Journal of Environmental Management 391 (2025) 126482

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Assessing the impact of private forest owner preferences on the supply of ecosystem services

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ARTICLE INFO

Keywords:
Ecosystem services
Forestry behavior
Forest values
Landowner objectives
Non-industrial private forests
Owner-oriented planning

ABSTRACT

Decisions made by forest owners impact the forest's ability to provide multiple ecosystem services. In Fennoscandia, production forests are primarily managed by hundreds of thousands of private owners with diverse preferences towards provision of wood, non-wood timber products, aesthetic value, carbon cycling and biodiversity conservation. Despite the key role of owners in shaping forest landscapes, studies exploring sustainable forest planning often ignore owner preferences when assessing future scenarios. We aim to explore how forest ownership structure can affect forest multifunctionality at landscape level.

Using a multiobjective forest planning tool, we explored (1) how owner preferences affect a forest's capacity to supply multiple ecosystem services, and how integrating preference information into the optimization affects (2) forest management and (3) the synergies and trade-offs between owner priorities.

We compared a landscape-level management scenario maximizing sustained yield with holding-level scenarios meeting forest owner preferences. We classified owner preferences for different objectives into six broad categories based on published surveys. Specific owner-level preferences were assigned to holdings through a Monte-Carlo approach.

Maximizing sustained yield contributed to wood provisioning and a selection of non-wood ecosystem services. In this case management was oriented to rotation forestry, which created strong trade-offs between multiple ecosystem services. Including forest owner preferences in the optimization problem resulted in economic loss but improved biodiversity and carbon cycling. Forest management was less intensive, oriented towards set-aside and continuous cover forestry. The synergies and trade-offs between ecosystem services depended on the owner priorities. Accounting for owner preferences supports integration of sectorial forest policies.

1. Introduction

Decisions made by forest owners impact the ability of a forest to provide ecosystem services (Blanco et al., 2017; Takala et al., 2022). Traditional forest management has focused on economic objectives like maximum sustained yield, achieved by applying one or few intensive management regimes to all the forest stands in the landscape (Duncker et al., 2012; Takala et al., 2017). More recently, the diversity of forest owners' preferences has been acknowledged, with a focus on achieving multiple objectives, ranging across the categories encompassed by the ecosystem service concept. The Millennium Ecosystem Assessment (2005) classifies ecosystem services into main categories: provisioning (wood production and non-wood forest products), regulating (carbon cycling), cultural (scenic beauty) and supporting (biodiversity) services (Bjärstig and Sténs, 2018; Eggers et al., 2018; Tiebel et al., 2024).

To facilitate the consideration of multiple values associated to forest landscapes, forest management planning has adopted the use of multiobjective optimization (Miettinen, 1999; Bettinger et al., 2016). This

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https://doi.org/10.1016/j.jenvman.2025.126482
Received 14 April 2025; Received in revised form 23 June 2025; Accepted 3 July 2025
Available online 10 July 2025
0301-4797/

requires the use of forest growth simulation to forecast indicators of multiple objectives, which are used as input data for the optimization approach. This approach results in a planning framework that enables an exploration of the impact diversification of management regimes can have to deliver ecosystem services, i.e., to maximize landscape multifunctionality (Duflot et al., 2022). This planning framework can also be used to compare the outcome of different management regimes or of scenarios based on sustainable management approaches (e.g., land sparing-land sharing-Triad approach, Blattert et al., 2023a), or to assess the performance of rotation forestry vs. continuous cover forestry (Eyvindson et al., 2021). Multiobjective optimization requires a determination of an agreed set of objectives, which will drive the management of the forest landscape. However, this landscape-level management plan does not represent the ownership structure of the landscape, where a variety of forest owners have a wide range of preferences for managing their forest for different objectives (Ingemarson et al., 2006; Andersson and Keskitalo, 2021).

Despite the key role of forest owners in forest management, the integration of their preferences remains unexplored in scenario-based multiobjective optimization studies. This is due to the difficulty of including owner preferences in forest management planning, creating a gap between management and policy (Nordström et al., 2010). Thus, scenarios of future forest development rely on exploring the consequences of applying a clearly defined set of objectives across the landscape. The proposed set of management actions in a forest can be informative to explore how specific policy targets can be fulfilled (e.g., bioeconomy, climate change mitigation or biodiversity conservation). This approach ignores the compatibility between multi-owner management objectives and policy objectives. This potentially hampers the achievement of regional or international forest policy goals, with the risk of increasing inconsistency in forest landscape management, which could increase trade-offs among multiple forest objectives (Sotirov et al., 2015). To circumvent this methodological shortcoming, it is important to develop optimization tools capable to integrate multi-ownership aspects (Borges et al., 2014; Eyvindson et al., 2024). Multi-objective optimization frameworks enable the integration of forest owner preferences and the spatial structure of the ownership, allowing for the development and evaluation of suitable policy tools to promote forest multifunctionality (Triviño et al., 2017; Pohjanmies et al., 2021).

In countries where private forest ownership is widespread, the management decisions taken by private forest owners can determine the way forest policies are adopted. For example, the adoption of the EU's Nature Restoration Law at governmental level requires adjusting forest management to fulfill nature conservation targets, but the effectiveness of the management strategies employed by member countries will depend on the willingness of forest owners to modify their goals, which ultimately depends on their preferences. While forest owners are each unique, their preferences and management strategies can be categorized and assessed in several countries (Wiersum et al., 2005; Nordlund and Westin, 2011; Ficko et al., 2019). The objectives and preferences of forest owners will directly impact the effectiveness of the policies, which will bring to scenarios of forest development not necessarily reflecting management decisions taken at national and regional levels.

In Finland, preferences of both the forest industry and small non-industrial private forest owners have predominantly focused on timber production (Kotilainen and Rytteri, 2011). Non-industrial owners manage over 60 % of the country's forests and supply around 80 % of the industrial roundwood (Karppinen et al., 2020). In addition to timber production, non-industrial owners control a wide range of both tangible and intangible forest-based ecosystem services (Häyrinen et al., 2017). A shift from traditional single-objective perspective towards landscape multifunctionality is occurring at the levels of national policies and of private forest owners (Häyrinen et al., 2017; Päivinen et al., 2018; Juutinen et al., 2021). The national policies aim to balance biodiversity protection, bioeconomy, and climate change mitigation (Luhas et al., 2021). Small non-industrial private owners share different priorities respect to large forest owners, as they prioritize recreation over production (Karppinen and Korhonen, 2013). This can create a mismatch between the forest management plans required to fulfill a general economic goal over the whole landscape and the plans considering also owner preferences (Blattert et al., 2023b). For example, this is the case when forest industry urges forest owners to prioritize resource extraction over conservation priorities (Olofsson, 2023). A challenge is that the implementation of forest management plans often does not correspond with the preferences and values of private forest owners which may result in the failure of the original plan to achieve the agreed (e.g., policy) goals, and in forest owners' objectives to remain unfulfilled (Pynnönen et al., 2018).

The main aim of this study is to explore how forest ownership structure can affect forest multifunctionality at landscape level. Improved integration of forest owner structures to landscape level planning enables clearer understanding of what planning objectives are feasible and may suggest opportunities to meet the challenges of landscape-level forest planning for multiple objectives. We simulate and optimize a real production forest landscape in Finland to explore (1) how owner preferences affect a forest's capacity to supply multiple ecosystem services, and how integrating preference information into the optimization affects (2) forest management and (3) the synergies and trade-offs among owner priorities.

