





OPEN **Optimizing sustainable and multifunctional management of Alpine Forests under climate change**

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Climate change is challenging the sustainable provision of biodiversity and ecosystem services in mountain forests, including the important protection service against gravitational natural hazards. Forests offer a relatively cost-efficient measure to protect humans and infrastructure from natural hazards. Forest managers are faced with the question of how to adapt their forest to climate change and optimally manage their forests to guarantee future forest multifunctionality. Usually, alternative close-to-nature forest management strategies can be implemented, but individual management objectives and forest resilience affect the optimal portfolio of management strategies. To address this planning task, we used the climate-sensitive forest growth model ForClim and developed a tailored multi-objective optimization method, considering particularities of forests with a protection service. We applied the method in an Alpine forest enterprise in Switzerland. We combined three climate change scenarios with three optimization scenarios. Our results show that a diversified and optimized portfolio of management strategies can safeguard and improve the provision of multiple ecosystem services and biodiversity concurrently. However, given the increasing intensity of climate change, a greater share of climate-adapted close-to-nature forest management strategies is necessary, reaching 78% in forests without a protection service and 68% in forests with a protection service under severe climate change and optimized for multifunctionality. Adaptation also enabled further improvement of biodiversity and ecosystem service provision, particularly for carbon sequestration. The presented simulation and optimization framework, tailored for mountain forests with a protection service, shows flexibility in the integration of management objectives, making it useful for decision support. Forest management planning should rely more on and make use of such frameworks to help support forests under the uncertainties of climate change and to achieve the future political ambitions of multifunctionality and climate resilient forest ecosystems.

Keywords Close-to-nature forestry, Forest management planning, Multi-objective optimization, Protection forest, Gravitational hazards

European Alpine forests provide many ecosystem services to society, including the provisioning of timber and of attractive landscapes for recreation, and they contribute to the mitigation of climate change^{1–3}. Further, they offer relatively cost-effective protection against gravitational hazards (we refer to this as a protection service or protection forest), particularly in densely populated areas with many infrastructures, as in the central European Alps^{4,5}. Additionally, forests provide habitats for manifold species and play a key role in biodiversity conservation^{6,7}.

Climate change and the resulting increase in biotic and abiotic forest disturbances^{8,9} are endangering the resistance and resilience of forest ecosystems¹⁰ and the sustainable provision of biodiversity and forest ecosystem

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services (BES)¹¹. Under such an increasingly uncertain future, the management of mountain forests for the provisioning of BES is becoming increasingly complex.

A well-established management approach in European Alpine forests for BES provisioning is close-to-nature forestry (CNF)^{12,13}, a common approach used to sustain the service of protection against gravitational hazards, e.g., in Switzerland⁴. This is achieved through the promotion of silvicultural interventions that support stand structural heterogeneity, natural regeneration, site-adapted tree species, and the maintenance of forest ecosystem integrity^{14,15}. In combination with the fostering of potentially climate-adapted tree species, CNF is also widely proposed to be considered a particularly suitable strategy for forest adaptation to climate change^{13,16,17}.

At the forest enterprise level, forest management planning usually guides the interventions for achieving objectives, e.g., by assigning forest areas that are important for protection against gravitational hazards or for biodiversity conservation^{18,19}. In many cases, this is supported by classical spatial data sources like stand maps, which provide information on stand conditions, such as size and structure, age, volume, productivity, and species composition. While the concept of BES and the need for forest management practices that promote resilience are widely acknowledged in practice (e.g. by the Federal Office for the Environment (FOEN) in Switzerland²⁰), timber production is still often considered the most important ecosystem service. Other non-timber ecosystem services are often secondary in forest management plans (e.g. carbon sequestration), or no standardized control mechanism exists for them (e.g. recreation). Exceptions are guidelines for protection forest management (NaiS⁴) and the dedication of priority areas for biodiversity conservation. Thus, there is potentially room left to improve the joint provision of multiple BES in many mountain forest enterprises, and to better achieve the political aim of multifunctionality (EU Forest Strategy²¹).

As there is no one-size-fits-all solution that fulfils all BES at the same time to a satisfying extent, a multifunctional landscape may only emerge through a spatial combination of management strategies^{22,23}. It is challenging to estimate the long-term consequences of silvicultural management strategies under climate change, while additionally covering the complex impacts on BES and the synergies and trade-offs among them^{1,3,24,25}. This makes the planning and management task difficult at the forest enterprise level. The question of where to put what can seem overwhelming. Such complex long-term forest planning tasks require a framework for modelling adaptive forest management and decision making under climate change^{26,27}.

Decision-support frameworks for optimizing management ideally integrate a climate-sensitive forest growth model, to consider potential climate impacts into the forest development forecast^{28–30}, in conjunction with multi-objective evaluation and optimization to assess silvicultural management effects on BES (e.g.^{31–33}), and facilitate risk-sensitive planning^{34,35}. Current optimization models are particularly adopted to address BES such as biodiversity, timber provision, and recreation, while protection against gravitational hazards is considered insufficiently or not at all. However, protection forests must be managed in a manner such that a certain level of a protection index is always fulfilled⁴. One well-established forest model to study the supply of BES – including the protection service – in European mountain forests and under alternative management strategies and climate change is ForClim (e.g.^{1,36,37}). Recently, ForClim has also been integrated for decision support across entire forest enterprises in investigations of the impacts of alternative CNF management on multiple management objectives²³. The authors showed that CNF and climate-adapted versions of it perform well overall for multifunctional managed Alpine forests. However, their evaluation also revealed that no single management strategy can fulfil all BES equally well. Instead, a portfolio of alternative CNF strategies might be required to satisfy future societal demands towards BES in Alpine forests.

In this research, we aim to combine the strengths of climate-sensitive forest modelling with multi-objective optimization to improve forest multifunctionality in European Alpine forests under climate change, to identify the management portfolio that optimally provides multiple benefits under future uncertainties. To do so, we present a multi-objective optimization approach that is particularly tailored for protection forests and that makes it possible to set flexible multiple management targets. The tool balances conflicts by finding compromise solutions. Input data for the tool are simulated trajectories of BES indicators under alternative management strategies and climate change scenarios. This joint application provides decision support by showing how forest management can improve and safeguard multiple BES under climate change uncertainties. The research questions addressed here are:

- Which portfolio of management strategies best fulfils the strategical management planning targets?
- How do the results differ under changing management priorities, either maximizing timber production, protection service or aiming for the highest forest multifunctionality?
- How is climate change altering the optimized solutions and the long-term provisioning of BES?
- How well do the optimized solutions perform compared with the ‘status quo’ of the forest enterprise? Can BES provisioning be improved with optimized management?

To answer these questions, we address the forest management planning scale, considering the fine-grained forest-stand resolution of a mountain forest enterprise.

Methods

The methodological study set-up included six major steps: (i) future forest trajectories were simulated under four alternative management strategies and climate change scenarios for the forest enterprise of Val Müstair (Section “[Forest growth and management simulations](#)”), (ii) indicators were calculated to assess the important management objectives for BES (Section “[Biodiversity and ecosystem services indicators](#)”). The first two steps are in line with²³. In addition, (iii) three multi-objective optimization scenarios were defined, reflecting various management objectives (Section “[Future management and optimization scenarios](#)”), and (iv) an optimization model was developed and used to assign the management strategies to the stands (Section “[Multi-objective](#)”).

optimization model”). Finally, (v) the outcomes of the scenarios were analysed (Section “Analysis of optimization outcomes”).

Case study site

The mountain forest enterprise of Val Müstair was selected as an Alpine case study site (CSS) (Figure 1). Val Müstair is located in the Central Alps of Switzerland in the canton of Grisons (46.6°N, 10.4°E) and covers a forest area of 4944 ha, ranging from ca. 1200 to 2400 m a.s.l. The forests are dominated by Swiss stone pine (*Pinus cembra*) and mountain pine (*Pinus mugo*) at high elevations close to the treeline, and by Norway spruce (*Picea abies*) and European larch (*Larix decidua*) at lower elevation ranges. The annual precipitation sum is 800 mm and the mean annual temperature is 5.3°C (mean values over 1981–2010), both measured in Santa Maria (1375 m a.s.l.). Soils have formed on sedimentary material and are relatively shallow and rocky, with low water holding capacities on steeper slopes (soil suitability map of Switzerland, <https://map.geo.admin.ch>).

Forest management with the principles of CNF for multifunctional purposes has a long history in this region. The main management objectives of the enterprise are protection services, timber production, biodiversity conservation and recreation (see optimization scenarios in Section “Future management and optimization scenarios”). The whole forest area consists of 5786 individual forest stands, some of which have management priorities according to the management plan (Office for Forest and Natural Hazards, 2023) (Fig. 2A). The majority of the forest area is assigned to the protection service (59.6%). Outside of the protection forest, ecologically important mountain pine forests (17.9%) and forest reserves (0.9%) are managed for conservation targets. Around 10.8% of the forest area is managed with priority as habitat for capercaillie (*Tetrao urogallus*). The remaining forest area (10.8%) has no management priority. While there are some mountain pine forests (6.0% of total area) and capercaillie habitat areas (10.3% of total area) within the protection forest area, the clear priority here is the management of the protection forest.

The recently applied forest management strategies differ across the forest enterprise, depending on the spatial management objectives. While mountain pine forests and forest reserves are mostly not managed, the capercaillie habitat is usually more intensively managed to ensure that the forest structure is sufficiently open, as preferred by this species³⁸.

