European Journal of Forest Research (2026) 145:101
https://doi.org/10.1007/s10342-026-01929-y

RESEARCH

# Regional impacts of increasing forest protection: scenario analysis of wood production, profitability, biodiversity and carbon storage in Southern Finland

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Received: 13 April 2026 / Revised: 29 May 2026 / Accepted: 11 June 2026


**Abstract**
The EU Biodiversity Strategy sets out targets to halt biodiversity loss. In Finland, achieving these goals would require the supplementary conservation (SC) of boreal forests, consequently reducing the area of production forests. Utilising scenario analyses, the large-scale impacts of SC were studied from two perspectives: environmental (deadwood, broadleaves, carbon) and forestry (removals, profitability). Two harvesting strategies were also considered: one in which the decrease in harvesting removals due to SC was compensated, and another without compensation. Circa 1.27 million hectares of forests in southern Finland were included into analyses. Motti simulator was used to produce stand projections for 50 years. The reference scenario, BAU (business-as-usual), represented the current production forest area, whereas in the SC scenarios, area of production forest reduced due to the SC. The SC levels were relative to the 10% regional strict forest protection target suggested by the Finnish Nature Panel. SC100 corresponded to the full required SC area in their suggestion, SC50 to half and SC25 to a quarter. The study revealed that SC increased the broadleaved volume (2–10% compared to BAU) and the accumulation of deadwood (7–29%), across all forests. The carbon storage of the living trees also increased (2–10%), but only without removal compensation. Prioritising older stands in SC resulted in a non-linear dependency between increasing environmental benefits and increasing SC area, leading to considerable differences in trade-offs. Furthermore, the harvesting strategy itself had a decisive impact on trade-offs. SC with removal compensation was distinctively more cost-efficient than without it.

**Keywords** Conservation · Forest management · Motti simulator · Silviculture · Trade-offs

## Introduction

A recent study by Allan et al. (2022) demonstrates that 44% of the global terrestrial area requires conservation attention. This includes changes in land-use policies, and protection of both important biodiversity and ecologically intact areas. Such a vast global area (44%) breaks down into significant regional numbers. For instance, *the European Union (EU) Biodiversity Strategy* aims to halt the loss of biodiversity by 2030 by increasing the protected areas so that at least 30% of EU land and sea areas are under legal protection by 2030 (European Commission 2020). Furthermore, one-third of that area must be under strict protection. The strategy also states that all remaining primary and old-growth forests must be strictly protected, irrespective of the surface area targets.

Communicated by John Shandra

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Published online: 28 July 2026

Finland has a total of three million hectares of protected productive and low-productive forest land (i.e., mean annual increment of growing stock > 1 and 0.1–1 $m^3$ $ha^{-1}$ $a^{-1}$, respectively), consisting of statutory protected areas and biodiversity conservation sites in commercial forests (Official Statistics of Finland, OSF 2025a). Strict protection covers about six percent of the productive forest land, and ten percent of the productive and low-productive forest land (numbers incl. categories 1A and 1B "no felling" in OSF (2025a). However, the state of protection remains unsatisfactory, and *the Finnish Nature Panel* (Kotiaho et al. 2021) suggested additional conservation to achieve at least 10% strict protection of Finnish productive forests in each region of the country. There are several reasons behind this need. First, among the European countries, Finland and Sweden have a pivotal role in maintaining the biodiversity and carbon balance of boreal forests (Gauthier et al. 2015). Therefore, the conservation targets for boreal forests set in *the EU Biodiversity strategy* (European Commission 2020) are strongly focused on these countries. At the same time, the impact of wood production on national economy has to be considered (Lindahl et al. 2017; Heinonen et al. 2018). Moreover, the loss of biodiversity is significant in production forests (Gauthier et al. 2015; Pötzelsberger et al. 2021). Secondly, the geographical distribution of protected forests is uneven in Finland, with the majority located in northern parts of the country (OSF 2025a). The reasons for this are related to, e.g., a greater proportion of state-owned land and a higher proportion of low-productive forests in northern than in southern Finland. Therefore, there is a crucial need for the enhancement of the conservation area network in southern Finland. Thirdly, it is especially important to recognise the value of old-growth and primary forests as components of the biodiversity of boreal forests (Paillet et al. 2010; Hekkala et al. 2016; Nirhamo et al. 2025). In the countries with a long history of forest management, such as Finland, there has been a decrease in primary and old forests (Shorohova et al. 2011; Sabatini et al. 2020). According to the 13$^{th}$ Finnish National Forest Inventory (NFI; Korhonen et al. 2024), the proportion of the forests older than 80 years is 27%, and older than 160 years 4% when all productive forest area is considered.

Among the structural characteristics of the forest stands (in addition to stand age), the large-sized deadwood and the deadwood of broadleaved tree species are particularly valuable (Hekkala et al. 2023). Deadwood provides a habitat for many forest species, including saproxylic organisms, whose richness depends strongly on the quantity and variety of dead organic matter (Hågvar and Ødegaard 2025). However, amounts of deadwood are low in managed Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) dominated forests (Eräjää et al. 2010; Shorohova et al. 2024). According to NFI13 (Korhonen et al. 2024), the average amount of deadwood in southern Finland is 4.8 and 23.0 $m^3$ $ha^{-1}$ in the forests available and not available for wood supply, respectively. Broadleaved tree species are also important for biodiversity (Felton et al. 2016; Huuskonen et al. 2021; Salemaa et al. 2023). A mixture of broadleaves increases the structural complexity and heterogeneity of a stand (Löfroth et al. 2023; Wijas et al. 2024) and enhances the functioning and resilience of the ecosystem (Hämäläinen et al. 2024). In Finnish forests, only a few broadleaved tree species are present, and their existence considerably depends on the site fertility, and is strongly affected by forestry practices. From a forestry point of view, only the silver birch (*Betula pendula* Roth.) is of greater importance (Hynynen et al. 2010; Oksanen 2021), and thus also used in forest regeneration. Other broadleaves are naturally regenerated on the sites but are then mainly removed in precommercial thinning and only maintained for biodiversity.

Forests contribute significantly to carbon sequestration. They will increasingly be used as a natural solution for enhancing carbon dioxide removal through afforestation, reforestation, and improved management of existing forests (von Hedemann et al. 2020). Forest carbon dynamics can be directly affected through forest management (Sevillano et al. 2025), which also impacts biodiversity. Increasing rotation lengths (Triviño et al. 2017), reducing harvest intensity (Gregor et al. 2022), and fertilising nutrient-deficient soils (Melikov et al. 2023) have been demonstrated to be efficient measures to enhance carbon sequestration in European forests.

Wood production plays an important role in the Finnish economy. In the last 10 years, annual cuttings have been ca. 56–69 million $m^3$ $a^{-1}$ (OSF 2025b), with forest industry products accounting for about 16% of all exported goods in Finland (Finnish Forest Industries 2025). Forest revenues are also important for the majority of forest owners, gross stumpage earnings constituting ca. 3.1 billion € in 2023 (OSF 2025c). At present, the need for additional protection is focused on the forests currently available for wood production. Increasing protection decreases the area of commercial forests and directly affects harvesting possibilities, the timing and spatial distribution of the cuttings, and the profitability of forest management. Recent literature demonstrates that with increasing forest conservation area, the total growing stock (Alrahahleh et al. 2017) and net present value tend to decrease compared to the situation with current level of conservation. However, with intensified forest management, these losses could be partly compensated (Pikkarainen et al. 2024).

This study focuses on assessing the impacts of increasing strict forest protection area on wood production, economic outcome, biodiversity (volume of broadleaves and accumulation of deadwood), and carbon (storage of living trees). The assessments are conducted for a vast forested area covering about 1.3 million hectares using scenario analyses. Trade-offs between the economic outcome and other factors (biodiversity and carbon) are calculated, which is, to our knowledge, the first attempt to consider trade-offs between all three factors simultaneously (cf. e.g., Alrahahleh et al. 2017; Díaz-Yáñez et al. 2019; Mazziotta et al. 2023).

The main study questions are:

(1) What are the impacts of increasing strict forest protection areas on wood production, profitability, biodiversity, and carbon storage at the regional level?
(2) How do the impacts differ when decreasing harvesting removals due to the increasing protection are compensated by increasing cuttings in the remaining area of production forests (i.e., reconciliation of wood production and protection) or not (no reconciliation)?

Three scenarios representing different levels of increasing strict protection areas and two strategies related to compensation of harvesting removals were applied. Business-as-usual (BAU) forest management was set as a reference scenario.

## Materials and methods

### Approach

The study was conducted as a scenario analysis. We focused on the large-scale effects of increasing strict forest protection area in southern Finland forests. The new protection area is supposed to be removed from production forests and added to the existing strictly protected area and is henceforth referred to as *a supplementary conservation* (SC) area. First, we selected three regions in southern Finland for the study area. Secondly, we constructed four alternative scenarios: BAU and three SC scenarios representing different levels of SC (Fig. 1). The selection of stands for SC followed predefined rules. Then, we simulated the development of the study area forests over 50 years within the framework of each scenario and compared the results to assess the overall effects of SC.