2. Materials and methods

2.1. Overview of the methods

The analysis was conducted by applying a standard simulation-optimization approach (Fig. 1D), that resembles the model approach as presented in Johnson and Scheurman (1977). This approach requires a range of management actions (Fig. 1B) to be applied to the forest stands (Fig. 1A) in the simulated landscape. The management actions simulated for each forest stand are defined in Table 1 and reflect both intensive and extensive forest management. To incorporate the preferences of the forest owners, we connected the property information with expert opinions of what their preferences could be (Fig. 1C). The preference information for each forest owner category was associated with priority-level weights, provided by the expert opinion of four forest researchers (Fig. 1C). This resulted in preferences for timber, non-timber, regulating, cultural, and supportive ecosystem services (Fig. 1C). The optimization was conducted at the forest holding level (the forest owned by a single forest owner), and the results were then aggregated at the forest landscape level (Fig. 1C). This framework was applied across different forest owner categories, resulting in specific management plans for each owner category (Fig. 1E). From the optimization results, we evaluated and visualized the development of forest uses and services averaged across the simulation horizon, as well as the optimal combination of management regimes to achieve specific forest owner objectives (Fig. 1E).

2.2. Study area

To explore the impact of forest owners' preferences on the supply of ecosystem services in a typical Fennoscandian production forest landscape, we used data from a landscape in Central Finland (coordinates: 61°7′31.8″ N, 25°6′49.7″ E). This landscape is 2,242 ha where we use the natural watershed boundaries to act as the borders of this landscape (Fig. 2A). The landscape is divided into 49 private forest owner holdings (Fig. 2B). On average, a forest holding covers only 1 % (22.4 ha) of the landscape, and 95 % of the holdings are between 1 and 72 ha. Each forest holding consists of several stands (Fig. 2C) which may not always be adjacent to each other. The landscape consists of 1,475 forest stands, with an average stand size of 1.5 ± 1.6 ha (mean ± SD). In this landscape, Scots pine (*Pinus sylvestris*) represents approximately 50.7 % of the total basal area, Norway spruce (*Picea abies*) 33.9 % and two birch

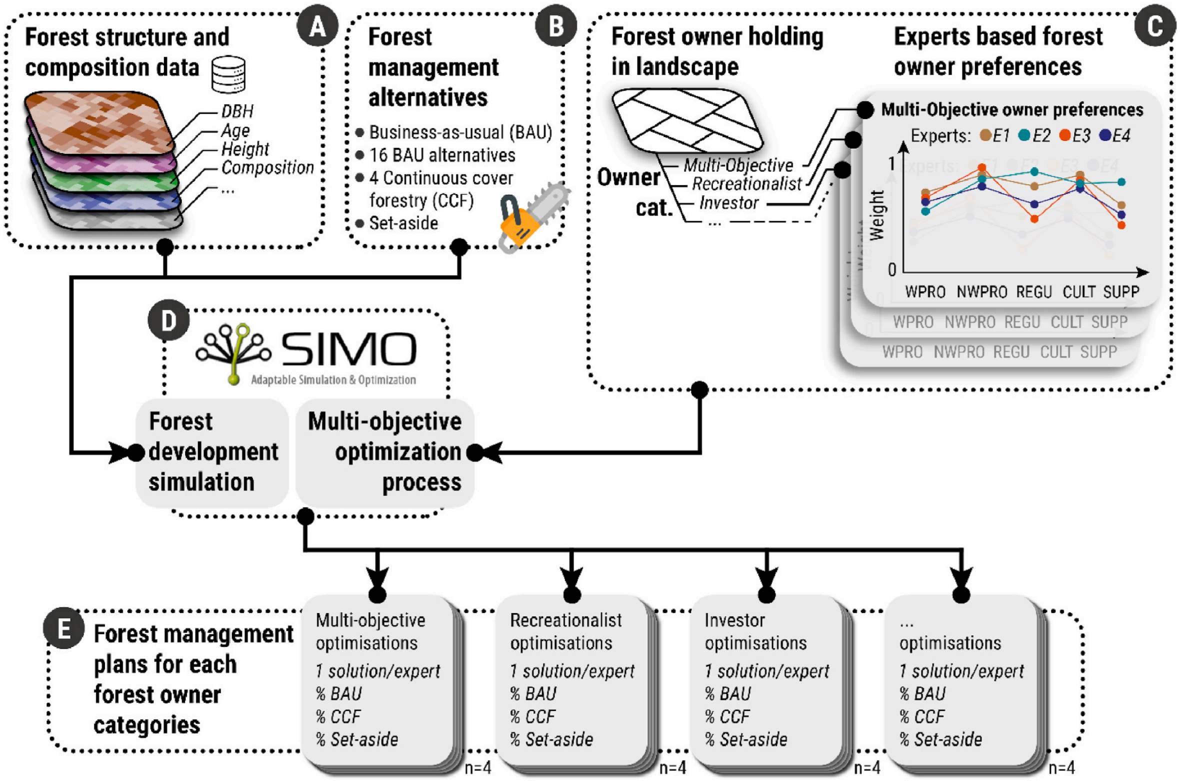

Fig. 1. Flow chart showing (A) the input data, (B) management regimes, (C) structure of the landscape and expert-based weights, (D) the simulations/optimization approach and (E) alternative management plans output from this study. In the figure, preference weights are simplified at the owner priority level, associated with different ecosystem service categories (WPRO: Wood Provisioning, NWPRO: Non-Wood Provisioning, REGU: Regulating, CULT: Cultural, SUPP: Supportive.), while in real data, four experts gave weights to all the 14 indicators of ecosystem services targeted by forest owners (Table 2; Table S1 in Appendix A).

species (*Betula pendula* and *Betula pubescens*) along with other less common broadleaved tree species represent the rest of the basal area (15.4 %). The dominant soil types are mineral (74.3 % of the total area) and organic (25.7 %), with 61.5 % of stands on high fertility sites and 38.5 % on low fertility sites. All forest stand-level data are publicly available through the Finnish Forest Centre (www.metsään.fi). Data is derived from laser scanning, aerial photography, and sample plot measurements, which are commonly used for stand-level forest management purposes.

2.3. Forest simulations

We simulated the development of the forest with the open-source forest simulator SIMO (Rasinmäki et al., 2009) for 100 years (2016–2116) divided into 20 five-year periods. For each forest plot we applied a maximum of 19 management regimes across the rotation period (a summary of the management options is reported in Table 1). These management regimes reflect the current sequence of actions taken in the forest, depending on the specific timing and intensity of harvesting. We followed the scheme of forest management regimes from Eyvindson et al. (2018), as follows: we modeled a reference management (business-as-usual, BAU) following best practice guidelines for forest management in Finland. The BAU regime typically includes an average rotation length of 80 years (varying between 70 and 90 years, depending on site fertility), 1–3 thinnings and a final clear cut with green tree retention, followed by artificial regeneration (Äijälä et al., 2014). We simulated 13 regimes modifying BAU. BAU management variations involve adjusting the timing and intensity of actions such as final felling, thinning, selection harvest, and tree retention. The timing of the final felling was modified by adjusting the required age where final felling can occur to at −20, −5, +5, +15 and + 30 years compared to business as usual. We simulated four regimes representing continuous cover forestry (CCF), and a set aside regime with no management actions, corresponding to free forest development, to represent the management applied in forest reserves. CCF management follows the rules from Äijälä et al. (2014), with harvesting based on site-specific basal area requirements and targeted tree diameters. Under CCF, no final clear cut occurs, and harvest activities are distributed over the rotation time, resulting in a permanently covered, uneven-aged forest structure. This approach relies on natural regeneration rather than planting, and tree growth is adjusted following an ingrowth model (Lappi and Pukkala, 2020).