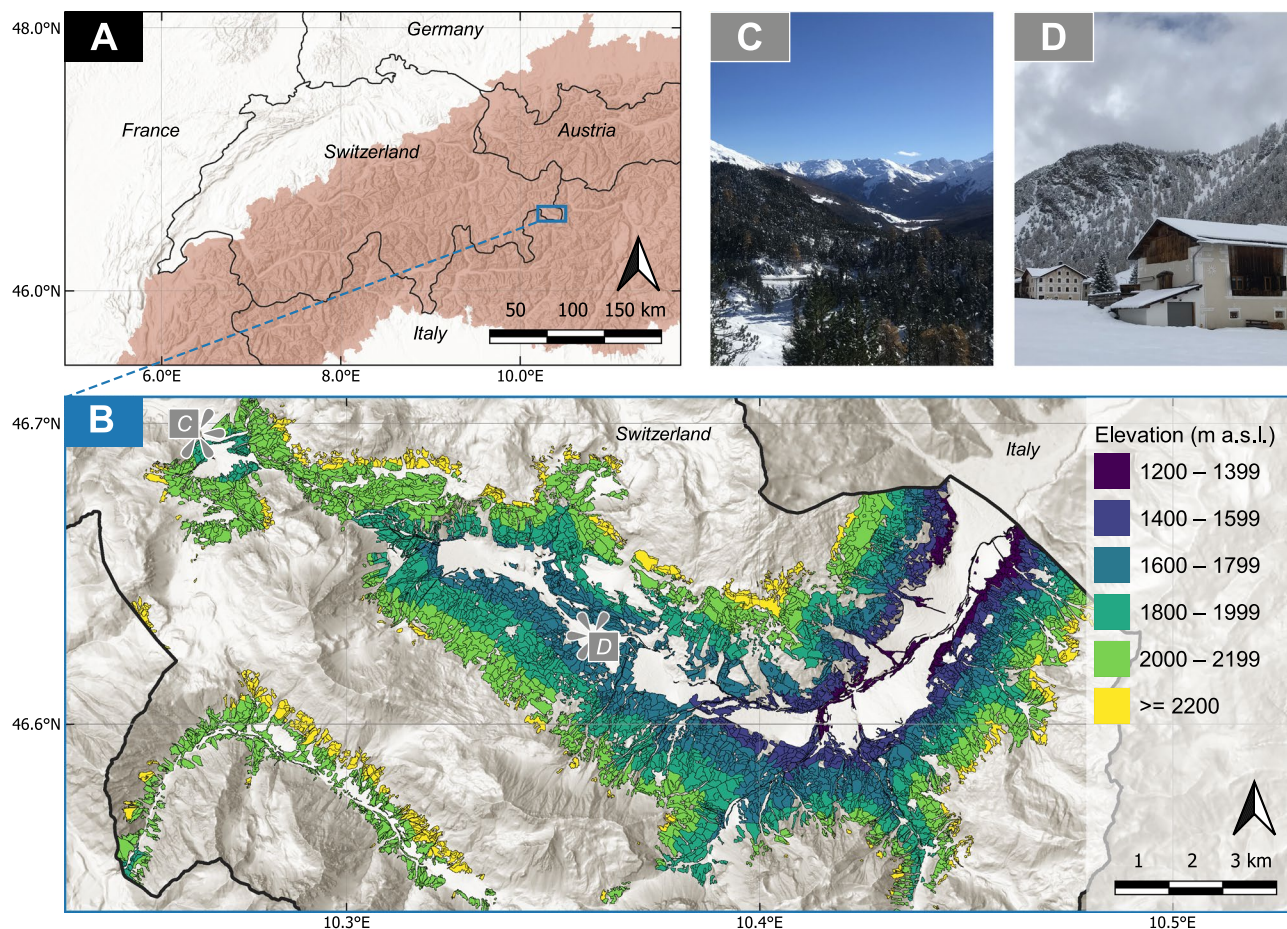


Fig. 1. Location of the case study site in Val Müstair (Switzerland) (A) and elevation of the 5786 individual forest stands (B). Photos of Val Müstair (C & D; © Simon Mutterer).

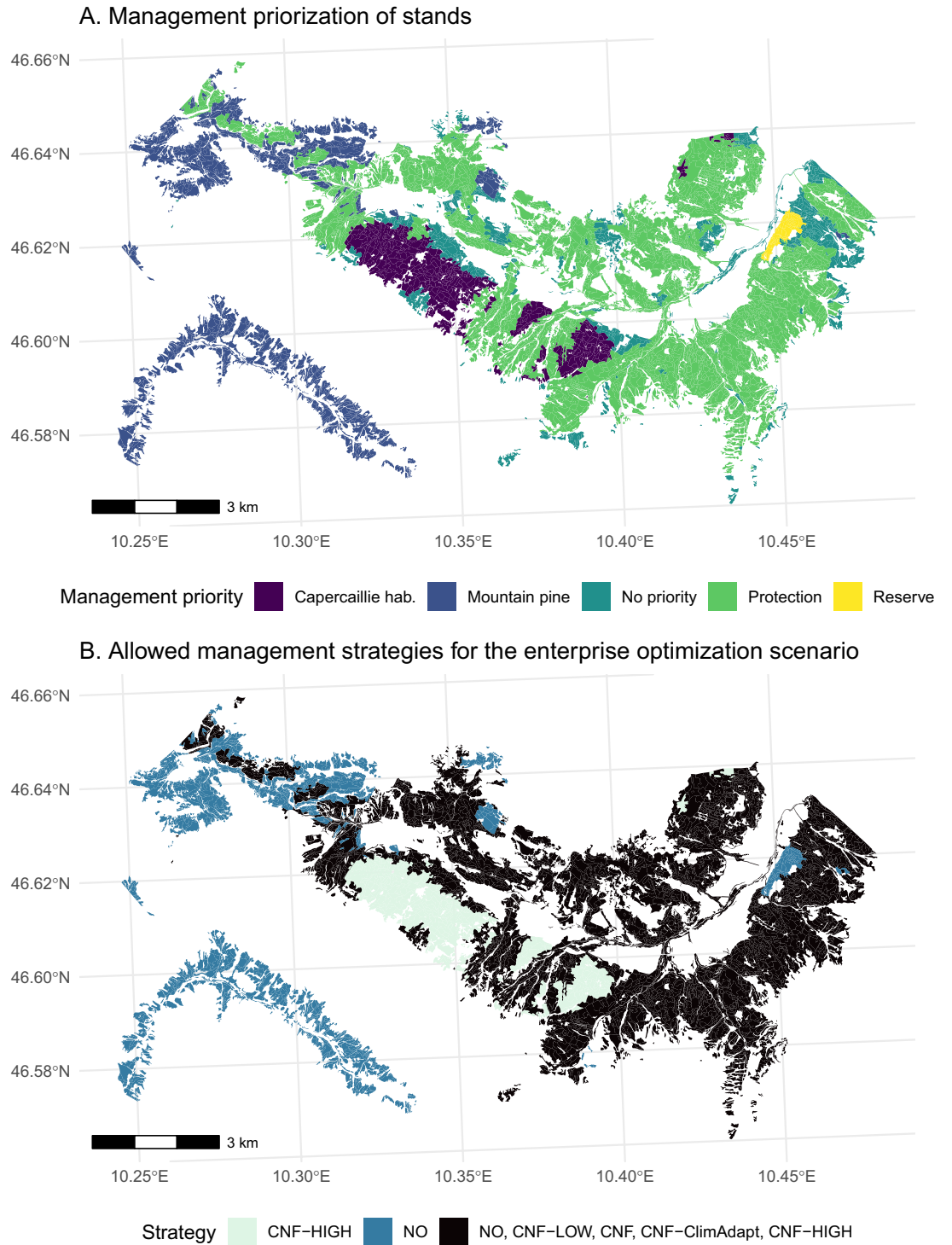


Fig. 2. (A) The case study site underlies spatial management priorities: forest with protection services and biodiversity and conservation services (reserves, mountain pine forest, habitat for capercaillie). (B) While mountain pine forests and forest reserves are mostly not managed (NO), the capercaillie habitat is usually more intensively managed to guarantee the species’ preferable open forest structures (CNF-HIGH). The remaining areas, including protection forests, are currently under close-to-nature forestry (CNF) management, but NO, CNF-LOW, CNF, CNF-ClimAdapt and CNF-HIGH are considered under the enterprise optimization scenarios (see Section “Future management and optimization scenarios”). For explanations of the CNF management categories, see Section “Forest growth and management simulations”.

Forest growth and management simulations

Forest simulations were performed using the climate-sensitive forest gap model ForClim (version 4.0.1)^{17,39} over a period of 90 years, from 2010 until 2100. ForClim has already been applied and validated along a large range of environmental conditions in Switzerland^{17,36,40}. Forest stands within ForClim are represented by a composition of 100 patches each equivalent to the size of a single large tree (500 m²). In each patch, tree development is represented in terms of ingrowth, height and diameter growth, and mortality for individual tree cohorts (i.e. groups of trees of the same age and species) at an annual resolution. Here, only natural mortality was included in the simulations and no large-scale disturbances were considered.

The simulation initialization of the individual forest stands utilized forest stand map data and regional forest inventories from the case study site. A representative stand type (RST) approach was used to generate individual tree datasets for each stand (e.g.^{41,42}). Forest stands were categorized into RSTs based on their dominant tree species, development stage and aspect (north vs south facing). Detailed forest structure information (e.g. tree diameter at breast height (DBH) and species identity of single trees) was taken from the forest inventory data, which was used to generate a model forest (100 patches) for each forest stand of the case study site.