We examined how SC affected the development of several indicators. Specifically, from a forestry perspective, we assessed impacts on harvesting removals ($m^3$) and net present values (NPV, €), and from an environmental perspective, on broadleaved and deadwood volumes ($m^3$) as well as the carbon storage of living trees (t $CO_2$). We also assessed the possibilities and impacts of reconciling wood production and SC targets by calculating each scenario with two alternative harvesting strategies: (i) maintaining initial cutting level (strategy of constant removals = CONSREM)

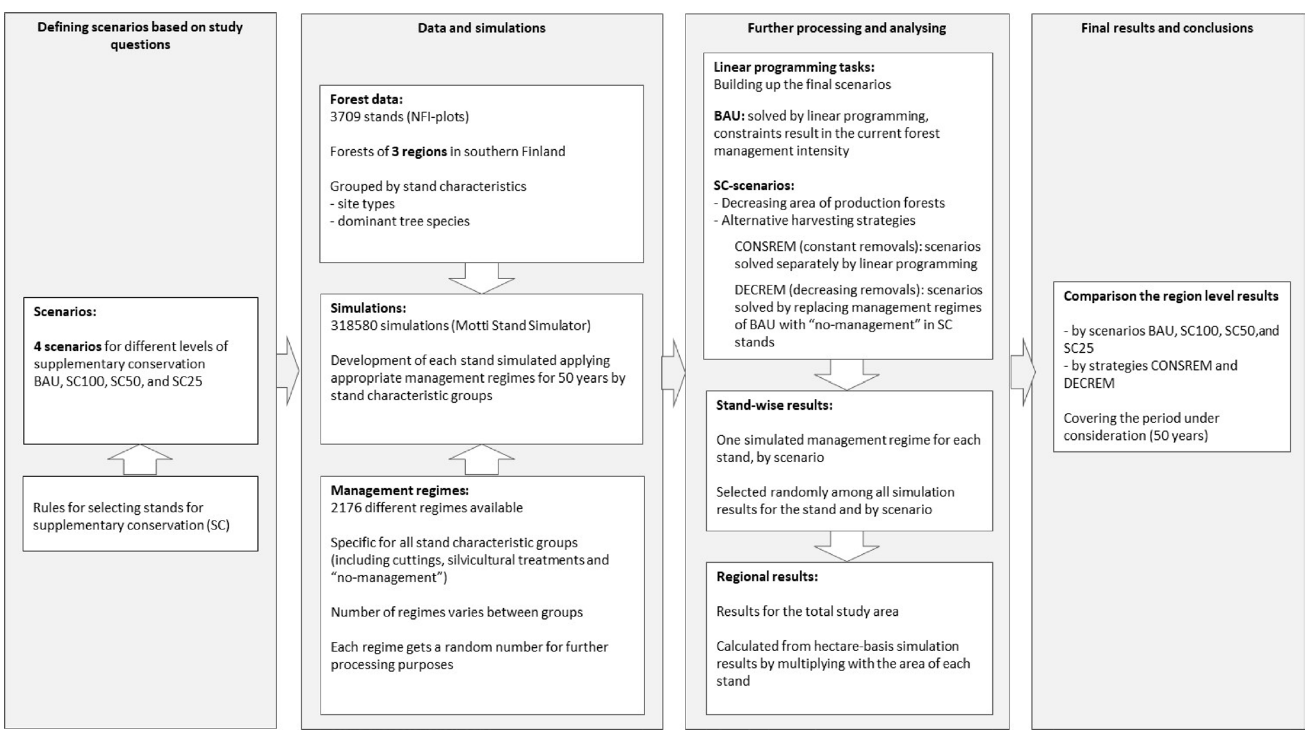


**Fig. 1** Overview of the process applied in the scenario analysis

and (ii) allowing cutting level decrease (strategy of decreasing removals = DECREM). Finally, we calculated trade-offs between the indicators.

The study builds on the same established framework used in our previous regional and national forest management analysis (e.g., Hynynen et al. 2015; Huuskonen et al. 2020; Haikarainen et al. 2021). We outline the key elements required to follow the present analysis in the sections below, with a focus on the study-specific adaptations. The analysis followed the process illustrated in Fig. 1.

## Forest data

We selected three regions of Finland (Fig. 2) to represent areas where forestry has a considerable socio-economic impact and which, being in the southern parts of the country, are considered to be in need of additional conservation.

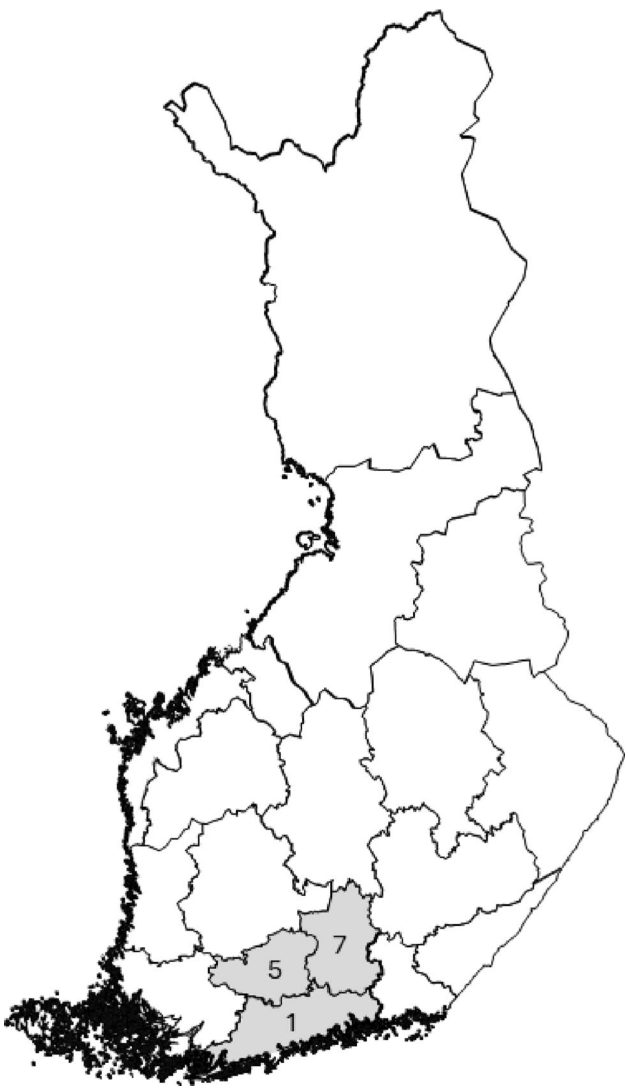


**Fig. 2** Administrative regions of Finland included in the analysis (1 = Uusimaa, 5 = Kanta-Häme, 7 = Päijät-Häme)

We used data from the NFI12 (Korhonen et al. 2021) to obtain a representative description of the forests, and as a basis for simulations (Fig. 1). Our data included a total of 3709 sample plots (hereafter referred to as stands), with one stand representing, on average, 340 hectares of forestry land. This resulted in the total area of 1.27 million hectares, including altogether 1.09 million hectares classified as the area available for forestry. Hereafter, we refer to these as “all forests” and “production forests”, respectively.

The study area represents hemiboreal and southern boreal forest vegetation zones. Site fertility varies from most fertile to barren sites, with the majority (76%) representing classes of mesic or herb-rich heath forest sites or corresponding peatland sites. The proportion of peatlands is 14%. The dominant tree species are Norway spruce (47% of the area) and Scots pine (34%). Broadleaved tree species such as birches (*Betula pendula* Roth., *Betula pubescens* Ehrh.) or aspen (*Populus tremula* L.) are less frequently dominant tree species (17%) but grow as mixed trees in coniferous stands. Most of the stands (90%) are younger than 100 years. The proportion of stands at least 100 years old is 10.6% among conifer-dominated stands and 0.6% among broadleaved-dominated stands.

## Scenarios

We constructed four scenarios: the reference scenario BAU, and three SC scenarios. Following the established framework, one scenario in its final form consists of a selected set of simulated stand projections—one for each stand (Fig. 1). The set is selected from the large number of simulated alternatives, i.e., stand projections, generated under different management regimes (see section ‘Management regimes and simulations’) so that the final combination over study area represents the forest management approach defined for the scenario.

The BAU scenario is based on the current forestry activity and proportions of protected and production forests. In line with the framework, annual harvesting removals and intensity of silvicultural practices in BAU are set to represent the level of current management of production forests in the study area and remain averagely at the same level over the given time horizon. Values are based on statistics and considered as constrains in linear programming phase (see section ‘Final scenario construction’). Thus, the forests are assumed to develop under the management broadly similar as current throughout the BAU scenario.