2.4. Ecosystem services

We calculated indicators for the ecosystem service categories (*sensu* Millennium Ecosystem Assessment, 2005) at the stand level, based on available models in the SIMO forest simulator and the simulated structural characteristics of each stand. The indicators are defined in Table 2 (Table 2 reports references for the calculation of each indicator). The indicators associated with wood provisioning services ("WPRO") include Net Present Value from timber harvesting and even flow income from timber. The indicators associated with non-wood provisioning services ("NWPRO") include forest collectable goods (bilberry yield, mushrooms yield and cowberry yield). The regulating services indicators ("REGU") include the two main processes of carbon cycling which are important for climate change mitigation, i.e., carbon storage, considered the mass of carbon contained within timber, dead wood, and soil, and carbon sequestration, i.e., changes in carbon storage over time from the atmosphere to the trees and vice-versa. The cultural services indicator ("CULT") is represented by forest scenic beauty. The supporting service indicators ("SUPP") include habitat services, such as deadwood diversity and habitat suitability for six vertebrate species representing a wide range of habitat types, and diverse social and economic values,

Table 1
Classification of the management regimes applied in the forest simulations.

Management regimes	Description
BAU, BAU with shortened (−5 years) or extended (+5,+15,+30 years) rotation	Regimes where thinning is not performed before final felling however thinning is conducted after final felling in the next rotation. Regeneration following final felling is done using scarification and planting site appropriate tree species within the next 5 years.
BAU with thinning and BAU with thinning with shortened (−5 years) or extended (+5,+15,+30 years) rotation	Regimes with thinning before and after final felling in the next rotation. Regeneration following final felling is done using scarification and planting site appropriate tree species within the next 5 years
BAU without thinning and BAU without thinning with shortened (−20 years) rotation	Regimes where thinning is not conducted either before or after final felling in the next rotation. Regeneration following final felling is done using scarification and planting site appropriate tree species within the next 5 years
BAU with or without thinning and higher tree retention	Regimes that use a seed tree method for regeneration, retaining either 30 trees or 30 m^3/ha after clearfelling. Regeneration following final felling is done using scarification and planting site appropriate tree species within the next 5 years
CCF, CCF with reduced, increased or further increased harvest threshold	Regimes where timber is obtained through thinning from above and natural regeneration is allowed to restock the stand.
Set-aside, no management	Regime where no forest management actions is conducted within the stand. Growth of the stand continues based on the previous management actions taken.

including huntable game birds, umbrella species, whose conservation efforts indirectly protect other species that share the same habitat, and threatened species, that are likely to become endangered in the near future.

2.5. Forest owners' preferences

To quantitatively assess the impact of forest owner preferences on the forest management and supply of ecosystem services, previous studies have conducted a targeted literature review of forest owner preferences and values. The socio-demographic background, forest ownership structures, and objectives of Finnish private forests, have been extensively studied previously through two large-scale surveys: Finnish Forest Owner 2010, which included over 5,000 respondents (Hänninen et al., 2011); Finnish Forest Owner 2020, with over 6,000 respondents (Karppinen et al., 2020). These national surveys have indicated that Finnish forest owners can be grouped into five main categories based on their objectives for forest ownership, defined as follows (Hänninen et al., 2011):

- Multi-objective (MO) owners value both the monetary and amenity benefits of their forests. They value less biodiversity and more recreation in the forest.
- Recreationalists (REC) emphasize non-timber and amenity aspects of their forest ownership.
- Investors (INV) regard their forest property as an asset and a source of economic security. They intensively harvest forests maximizing the forest economic functions and value of timber.
- Self-employed (SE) owners value an even flow of income as well as employment provided by their forests, which can be quantified as the sustained yield of timber products. Managing the forests by themselves, they sale less timber and are more likely to apply CCF.
- Passive forest owners, in principle, do not have specific priorities for their forest. In this study we separated passive owners into two

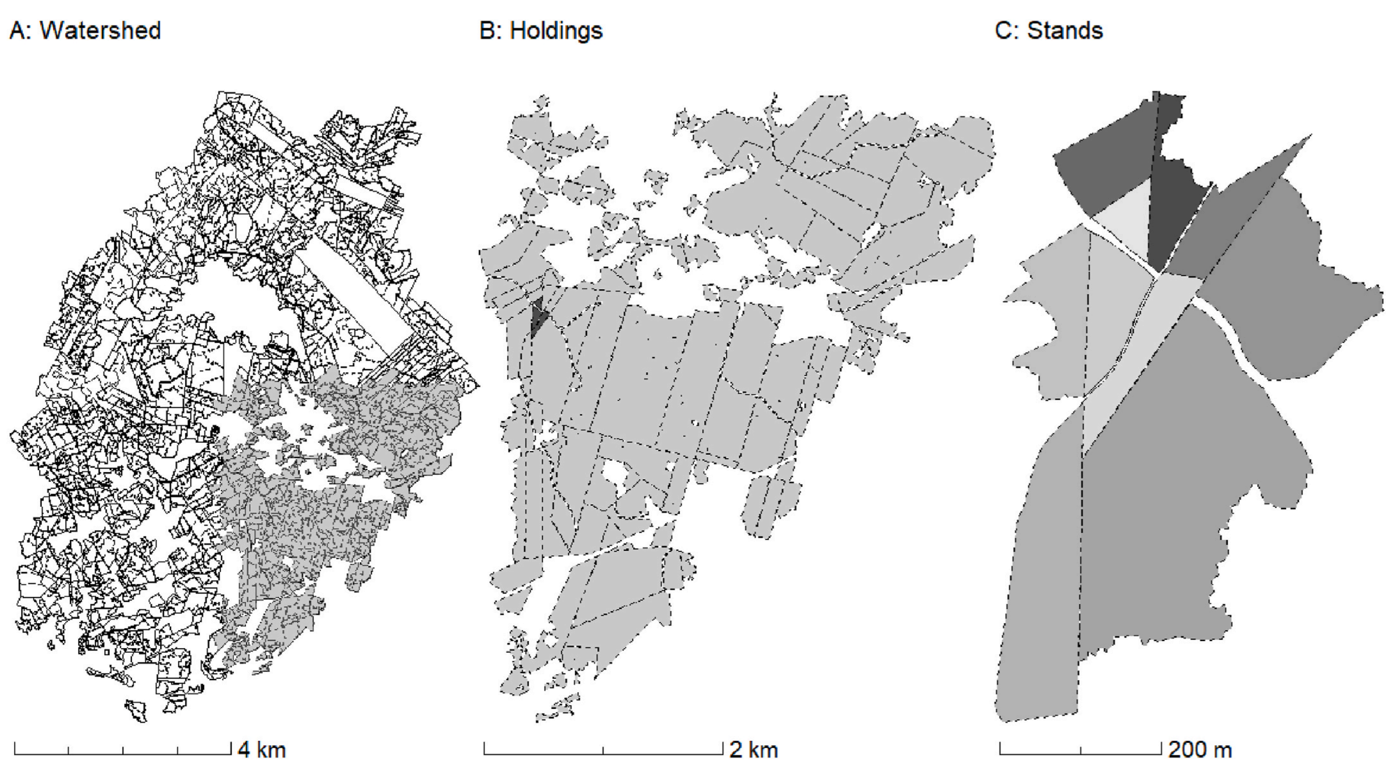

Fig. 2. Examples of the sub-regional scales analyzed. (A) The watershed boundaries of the study area. The grey area marks the holdings shown in B. (B) An example of large forest holdings, with boundaries drawn in dashed lines. The dark grey area marks the holding shown in C; (C) An example of a small forest holding with individual forest stands drawn in different colors and boundaries drawn in dashed lines.