The simulations were carried out under three climate scenarios: current climatic conditions ('hist') and the two socioeconomic global emission pathways 'Middle of the Road' (SSP2 4.5) and 'Fossil-fuelled Development' (SSP5-8.5)⁴³. The aim was to consider a large gradient of possible future climatic conditions. The historical climate data (1981–2010) for temperature and precipitation came from the Federal Office of Meteorology and Climatology (MeteoSwiss) and were downscaled and provided at a resolution of 50 × 50 m⁴⁴. The respective climate projection data of the emission pathway were derived from the CMIP6 Multi-Model Ensemble⁴⁵ accessed via the Climate Change Knowledge Portal⁴⁶ on a sub-national level for the canton of Grisons.

The future forest development of each forest stand was simulated for six management strategies: (1) a 'business-as-usual' strategy representing the current CNF practices in the case study site; (2) increased (CNF-HIGH) or (3) decreased (CNF-LOW) management intensity compared with CNF, to promote either timber production or biodiversity; (4) a climate-adapted strategy (CNF-ClimAdapt), which is similar to CNF but aims to enhance forests' adaptive capacity by fostering tree species (including planting) with a favourable adaption potential with respect to climate change. Additionally, (5) a reference strategy was simulated under which all trees are harvested after reaching the end of the rotation period (Clearcut). The Clearcut strategy is not representative of the case study site but made it possible to cover a broad spectrum of forest management practices and to enable comparisons of the results with international practices. Finally, (6) a strategy without any management activity (NO) was simulated, under which only natural forest dynamics under the alternative climate trajectories were considered.

Biodiversity and ecosystem services indicators

To assess the effect of the climate scenarios and management strategies on the achievement of the management objectives of the enterprise, 16 individual BES indicators were defined, following⁴⁷ and²⁶. In addition to the main management objective of the enterprise—protection services, timber production, biodiversity conservation and recreation—climate change mitigation was considered by assessing the carbon sequestration potential of forests and their products (Table 1). All 16 BES indicators were calculated based on the properties of the simulated forest stands.

The protection service of the case study site, which is a major objective of the enterprise (Fig. 2), was assessed using two indices: rockfall protection index (RPI) and avalanche protection index (API)^{48,49}. These indices are based on stand characteristics and on slope conditions, and express the protection effect on a scale between 0 (low protection function) and 1 (very high protection function). The RPI quantifies the probability that a rock will pass through a stand and was developed on the basis of the RockforNet model⁵⁰. The API expresses the protection service based on the relationship between the stand characteristics required for optimal protection from avalanches and the current stand characteristics.

Timber production was assessed as the amount of timber harvested (m³ ha⁻¹ year⁻¹) and the productivity of the stand (annual net volume increment, m³ ha⁻¹ year⁻¹).

Biodiversity conservation was evaluated based on four indicators. (1) The number of habitat trees (defined as the number of trees per ha with a DBH > 70 cm [ha⁻¹]) and (2) the amount of deadwood [m³ ha⁻¹] are both important structural attributes for biodiversity conservation in forests⁵¹. The deadwood volume includes decomposition, using exponential deadwood decay models⁵², and temperature-sensitive wood decomposition factors⁵³. The remaining indicators were (3) the stand diversity, referring to the tree species diversity (expressed by the Shannon index⁵⁴), and (4) the structural diversity (post-hoc index⁵⁵).

The objective of recreation was assessed following the guidelines of⁵⁶, accounting for the visual attractiveness of forest structures. Forest structure is directly affected by forest management aspects. For this study, six indicators were included that assess the visual attractiveness of forest structures: (1) height of the largest trees (m), (2) variation in tree size (post-hoc index), (3) visual permeation through the stand (expressed as the stand density index, SDI), (4) variation in tree species (Shannon index), (5) residues from harvesting and thinning (m³ ha⁻¹; considering also decomposition), and (6) deadwood from natural mortality (deadwood volume in m³ ha⁻¹). The indicators used to assess the visual attractiveness were normalized before the multi-objective optimization (see Supplementary Material S1). Reasons for this normalization were: (i) the assessment of 'visual attractiveness' as a surrogate for recreation is rather an 'artificial construct', and attractiveness strongly depends on the preferences of individuals⁵⁷. Thus, absolute values of the measured forest structural attributes are less important than relative behaviours among indicators. (ii) Normalization makes it possible to take into account bell-shaped and negative correlations between indicator values and human perception of attractiveness, e.g. a high forest stand density (low visual penetration) and many harvest residues and deadwood in the forest are usually perceived negatively by visitors⁵⁶.

Indicator group	Indicator	Unit	Indicator weights for opt. scenario		Objective function
			Timber / Multifunctionality	Enterprise	
Protection	Rockfall protection index	–	0.5	0.5	Minimize the sum of downside deviations from the MaxMin value for each forest stand
	Avalanche protection index	–	0.5	0.5	
Timber production	Timber harvested	$m^3 ha^{-1}$	0.8	0.8	Maximize the sum over all periods
	Productivity	$m^3 ha^{-1} yr^{-1}$	0.2	0.2	
Biodiversity conservation	Number of habitat trees	n	0.25	0.23	Maximize the sum over all periods
	Amount of deadwood	$m^3 ha^{-1}$	0.25	0.15	
	Shannon index (species diversity)	–	0.25	0.31	
	Post-hoc index (structural diversity)	–	0.25	0.31	
Recreation	Size of largest trees	m	0.22	0.22	Maximize the sum over all periods
	Variation in tree size (post-hoc index)	–	0.17	0.17	
	Variation in tree species (Shannon index)	–	0.11	0.11	
	Visual permeation through stand (stand density index)	–	0.17	0.17	
	Deadwood (harvest residue)	$m^3 ha^{-1}$	0.22	0.22	
	Deadwood (natural mortality)	$m^3 ha^{-1}$	0.11	0.11	
Carbon sequestration	Carbon sequestration	$tC ha^{-1}$	1	0	Maximize the sum over all periods

Table 1. Simulated indicators used to measure forest management effects on biodiversity and ecosystem services (BES). Indicators were used as input for the optimization scenarios. Indicator weights define the importance of each indicator within a BES group during the optimization. Each individual optimization function defines how an indicator was addressed, either maximizing or minimizing the sum over all planning periods.

Additionally, the carbon sequestration (CS) potential of forests was assessed. This objective is currently not a major objective from the forest enterprise perspective, but it plays a strategic role in current EU policies, like the EU Forest Policy²¹ and the Land Use, Land-Use Change and Forestry (LULUCF) regulation²¹. This objective was assessed in terms of the carbon sequestered within the forest ecosystem (in-situ) and the harvested timber entering the wood value chain (ex-situ), following²⁶ and²³. The aim was to address the overall mitigation potential of the forest sector and not only the storage capacity of the forest ecosystem. Therefore, the following five compartments were addressed:

- The amount of carbon stored in living above- and belowground tree biomass
- Carbon in deadwood pools originating from natural mortality and harvest residues
- Carbon stored in harvested wood products (HWP) and their respective half-lives: sawnwood, wood-based panels, paper and paperboard
- Substitution of fossil fuels by using wood for energy purposes
- Substitution of non-timber construction materials requiring substantial amounts of fossil energy for their production (e.g. concrete, steel) with harvested wood products

Carbon sequestration was then expressed as the combination of all compartments and its change compared with the initialized simulation year. The simulated timber volumes of broadleaved trees and conifers were converted into the corresponding carbon equivalents to assess the carbon sequestered in living tree biomass (above and below ground). Similarly, deadwood pools and their dynamics (decomposition) were converted into carbon equivalents (no initial pools of deadwood were considered).

The assessment of the HWP classification followed the recommendation of the⁵⁸, considering also the corresponding half-lives of products for sawnwood, wood-based panels, paper incl. paperboard, and energy wood (instant oxidation assumed). Therefore, the simulated harvested timber was classified into three HWPs, separately for broadleaved trees and conifers (see Supplementary Material S2). The substitution effects of HWPs followed⁵⁹, who suggested a general substitution factor of $1.2 t C (t CHWP)^{-1}$, to account for a broad spectrum of product categories in the entire HWP pool. For the substitution effects of energy wood a factor of $0.67 t C (t C_{wood})^{-1}$ was used⁶⁰.

Future management and optimization scenarios

Three different optimization scenarios were considered. They were used to map different management preferences, to find optimal solutions for them, and to study their effects on BES provision. Therefore, a scenario aiming for maximum timber production ('Timber'), a scenario aiming for the highest multifunctionality ('Multifunctionality'), and a scenario tailored to the existing enterprise objectives ('Enterprise') were defined. The representation of the different scenarios within the optimization model was done by:

Indicator group	Stands without protection service			Stands with protection service		
	Timber	Multifunct.	Enterprise	Timber	Multifunct.	Enterprise
Protection	0	0	0	0.9	0.9	0.9
Timber production	0.7	0.25	0.33	0.07	0.025	0.033
Biodiversity conservation	0.1	0.25	0.33	0.01	0.025	0.033
Recreation	0.1	0.25	0.33	0.01	0.025	0.033
Carbon sequestration	0.1	0.25	0	0.01	0.025	0

Table 2. Weights given to the indicator groups of biodiversity and ecosystem services (W_g) for the different optimization scenarios, separated for forest areas with and without a protection service.

