiple-objective optimizations was a critical task, since it significantly affected the results of this study. The policy framework of Primmer et al. (2021) provided a structured approach for the national policy analysis (Appendix S3). According to Primmer et al. (2021) and our analysis, FES were generally recognised in sectoral policies, but the number and detail in which they were addressed varied strongly, with NFS being the most comprehensive one. The most strongly emphasised FES were centred around existing value chains of wood and bioenergy (NFS and BES), as well as biodiversity conservation (BDS). In contrast, non-wood forest products, game, and the aspect of recreation, received little attention in individual policies. Further, those were generally described rather “fluffily”, without clear targets and measurements, which impedes their implementation and effectiveness. This vagueness is also partially deliberated and connected with the engagement of diverse interest coalitions with contradictory expectations on the formulation of policy agendas (Harrinkari et al., 2016). Resilience and climate regulation were mainly addressed indirectly through two different and contradictory mechanisms: forest area under protection (BDS), or sustainable use of timber resources (BES).

The translation of policy demands into an optimization problem required inherent simplifications, representing the opinions and knowledge of the authors of this study, since only the NFS scenario provided clear quantitative targets. A slightly different preference setting (optimization steps) or implementation of each optimization objective might change the results considerably (as illustrated for the NFS scenario without increment constraint in Appendix S8). A sensitivity analysis could show how stable results are, for example by adjusting constraint thresholds, or implementing individual objectives differently (e.g. switch constraints into maximize objective). Nevertheless, the size of our simulated forest data and the overall complexity of the optimization problem (several constraints often lead to infeasible solutions) would have made a sensitivity analysis very time-consuming. The optimal management outcomes we present thus cannot be taken for absolute, but rather represent one possible realization under each national forest policy, acknowledging that in practice all policies drive management and FES provision simultaneously.

4.2. Climate change

Climate change showed almost no effects on the optimal management programs (Fig. 3), whereas the effects of climate were visible on the level of FES indicators (Figs. 7, 8). However, this result should not lead to the conclusion that the management effect on the final optimal solution is more important than climate change, as recent studies have shown the opposite (Seidl et al., 2019). One reason for the rather small effect on the optimal management was that climate-induced disturbances were not considered in our study. However, Finnish forests will likely experience higher disturbance activities under climate change, mainly caused by extreme drought, storm events, insect pests and forest fires (Venäläinen et al., 2020). Including disturbances, either within the simulations (Perera et al., 2015; Seidl et al., 2011), or by additional