Table 2
Categories of ecosystem services and related indicators evaluated as targets for forest owner preferences.

Ecosystem Service Category		Indicators		
Abbreviation	Decription	Code	Description	Extended description
WPRO	Wood Provisioning Services	NPV	Timber production (Net present Value)	Timber net present value (€ ha^{-1}) at different discount rates 1–5 % (Mönkkönen et al., 2014)
		INC	Even flow income	Minimum periodic timber value across the planning horizon (€ ha^{-1}) Mönkkönen et al. (2014)
NWPRO	Non Wood Provisioning Services	BIL	Bilberry yield	Bilberry yield (kg ha^{-1} year^{-1}) (Miina et al., 2016)
		MUS	Marketed mushrooms yields	Yield of marketed mushrooms in Finland (primarily *Boletus edulis* and *Lactarius* spp.) (kg ha^{-1} year^{-1}) Tahvanainen et al. (2016)
		COW	Cowberry yield	Cowberry yield (kg ha^{-1} year^{-1}) (Turtiainen et al., 2013)
REGU	Regulating Services	CSE	Carbon sequestration	Change in carbon storage between consecutive time steps (t C ha^{-1} year^{-1}) Liski and Westman (1997)
		CST	Carbon storage	Carbon stored in the soil and in the biomass of living and dead trees (t C ha^{-1}, average over 100 years) (Liski and Westman, 1997)
CULT	Cultural Services	SCE	Scenic beauty index	Scenic beauty of forest (ha^{-1}, average over 100 years); increases with the size and age of trees, with a share of pines and deciduous trees, and with decreasing number of stems Pukkala et al. (1988)
SUPP	Supporting Services	DWD	Deadwood diversity index	Volume of dead wood weighted by diversity (m^3 ha^{-1}, average over 100 years) Triviño et al. (2017)
		TTW	Habitat suitability index for Eurasian Three toed woodpecker (*Picoides tridactylus* (Linnaeus 1758))	Indicator species associated with high volume of trees (min 60 m^3 ha^{-1}) and fresh deadwood (ha, average over 100 years) (Mönkkönen et al., 2014)
		LSW	Habitat suitability index for Lesser spotted woodpecker (*Dryobates minor* (Linnaeus, 1758))	Indicator species associated with old deciduous trees (min 60 years) and deciduous snags (ha, average over 100 years) Mönkkönen et al. (2014)
		SFS	Habitat suitability index for Siberian flying squirrel (*Pteromys volans* (Linnaeus, 1758))	Red-listed species associated with high volume of spruce (min 140 m^3 ha^{-1}) with deciduous mixture (min 12 m^3 ha^{-1}) (ha, average over 100 years) (Mönkkönen et al., 2014)
		LTT	Habitat suitability index for Long-tailed tit (*Aegithalos caudatus* (Linnaeus, 1758))	Indicator species associated with mature forests (min 30 years) deciduous trees (20–60 %) (ha, average over 100 years) (Mönkkönen et al., 2014)
		CAP	Habitat suitability index for Capercaillie (*Tetrao urogallus* Linnaeus, 1758)	Game bird with social and economic value, associated with pine volume (min 60 m^3 ha^{-1}) with intermediate spruce mixture and stem density (ha, average over 100 years) Mönkkönen et al. (2014)
		HG	Habitat suitability index for Hazel grouse (*Tetrastes bonasia* (Linnaeus, 1758))	Game bird species indicating adequate levels of deciduous mixture (20–40 %) with spruce (>20 %) (ha, average over 100 years) Mönkkönen et al. (2014)

categories that are expected to manage their forest differently depending on whether they are contacted by forest marketing professionals (i.e., timber buyers):

- Not-contacted passive owners (PA1) set-aside their forest and let it grow without management.
- Contacted passive owners (PA2) harvest intensively their forests maximizing the economic value of timber.

In our optimization, landscapes were 100 % managed by a single forest owner category at a time. To link forest owner categories to forest owner preferences, we used elicited opinions from four experts in multi-objective forest planning authoring the present paper (i.e., AM, MS, MT, RD). We asked the experts to provide their opinion on how much weight is given to each indicator listed in Table 2, by each of the six owner categories listed above. To reflect variation within a category, the expert opinions reflect a potential individual opinion within the specific category of forest owner. Therefore, based on experts, the preference weights, ranging from 0 to 1, quantify the relative importance given by each forest owner category to every indicator belonging to the five main priorities corresponding to the five service categories (i.e., wood provisioning, non-wood provisioning, regulating, cultural and supportive services; see Table 2 for a classification of the indicators and priorities, Table S1 in Appendix A for the experts' preference weights). We opted to rely on expert opinions for this study to ease the collection of preference data while ensuring complete preference information is obtained. We assume that the variability in the expert opinions reflects a potential variability of preferences within a specific category of forest owner. We applied a Monte-Carlo algorithm to pseudo-randomly match owners' preference profiles, represented by the four experts' opinions, to each forest holding. We created 100 virtual landscapes for each owner category where forest holdings were pseudo-randomly assigned the preference weights of one of the four experts, ensuring that each preference weight is allocated to a minimum of 20 % of the forest holdings.

2.6. Optimization of forest holdings according to a set of preferences

To quantify the impact of forest owner preferences on the forest landscape multifunctionality, we constructed management plans at the forest holding level (i.e., one or more stands owned by a single forest owner) for each forest owner category, i.e., a combination of management regimes applied to the stands belonging to the same holding maximizing the weighted objectives. Variability in preferences of forest owner categories for each indicator has been acknowledged by performing optimization for each preference profile obtained from the four experts (Fig. 1). Such optimization process enables the creation of landscape forest development (i.e., a single optimization solution) for each ownership category and within owner category, for each set of expert's opinions.

To construct the forest holding plans, we linked the preference information with a multi-objective optimization process (Miettinen, 1999). We used the achievement scalarizing function (proposed by Wierzbick, 1977) to incorporate weighs for each single indicator as targets between the minimum and maximum values of the considered indicators. For each private holding, we constructed a matrix of preference outcomes representing the range of possible values for each indicator, normalized against their maximum potential values. The matrix of preferences was used to construct holding specific preference information as targets for the optimization problem. The results were analyzed at priority/service category level to simplify the analysis of multiple indicators (Fig. S1). We reduced the multiple dimensions by summarizing all the forest indicators' preferences related with a single priority/service category (following Table 2) in the eigenvalues of the first principal component (PC1) of a Principal Component Analysis (Table 3). For example, NPV and INC were summarized as the eigenvalues of WPRO_PC1. The preference of each forest indicator was maximized separately for all forest holdings. To appropriately normalize the forest indicator values at the holding level, we conducted separate optimizations to maximize each indicator separately for all forest holdings.

The specific optimization problem we used is similar to the method proposed by Hartikainen et al. (2016). The optimization function first minimizes the maximum deviations from these targets and then, using an augmentation term, drives all objectives towards the Pareto frontier, a set of solutions where no objective can be improved without deteriorating at least another objective. As each objective is normalized respect to the target value, the percent preference is used to identify the target value from the range of the preferred indicator values. The formulation is as follows:

$$\left(\min_{x}\max_{1\le i\le n}\left(\frac{\left(f_{ip}(x)-z_{ip}^{ref}\right)}{\left(z_{ip}^{ideal}-z_{ip}^{nadir}\right)}\right)+\rho\sum_{i=1}^{n}\frac{f_{ip}(x)}{\left(z_{ip}^{ideal}-z_{ip}^{nadir}\right)}\right),x\in S,p\in P$$

where $f_{ip}(x)$ is the function to assess the indicator i of the property p, z_{ip}^{ref}, z_{ip}^{ideal} and z_{ip}^{nadir} are the reference value, best possible value and worst possible value for each indicator for the specific property, S is the set of alternative management regimes (i.e., x) for each forest stand, and P is the set of properties in the landscape. The objective functions maximize the values of the indicators in Table 2.