Optimization scenario	Specific area	Possible management strategies					
		NO	CNF-LOW	CNF	CNF-ClimAdapt	CNF-HIGH	Clearcut
Timber	Complete area	x	x	x	x	x	x
Multifunctionality	Complete area	x	x	x	x	x	x
Enterprise	Capercaillie habitat					x	
	Mountain pine forests	x					
	Forest reserve	x					
	Protection service	x	x	x	x	x	
	Remaining areas	x	x	x	x	x	

Table 3. Restrictions of management strategies that can be assigned to a stand for the different optimization scenarios. While there are no restrictions for the optimization scenarios Timber and Multifunctionality, the Enterprise scenario followed the spatial management restrictions of the case study site (Section “Case study site” and Fig. 2B).

- defining specific weighting for indicators (Table 1) and indicator groups (Table 2) matching the scenario narrative
- setting management constraints / restrictions (allowed management strategies) for particular forest stands (Table 3).

The three scenarios have in common that protection against gravitational natural hazards plays the most important role in forest management in stands with a protection service. Therefore, all of the scenarios differentiate between forest with and without protection services (Table 2). For both cases, the optimization was carried out individually and independently of each other. For forests with protection services, the aim is to provide a continuous forest cover for all stands that fulfil the requirements according to the NaiS guideline⁴. This was addressed by minimizing the sum of downside deviations from the maximum value of the minimum values possible per management strategy across all periods (MaxMin value) of the two protection indicators (RPI, API) over all planning periods for each stand, with the aim that the protection service is continuously provided. By contrast, an overall maximization of the protection indicators over all stands and periods would lead to a spatially and temporally less balanced level of protection. In forests with a protection service, the weight of the protection indicator group was set to 0.9 (the weight of all other remaining indicator groups together was 0.1), whereas in forests without a protection service the protection indicator group weight was 0.

Generally, indicators were weighted equally among the different optimization scenarios, except for biodiversity in the Enterprise scenario (Table 1). There, the preferences of the forest manager of the enterprise, which were discussed in an in-person meeting, were considered. The weights for the recreational indicators followed the preferences defined by⁵⁶.

Timber production

In general, protection against gravitational natural hazards are given the most attention in the management of Alpine forests. From this starting point, the economy must also be subordinated to the fulfilment of protection services, which is also of economic interest for forest enterprises (as it is financed by the state). For this reason, the forest areas with protection services were tackled separately. For the remaining areas, a high weight of 0.7 were given to the timber production objective. Low weights of 0.1 were given to services (Table 2) which were not part of the ‘main focus’.

Multifunctionality

In the multifunctionality scenario, all four services (timber production, carbon sequestration, biodiversity conservation and recreation) are defined as important in the stands without a protection service, and they are assigned the same weight of 0.25 (Table 2).

Forest enterprise

The forest-enterprise-specific scenario was developed during an in-person meeting with the forest managers of Val Müstair. The weights of the indicator groups are listed in Table 4, and they represent the priorities of the enterprise. In stands without a protection service, timber production, biodiversity and recreation are the most important objectives and are equally important (assigned a weight of 0.33), whereas carbon sequestration is currently not a focus of their management and was therefore assigned a weight of 0 (Table 4). Further, there are stands with a restriction of the management strategy for reasons of conservation of specific target species (capercaillie habitat was assigned to CNF-HIGH, reserves to NO) and also for economic reasons (mountain pine forests was assigned to NO, due to difficult access, only low growth and small growing stock). To represent this, the input data were filtered for the optimization, meaning that stands that fell into those areas only had the above management strategy available. The remaining stands were assigned to the management strategies NO, CNF-LOW, CNF, CNF-ClimAdapt or CNF-HIGH (Fig. 2B).

Additionally, a reference scenario (EnterpriseRef) without optimization was defined. Under this scenario, it was assumed that future management will be conducted under current management practices and spatial management priorities (see Section “Case study site”). This means that stands that were assigned to only NO or CNF-HIGH (Fig. 2B) in the Enterprise optimization scenario were also assigned to those management strategies in the EnterpriseRef scenario, and the remaining stands were assigned to CNF only, instead of having the option of NO, CNF-LOW, CNF, CNF-ClimAdapt or CNF-HIGH. This led to a portfolio composed of 100% CNF in forests with a protection service and of 47% NO, 27% CNF-HIGH, and 27% CNF in forests without a protection service.

Multi-objective optimization model

The defined optimization scenarios (Section “Future management and optimization scenarios”) were translated into an optimization problem and were implemented in the optimization framework. The periodically (10-year time steps) simulated indicator values for each stand under alternative management and climate change scenarios were used as inputs for the optimization model. The aim of the optimization was to assign each of the stands to one of the possible management strategies. The problem was solved with the help of the following mathematical model, which was used 18 times separately for each of the 3 climate scenarios (*cli*) (Hist, SSP2-4.5, SSP5-8.5) combined with the 3 optimization scenarios (*opt*) (Timber, Multifunctionality, Enterprise) and for forests with and without a protection service (*p*). The mathematical model is presented below. All notations used are listed in Table 4.

Sets	
\mathcal{S}	Set of all stands s
\mathcal{S}_g	Set of all stands s in group g
\mathcal{G}	Set of all groups g
\mathcal{I}	Set of all indicators i
\mathcal{I}_g	Set of all indicators i considered in group g
\mathcal{M}_s	Set of all permitted management strategies m in stand s (Table 3)
\mathcal{T}	Set of all periods t (one period equals 10 years)
Parameters	
$B_{i,s,t,m}$	Value of indicator i in stand s in period t if management strategy m is applied
A_s	Size of stand s in hectares
W_g	Weight of group g (Table 2), $\sum_{g \in \mathcal{G}} W_g = 1$
$W_{i,g}$	Weight of indicator i in group g (Table 1), $\sum_{i \in \mathcal{I}_g} W_{i,g} = 1 \quad \forall g \in \mathcal{G}$
$\bar{Y}_{i,g}$	Upper bound for indicator i in group g
$\underline{Y}_{i,g}$	Lower bound for indicator i in group g
Variables	
$d_{i,g,t,s}^-$	Continuous, indicates lower deviation to MaxMin value of indicator i in group g in stand s in period t
$d_{i,g,t,s}^+$	Continuous, indicates upper deviation to MaxMin value of indicator i in group g in stand s in period t
$d_{i,g,t,s}^{binary}$	Binary, 1 if MaxMin value of indicator i in group g is undercut in stand s in period t , 0 otherwise
$x_{s,m}$	Binary, 1 if management strategy m is assigned to stand s , 0 otherwise
$y_{i,g}$	Continuous, cumulated value of indicator i in group g
$y_{i,g}^*$	Continuous, normalized cumulated value of indicator i in group g

Table 4. Mathematical notation.

Weighted sum – objective

$$\max \sum_{g \in \mathcal{G}} W_g \cdot \left(\sum_{i \in \mathcal{I}_g} (W_{i,g} \cdot y_{i,g}^*) \right) \quad (1)$$

Normalization constraints

$$y_{i,g}^* = \frac{y_{i,g} - \underline{Y}_{i,g}}{\overline{Y}_{i,g} - \underline{Y}_{i,g}} \quad \forall i \in \mathcal{I}_g, g \in \mathcal{G} \quad (2)$$

Indicator value constraints

$$y_{i,g} = \sum_{s \in \mathcal{S}_g} \sum_{t \in \mathcal{T}} \sum_{m \in \mathcal{M}_s} x_{s,m} \cdot B_{i,s,t,m} \cdot A_s \quad \forall i \in \mathcal{I}_g : i \neq \{\text{API, RPI}\}, g \in \mathcal{G} \quad (3)$$

$$y_{i,g} = \sum_{s \in \mathcal{S}_g} \sum_{t \in \mathcal{T}} -d_{i,g,t,s}^- \cdot A_s \quad \forall i \in \mathcal{I}_g : i = \{\text{API, RPI}\}, g \in \mathcal{G} \quad (4)$$

Calculation of deviation (protection indicators)

$$\sum_{m \in \mathcal{M}_c} B_{i,s,t,m} \cdot x_{s,m} + d_{i,g,t,s}^- - d_{i,g,t,s}^+ = \text{MaxMin}_{i,s} \quad i = \{\text{API, RPI}\}, g = \text{Protection}, \forall t \in \mathcal{T}, s \in \mathcal{S} \quad (5)$$

$$d_{i,g,t,s}^- \leq d_{i,g,t,s}^{\text{binary}} \quad i = \{\text{API, RPI}\}, g = \text{Protection}, \forall t \in \mathcal{T}, s \in \mathcal{S} \quad (6)$$

$$d_{i,g,t,s}^+ \leq 1 - d_{i,g,t,s}^{\text{binary}} \quad i = \{\text{API, RPI}\}, g = \text{Protection}, \forall t \in \mathcal{T}, s \in \mathcal{S} \quad (7)$$

Management strategy selection constraints

$$\sum_{m \in \mathcal{M}_s} x_{s,m} = 1 \quad \forall s \in \mathcal{S} \quad (8)$$

$$x_{s,m} = 0 \quad \forall s \in \mathcal{S}, m \notin \mathcal{M}_s \quad (9)$$

Domains

$$d_{i,g,t,s}^{\text{binary}} \in \{0, 1\} \quad i = \{\text{API, RPI}\}, g = \text{Protection}, \forall t \in \mathcal{T}, s \in \mathcal{S} \quad (10)$$

$$x_{s,m} \in \{0, 1\} \quad \forall s \in \mathcal{S}, m \in \mathcal{M}_s \quad (11)$$

$$\underline{Y}_{i,g} \leq y_{i,g} \leq \overline{Y}_{i,g} \quad \forall i \in \mathcal{I}_g, g \in \mathcal{G} \quad (12)$$

$$0 \leq y_{i,g}^* \leq 1 \quad \forall i \in \mathcal{I}_g, g \in \mathcal{G} \quad (13)$$

$$0 \leq d_{i,g,t,s}^- \leq 1 \quad i = \{\text{API, RPI}\}, g = \text{Protection}, \forall t \in \mathcal{T}, s \in \mathcal{S} \quad (14)$$

$$0 \leq d_{i,g,t,s}^+ \leq 1 \quad i = \{\text{API, RPI}\}, g = \text{Protection}, \forall t \in \mathcal{T}, s \in \mathcal{S} \quad (15)$$

The weighted sum objective to be maximized is stated in Eq. (1). Indicators are grouped according to Table 1 and the stands under consideration, i.e. stands either with or without a protection service, are assigned to those groups. The weights $W_{i,g}$ of each indicator in the group (Table 1) are multiplied by the normalized and cumulated value $y_{i,g}^*$ of these indicators. The sum of this product is then multiplied by the weights W_g defined for each group (Table 2).