The SC scenarios, specific for this study, differ from the BAU scenario in terms of changes in production and protected forest area. The SC scenarios were constructed according to the forest protection targets suggested by *the Finnish Nature Panel* (Kotiaho et al. 2021) (i.e., the share of current and new strictly protected forests should be regionally at least 10%). The SC100 scenario was set to align with this suggestion, and the suggested areas of productive forest land were allocated from production forests to conservation (i.e., 28,000 ha, 26,000 ha, and 28,000 ha in regions 1, 5, and 7, respectively; Fig. 2). In SC50 and SC25, these areas were 50% and 25% of the SC areas of SC100, respectively. In the SC scenarios, management of the production forests follows a similar procedure to that in BAU, but due to the reduced area the intensity of forestry may change. For that we defined two possible outcomes related to harvesting intensity.

## Harvesting strategies

For the SC scenarios, we applied two alternative harvesting strategies. In the first strategy, CONSREM (constant removals), we assumed that annual removals of commercial wood are not affected by the increase in protected forest areas, i.e., harvesting removals remain at the same level by increasing cuttings on the reduced area of production forests. The second strategy, DECREM (decreasing removals), based on the assumption that SC decreases annual removals because of the strict protection of former production forests. The decrease in removals was proportional to the SC area, which varied between the SC scenarios. Technically, these two harvesting strategies are incorporated into the SC scenarios in two different ways after the simulations, as described in section 'Final scenario construction'.

## Selecting stands for supplementary conservation

The forest stands allocated to SC were determined in line with the suggestions of *the Finnish Nature Panel* (Kotiaho et al. 2021), which include both an area target and its distribution across different forest types. All remaining old-growth and primary forests should be strictly protected. Stand age is used as a criterion for the suggested protection forests. The age limit varies by geographical location, by dominant tree species (pine, spruce, broadleaves) and is set separately for the classes of productive and low-productive forest land.

In our study, the allocation of SC area to the specific type of stands was done in two phases: First, we selected the oldest forests, i.e., over 120-year-old conifer-dominated stands and over 100-year-old broadleaved-dominated stands, following the criteria of Kotiaho et al. (2021). Secondly, we selected younger stands that contained important structural characteristics for forest biodiversity. For this, we used a selection procedure in which we calculated a specific conservation value index (cv-index) for each, currently unprotected, stand. Indexes were calculated according to site fertility class, stand age, and dominant tree species. The most fertile sites had the highest classification. In the ranking of tree species, silver and downy birch, aspen, grey and common alder (*Alnus incana* (L.) Moench, *Alnus glutinosa* (L.) Gaertn.), and other broadleaves had the highest classifications—in that order, and Scots pine and Norway spruce had the lowest classification (1 and 2, respectively). Both the ordered categorical variables, site fertility class and dominant tree species, and the continuous variable stand age were then indexed, i.e., divided by their grand means. The resulting indexes varied on both sides of one, with the range being greatest for age [0…9], then for tree species [0…6], and then for site [0…3]. The conservation value was defined as the product of indexes: '*site x dominant tree species x stand age*', the range of each index reflecting their relative weight. The stands with the highest index values were then selected alongside the oldest stands selected in the first phase, until the intended SC area was reached.

## Management regimes and simulations

We used Motti stand simulator (Hynynen et al. 2005) to predict the development of each NFI-sample-plot stand according to the pre-defined management regimes. Using Motti, we were able to use a large set of models to predict not only natural dynamics such as regeneration, growth, and mortality, but also the effects of silvicultural treatments on stand dynamics, wood production, and on forest management profitability (Hynynen et al. 2015). Tree-species specific stand- and tree-level models included in Motti produce projections for stands at different stages of development and under various growth conditions (e.g., on mineral soils or drained peatlands, and in relation to site fertility, climate, and forest management intensity) (Hynynen et al. 2014, 2015; Repola et al. 2018; Suppl. A in Lee et al. 2025). Motti carries out harvesting process in accordance with the given instructions. This may involve e.g., thinnings and clearcuttings, as well as specifying the timing and intensity of the cuttings. Data on removals is collected by timber assortments for further calculations. The impact of thinning on the development on the remaining stand is also predicted (Suppl. A in Lee et al. 2025). The natural mortality rate affects deadwood accumulation and depends on factors such as stand tree-species composition, age, and density (Siipilehto et al. 2020, 2021). The decaying of deadwood, in turn, decreases the total accumulated deadwood volume. Decaying depends on factors such as tree species, stem size, stem type (standing or fallen), and the time elapsed since tree death (Mäkinen et al. 2006).

Following the established framework, we constructed several alternative forest management regimes for each forest stand to be executed in the simulations (Fig. 1). They ranged from 'no-management' to different combinations of silvicultural treatments, mainly following the prevailing silvicultural guidelines (Äijälä et al. 2024; Best Practices for… 2025) with variation in the timing and intensity of treatments. Technically, the management regimes are chains of treatments encoded as control vectors for simulations. They are specified by sites and tree species, and controlling e.g., precommercial and commercial thinnings, final cuttings, regeneration activities, ditch network maintenance, fertilisation, etc. During simulations, treatments are applied when a stand reaches a suitable development stage for the treatment and carried out with the intensity defined in the control vector. Details of the treatments and the examples of the management regimes can be found e.g., in Huuskonen et al. (2020, Table 2) and Haikarainen et al. (2021, Table 2). In this study, the final number of simulated regimes was ca. 319,000. The time span of our simulations was 50 years.

## Final scenario construction

The basic procedure for selecting the final set of the simulated stand projections for each scenario involves processing a large dataset with linear programming software J (Lappi and Lempinen 2014). Across all scenarios (BAU, SC100, SC50, and SC25), we applied a similar linear programming problem setting for the management of production forests. We set constraints on annual harvesting removals and intensity of silvicultural practices, which represent the current management of production forests (based on statistics from the years 2017–2021 (OSF 2024a; b). We applied a selection procedure (documented in Huuskonen et al. 2020) to ensure that for a given stand, each simulated alternative in agreement with the constraints had an equal probability to be selected into the final solution. The final solution, obtained through linear programming, included exactly one regime (management or no-management) for each individual stand.

To account for two harvesting strategies, we adopted separated approaches to reach the final solutions for the SC scenarios (BAU remained the same in both cases). For CONSREM, the procedure was similar for the SC and BAU scenarios: linear programming was used to provide a solution that required SC stands to remain unmanaged and cuttings in production forests to remain at the same level in all scenarios. For DECREM, we used BAU as a reference and constructed the SC scenarios applying rule-based adjustments. Among the stand projections in the BAU solution, those included in SC area and involving management treatments were replaced with corresponding no-management projections. This resulted in a set of stand projections being identical for those in BAU for the production forests and being no-management projections for the SC forests (Fig. 3). As a result, the annual harvesting removals, and the areas under silvicultural practices in the SC scenarios with DECREM were lower than those in BAU and varied

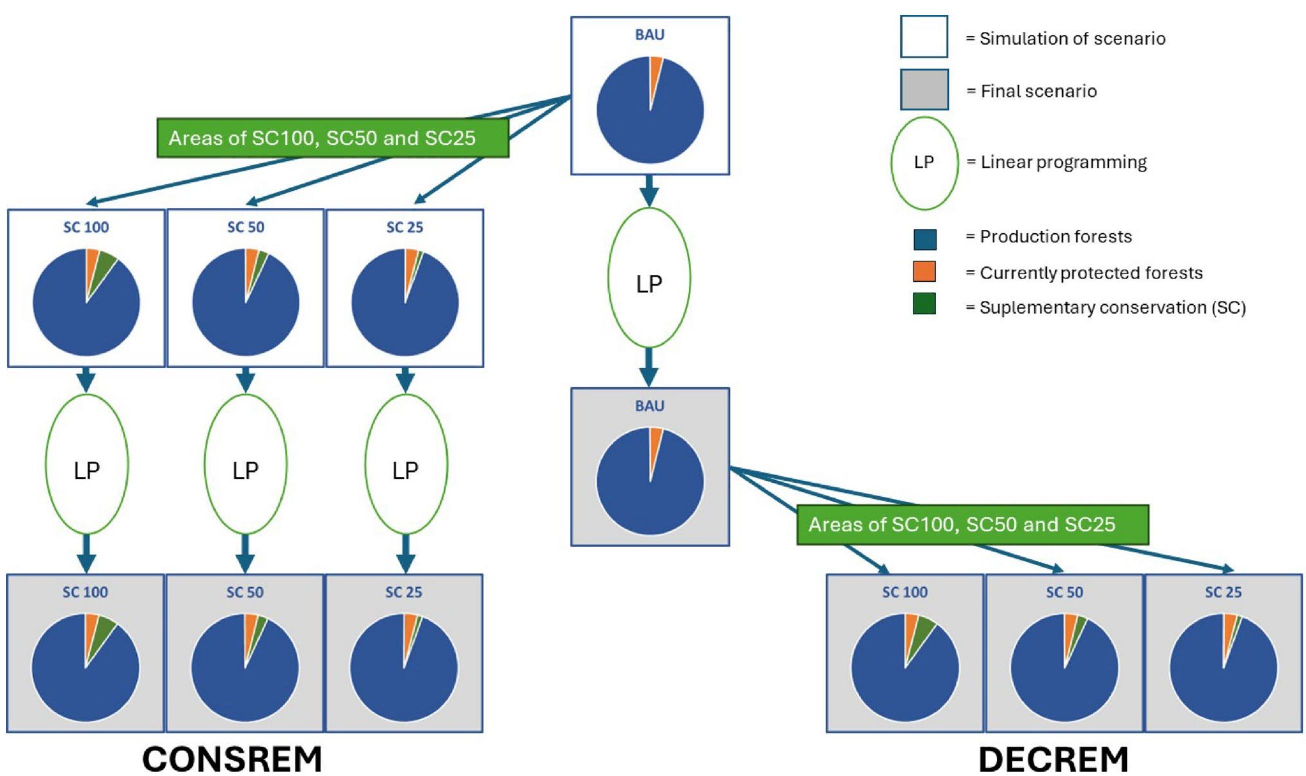


**Fig. 3** Diagram illustrating calculation procedure of the scenarios in the CONSREM and DECREM strategies

according to the SC area in the SC100, SC50 and SC25 scenarios, unlike in CONSREM.