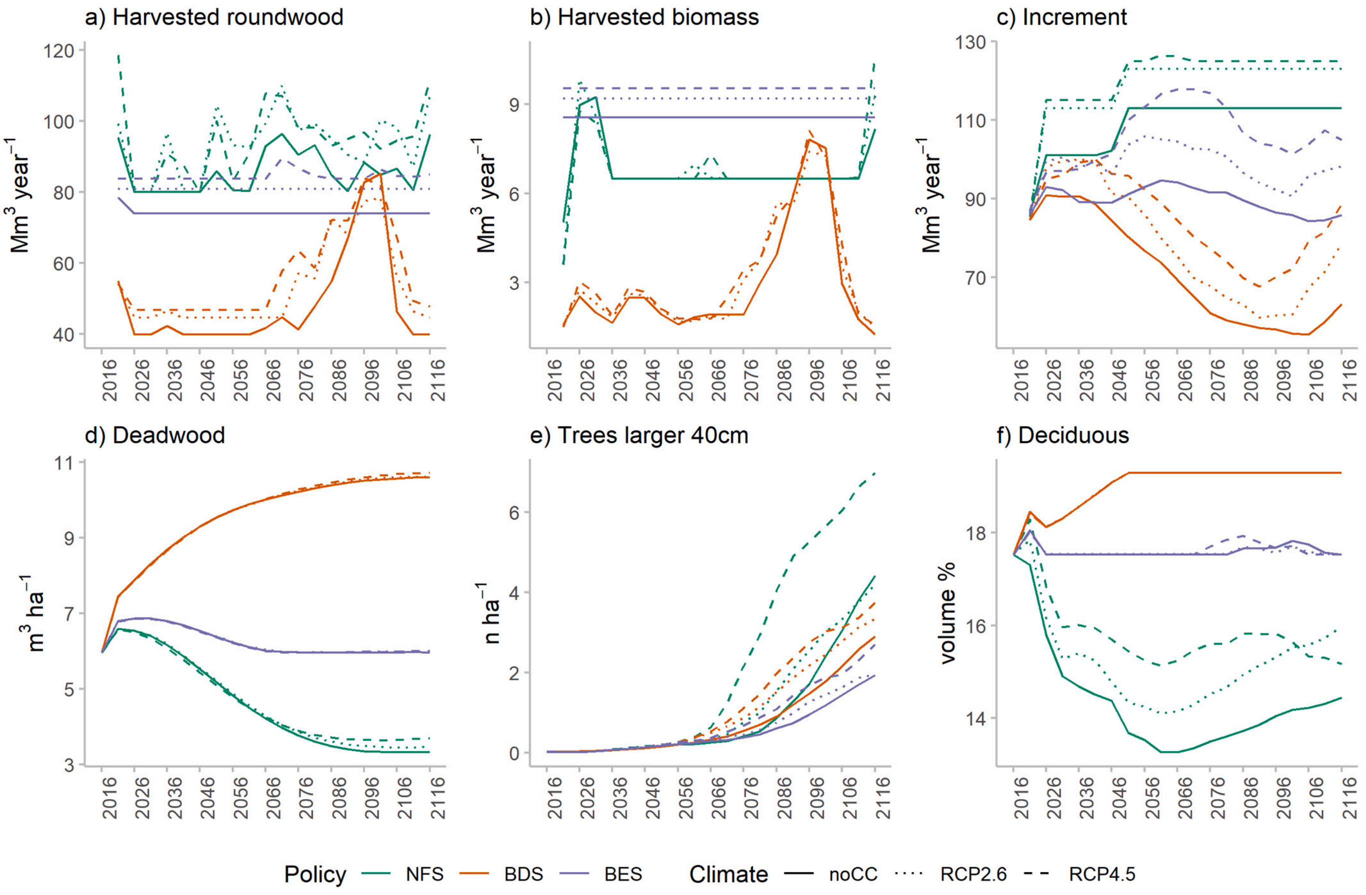

Fig. 7. Effect of the optimal management for policy scenarios on the future development of forest ecosystem service indictors under three climate change scenarios: current climate (no CC), RCP2.6, RCP4.5. Figure: a) - c) represent the area weighted sum and d) - e) the area weighted average over stands (NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy).

disturbance risk indicators within the optimization (Díaz-Yáñez et al., 2019; Temperli et al., 2020), might affect the optimal management. Taking into account wind damage risk during our optimizations would probably decrease even-aged rotation forestry regimes in favour of less vulnerable uneven-sized stand structures (Pukkala et al., 2016), and regimes that increase broadleaves in forests (Hahn et al., 2021).

Another reason for the small effect of climate change on the optimal management depends on the optimization problem itself. The BES and BDS scenarios strive for maximal harvests, under the constraints of biodiversity. The NFS scenario in contrast aims for high increment demands that were only achieved under RCP4.5 (Fig. 4b). Both demands forced the harvesting of the increased growth due to warming, resulting in similar management programs under all the climate scenarios (see for example Appendix S8 and the changed management program under relaxed constraints on the increment). Hence, the non-effect of climate change on the optimal management was also driven by the targeted societal demands in our optimization. However, climate change will not only increase productivities in northern latitudes, but it is also expected to create suboptimal conditions for certain tree species (Kellomäki et al., 2008; Torssonen et al., 2015; Venäläinen et al., 2020). Future studies should account for the potential negative effects of climate change on forest growth and FES provisioning (Hanewinkel et al., 2013; Jonsson et al., 2020).