The normalization of the cumulated indicator values is calculated according to Eq. (2), in which the actual cumulated indicator value $y_{i,g}$ is set in relation to the upper ($\overline{Y}_{i,g}$) and lower bound ($\underline{Y}_{i,g}$), i.e. the worst possible value and best possible value, respectively, that can be achieved for this indicator. The calculation of the bounds takes place before the actual optimization by minimizing or maximizing the respective cumulative indicator value, each in a single objective model. This normalization makes the different indicators comparable with each other and allows them to be combined in a single objective function.

For the calculation of the cumulative indicator values, a distinction is made between the protection indicators (rockfall, avalanche) and all other indicators. As stated in Eq. (3), for the indicators that are not related to protection, the value is calculated by multiplying the simulated indicator value $B_{i,s,t,m}$ by the respective area of the stand A_c and the decision variable $x_{s,m}$ that indicates the assignment of a management strategy m to stand s . By contrast, the aim of optimizing the protection indicators is not to reach a simple maximization, but to achieve a balanced level of protection over time. Therefore, the first step is to determine the minimum level of protection indicator performance that can be achieved consistently over time in the various management strategies. In

order to find the most promising of the possibilities, we calculate the maximum of the worst possible values per management strategy across all periods ($MaxMin_{i,s}$). In order to maintain this level as best as possible in combination with the other indicators, the downside deviations from this MaxMin value should be minimized in the objective function (see Equation 4). The actual calculation of the downside deviation is carried out using Eqs. (5)–(7). In order to fulfill these equations for all conditions, it is necessary to introduce the variable $d_{i,g,t,s}^+$, which describes the upward deviations. However, this variable is not relevant for the objective function and therefore does not appear in Eq. (4).

Equations (8) and (9) ensure that exactly one of the permitted management strategies is assigned to each stand, taking into account the restrictions of Table 3. Finally, Eqs. (10)–(15) define the domains of all variables.

Analysis of optimization outcomes

The outcomes of the 18 optimization runs were further analysed calculating first a portfolio of the management strategies that were assigned to the forest stands (AS_m area share of management strategies m [%]). This was derived for each optimization opt and climate cli scenario according to Eq. (16).

$$AS_m = \frac{\sum_{s \in \mathcal{S}} x_{s,m} \cdot A_s}{\sum_{s \in \mathcal{S}} A_s} \quad \forall m \in \mathcal{M}_s \quad (16)$$

Second, the partial utility of each indicator group was derived (Eq. 17). The normalization was done using the global lower and upper bound (over all optimization and climate scenarios) separately for forest areas with and without a protection service (Eq. 18).

$$PU_{g,p,cli,opt} = \left(\sum_{i \in \mathcal{I}_g} (W_{i,g} \cdot y_{i,g,p,cli,opt}^*) \right) \quad \forall g \in \mathcal{G}, p \in \mathcal{P}, opt \in OPT, cli \in CLI \quad (17)$$

$$y_{i,g,p,cli,opt}^* = \frac{y_{i,g,p,cli,opt} - \underline{Y}_{i,g,p}}{\bar{Y}_{i,g,p} - \underline{Y}_{i,g,p}} \quad \forall i \in \mathcal{I}_g, g \in \mathcal{G}, p \in \mathcal{P}, opt \in OPT, cli \in CLI \quad (18)$$

Third, a relative comparison of the scenarios was carried out in order to compare the optimization scenarios and the reference scenario (EnterpriseRef) for the various indicator groups and climate scenarios outside and inside of the protection forest:

$$dPU_{g,p,cli,opt} = PU_{g,p,cli,opt} - PU_{g,p,cli,EnterpriseRef} \quad \forall g \in \mathcal{G}, p \in \mathcal{P}, opt \in OPT, cli \in CLI \quad (19)$$

A fourth analysis involved inspecting the partial utilities along an elevation and time gradient for each optimization and climate scenario. This was computed according Equation 20. The normalization was done using global maximum and minimum indicators values of stands (Eq. 21, not for indicators of indicator groups recreation and protection, those are already normalized).

$$U_{g,cli,opt,t,elv} = \sum_{i \in \mathcal{I}_g} W_{i,g} \left(\frac{\sum_{s \in elv} \sum_{m \in \mathcal{M}_s} (x_{s,m} \cdot B_{i,s,t,m,cli,opt}^* \cdot A_s)}{\sum_{s \in \mathcal{S}} A_s} \right) \quad (20)$$

$$\forall g \in \mathcal{G}, cli \in CLI, opt \in OPT, t \in T, elv \in E$$

$$B_{i,s,t,m,cli,opt}^* = \frac{B_{i,s,t,m,cli,opt} - \min(B_i)}{\max(B_i) - \min(B_i)} \quad \forall s \in \mathcal{S}, t \in T, m \in \mathcal{M}_c, opt \in OPT, cli \in CLI \quad (21)$$

Finally, the non-normalized indicator values were plotted over time for each climate and optimization scenario (Supplementary Material S4). The mathematical notation was therefore extended as described in Table 5.

Results

Optimized forest management portfolios

Whole enterprise

The portfolio of the optimized management solutions under the three optimization scenarios is displayed in Fig. 3, differentiated between forests with (left) and without a protection service (right). In the forests with a protection service and under the HIST climate scenario, the dominant management strategies were NO and CNF-ClimAdapt, which covered together around 90% of the forest area. Except for the Timber optimization scenario, the NO management strategy had a higher proportion than CNF-ClimAdapt in the protection forest perimeter. However, the various optimized portfolios differed only slightly, due to the high weight for protection indicators (90%). However, under increasing intensity of climate change, CNF-ClimAdapt became the dominant management strategy, and the share of NO decreased considerably under SSP5-8.5.

In the forests without a protection service, it is first noticeable that the composition within the Enterprise optimization scenario marginally changed under alternative climate change scenarios and that the optimized management portfolio was largely based on NO, CNF-ClimAdapt and CNF-HIGH. The main difference compared

Notation	
$B_{i,s,t,m,cli,opt}$	Value of indicator i in stand s in period t if management strategy m is applied under climate scenarios cli and optimization scenarios opt
CLI	Set of all climate scenarios cli
E	Set of all elevation ranges elv
OPT	Set of all optimization scenarios opt
P	Set indicating whether a stand has a protection service or not (p)
$PU_{g,p,s,o}$	Partial utility of indicator group g in forests with / without a protection service p for all optimization opt and climate cli scenarios
$dPU_{g,p,s,o}$	Difference in partial utility of indicator group g in forests with / without a protection service p for all optimization opt and climate cli scenarios compared with the EnterpriseRef scenario
$PU_{g,cli,opt,t,elv}$	Partial utility of indicator group g , for all elevational ranges elv , periods t , optimization scenarios opt and climate cli scenarios
$\bar{Y}_{i,g,p}; \underline{Y}_{i,g,p}$	Upper / lower bound for indicator i in group g and forests with or without a protection service p over all optimization opt and climate cli scenarios
$\max; \min(B_i)$	Stand-based global maximum and minimum indicators values over all stands s , periods t , climate scenarios cli , and optimization scenarios opt

Table 5. Extended mathematical notation.

with the EnterpriseRef scenario (current situation) was that CNF was mainly replaced with CNF-ClimAdapt. Under the Timber optimization scenario, CNF-ClimAdapt (59–75%) and Clearcut (19–30%) dominated the optimized portfolio. With increasing intensity of climate change, the share of Clearcut first decreased from 27% (Hist) to 19% (SSP2-4.5) and then increased again to 30% (SSP5-8.5). Under the Multifunctionality optimization scenario, CNF-ClimAdapt was the most common management strategy, ranging from 64% (Hist) to 82% (SSP2-4.5). This portfolio was further complemented by NO management and CNF-LOW.

Forest-stand scale

The spatial allocation of the optimized portfolios for Enterprise and Multifunctionality is presented in Fig. 4 (upper panel), both for the climate change scenario SSP5-8.5 (a realistic trajectory given the current climate crisis). Under the Enterprise optimization scenario the spatial constraints were visible for forest reserves and capercaillie habitat (see section “Case study site”), restricting the management strategy to NO and to CNF-HIGH, respectively. The remaining area, including the forests with and without a protection service, showed instead large assignments of CNF-ClimAdapt and NO. This represents a major change compared with the current situation, where CNF is dominant for those stands (see also Portfolio in Fig. 3).