### Monetary values

Monetary values were calculated according to harvesting removals and silvicultural measures associated with each individual stand projection. The values in the final set of projections within each scenario were summed for comparison between scenarios. The values were based on costs of silvicultural treatments and stumpage prices. Costs of the silvicultural treatments were based on the unit costs and/or time-consumption models built into Motti. Average stumpage prices by timber assortment and unit costs were based on the statistics from 2012 to 2021 (OSF 2024c), and the nominal time series were deflated by the cost-of-living index to the year 2017 (OSF 2024d). Technically, the net present value (NPV) for each stand was assessed according to:

$$NPV = \sum_{t=0}^{T} R(t) * (1+r)^{-t} - c$$

NPV = present value of net incomes (EUR $ha^{-1}$), r = interest rate (here 3%), T = time horizon (years), t = time in years, R(t) = net revenue at time t (EUR $ha^{-1}$), and c = discounted silvicultural costs according to interest rate r within the time span {t,T} (EUR $ha^{-1}$), T = 50 years. Finally, the NPVs of individual stands were summed up for BAU and each SC scenario (SC100, SC50 and SC25) according to both harvesting strategies (CONSREM and DECREM).

## Results

### Characteristics and development of the SC forests

All scenarios used the same prioritisation criteria for selecting SC stands. Nevertheless, the total size of the SC area distinctively affects the age structure and site-class distribution of the SC forests (Table 1). The area of SC stands that fulfilled the primary selection criterion of age covered 30% of the total SC area in SC100, but up to 91% in SC25. It is known that in production forests the oldest stands are found in relatively infertile pine-dominated sites, with low productivity. This is also reflected in this study, such as in the site-class distribution and tree-species dominance in SC25 (Table 1). This also means that enlarging the SC area increases the proportion of more fertile sites, which are typically dominated by spruce and broadleaves. Thus, the combination of age criterion and using cv-indexes to fulfil the SC-area target in each scenario resulted in the SC scenarios being quite divergent with respect to stand structure and tree species dominance in relative terms.

At the onset of the simulations, the average stand ages of the SC stands were 93, 111, and 141 years, in SC100, SC50, and SC25, respectively (Table 2), the oldest stands being 275–300 years old. The highest mean volume, 260 $m^3$ $ha^{-1}$, was obtained in SC100, and in some individual stands, mean volumes reached 600–700 $m^3$ $ha^{-1}$.

### Development of the growing stock

In all forests, the total volume of growing stock decreases from the initial volume (210 million $m^3$) both in the BAU and in the SC scenarios under CONSREM but increases in the SC scenarios under DECREM in 50 years (Table 3). In

**Table 1** Area distribution of some characteristics of supplementary conservation (SC) stands in the SC100, SC50, and SC25 scenarios

| | | SC100 | | SC50 | | SC25 | |
|---|---|---|---|---|---|---|---|
| | | ha | % | ha | % | ha | % |
| | Total area | 82,000 | | 41,000 | | 20,500 | |
| Criteria | Age | 24,959 | *30* | 24,959 | *61* | 18,570 | *91* |
| | Cv-index[a] | 57,041 | *70* | 16,041 | *39* | 1930 | *9* |
| Subgroup | Mineral soil | 73,459 | *90* | 34,838 | *85* | 16,396 | *80* |
| | Peatland | 8541 | *10* | 6162 | *15* | 4104 | *20* |
| Site type[b] | Herb-rich | 20,783 | *25* | 9537 | *23* | 1697 | *8* |
| | Herb-rich heath | 36,944 | *45* | 8889 | *22* | 2620 | *13* |
| | Mesic | 14,028 | *17* | 12,329 | *30* | 8679 | *42* |
| | Sub-xeric | 7171 | *9* | 7171 | *17* | 5457 | *27* |
| | Xeric | 1710 | *2* | 1710 | *4* | 1024 | *5* |
| | Barren or rocky | 1365 | *2* | 1365 | *3* | 1023 | *5* |
| Dominant tree species | Pine | 17,413 | *21* | 17,068 | *42* | 13,140 | *64* |
| | Spruce | 34,260 | *42* | 9257 | *23* | 5092 | *25* |
| | Broadleaves | 30,327 | *37* | 14,675 | *36* | 2268 | *11* |

[a]cv-index = conservation value index

[b]Mineral soil site types and corresponding peatland site types

**Table 2** Values of some key variables of supplementary conservation (SC) stands at the onset and at the end of the 50-year simulation period in the SC100, SC50, and SC25 scenarios

| | | SC100 | | SC50 | | SC25 | |
|---|---|---|---|---|---|---|---|
| | | ONSET | END | ONSET | END | ONSET | END |
| SC forests | Mean dominant age, yr | 93 | 142 | 111 | 161 | 141 | 190 |
| | Growing stock, mill.m$^3$ | 21 | 38 | 9 | 16 | 5 | 8 |
| | Growing stock, m$^3$ha$^{-1}$ | 260 | 467 | 230 | 397 | 229 | 401 |
| | Broadleaves, mill.m$^3$ | 6 | 8 | 3 | 4 | 1 | 1 |
| | Broadleaves, m$^3$ha$^{-1}$ | 72 | 103 | 75 | 91 | 36 | 40 |
| | Deadwood[a], m$^3$ha$^{-1}$ | 0 | 76 | 0 | 74 | 0 | 61 |
| | Carbon (living trees), mill. t $CO_2$eq | 26 | 44 | 12 | 19 | 6 | 9 |
| | Carbon (living trees), t $CO_2$eq ha$^{-1}$ | 313 | 535 | 286 | 463 | 278 | 458 |

[a]Accumulated volume of deadwood (=mortality + decaying)

**Table 3** Values of key variables at the onset and at the end of the 50-year simulation period in the SC100, SC50, and SC25 scenarios according to the CONSREM and DECREM strategies

| | | BAU | | CONSREM | | | DECREM | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | SC100 | SC50 | SC25 | SC100 | SC50 | SC25 |
| | | ONSET | END | END | END | END | END | END | END |
| All forests | Growing stock, mill.m$^3$ | 210 | 198 | 189 | 194 | 197 | 222 | 207 | 203 |
| | Growing stock, m$^3$ha$^{-1}$ | 165 | 156 | 149 | 152 | 155 | 175 | 163 | 160 |
| | Broadleaves, mill.m$^3$ | 42 | 50 | 52 | 54 | 53 | 55 | 52 | 51 |
| | Broadleaves, m$^3$ha$^{-1}$ | 33 | 40 | 41 | 42 | 42 | 43 | 41 | 40 |
| | Deadwood [a)], m$^3$ha$^{-1}$ | - | 14 | 17 | 16 | 15 | 18 | 16 | 15 |
| | Carbon (living trees), mill. t $CO_2$eq | 257 | 252 | 238 | 246 | 250 | 277 | 262 | 257 |
| | Carbon (living trees), t $CO_2$eq ha$^{-1}$ | 203 | 199 | 188 | 194 | 198 | 219 | 207 | 203 |
| Production forests | Growing stock, mill.m$^3$ | 177 | 143 | 97 | 122 | 133 | 129 | 136 | 139 |
| | Growing stock, m$^3$ha$^{-1}$ | 163 | 131 | 96 | 117 | 125 | 128 | 130 | 131 |
| | Removals, mill.m$^3$ | 0 | 381 | 380 | 381 | 381 | 348 | 367 | 374 |
| | NPV, mill. €, 50 yr, 3% | 0 | 7902 | 7661 | 7858 | 7876 | 7028 | 7558 | 7718 |
| | Broadleaves, mill.m$^3$ | 33 | 41 | 34 | 39 | 42 | 37 | 39 | 40 |
| | Broadleaves, m$^3$ha$^{-1}$ | 31 | 37 | 34 | 38 | 40 | 36 | 37 | 38 |
| | Deadwood [a)], m$^3$ha$^{-1}$ | - | 10 | 8 | 9 | 9 | 9 | 9 | 10 |
| | Carbon (living trees), mill. t $CO_2$eq | 217 | 188 | 132 | 163 | 176 | 169 | 179 | 184 |
| | Carbon (living trees), t $CO_2$eq ha$^{-1}$ | 199 | 173 | 131 | 156 | 165 | 168 | 171 | 172 |

[a]Accumulated volume of deadwood (=mortality + decaying)

production forests, the total volume of growing stock (initially 177 million m$^3$) firstly decreases due to the reduced area in the SC scenarios. Furthermore, in CONSREM, the decrease is affected by the cuttings, which remain at the initial level despite the reduction in area.