4.3. *Forest ecosystem services*

The FES demands for resilience were rather weakly addressed within all sectoral policies (Appendix S3), which also contributed to the low climate sensitivity of the scenarios. In the BDS, resilience is strived for with the logic to integrate protected areas into the forest landscape (FME, 2012). The primary logic of the BES and NFS policy documents is that resilience will be achieved, if the increased growth potential will be exploited sustainably for timber production (FMAF, 2015, 2019; FMME et al., 2014). Due to these rather weak resilience targets, our adaptation regimes that aimed for higher broadleaves shares remained zero under NFS, and reached only a few percent for BDS and BES in the optimal management solution (Fig. 3). Sufficient resistance and resilience capacity of forests against future uncertainties, however, requires the use of the most efficient management and silvicultural practices across the forest landscape (Messier et al., 2019; Mina et al., 2020), addressing ideally also the social resilience component that focuses on the consistent flow of societal demands (Nikinmaa et al., 2020). Striving primary for high timber production and high growth rates are as such not appropriate policy targets to face the future uncertainties.

Strong growth paradigms of the policies showed negative consequences for biodiversity targets, by reducing deadwood amounts and shares of broadleaves in forests (Fig. 7d). This especially concerned the NFS scenario and led to strong incoherence within the policy (Fig. 4b). Trade-offs between an economically oriented management and biodiversity have also been reported by several other optimization studies (Eggers et al., 2020b; Eyvindson et al., 2018; Pohjanmies et al., 2017; Repo et al., 2020). The growth rates of forests are the highest in the early succession (Lynch and Zhang, 2011). Policy targets that aim for high increments thus hinder biodiversity objectives of old forest structures. According to Otero et al. (2020), policies should acknowledge the conflict between economic growth and biodiversity conservation and move beyond the growth paradigm to halt the global biodiversity decline, and enhance overall prosperity. Relaxing the increment constraint in the