In the Multifunctionality portfolio, the assignment of management strategies was not restricted, even in conservation areas. This resulted in a considerable change in conservation areas from NO or CNF-HIGH to CNF-ClimAdapt in most cases (Fig. 4, lower panel). CNF, which is currently the dominant management strategy (EnterpriseRef) was again almost not represented in the optimized portfolio. Instead, CNF-ClimAdapt and NO were dominant (Fig. 3). The spatial distribution of management strategies under the Enterprise optimization scenario and under other climate change scenarios is presented in Supplementary Material S6.

Effect of optimization on BES provision

Whole enterprise

The change in BES achievement under the alternative optimization scenarios is presented in Fig. 5, showing the difference in partial utility compared with the EnterpriseRef scenario under alternative climate scenarios. For the forests with a protection service (upper panel), the values differed only slightly between the different optimization scenarios, showing an improvement for all groups except for timber production. The rather homogeneous pattern among optimization scenarios can be explained by the high weight for the protection objective for the forests with a protection function (Table 2). Carbon sequestration benefited the most from the optimized management (compared with EnterpriseRef), particularly under the Multifunctionality scenario. The improvements were smaller under intensive climate change (SSP5-8.5). The service of timber production was negatively affected under almost all optimization scenarios, except under Timber when combined with climate scenario SSP5-8.5.

In the forests without a protection service (Fig. 5, lower panel), differences among the optimization scenarios were more distinctive, as the weights of the indicators and indicator groups also differed among the scenarios. For biodiversity conservation and the services of protection and recreation, the optimization scenarios Enterprise and Multifunctionality perform considerably better than the Timber optimization scenario. For carbon sequestration, the Multifunctionality optimization scenario improved the partial utilities the most, followed by the optimization scenarios Timber and Enterprise. While the Timber optimization scenario outperformed in the timber production indicator group, it negatively affected biodiversity conservation, protection against gravitational hazards, and recreation. Further, it was visible that the optimization scenario Enterprise only marginally improved the partial utilities compared with the reference scenario (EnterpriseRef), which was due to the fact that the optimized management portfolios showed very similar proportions of management strategies (see Eq. 16). Absolute values for the partial utilities under the alternative scenarios are shown in Supplementary Material S3. Individual results for the BES indicators used to calculate the partial utilities are shown in Supplementary Material S4 and S5.

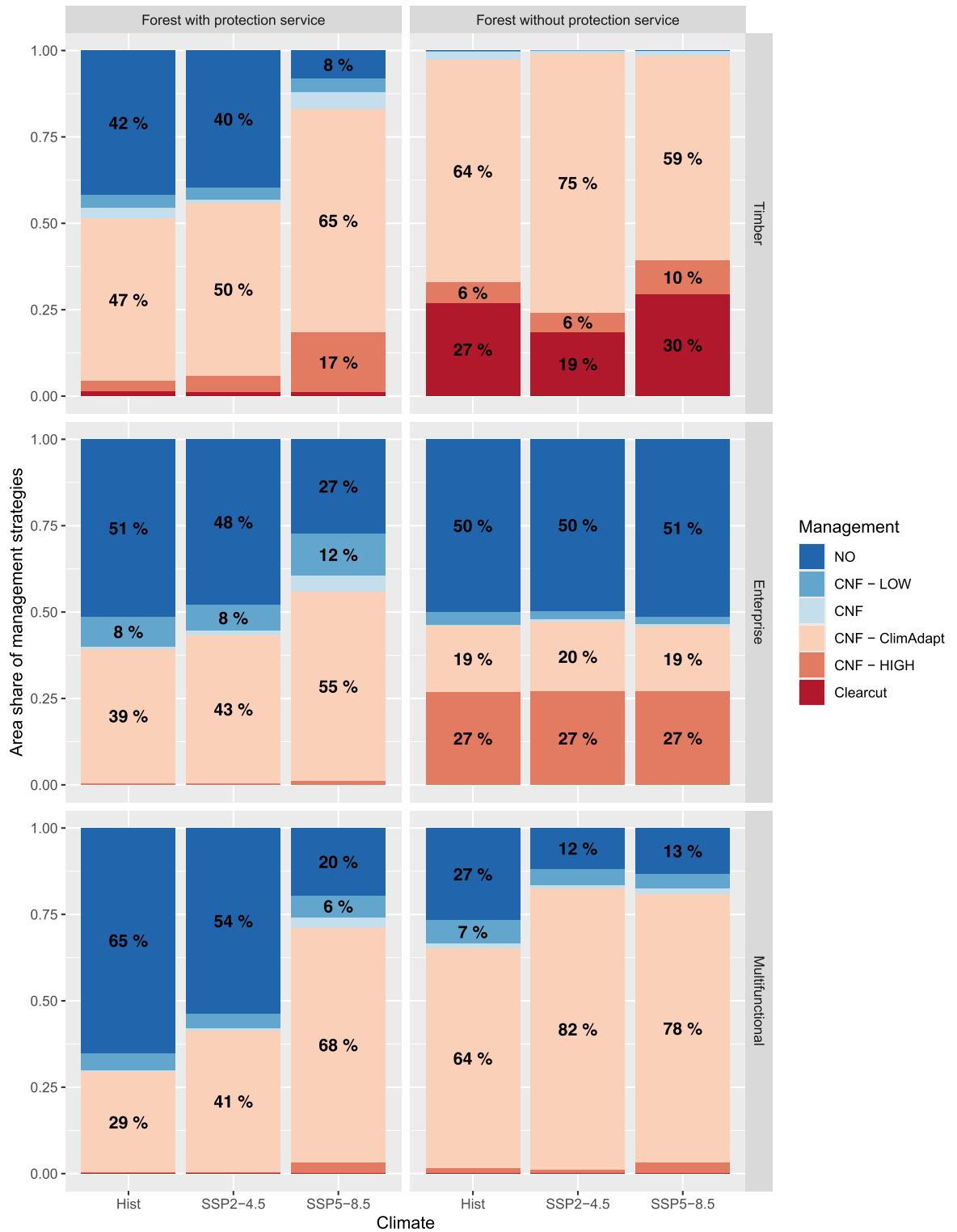


Fig. 3. Optimized portfolio of management strategies for the different optimization scenarios and under different climate change scenarios. Portfolios are displayed for forest with and without a protection service. Numbers are only displayed for values $\geq 6\%$.

Development over time and along elevation gradients

Figure 6 shows the temporal development of BES provision under the optimization scenarios along the elevation gradient of the case study site. The panels depicting carbon sequestration (considering both in-situ and ex-situ) show that, under all optimization scenarios and under the HIST and moderate SSP2-4.5 climate scenarios, forests at lower elevations (below 1600 m a.s.l.) were important for carbon sequestration. Under the severe climate