## Harvesting removals and areas

Despite the same removal targets between the BAU and SC scenarios in CONSREM (on average 7.6 million m$^3$ a$^{-1}$), there are small differences in the structure of the removals—the proportion of sawlog decreases slightly compared to BAU, most clearly in SC100 (Fig. 4. left). This is due to allocating higher stocked stands to conservation and conducting compensatory cuttings to lower stocked stands. In DECREM, the removals are lower (7.0–7.5 million m$^3$ a$^{-1}$) (Fig. 4. right). The relatively large drop in removals in the first 10-year period in DECREM is due to the oldest and higher stocked SC stands, which would have been mature for final cutting but are excluded from production forests in the SC scenarios. This also explains the lower sawlog removal in the first period of the SC scenarios. Within 50 years, removals return towards the level of BAU in DECREM.

## Profitability

Harvesting revenues reflect the removals and are therefore quite stable between scenarios in CONSREM, although changes in the structure of removals (sawlogs vs. pulpwood; Fig. 4) lead to slight variations in profitability (Fig. 5; Table 3). Compared to the profitability of BAU (7900 million €; ca. 7250 € ha$^{-1}$; expressed as NPV with 3% interest rate), the profitability is slightly lower in the SC100 scenario, while the other SC scenarios have a negligible effect on profitability (Fig. 5; Table 3). This means that if the

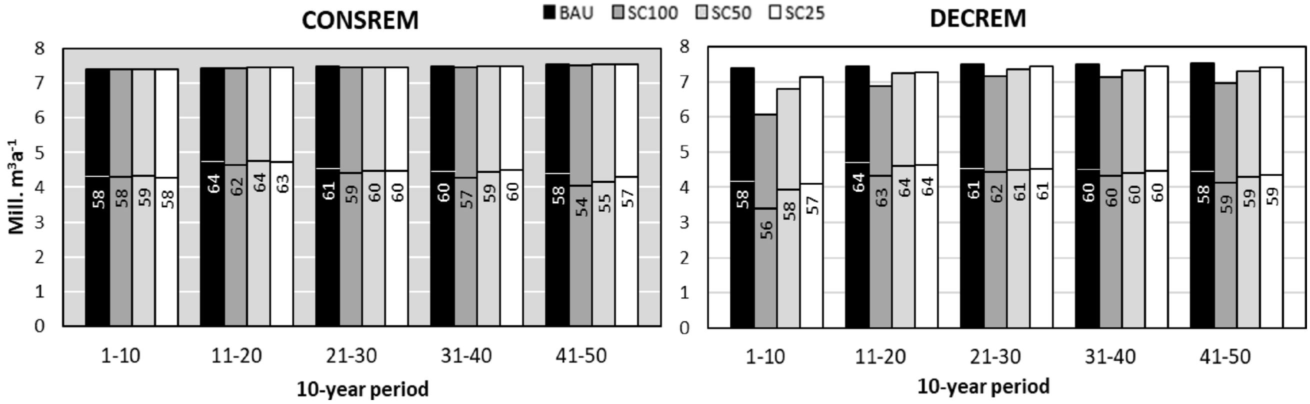


**Fig. 4** Annual harvesting removals by 10-year periods divided into saw logs (lower segment, with numbers indicating the proportion of saw logs, %) and pulpwood (upper segment), million $m^3$ $a^{-1}$. Results according to the BAU, SC100, SC50, and SC25 scenarios and by the CONSREM (left) and DECREM (right) strategies

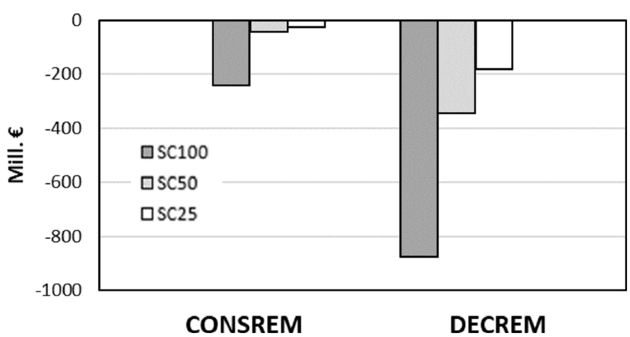


**Fig. 5** The decrease of the net present values (NPV from 50 years, interest rate 3%; million €) of the SC scenarios according to the CONSREM and DECREM strategies, compared to NPV of the BAU scenario

SC area is kept small (as in SC50 or SC25), there are still enough suitable production forests to enable compensatory cuttings. In SC100, the larger area of SC reduces the overall profitability. In DECREM, cutting revenues of the SC scenarios clearly decreases compared to BAU, especially in SC100, and have a clear impact on profitability, with reductions of 2–11% depending on the scenario (Fig. 5; Table 3).

## Broadleaves and deadwood

The broadleaved volume of all forests increases from the initial volume (42 million $m^3$) in all scenarios, despite a drop in the first 10-year period (Fig. 6). The increase is highest in SC50 of CONSREM (29% increase) and in SC100 of DECREM (31% increase) (Table 3). In 50 years, the broadleaved volume increases also in the BAU scenario, reflecting current silvicultural guidelines (Äijälä et al. 2024; Best Practices for… 2025), which suggests that at least small amounts (10%) of broadleaves should be retained in thinnings on suitable sites. Compared to BAU, the SC scenarios ended up with 2–10% higher broadleaved volumes in all forests.

In production forests, the broadleaved volume was 33 million $m^3$ at the onset (Table 3). The end volumes, formed as a sum of the reduced area and the development of the stands, result in 2–17% lower broadleaved volumes in SCs compared to BAU (Table 3). Only the SC25 in CONSREM results in 2% higher broadleaved volume. In general, the trends of broadleaved volumes in production forests are the same in both CONSREM and DECREM, but compensatory cuttings reduce broadleaves, especially in SC100 (Fig. 6).

Deadwood accumulates steadily over time in all scenarios (Fig. 7; Table 3). Increasing conservation increases mortality in the forests, and as anticipated, the majority of deadwood (per ha) is produced in SC stands. At the same time, however, this causes a shift: allocating high-stocked stands to SC is unfavourable for deadwood accumulation in production forests, since the remaining production forests are, on average, younger than before.

In 50 years, accumulated deadwood reaches the level of 15–18 $m^3$ $ha^{-1}$ in all forests (the highest level is found in SC100 and the lowest in BAU), whereas in production forests, the volume varies between 8 and 10 $m^3$ $ha^{-1}$ (Table 3). Trends are similar in DECREM and CONSREM (Fig. 7). At the end, the deadwood volumes of the SC scenarios are 7–29% higher compared to BAU in all forests (Table 3). In production forests, the trends are opposite, and the deadwood volumes are 10–20% lower at the end compared to BAU in all scenarios but SC25 of DECREM, which reached the same amount of deadwood as BAU (Table 3).

## Carbon

Considering all forests, the carbon storage of living trees after 50 years varies from 93 to 108% of the initial storage (257 million tonnes $CO_2$eq), depending on the scenario and strategy (Table 3). In production forests, the end