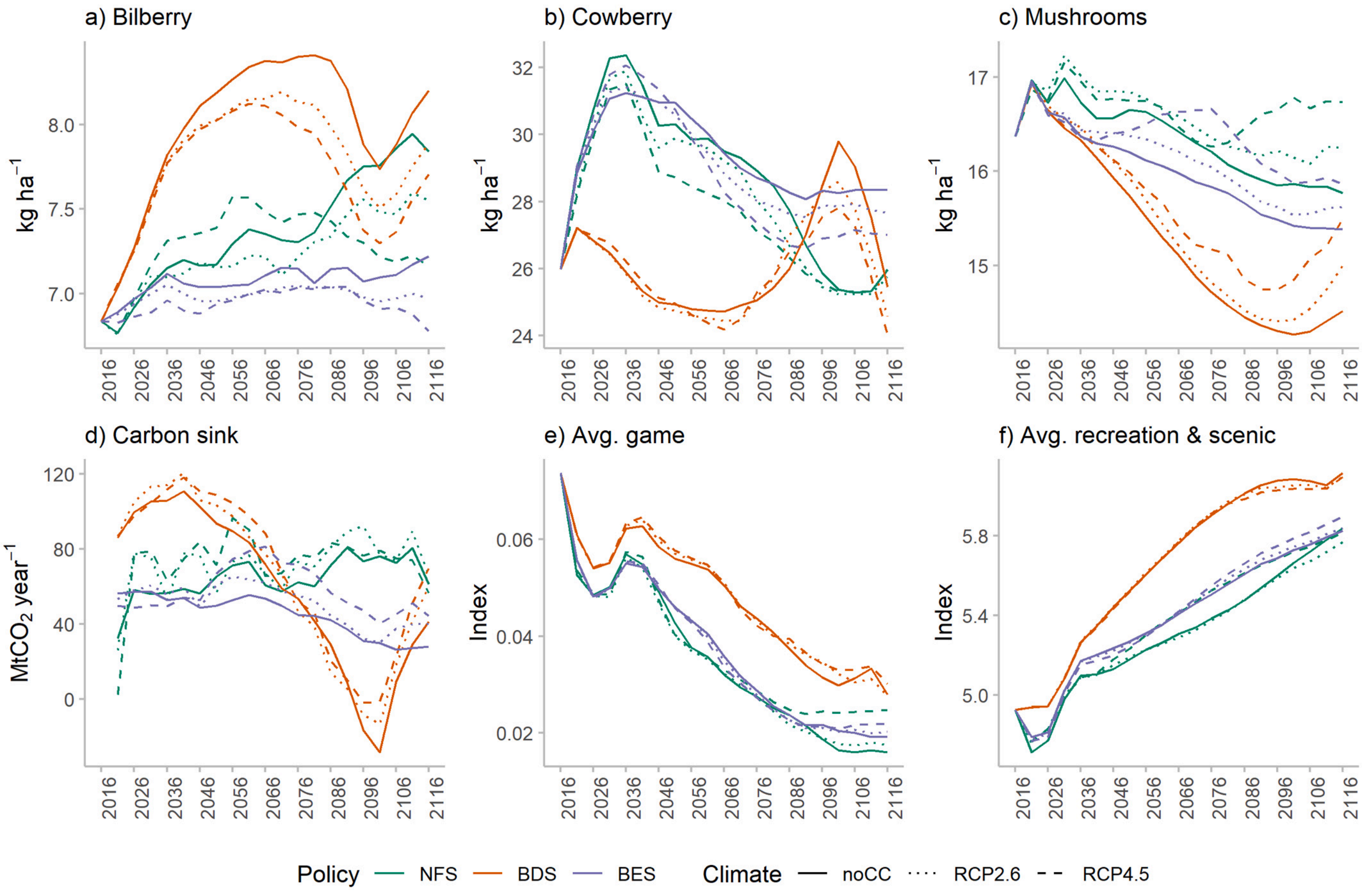

Fig. 8. Effect of the optimal management for policy scenarios on the future development of forest ecosystem service indicators, under three climate change scenarios: current climate (noCC), RCP2.6, RCP4.5. Figure: d) represents the area weighted sum and all others the area weighted average over stands (NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy). Fuzzy indicators of three habitat suitability indices (HSI) for game, and two recreation indices were averaged.

NFS scenario considerably increased the deadwood amount in forests while simultaneously achieving the roundwood and biomass targets of the policy (Appendix S8). Compared to the 1950s, the total increment in Finland has almost doubled, with 108 Mm^3 in the latest NFI (Peltola et al., 2019). Thus, stepping back from the high increment targets could considerably increase the coherence among multiple FES. We found that decoupling the policy from economic growth, as suggested by Otero et al. (2020), will offer higher shares of protected forest sites (Appendix S8). The SA shares even increased under climate change (36% no CC, 44% RCP 4.5), as the harvest targets could be achieved on a smaller managed forest area (due to climate-induced growth). This offered in turn more room for protection (Appendix S8).

Within policy conflicts among FES did not only result from incoherent policy targets but also due to real-life trade-offs among services and indicators. An example was the targeted FES game under NFS and BDS, which decreased under both scenarios, caused by the indicators for capercaillie and hazel grouse (Fig. 8, Appendix S6). According to Mönkkönen et al. (2014), those species mainly benefit from extensified BAU regimes, with longer rotation age and green tree retention, whereas both policy scenarios showed high shares of continuous cover forestry combined with setting aside. In contrast, indicator moose benefited from more intensified management with shorter rotation (I-BAU), since moose prefers younger stands as habitats (Kurttila et al., 2002). Policies need to consider such “real-life” trade-offs and provide solutions and instruments helping to disentangle them at the level of forest management.

4.4. *Optimal forest management*

The regimes continuous cover forestry (CCF) and setting aside (SA), together with the more extensive managements (EBAU and ACC), contributed to 2/3 of the optimal management under NFS and BES. Considering CCF and EBAU as more conservation oriented managements, both scenarios would thus easily exceed the 30% protection targets of EU policies (EC, 2020, 2021). The remaining 1/3 of the area was covered by intensified management (IBAU). Under the BDS scenario, half of the forest landscape was instead suggested to be protected (Fig. 3), with strong negative effects on wood production and bioenergy services (Fig. 7). The suggested separation of the forest landscape into clearly protected, and more extensively managed areas (combining CCF, EBAU, and ACC) with primary focus on non-wood and conservation values, as well as intensively used areas for production purposes follows the land sparing or segregation approach (Blattert et al., 2018; Carpentier et al., 2016; Côté et al., 2010; Messier et al., 2009). By allocating the land to areas with different management purposes, conflicts among FES will be minimized and the overall multifunctionality of the forest landscape will increase. Further, our suggested management regime shares are in line with the recently presented reference model for boreal forests of Berglund and Kuuluvainen (2021) (ASIO model), a management guideline that aims to mimic natural disturbance processes. For attaining favourable forest conservation and ecosystem status, the model suggests that approximately 1/3 of the forests should be managed by even-aged, and 2/3 with individual gap and cohort dynamics (mainly corresponding to SA and CCF), while additionally emphasizing late successional forests.