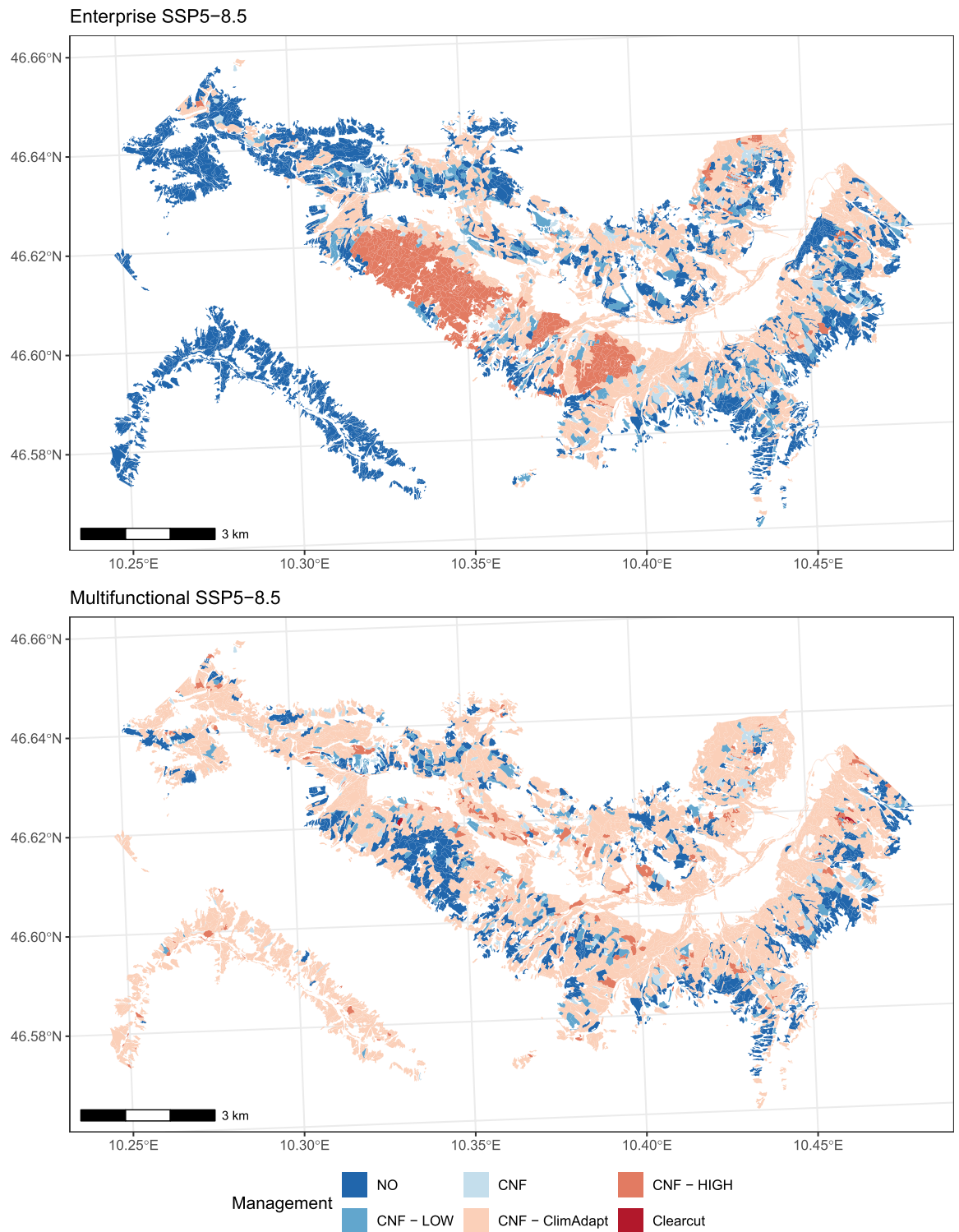


Fig. 4. Optimized spatial distribution of management strategies for the optimization scenarios Enterprise (top) and Multifunctionality (bottom), both for the climate change scenario SSP5-8.5. The spatial distributions of all optimization and climate change scenarios are presented in Supplementary Material S6.

change (SSP5-8.5) scenario, the sequestration potential decreased at lower elevations, with a peak reached in the years 2070 and 2080 under all optimization scenarios.

For biodiversity conservation, a shift was observed of stands with high partial utilities moving to higher elevations over the planning period. This was particularly visible for the Enterprise optimization scenario. The effect of alternative climate change scenarios was less pronounced, but still showed slightly better outcomes

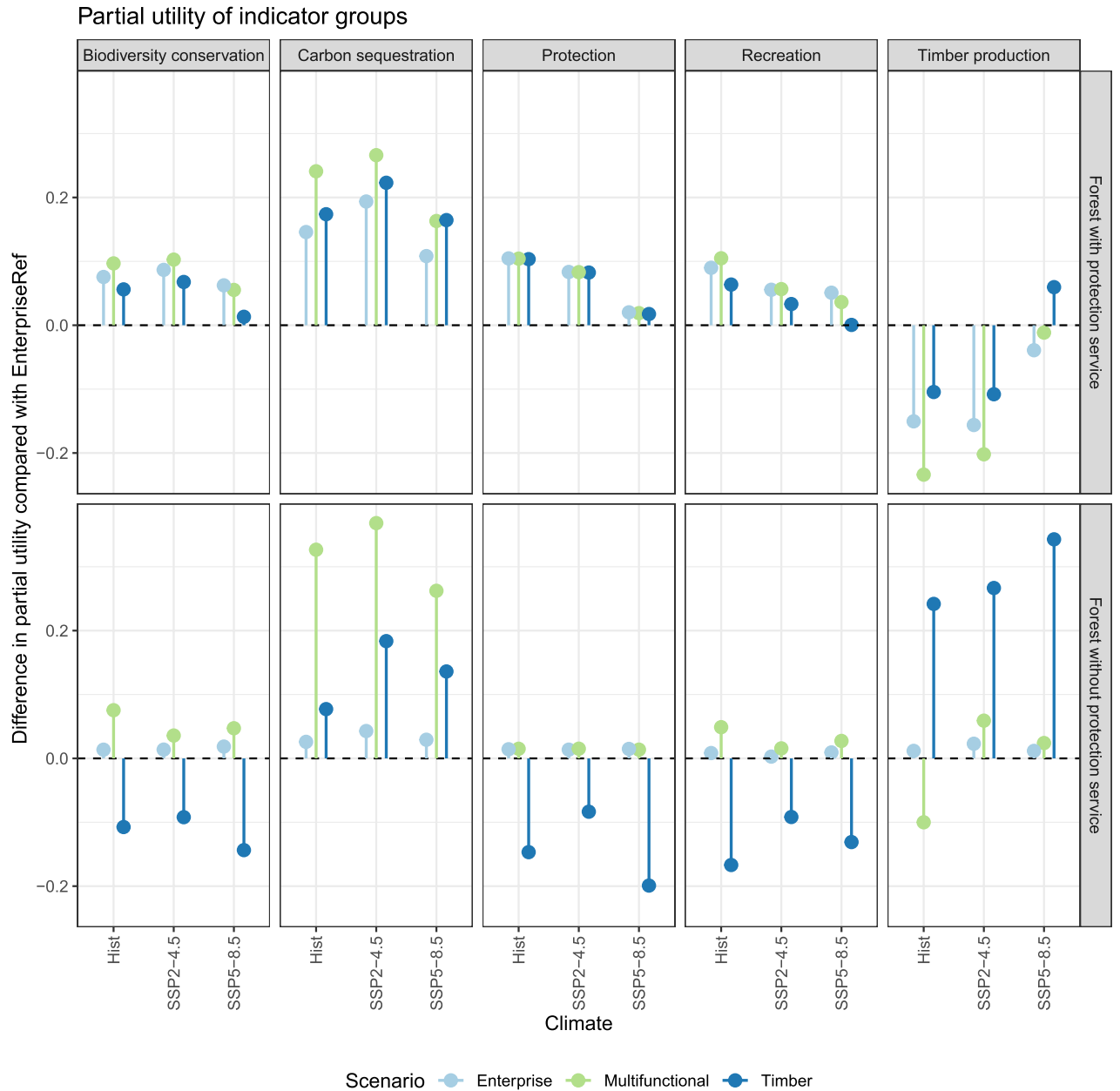


Fig. 5. Changes in biodiversity and ecosystem services (BES) provision in forests with (upper row) and without a protection service (lower row) under alternative optimization and climate change scenarios. The differences in partial utility values relative to the reference scenario EnterpriseRef (which assumes future management under the currently applied management regimes) are shown.

regarding the biodiversity objective under the moderate climate scenario SSP2-4.5. Thus, the current management strategy has a larger effect on this objective than changing climate conditions.

For recreation indicators, similar effects were observed as for biodiversity; stands with high partial utility values shifted to higher elevations. This effect was slightly more pronounced in the case of the moderate climate change scenario SSP2-4.5. Almost no differences were visible among the optimization strategies, indicating the comparatively small effect of changing CNF approaches.

For timber indicators, the stands with the highest partial utilities remained at low elevations (below 1600 m a.s.l.). This applied to all optimization scenarios. Partial utility increased under the Hist and moderate SSP2-4.5 climate scenarios until the end of the planning time, while the more intense climate scenario SSP5-8.5 showed noticeably lower partial utilities at lower elevations.