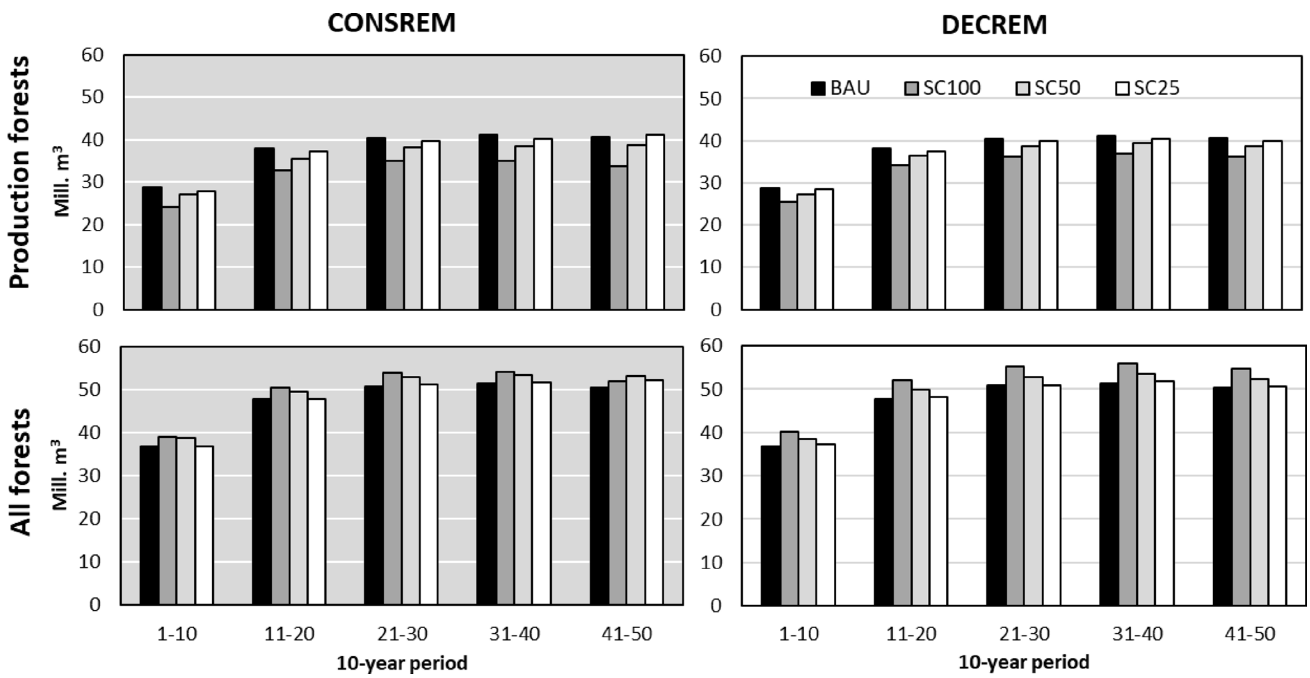


**Fig. 6** The volume of the broadleaved trees by 10-year periods, million $m^3$. Results according to the BAU, SC100, SC50, and SC25 scenarios, and by the CONSREM (left) and DECREM (right) strategies. Top row: Production forests, bottom row: Total forest area

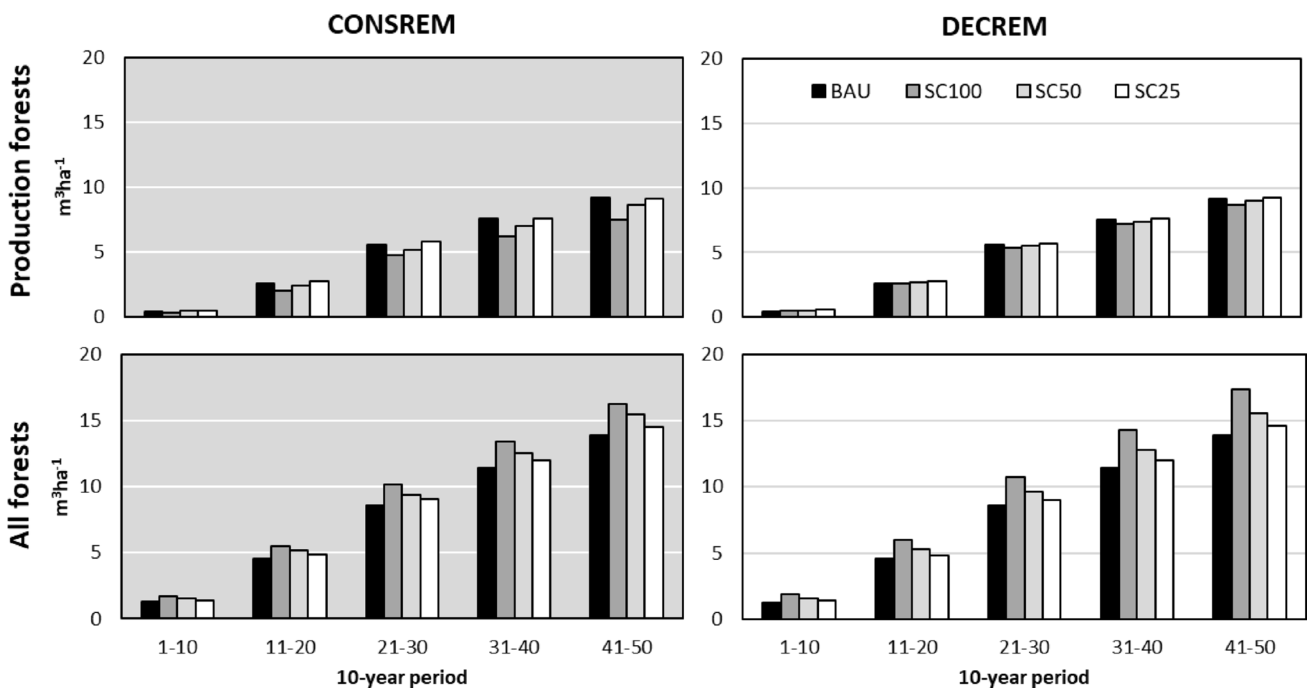


**Fig. 7** Accumulated stem volumes of deadwood by 10-year period, $m^3 ha^{-1}$. Results according to the BAU, SC100, SC50, and SC25 scenarios and by the CONSREM (left) and DECREM (right) strategies. Top row: Productive forests, bottom row: Total forest area

storage varies from 61 to 87% of the initial storage (217 million tonnes $CO_2$eq), being highest in BAU and lowest in SC100 of CONSREM (Fig. 8, Table 3). In CONSREM, carbon storage of living trees in all forests develops quite similarly in all scenarios, due to the similar cuttings (Fig. 8, bottom), and in 50 years result in slightly lower (1–5%) carbon storage compared to BAU. In DECREM, the SC scenarios result in 2–10% larger carbon storage, due to the reduced cuttings. In production forests, all SC scenarios result in lower carbon storage compared to BAU (2–10%

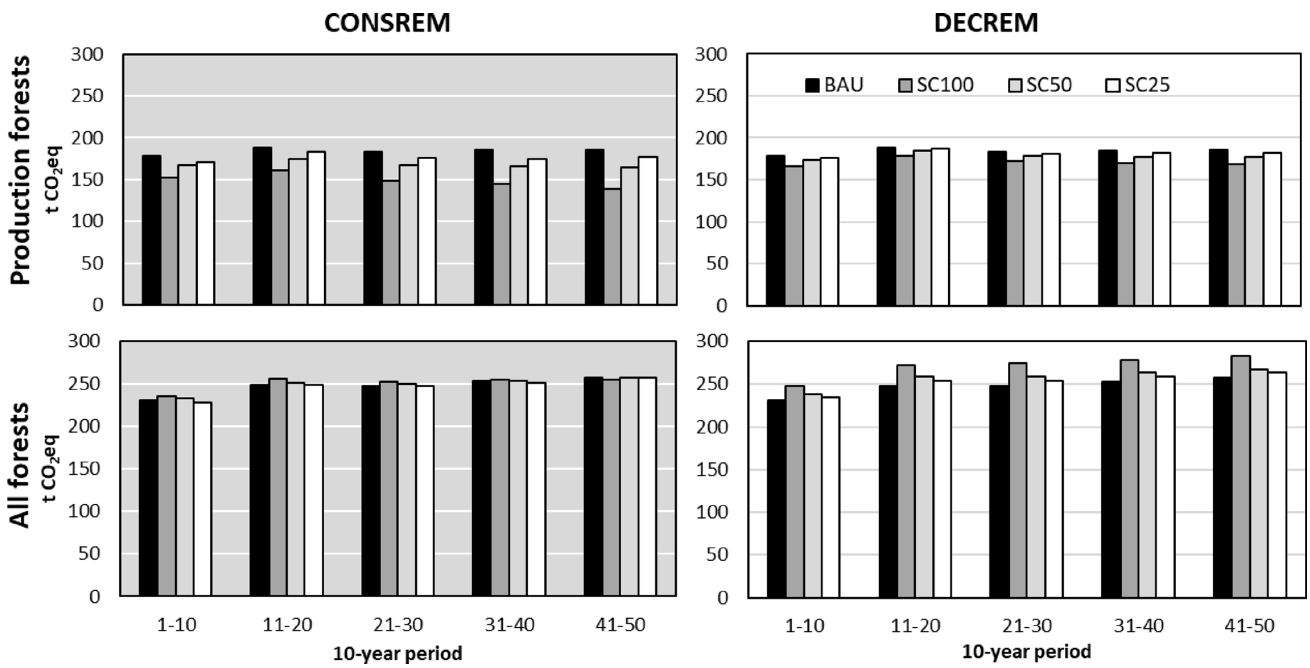


**Fig. 8** Development of the carbon storage of living trees by 10-year periods, million t $CO_2$eq. Results according to the BAU, SC100, SC50, and SC25 scenarios, and by the CONSREM (left) and DECREM (right) strategies. Top row: Production forests, bottom row: Total forest area

**Table 4** Trade-offs between harvesting removals and increases in deadwood, broadleaves, and carbon storage of living trees

| | SC25 | SC50 | SC100 |
|---|---|---|---|
| | Losses in removals, $m^3$ | | |
| Broadleaves, $m^3$ | 0.08 (34.51) | 0.03 (7.41) | 0.52 (7.88) |
| Deadwood, $m^3$ | 0.21 (7.25) | 0.04 (6.42) | 0.31 (6.96) |
| Carbon storage of living trees, t $CO_2$eq | NR* (1.28) | NR*(1.38) | NR* (1.28) |