The optimization study of Eyvindson et al. (2021) recently also suggested that larger proportions of the forests in Finland should be managed by CCF to achieve higher landscape multifunctionality. Indeed, CCF has the potential to become an important management in boreal forests, as it has greater ability to simultaneously provide multiple FES (Peura et al., 2018; Pukkala et al., 2016). CCF is considered more efficient than rotation forestry as the resulting forest conditions are less sensitive to changes in management objectives (Pukkala, 2016). The main difference between our results and Eyvindson et al. (2021) is that large proportions of the forest landscape suggested to be managed with intensified regimes, including fertilization (Appendix S5). The simulated fertilization increased the stand growth, explaining why the regimes were primary selected in the optimization aiming to achieve demands for wood production and bioenergy. However, we did not consider the negative ecological consequences of fertilization activities (Hedwall et al., 2014), neither the costs of fertilization, both reducing the share of fertilization regimes. Thus, our result should not be interpreted as a promotion of fertilization, but highlight that also intensive rotation forestry is required to satisfy future demands for timber resources, particularly in the era of circular bioeconomy (Hetemäki et al., 2017).

All scenarios suggested a major change from current management practices in Finland, which is dominated by even-aged rotation forestry (our BAU) (Peltola et al., 2019). Policies should therefore also define instruments that support the management transition, since the optimized managements currently seem not to be feasible in a market economy with multiple actors. This would require appropriate subsidizing systems that motivate forest owners to manage their forests for biodiversity policy targets and compensate harvest revenue losses (i.e., subsidize longer rotations, CCF management actions and setting aside). Additionally, instruments would be needed that motivate forest owners to adjust their management for bioeconomy purpose and intensify forest use. Corresponding programs already exist in Finland, like the METSO-program, which compensates forest owners for setting-aside their forests for protection, or the KEMERA-program, which subsidizes tending and thinning of forest stands, building roads and fertilization. Such incentives would require further developments if policy targets should be implemented successfully in the future.

5. Conclusion

The combination of governance and long-term forest management planning research provided novel insights into the design of Finnish forest management resulting from sectoral policies. Our research highlighted the incoherence among inspected policies in terms of management and impact on forest ecosystem services (FES). Studying the policy drivers for forest management and the resulting FES trade-offs is particularly relevant when developing new policies and forest management paradigms. It provides leverage points for better integration of multiple FES in future policies to overcome socio-ecological land-use conflicts in forests.

All scenarios suggested major changes in forest management compared with the current practices to meet the policy demands for FES. However, to successfully achieve such demands in the future there would be a need to develop policy instruments guiding forest owners in their management (e.g. subsidizing). From a management decision and implementation point of view, it would also be beneficial if multiple FES are addressed clearly and holistically in sectoral policies, including non-timber objectives, and describing the management types to achieve the policy objectives. Further, the Finnish forest policies have to go beyond an economic growth paradigm (e.g., high annual increment targets under NFS) to achieve higher multifunctionality, as current policies lead to strong incoherence with biodiversity targets. We also underline that future policies need to more clearly address the targets and management approaches to increase the resilience of the Finnish forest against the uncertainties of climate change.

Author contributions

CB, MM, KE: conceptualization of the study. CB, MP, KE, JL: data curation. MM, TS: Funding acquisition. MH, KE, CB, AT: Optimization methodology and software. CB, KE: Simulation and optimization. DB, KE: Project admin and supervision. CB: Data analysis and writing of original draft. All authors contributed substantially to the writing of the article and approved the submitted version.

Declaration of Competing Interest

The authors declare no competing interests.

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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.2022.102689.

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