2.7. Constructing landscape level scenarios

In the optimization phase, forest holding level scenarios were constructed to reflect the forest owner preferences for the set of indicators elicited by experts' opinions. This information is used as input data to construct landscape level outcomes. During the optimization we do not have location-specific information about which forest holdings belong to which owner category in the studied landscape. We contrasted the priority scores derived from the solutions maximizing sustained yield with the solutions obtained from maximizing priority indicators according to the preferences of each forest owner categories. This provides information on how a scenario maximizing yield from timber at landscape level can be different from landscape scenarios generated from forest owner preferences.

2.8. Synergies and trade-offs between owner priorities

We evaluated if forest holdings would be able to co-produce bundles of ecosystem services, tending to be co-maximized in the same holding, if managed for different owner preferences. This was done by calculating pairwise Pearson correlations between PC1 eigenvalues for the different priorities for each ecosystem service category, i.e., WPRO_PC1, NWPRO_PC1, REGU_PC1, CULT_PC1, SUPP_PC1. Positive correlations between PC1 priorities were considered as spatial synergies, indicating that the priorities were co-maximized in the same forest holding, while negative correlations between priorities were considered as spatial trade-offs, where priorities were co-maximized in different forest holdings for each owner category.

3. Results

3.1. Achievement of forest owner priorities

The maximum sustained yield achieved the highest priority scores

Table 3
Loadings of individual indicators on the first principal component (PC1), calculated separately for each priority/ecosystem service category group. The PCA was based on standardized mean preference scores across forest owner categories. Positive or negative signs indicate the direction of contribution relative to the PC1 axis, which was flipped where necessary to ensure consistent interpretation (i.e., higher PC1 scores correspond to higher overall preference alignment). Loadings with larger absolute values contribute more strongly to the component structure. Abbreviations like in Table 2.

ES Category	WPRO		NWPRO			REGU		CULT	SUPP						
Indicator	NPV	INC	BIL	MUS	COW	CSE	CST	SCE	DWD	TTW	LSW	SFS	LTT	CAP	HG
PC1 Loading	0.707	0.707	0.671	0.397	−0.625	0.707	0.707	1.000	0.378	0.376	0.394	0.397	0.394	0.370	0.334

for wood and non-wood provisioning services but the lowest scores for the regulating, cultural and supportive services compared to all forest owner categories (Fig. 3).

We found that the six categories of forest owners had varying capacity to manage their forests to maximize indicators according to their different priorities towards the ecosystem service categories (WPRO, NWPRO, REGU, CULT, SUPP) (Fig. 3; preference scores for each indicator are reported in Appendix A in Fig. S1):

- Multiobjective (MO) forest owners show relatively low priority score for WPRO services but intermediate scores for NWPRO, REGU, CULT and SUPP services compared with other owner categories.
- Recreationalist (REC) forest owners consistently show the lowest priority score for WPRO services but among the highest scores for NWPRO, REGU, CULT and SUPP services.
- Investor (INV) forest owners have one of the highest priority scores for WPRO services and intermediate scores for NWPRO, REGU, CULT and SUPP services.
- Self-employed (SE) forest owners have the highest priority score for WPRO services but the lowest scores for NWPRO, REGU, CULT and SUPP services.
- Contacted passive (PA2) forest owners have intermediate priority score for WPRO services and among the lowest scores for NWPRO, REGU, CULT and SUPP services.
- Non-contacted passive (PA1) forest owners have among the lowest priority score for WPRO services, but they achieve high scores for NWPRO and CULT and the highest scores for REGU and SUPP services.

3.2. Management for forest owner priorities

Results showed that the management applied to maximize sustained timber yield was dominated by Business-As-Usual regimes while Continuous Cover Forestry (CCF) and set-aside were applied in limited proportions in the forest landscape. Instead, the management options needed to maximize different sets of ecosystem services were diversified across forest owner categories (Fig. 4). Multiobjective (MO) owners assign a large portion of land to set-aside and to ordinary rotation without thinning, but they also apply, to a limited extent, CCF, especially with an extended harvest threshold, thinning and extended or shortened rotation. Likewise, Recreationalists (REC) favor set-aside but apply less thinning and changes in rotation length than multiobjective owners, with which they share the limited use of CCF. Self-employed (SE) owners leave forests unmanaged but at a lesser extent than multiobjective owners and recreationalists, they instead apply more rotation forestry with thinning and diverse rotation time and CCF. Investors (INV) make the lowest use of set-aside among all owner categories. However, they apply more the classical rotation forestry (BAU) and its modifications with extended thinning and diverse rotation lengths than the previous owner categories. Passive (PA1) forest owners' management profile is in-between the profiles of multiobjective and recreationalist owners, but they leave a slightly higher proportion of the holdings unmanaged than these two categories, have a similar proportion of CCF, a high proportion of BAU without thinning and with higher tree retention, and a reduced proportion of ordinary rotation forestry, thinning and diversified rotation length. Finally, Passive (PA2) owners contacted by buyers resemble the management style of self-employed owners, but they apply traditional rotation forestry with thinning on a high proportion of the holdings, similarly to Investors.

3.3. Synergies and trade-off among forest owner priorities

The analysis of pairwise correlations between priorities across owner categories highlights notable synergies (highly positive Pearson correlations, closer to 1) and trade-offs (highly negative correlations, closer to −1) but also close to zero correlations, denoting a checkerboard distribution in the holdings of high/low indicator values (Fig. 5):

- For Maximum Sustained Yield, there were moderate/strong synergies between WPRO and NWPRO services and between CULT and SUPP services, and strong trade-offs between WPRO/NWPRO and CULT/SUPP services.
- For Multiobjective (MO) Owners, there was only one moderate synergy between NWPRO and REGU and moderate/strong trade-offs between WPRO and NWPRO/REGU services.
- For Recreationalists (REC), there was a strong synergy between WPRO and NWPRO/REGU services and between NWPRO and REGU