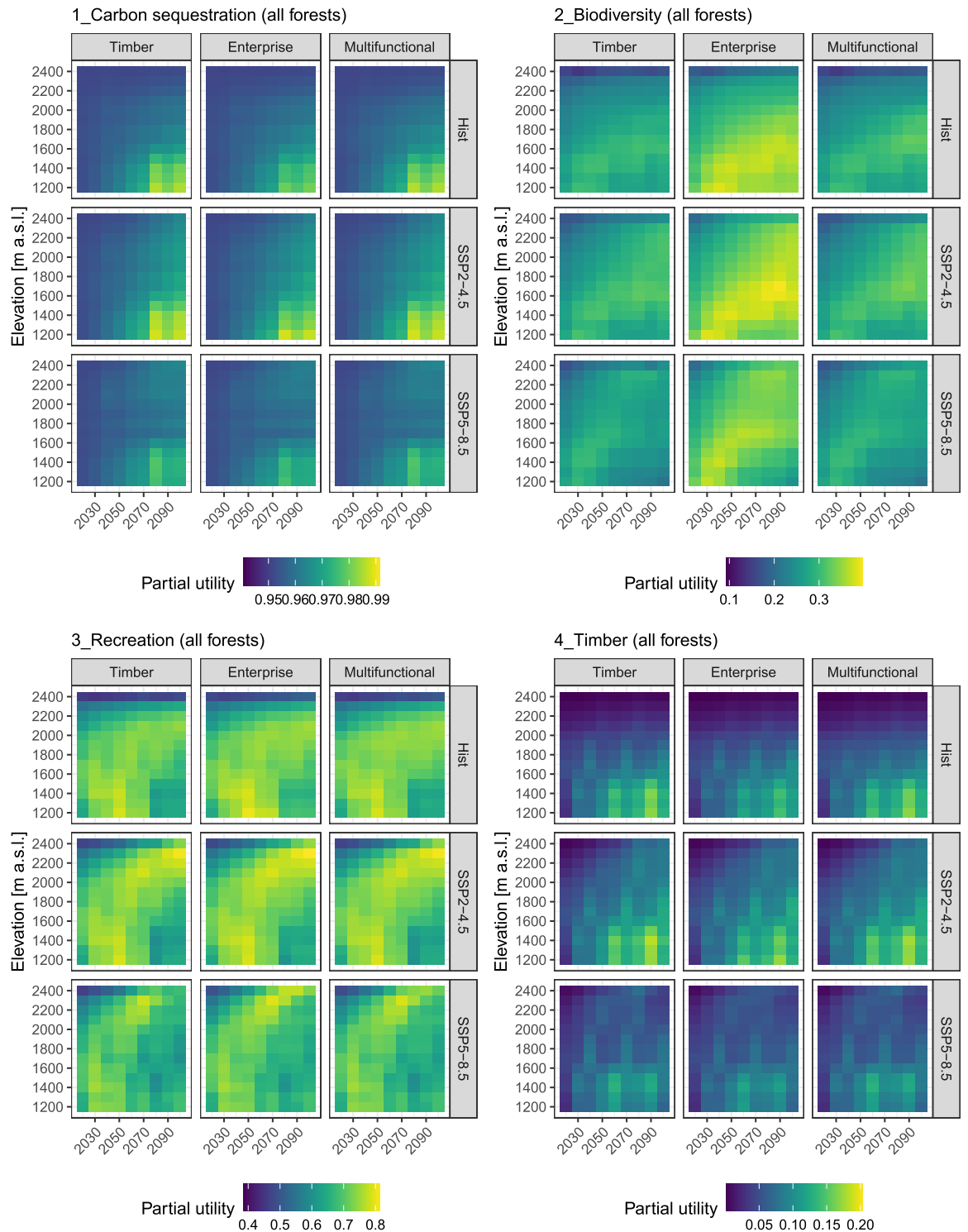


Fig. 6. Partial utilities of the biodiversity and ecosystem service (BES) indicator groups carbon sequestration (1), biodiversity conservation (2), recreation (3), and timber production (4) over the observed planning period (x-axis) and elevation gradient (y-axis). Values were computed according to Eq. (20) and for all climate change and optimization scenarios. Results are shown for all forest stands (with and without protection) why protection against gravitational hazards is not shown here. Please notice the different scales for the colour schemes in the different panels.

Discussion

Optimized management for forest multifunctionality

In general, our results show that a diversified management portfolio is an important planning strategy for multifunctionality, as shown by other studies (e.g.^{61,62}). Similarly, admixing of the tree species portfolio has been reported to be important for adaptation to climate change^{17,63}.

In forests with a protection service, optimized management portfolios suggested larger contributions of CNF-ClimAdapt and NO management strategies, with increasing shares of CNF-ClimAdapt under an increasing intensity of climate change. The large shares of NO might seem counter-intuitive at first glance, but this result relates to the fact that both indices (API, RPI) include the stem density, which is higher in unmanaged areas than in managed ones^{1,64}. However, shares of NO declined considerably under optimized management with increased severity of climate change. This is in accordance with previous modelling studies showing that the protective effects of forests may decline substantially under climate change unless there are active counter-measures^{26,65}. Additionally, stand structures under NO might be associated with a higher predisposition to disturbances^{66,67}. Considering management objectives related to disturbance mitigation may introduce additional trade-offs with BES provision^{25,67}, which were not accounted for in our approach but are gaining increasing importance under climate change (see Section 4.3). Further portfolio composition differed only slightly for the various optimization scenarios within forests with a protection service, as protection indicators received a high objective weight of 90%. As such, partial utilities also just slightly differed among the scenarios, and relevant differences mainly occurred for carbon sequestration and timber production.

The differences in terms of portfolio composition and partial utility values were larger in forests without a protection service. On the one hand, the objective weights differed more, and on the other hand, there were already predefined strategies for capercaillie habitat areas, forest reserves, and mountain pine forests for the Enterprise optimization scenario. Still, CNF-ClimAdapt was a central management strategy and became more important as climate change progressed.

The large share of CNF-ClimAdapt (in forests with and without a protection service) can be explained by its improved resistance against climate change and also by the benefits of planting for certain biodiversity indicators (e.g. stand structure, tree species diversity). However, ecological indicators that benefit from open forest structures, such as habitat suitability for capercaillie, are also conceivable³⁸ and might foster strategies that would be comparable to our CNF-HIGH approach. This interesting Alpine-specific trade-off could be elaborated in a future study.

Management implications and wider application

The complex topography, elevation gradients and site conditions make the management planning of Alpine forests particularly challenging. In the case of Switzerland, forest development plans on the landscape level¹⁸ provide guidance, assigning priority areas for certain management objectives. In our case study site, as in many other mountainous areas, the protection forest is of utmost importance and silvicultural measures are usually clearly defined⁴. This spatial constraint was considered as the starting point for our optimization scenarios.

To guarantee the protection against gravitational hazards, protection forests are managed under CNF approaches like Mountain forest plentering, which represents the small-scale removal of groups of trees with the objective of fostering regeneration³⁶. Our optimization study demonstrates that this silvicultural approach needs adaptation through the fostering of future climate-adapted provenances and tree species. Although most experts are aware of this^{13,15}, our modelling results suggest that immediate action is needed.

The management objectives of the forests without a protection service mostly underlie the interests of the forest enterprises, which is why flexibility remains of interest for individual management objectives. The current forest management plan of the case study site included additional conservation areas (reserves, capercaillie habitat, mountain pine forest), which we followed in the Enterprise optimization scenario where we constrained the management (to NO and CNF-HIGH). Thus, management flexibility remains only in a subarea. Nevertheless, our optimization showed a shift from currently applied CNF to CNF-ClimAdapt even for these areas. The importance of CNF-ClimAdapt became even more important once we relaxed the area constraint under the optimization scenarios Timber and Multifunctionality, with further benefits for multiple BES.

Overall, our study results provide valuable insights for local forest management. Nevertheless, complex mountain environments hinder the generality of our outcomes, as conditions might be very different in other regions^{1,23,68}. Thus, such joint simulation- and optimization-supported planning tasks need to be conducted in a case-specific manner, considering local management objectives as well. Future work should focus on the urgent task of standardizing science-based decision support frameworks, making them more accessible to forest planners. Only in this way can the future political ambitions of multifunctional and resilient forest ecosystems be reached^{15,21}.

Limitations

Which set of indicators best represents the conditions of Alpine forests has been developed in previous studies⁶⁹. We here presented an implementation of the previous indicator models^{23,26} within an multi-objective optimization framework. Even the indicator set addresses a wide set of BES, our model could be further improved by e.g. including habitat suitability for capercaillie, a relevant characteristics of the region, or recreational hot-spots along hiking paths. However, capercaillie habitat suitability was implicitly captured, as it requires low stand density, which is correlated with the indicators *timber harvested* and *productivity*. The very important recreational hotspots in the region (along the hiking trails) were covered during the optimization by addressing the general visual attractiveness of forest stands.

Additionally, no economic indicator was included, covering costs for harvesting operations and timber revenues. Harvesting costs in Switzerland, particularly in the Alpine region, are among the highest in Europe⁷⁰.

Considering this aspect might influence the spatial allocation of management strategies in remote and less accessible areas with high harvesting costs. In Alpine forests, however, forest operations often rely on public subsidies, as costs for forest operations tend to exceed revenues from timber selling, due to the challenging topography⁷¹. This is why we decided to focus on pure provided services and to exclude economic aspects. Nevertheless, future work should ideally account for these aspects, which would make it possible to highlight corresponding levels of compensation.

Our forest simulation did not consider biotic or abiotic disturbances, which are expected to increase in the future^{8,9} and impact mountain forests⁷². As simulating disturbance regimes is particularly challenging, an option could be to assess forests' susceptibility indicators to disturbances^{67,73,74}. Such indicator-based assessments of disturbance predisposition enable the identification of conflicting management objectives between BES provision and disturbance mitigation efforts^{25,67}. Those could then be directly targeted in the multi-objective optimization framework, aiming for a management plan that minimizes future susceptibility against disturbances. In this way, neighbour effects of adjacent disturbed stands could also be considered⁷⁵. Such spatial dependencies as described by^{76,77} (positive or negative) are currently not considered in the optimization framework.

In practice, mountain forest stands are usually grouped into management units with similar treatments, in order to harmonize e.g. the harvesting methods on a larger spatial scale. Considering operational aspects is important in steep mountainous terrain, where timber extraction is cable-based and thus involves high fixed costs for the cable road installation. This could be the set-up and dismantling of the intermediate supports, for which costs occur independently of the amount of wood that is extracted.⁷⁸ have shown that the spatial and hierarchical aggregation of planning units can influence the distribution of optimal management strategies. Thus, definition of more realistic management units within the case study area might alter the optimization results presented here. Future work should thus ideally address this spatial aspect, e.g. by the approach present by⁷⁹ which allocates mountain forest into homogeneous planning entities with regard to silvicultural and operational constraints.

Conclusion

In this study, we combined a climate-sensitive forest model and a multi-objective optimization framework to study how to improve the provision of ecosystem services and safeguard biodiversity under climate change in Alpine forests. A key focus was on the protection function of mountain forest. We draw three major conclusions from our European Alpine case study. First, we could show that an optimal portfolio of forest management strategies can improve forest multifunctionality: depending on the targeted objectives, the provision of multiple BES can be improved. This would, however, require including larger shares of climate-adapted CNF management strategies to cope with the impacts of climate change, for both forests with and without a protection service. Second, our presented simulation and optimization framework tailored for mountain forests with a protection service showed flexibility in the integration of management objectives, rendering it useful for decision support. Forest management planning should rely more on and make use of such frameworks to help forest adapt to climate change and to support future sustainability and multifunctionality. Third, as planning tasks need to be conducted in a case-specific manner, future work should focus on standardized science-based decision support frameworks, making them more accessible to forest planners. Only in this way can the future political ambitions of multifunctionality and resilient forest ecosystems be reached.

Data availability

The datasets supporting the findings of this study are available at <https://doi.org/10.5281/zenodo.13681049>.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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