Values indicate decreases in removals for one additional cubic meter ($m^3$) of deadwood or broadleaves, or one additional tonne of carbon dioxide (t $CO_2$eq) sequestered in the growing stock. Plain numbers represent results for CONSREM, numbers in parenthesis for DECREM. Values apply for total area (1.27 million ha) within a time horizon of 50 years

*NR, Not Relevant since the average carbon storage associated with the SC scenarios is lower than with BAU

**Table 5** Effect of increasing deadwood, broadleaves, and carbon storage on profitability

| | SC25 | SC50 | SC100 |
|---|---|---|---|
| | Losses in NPV, € | | |
| Broadleaves, $m^3$ | 11.28 (923.76) | 14.58 (183.99) | 123.82 (212.53) |
| Deadwood, $m^3$ | 28.47 (193.98) | 20.44 (159.41) | 75.13 (187.76) |
| Carbon storage of living trees, t $CO_2$eq | NR* (34.16) | NR* (34.32) | NR* (34.52) |

Values indicate losses in NPV. For deadwood and broadleaves, the NPV loss is expressed as € per additional $m^3$ and for carbon storage as € per additional t $CO_2$eq. NPVs assessed for 50-year time horizon using a 3% interest rate. Plain numbers correspond to CONSREM and numbers in parenthesis to DECREM scenario. Values apply for total area (1.27 million ha)

*NR, Not Relevant since the average carbon storage associated with the SC scenarios is lower than with BAU

lower in DECREM, 6–30% lower in CONSREM), due to the changes both in area and cuttings.

## Trade-offs

In the trade-off analyses, the baseline was set at BAU with respect to the amount of accumulated deadwood, broadleaves, carbon storage of living trees, removals, and financial performance (NPV). The SC scenarios were compared to the baseline. The analyses revealed the distinctive difference between CONSREM and DECREM. For example, in SC25 with a 50-year time horizon, harvesting removals decrease by only 0.21 $m^3$ for an additional cubic meter of deadwood in CONSREM, while in DECREM, removals decrease by as much as 7.25 $m^3$ (Table 4). Furthermore, for an additional cubic meter of broadleaves in SC100 of CONSREM, removals decrease by 0.52 $m^3$, while in DECREM, the decrease is as high as 7.88 $m^3$ (Table 4).

Since harvesting removals constitute a main component of NPV, one would expect losses in NPV to follow the patterns presented in Table 4. Thus, large decreases in removals might indicate large losses in NPV, too. This is depicted in Table 5: a loss of NPV can be considered as the cost of producing an additional cubic meter of deadwood and broadleaves or a tonne of carbon dioxide. For example, the cost of an additional cubic meter of broadleaves is as high as 923.76 € $m^{-3}$ in the SC25 scenario in DECREM, while in the same scenario it is only 11.28 € $m^{-3}$ in CONSREM (Table 5). A surprising result is that the cost of an additional tonne of carbon dioxide is insensitive to the SC alternatives in DECREM, the cost varying only between 35.16 and 34.52 € per t $CO_2$eq (Table 5).

The overall results show the benefits of the SC for biodiversity (i.e., broadleaves and deadwood) and carbon storage. That benefit depends on both the SC-area (total hectares) and the structure of the forests selected for the SC. However, the SC-area combined with the structure of forests within the particular SC area makes the results nonlinear. This can be easily seen in Table 5 for deadwood, where the NPV loss is the lowest (20.44 € $m^{-3}$) for the middlemost scenario SC50.

## Discussion

This study aimed to examine the impacts of supplementary conservation (SC) on wood production, biodiversity, and carbon storage applying scenario analysis. Current literature presents a vast body of scenario analyses applied in forest management framework (e.g., Verkerk et al. 2014; Hynynen et al. 2015; Heinonen et al. 2017; Wen et al. 2022; Mäkelä et al. 2023; Repo et al. 2024; Sevillano et al. 2025). Typically, these studies use beforehand structured management options that follow a particular course of action towards a specific target or goal (Repo et al. 2024). Here, the method has been developed further to highlight the effects that alternative conservation targets have on selected indicators. For example, Räty et al. (2023) and Pikkarainen et al. (2024) have used a broadly similar approach when studying the effects of forest protection in Finland. The choice of a 50-year time span for the analysis in our study was driven by wood production and economy: it is short enough for reliable estimates of timber values and costs, as well as the estimates of stand development, and conversely, long enough to reveal trends in slow-changing biodiversity. SC changes the management immediately, while the consequences of selecting different harvesting strategies (DECREM or CONSREM) appear gradually but within the selected time span.

As anticipated, our results showed that SC increased both the broadleaved volume and the accumulation of deadwood in the study region's forests. During the 50-year time horizon, the amount of broadleaves increases on average by 7–10 $m^3ha^{-1}$, and the amount of deadwood on average 14–18 $m^3ha^{-1}$. When interpreting these results, it should be highlighted that the BAU as a reference scenario does not represent a 'zero level' in terms of these biodiversity enhancements. This is mainly due to the current silvicultural guidelines (Äijälä et al. 2024; Best Practices for… 2025), where deadwood, as well as broadleaved trees, are recommended to be left on sites. Further, even in production forests, some sites have remained unused. The broadleaved volume at the onset of the simulations is based on the NFI-data and can therefore be considered representative (on average 33 $m^3$ $ha^{-1}$ in our study area versus 31.3 $m^3ha^{-1}$ according to NFI13 in southern Finland reported by Korhonen et al. (2024 Appendix Table 54). In our study, SC stands had significantly more broadleaves (72 $m^3ha^{-1}$ in SC100) than production forests (31 $m^3$ $ha^{-1}$). As a total, the volume-weighted proportion of broadleaves is at its highest (ca. 27%) at 25–30 years. The slight decrease at the end of the 50-year scenarios is due to the deterioration of broadleaved trees in mature stands, particularly in conservation areas. In production forests, the number and volume of broadleaves may increase through planting and retaining broadleaves in thinnings. This is in line with Lee et al. (2023), who demonstrated that the proportion of mixed forests (mostly broadleaved mixtures) in Finland increases towards older development classes.

The amount of deadwood is commonly observed to be low in production forests (below 5 $m^3ha^{-1}$ in southern Finland; NFI13 (Korhonen et al. 2024)). For example, Siitonen et al. (2000) reported deadwood volumes ranging from 2 to 28 $m^3ha^{-1}$ in mature managed forests. Natural boreal forests can contain markedly more deadwood. Reported amounts often range from 60 to 120 $m^3ha^{-1}$ (e.g., Siitonen 2001; Ranius et al. 2004; Aakala 2010; Shorohova and Kapitsa 2015). A threshold deadwood volume of 20–30 $m^3ha^{-1}$ is supposed to support the majority of saproxylic species in boreal forests (Müller and Bütler 2010; Hekkala et al. 2016). As the selected SC stands in our study are initially production forests, the deadwood volume is relatively low in the beginning and only gradually reaches higher volumes. After 50 years, SC stands had accumulated only a small proportion of the deadwood volumes typically found in natural boreal forests. As a whole (in all forests), SC improved the accumulation of deadwood by ca. 7–29%, depending on the scenario. Similar increases in deadwood have been reported, e.g., by Pikkarainen et al. (2024). Hynynen et al. (2025) reported comparable accumulation trends but higher total amounts of deadwood (ca. 44 $m^3ha^{-1}$ in 50 years) than those forecasted in our study. However, Hynynen et al. (2025) estimated deadwood accumulation without considering the loss of deadwood volume due to the decaying process while in this study decaying was included. Regarding NPV losses related to increasing deadwood, our results are consistent with Swedish studies (Ranius et al. 2005; Jonsson et al. 2010). For instance, an additional cubic meter of deadwood associated with SC100 with DECREM costs €188 (Table 5), whereas in southern Sweden, the corresponding cost fluctuated between €185 and €227 (Jonsson et al. 2010).

Furthermore, our results align with those of a recent study by (Hynynen et al. 2025), which indicates that increasing deadwood by one cubic meter generates a manyfold loss in harvested volume (Table 3 in this study and Hynynen et al. 2025, p. 9).

The average carbon storage of the living trees in our study area was ca. 200 t $CO_2$eq ha$^{-1}$ in the beginning, reaching a maximum of 220 t $CO_2$eq ha$^{-1}$ at the end of the 50-year time horizon. These values were calculated from the biomass of the growing stock (ca. 109 and 120 t ha$^{-1}$, respectively) and are therefore directly related to the development of the forests in the scenarios. The development, in turn, is dependent on the structure of the stands at the onset (e.g., tree species, age, site type, stocking, etc.) and is further affected by growth rate, cuttings, and natural mortality over 50 years. The average values are in line with the earlier studies in similar conditions. The average living tree biomass in productive and poorly productive forests in southern Finland is ca. 99 t ha$^{-1}$ (NFI13; Korhonen et al. 2024), the average carbon storage of living trees ca. 190 t $CO_2$eq ha$^{-1}$ in five regions of southern Finland (Hynynen et al. 2025), and ca. 200 t $CO_2$eq ha$^{-1}$ in pine stands in central and northern Sweden (Larsson et al. 2025). As expected, cutting level has a significant impact on the development of carbon storage of living trees in production forests (similarly to e.g., Mäkelä et al. 2023). If cuttings are kept at the constant level (CONSREM), despite the SC, the carbon storage of living trees in all forest area at the end of the 50-year period is ca. 15% lower than without SC (SC100 vs. BAU). Although carbon storage in SC forests increases due to the absence of cuttings, it cannot fully compensate for the loss in the production forest.