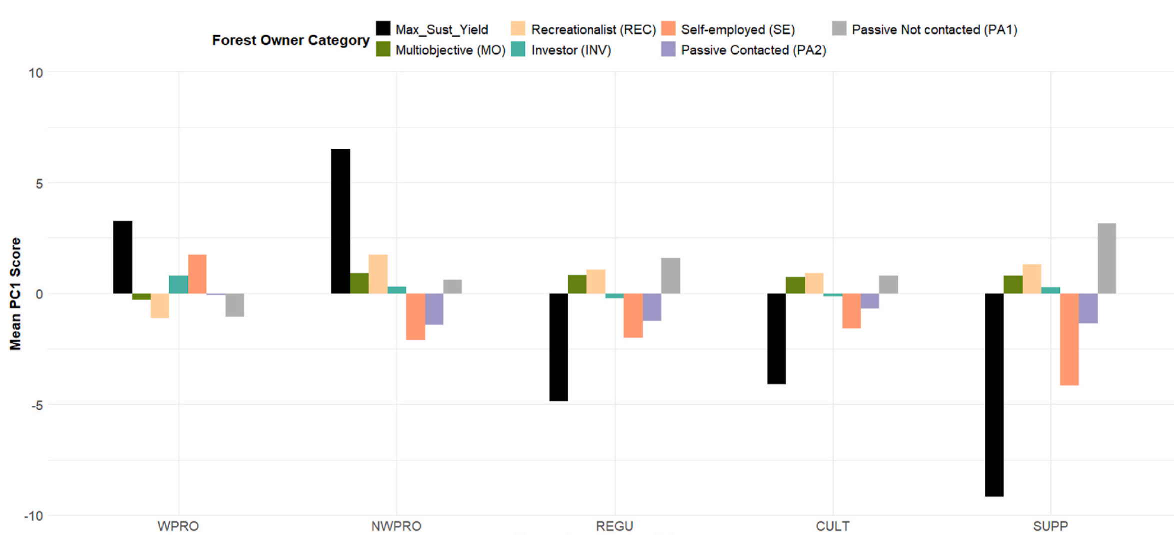

Fig. 3. Bar plots representing the potential of the forest holdings (in y-axis: normalized PC1 scores) to provide the main ecosystem service categories (in x-axis: WPRO = Wood Provisioning Services, NWPRO = Non-Wood Provisioning Services, REGU = Regulating Services, CULT = Cultural Services, SUPP = Supportive Services) when maximized according to the preferences of each forest owner category. PC1 priority scores derive from preference scores derived by expert opinions for the indicators for each owner category. The averages for the PC1 priority scores derive from the Monte-Carlo pseudo-allocation of owners' preferences to forest holdings (see section 2.6). Definitions of the indicators associated with each priority are reported in Table 2. Owner categories are based on Hänninen et al. (2011, see section 2.4).

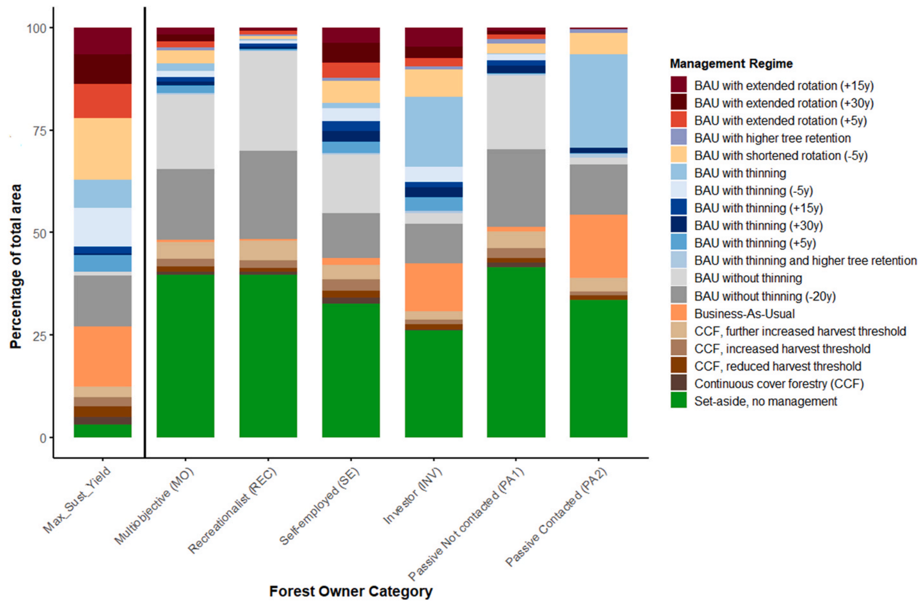

Fig. 4. Percentages of the total study area where individual management regimes were applied when maximizing for sustained yield (Max_Sust_Yield) and for the set of preferences of each forest owner category. Proportion areas allocated to each management regimes are averages across the solutions obtained from each of the allocation of preferences for owners' categories by the four experts.

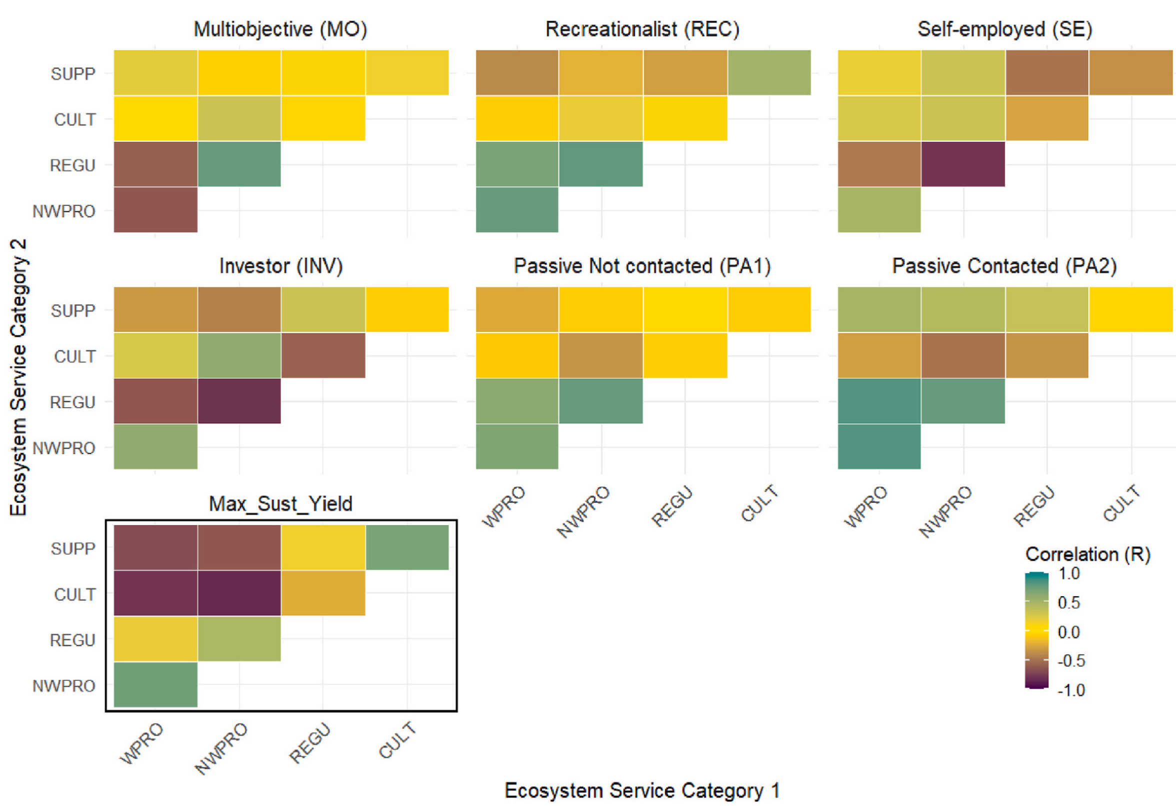

Fig. 5. Forest holdings' capacity to co-produce bundles of ecosystem service categories if managed by forest owners with different preferences. Heatmaps display pairwise synergies (positive Pearson correlations) and trade-offs (negative Pearson correlations) between forest owner priorities for each owner category and for maximum sustained yield (Max_Sust_Yield). Heatmaps show how much high/low priority values (Principal Components (PC1) for each group of indicators associated with the same priority/category) match for the same holding for each owner category. Close to zero correlations suggests that high and low values of the priorities occur independently across holdings, reflecting a non-aggregated spatial distribution. The empty cells represent correlations that are already mirrored elsewhere in the heatmap. Abbreviations of categories: (WPRO = Wood Provisioning Services, NWPRO = Non-Wood Provisioning Services, REGU = Regulating Services, CULT = Cultural Services, SUPP = Supportive Services).

services. On the other hand, there were low trade-offs between SUPP and WPRO/REGU services.

- For Self-employed (SE) Owners, there was a moderate synergy between WPRO and NWPRO services and strong trade-offs between REGU and WPRO/NWPRO and between SUPP and REGU services.
- For Investors (INV), there was a moderate synergy between WPRO and NWPRO services and between NWPRO and CULT services. On the other hand, there were moderate/strong trade-offs between REGU and WPRO/NWPRO/CULT services and between NWPRO and REGU services.
- For Passive Not Contacted (PA1) Owners, there was a moderate synergy between WPRO and NWPRO services and between REGU and WPRO/NWPRO services. On the other hand, there was a moderate trade-off between NWPRO and CULT services and between WPRO and SUPP services.
- For Passive Contacted (PA2), there was a strong synergy between WPRO and NWPRO services and between REGU and WPRO/NWPRO services. On the other hand, there was a moderate trade-off between CULT and WPRO/NWPRO/REGU services.

4. Discussion

4.1. Achievement of forest owner priorities

Prioritizing maximum sustained harvested yield promotes primarily provisioning ecosystem services derived from timber harvesting and collectable goods. Alternatively, prioritizing forest owner preferences benefits also non-provisioning services, including carbon cycling, aesthetic value and biodiversity. This supports the idea that different forest owner categories have varying capacities to improve management in their forest holdings to prioritize economic gains derived by wood and non-wood sources, climate regulation, cultural values and species habitats (Urquhart and Courtney, 2011; Ficko et al., 2019). This highlights that a diversity in forest management due to variation in forest owner preferences supports sustainable forest-based value creation beyond prioritizing only the economic value derived from the forest. In this way forest owners can play a complementary role with forest companies to create sustainable forests that are also oriented towards environmental and social dimensions (Rusanen et al., 2024).

The six owner categories used in our analyses can be clustered into two groups sharing similar priorities: 1) multi-objective owners, recreationalists and passive not contacted owners all achieve low levels for wood provisioning services but high levels for non-wood forest products, carbon cycling, cultural and supporting service; 2) investors, self-employed and passive contacted owners, on the contrary, achieve high or moderate levels for wood-provisioning services but intermediate or low levels for non-wood ecosystem services. The general preferences of these forest owner categories are similar to the preferences of private forest owner categories in other countries, such as Austria (Hogl et al., 2005). However, Butler et al. (2007) suggest that the decisions forest owners take are often more complex than this categorization. Karppinen and Korhonen (2013) have interpreted the proximity in the preferences that we have found here between multiobjective owners and recreationalists with the Schwartz's value theory (Schwartz et al., 1992). According to this theory, the value profile of both these owner categories is related to universalism, self-direction, tradition, benevolence, conformity and security.

The high priority scores for a set of ecosystem services depends on the preferences of the owner groups. The multi-objective owners tend to achieve only moderate values across all ecosystem service indicators due to the need to balance multiple forest functions. Recreationalists tend to achieve the highest values for all non-wood ecosystem services, but they are weak performers for wood provisioning services. Likewise, not contacted passive owners score very high in carbon cycling and biodiversity and moderately high also in non-wood forest products and aesthetic value. This is due to their hands-off approach, letting their forests grow unmanaged and achieving poor economic returns from timber harvesting. Multiobjective, recreationalist and not contacted passive owners share low intensity management, reflecting an either balanced or limited approach to forest use for timber, allowing biodiversity to thrive while benefitting from non-timber forest products and promoting carbon cycling and aesthetic value (cf., Kuuluvainen et al., 2012).

The alignment in the priorities of investors, self-employed and passive contacted owners was also described by Karppinen and Korhonen (2013). Investors tend to achieve the highest economic returns, but they have intermediate values for other ecosystem services. Likewise, self-employed forest owners tend to achieve the highest economic returns, adopting management strategies that focus on prioritizing market-driven decisions using intensive logging, but this results in low values for other forest services as well (cf., Korosuo et al., 2023). Instead, passive contacted owners are only marginally able to improve their economic returns but, like investors and self-employed owners, they also have very low values for other ecosystem services.

The behavior of passive forest owners is of pure *laissez-faire*: they leave their forests grow almost completely unmanaged, which may limit the potential of forests to provide some ecosystem services. For example, the total lack of or limited intervention may result in forests that provide minimal amenity or recreational benefits, but biodiversity and some ecological functions are preserved through passive management (Paillet et al., 2010). Advisory and consulting services, supported by advancements in technology such as mechanized harvesting, play a critical role in encouraging or discouraging forest owners to adopt management practices that align with these diverse objectives (Hujala et al., 2007).

4.2. Management for forest owner priorities

While management to maximize economic returns from timber was intensive and oriented towards rotation forestry, management fulfilling owner priorities for different sets of ecosystem services was generally more extensive and more oriented towards set-aside and continuous cover forestry (Schulze et al., 2018). Even though we focus on only six categories of owner preferences, the resulting management is rather diverse. Multiobjective owners balance management for conservation and active management with limited intensity, indicating a focus on sustainable timber production with interest in preserving non-timber values (c.f., Eggers et al., 2018). Recreationalists prioritize management favoring forest beauty and recreation, resulting in less active forest management than multiobjective owners, prioritizing extensive management approaches (motivations like those already observed for the analogous owner category in the U.S.A., c. f., Bengston et al., 2011). Self-employed owners have a management strategy of intermediate intensity between the extensive management applied by multiobjective and recreationalist owners and the intensive management applied by investors. The management applied results in less economic returns than investors, preferring to diversify management across the spectrum of thinning, clear-felling and continuous cover forestry. Investors prioritize management that focuses on fast returns and long-term timber profit, reflecting a pure economic approach and leaving limited options for forest protection. Passive owners disengage almost entirely from forest management, resembling multiobjective and recreationalist owners for the large area left unmanaged or with less intensive management options, including rotation forestry without thinning or with high tree retention. On the other hand, if contacted by forest buyers, passive owners may start to apply strictly more intensive management options in their holdings, based on ordinary rotation forestry than passive owners that were not contacted, with an intensity between self-employed and investor owners.

Enabling forest owners to focus on their priorities should encourage local diversification of management. Rather than employing a uniform style of management across the landscape, diversity in management can be expected to provide more plasticity in the responses to climate change and induced disturbances, resulting in increased forest resilience (Knoke et al., 2017). In addition, management diversification can play an important role in creating heterogeneous landscapes to the benefit of overall biodiversity (Duflot et al., 2022; Uhl et al., 2024). The impacts of improved preference integration to forest development scenarios remain unsure, however including forest owner preferences will provide a structured approach to assess and quantify the potential effects of forest policies at both national and international level. A better understanding of why and how forest owners make decisions can support the design of cost-effective and targeted mechanisms to enact policies.

While this study uses the Finnish context of small-scale private forest ownership, the underlying method can be used to assess diverse owner preferences in other countries. The approach is transferable to countries with similar forest ownership structures (such as other Nordic countries), and with adjustments in forest management applications, could also be adapted to Central European contexts. In countries with more centralized control of forest resources, a modification of this approach could be used to highlight the importance of coherent forest policies.