Two intriguing and separate issues came up with the results. First, the results revealed the importance of the criteria for forests to be selected for protection. Building on the approach of *the Finnish Nature Panel* (Kotiaho et al. 2021), we applied a two-phase selection procedure using stand age as a primary criterion, and then a conservation value index comprising tree species composition and site characteristics in addition to stand age. The results showed a notable effect of the selection criteria on the structures of selected SC stands. This is because in production forests, managed according to the principles of rotation forestry, the oldest forests are most frequently found in less fertile sites with low-growing pine-dominated stands, where long rotations are typical (Table 1). In SC100, only 30% of the selected SC forests fulfilled the age criterion, whereas in SC25, even 91% (Table 1). Conversely, the number of stands selected by cv-index was low in SC25, indicating that their enhancing impact on biodiversity was minor. Further, during the 50-year scenario period, the increase in volume of broadleaves (m$^3$ ha$^{-1}$), as well as the accumulated deadwood (m$^3$ ha$^{-1}$) in SC25 were marginal compared to those in SC100. Thus, our results suggest that stand age as such is not an efficient criterion for selecting SC areas from production forests, at least in Southern Finland. Finally, the relatively simple cv-index applied here identifies NFI-plots with interesting factors relating to biodiversity and supports, at least to some extent, the goals of *the EU Biodiversity Strategy* that "when selecting areas to protection, the areas with high or potential biodiversity-value should be prioritised" (European Commission 2020). On the other hand, using stand-related criteria alone may not produce an effective and well-connected conservation area network since habitat composition and site connectivity are vitally important when selecting SC sites, as they contribute to the development of a well-connected and ecologically diverse conservation area network.

The other interesting issue to come up with the results, was the importance of harvesting strategy—to compensate (CONSREM) or not (DECREM). As expected, the SC with removal compensation (CONSREM) increased cuttings in the remaining production forests, further affecting their future. Due to that, the age structure of these forests became younger, and their mean volume along with the total biomass of living trees decreased. For example, in SC100, the mean volume of production forests dropped by 27% under CONSREM compared to BAU by the end of the 50 years. Räty et al. (2023) reported similar changes in the forest structure in their study of enhancing biodiversity according to the EU strategy with prevailing cuttings. On the contrary, the SC without compensation (DECREM) maintained the equivalent structure of the remaining production forests as in BAU but resulted in a decrease in harvesting removals (ca. 9% in SC100). Pikkarainen et al. (2024) reported a decrease of harvested timber yield corresponding to 5–30% in 30 years due to SC, depending on the specific growth-promoting efforts applied. In our study area, the current annual harvesting intensity is at high level approaching or even exceeding the maximum sustainable harvesting level, resulting in notable reduction of the growing stock volume in production forests due to SC if constant removals are assumed (CONSREM). In the study of Salminen et al. (2023) increase of conservation area under 'high-cuttings' assumption (85 mill. m$^3$ a$^{-1}$ for Finland) decreased the growing stock by 5% in southern Finland over 50 years, whereas the 'normal-level cuttings' default (i.e., 70 mill. m$^3$ a$^{-1}$) increased the growing stock. Further, the cost-effectiveness of increasing deadwood or broadleaved volumes and carbon storage is directly linked to whether the decrease in harvesting removals can be compensated elsewhere in the region. In other words, without compensation, losses in NPV tend to drastically increase, and the cost-efficiency would drop accordingly (Table 5). An intriguing result was that the cost of increasing the protected area was not linear (Table 5: SC25, SC50 vs. SC100). This was because the old forests were prioritised for SC. Since the area of old forests has a regional limit (i.e., an absolute numerical limit), this leads to discontinuity points where more land for conservation needs to be taken from areas other than old forests. This creates non-linearity to cost-efficiency: for instance, when comparing the cost efficiency of SC25 with that of SC100, the two alternatives have considerably different forest structures within the SC area. At the same time, they also have deviating magnitudes of NPV losses (see Table 3 for the differences in NPV between SC25 and SC100). The non-linearity becomes an interesting aspect when deciding on instruments (e.g., cost compensation or an auction mechanism) to encourage forest owners to conserve forests (Kangas and Ollikainen 2025).

In general, allocating production forests to SC enhances biodiversity. However, how we respond to reduced removals due to SC (i.e., which strategy we choose) has several impacts on the economy (in terms of the current and future opportunities), carbon stocks, and biodiversity, especially in the remaining production forests. These impacts can be seen as the price of SC at the regional level. In summary, it can be argued that removal compensation plays a key role in the cost-efficiency of forest protection. The issue of compensatory cuttings is essentially a matter of national forest policies and political decision-making according to the principle of equal public burden (Wu et al. 2020). Of course, decision-makers are also bound to follow the international and national agreements (Ahtikoski et al. 2024) affecting overall cutting volumes, which could lead to situations where possibilities for compensatory cuttings are limited. Considering the substantial proportion of privately-owned forests in southern Finland, increasing the share of protected forests and creating a well-connected network of conservation areas poses a challenge. In Finland, the most important instrument for voluntary forest conservation is *the Forest Biodiversity Programme* METSO (Finnish Government 2014, 2026), in which the forest owners can offer their forest sites for protection and receive monetary compensation for it. The supply of the forest sites for protection under the programme depends on forest owners' willingness to offer them. The programme has ecological selection criteria that are used to identify the sites with high biodiversity values (Syrjänen et al. 2016). A voluntary approach has been a core principle of METSO's implementation, and the programme has gained widespread acceptance (Horne et al. 2025). Forest owners have diverse objectives for their forest ownership. Although many forest owners emphasise wood-production and economic goals, their objectives are often multiple and may also include, for example, nature conservation and recreation (Karppinen et al. 2020). Finally, the results of this study are based on modelled calculations, which represent simplifications that cannot be directly applied to the implementation of strict protection on privately owned land. The scenario analysis was not able to integrate factors such as spatial arrangement, size of the individual SC sites, their proximity to each other and existing protected areas, or the potential interest of forest owners to participate in conservation, all of which are important considerations in designing SC. Nevertheless, the analysis contributes a deeper understanding of the potential impacts of strict forest protection, associated trade-offs, and cost-effectiveness. These findings can be used in policymaking to support the design of biodiversity conservation policies and instruments as well as the development of selection criteria.

## Conclusions

Our results show that supplementary conservation can enhance important characteristics of forest biodiversity, such as the volume of broadleaved trees and deadwood. It can also increase the carbon storage of living trees, although this depends on the overall harvesting intensity of retaining production forests in the region. Furthermore, the criteria used to select forests for supplementary conservation play a significant role in enhancing biodiversity. It seems that an age criterion itself may result in a higher proportion of relatively infertile, pine-dominated sites, which are less effective at enhancing biodiversity. Habitat composition and site connectivity are criteria that should be included in the selection process of supplementary conservation abreast with stand-related attributes. Last but not least, compensating for the decrease in removals due to supplementary conservation is essential for cost-efficiency. Supplementary conservation with compensatory cuttings tends to be distinctively more cost-efficient for enhancing biodiversity than supplementary conservation without any removal compensation. The potential to execute compensatory cuttings is, however, is conditional to the initial stand structures of the forests in question.

**Acknowledgements** This study was performed based on data from the National Forest Inventory compiled by Natural Resources Institute Finland (Luke) between 2014 and 2018. The authors wish to thank all the associated members for their invaluable efforts in fieldwork and data maintenance support.

**Author contributions** SHa conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft, writing – review and editing; AA conceptualization, formal analysis, investigation, validation, visualization, writing – review and editing; SHu conceptualization, investigation, methodology, validation, visualization, writing – review and editing; TK conceptualization, investigation, recourses, validation, visualization, writing – review and editing; ML conceptualization, data curation, formal analysis investigation, software, visualization, writing – review and editing;

HS conceptualization, data curation, formal analysis investigation, methodology, software, validation, visualization, writing – review and editing; JH conceptualization, investigation, methodology, recourses, validation, visualization, writing – review and editing; All authors read and approved the final manuscript.

**Funding** Open access funding provided by Natural Resources Institute Finland.

**Data availability** The original NFI dataset and the further generated input data for Motti simulations are not publicly available to protect the privacy of forest owners and to keep the location of permanent plots secret.

## Declarations

**Conflict of interest** The authors declare no competing interests.



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