4.3. Synergies and trade-off among forest owner priorities

Maximizing timber production creates the strongest trade-offs between indicators of provisioning (wood/collectable goods) and supportive (biodiversity)/cultural (aesthetic value) services (Mönkkönen et al., 2014; Triviño et al., 2017; Mazziotta et al., 2022). When prioritizing other objectives, the synergies and trade-offs varied widely based on the owner priorities (Duncker et al., 2012). Multiobjective owners' balanced priorities lead to moderate synergies but also conflicts, as their recreational emphasis reduces the weight placed on biodiversity and economic returns (Karppinen, 1998). Specifically, this owner category displays moderate synergies between carbon and non-wood products. This reflects their balanced approach to managing forests for recreation and environmental benefits (Haugen et al., 2016). By trying to attain everything, they fail to acknowledge the significant trade-offs between wood provisioning and non-wood services' indicators causing challenges to align economic goals with environmental or climate objectives (Lindahl et al., 2017; Takala et al., 2019). In contrast, recreationalist owners, by prioritizing non-timber benefits, foster strong synergies across diverse priorities while avoiding significant trade-offs. Their management approach effectively balances ecological and amenity values (Hogl et al., 2005). Specifically, this owner category aligns provisioning of wood services with non-wood products and carbon cycling through a non-intensive, diverse management approach. The minor trade-offs between wood provisioning and biodiversity or biodiversity and carbon cycling indicate a capacity to integrate amenity and ecological objectives with minimal conflict.

Self-employed owners' focus on ensuring balanced economic return over time promotes the use of continuous cover forestry (CCF) and creates synergies with non-wood forest products but leads to trade-offs with carbon services and between carbon and biodiversity. There is still a high trade-off between carbon cycling and all the other ecosystem service categories. The strongest trade-off occurs between regulating services and the yield of non-wood provisioning services. All these trade-offs reflect the impossibility of this owner category to balance timber harvesting with climate and biodiversity goals (Korosuo et al., 2023). Investor owners' priorities led to similar but stronger trade-offs. The investor's focus on maximizing wood provisioning services enables only limited synergies with other priorities. The trade-off occurs between regulating services and almost all the other service categories. The use of intensive harvesting actions for economic returns limits the ability to provide at the same time benefits for the climate and the supply of other ecosystem services.

Both groups of passive forest owners tend to have more set-aside management in their forests at the expenses of timber harvesting. This fosters synergies between both wood and non-wood provisioning services and regulating services, likely due to the absence of active management allowing forests to passively sequester carbon. Passive forest owners also show moderate trade-offs between cultural services (aesthetic value) and provisioning and regulating services, which intensify when contacted by potential buyers. This trade-off intensification happens also when a self-employed owner becomes an investor.

Patterns in synergies and trade-offs among ecosystem service categories highlight the complexity of spatial interactions between priorities, influenced by owner-specific management practices and pre-existing holding characteristics. The suitability of a forest holding to supply high levels of indicators associated with a certain ecosystem service category depends on multiple factors related to the forest ownership structure, which is determined by, among others, geographic location, forest productivity, forest biodiversity value, other economic historical and cultural values. When most of the forest holdings would be particularly suitable to supply high levels of one or more service categories, we would assume that most of the forest owners' preferences would be aligned with the holding's potential, consequently allocating adequate management strategies to achieve their priorities. Spatially-explicit forest planning that integrates information on forest owner preferences is expected to facilitate decision-making (Borges et al., 2014), achieve multiple forest management objectives (e.g., Mast et al., 2025) and facilitate integration of sectorial policies (Lazdinis et al., 2019; Winkel et al., 2022).

4.4. Limitations of the present study

In this study we assumed that forest owner management goals are fixed but the reality is that owner preferences are heterogeneous and not necessary stable (Lidskog and Sjödin, 2016), and can be influenced by multiple factors (cf., Eggers et al., 2014). Forest owners can shift their personal beliefs and preferences, due to a change in the society and environment, or even due to technological advancements (Laakkonen et al., 2018; Juutinen et al., 2020). The preferences of the forest owners were also limited to the predefined set of ecosystem services. This was a technical and scientific limitation, as we included those indicators that have models that link to forests structural characteristics. Additionally, automatization of timber production and periods of economic uncertainty may both orient forest owners towards management procuring higher timber revenues. Alternatively, forest owners may embrace a more environmentally friendly lifestyle and start to use less intensive management options with an aim to create habitat for biodiversity (Häyrinen et al., 2016; Vainio et al., 2018). Changes in forest owners' behavior are likely to occur within the long-term time horizon used here in the simulation. However, accurately assessing how changes in the structure of forest ownership preferences will influence the development of forested landscapes is challenging due to limited information on their spatial distribution and on their specific preferences, due to privacy regulations and limitations in survey methodologies.

Furthermore, the relationship between values, preferences and forest management actions remains ambiguous (Hujala et al., 2007; Karppinen and Korhonen, 2013). If we look at the optimized management regimes under any of the forest owner categories, the landscape is partly different from the present-day Finnish one. For example, set-aside area is considerably higher in all categories, near the 30 % target protected area set by the EU biodiversity strategy (European Commission, 2021). The maximum sustainable yield option produced a forest landscape closer to the current Finnish one. In other words, when we included any other than wood production preferences in our optimization task, the result was something different from the current commonly applied forestry scheme. The question arises, whether the well-established (Karppinen, 1998) forest owners' multiplicity of expressed values and preferences is detached by how they actually manage their forest, or forest owner values and preferences are suppressed by the Finnish wood production system. As a matter of fact, income from forests is mainly linked to wood production and, unless profitability gaps are bridged by innovative policies and markets, these essential forest ecosystem services will continuously remain under-supplied despite the expanding societal demands (Lovrić et al., 2025).

Another limitation of this study was that preferences of the forest owners for ecosystem service indicators were generated through the use of expert opinion. These judgements may not necessarily reflect the actual preferences of the forest owners. To address this limitation, we envision the application of our optimization approach to be integrated with preference information obtained from an empirical study. This would better reflect the preferences of forest owners at the landscape scale.

5. Conclusions

In this paper we highlight the impact forest owner goals can have to support ecosystem services at the forest landscape scale. We explored how management practices based on six distinct forest owner categories influence the potential supply of ecosystem services. Forest plans do not always reflect real world decisions as they are influenced by the individual life situation of the forest owner, in addition to marketing impacts and fluctuations in timber prices. We tried to address this by introducing variability in experts' judgement and casual allocation of holdings priorities. Although the management plans applied in our case study may not always reflect reality, they provide valuable insights into how different priorities can be achieved across different forest owner categories and through which management regimes.

Our classification of forest owners reveals distinct management behaviors and trade-offs. Some owner categories prioritize timber harvesting applying intensive management often at the cost of other non-wood ecosystem services, while others prioritize non-timber services via extensive management. Owners practicing passive management foster biodiversity and carbon cycling, though they tend to limit economic outcomes. Synergies and trade-offs among priorities vary widely depending on owner category, indicating that careful spatial forest planning is necessary to optimize multifunctionality. In fact, forest management planning is impacted both by the priorities of forest owners and by the same holding spatial structure (Pohjanmies et al., 2021; Bakx et al., 2024). For this reason, studies like this that explicitly account both for owner preferences and the ownership structure are necessary to improve forest management planning favoring the integration of sectorial forest policies at the landscape scale.

CRediT authorship contribution statement

Adriano Mazziotta: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Kyle Eyvindson:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Jérémy Cours:** Writing – review & editing, Visualization. **Rémi Duflot:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Anna Repo:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Mari Selkimäki:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Tuomo Takala:** Writing – review & editing, Writing – original draft, Conceptualization. **María Triviño:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Mikko Mönkkönen:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization.

Funding

Open Access funding was provided by Natural Resources Institute Finland (LUKE). This work was funded by the Strategic Research Council at the Academy of Finland (Mönkkönen 358473).

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126482.

Data availability

Data will be made available on request. Working code is available in GitHub and access can be given with permission from KE. Optimization was performed on CSC – IT Center for Science. Puhti Supercomputer, and the authors wish to acknowledge CSC – IT Center for Science, Finland, for computational resources.

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