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Research article

Enhancing multifunctionality in European boreal forests: The potential role of Triad landscape functional zoning

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A R T I C L E I N F O

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A B S T R A C T

Land-use policies aim at enhancing the sustainable use of natural resources. The Triad approach has been suggested to balance the social, ecological, and economic demands of forested landscapes. The core idea is to enhance multifunctionality at the landscape level by allocating landscape zones with specific management priorities, i.e., production (intensive management), multiple use (extensive management), and conservation (forest reserves). We tested the efficiency of the Triad approach and identified the respective proportion of above-mentioned zones needed to enhance multifunctionality in Finnish forest landscapes. Through a simulation and optimization framework, we explored a range of scenarios of the three zones and evaluated how changing their relative proportion (each ranging from 0 to 100%) impacted landscape multifunctionality, measured by various biodiversity and ecosystem service indicators. The results show that maximizing multifunctionality required around 20% forest area managed intensively, 50% extensively, and 30% allocated to forest reserves. In our case studies, such landscape zoning represented a good compromise between the studied multifunctionality components and maintained 61% of the maximum achievable net present value (i.e., total timber economic value). Allocating specific proportion of the landscape to a management zone had distinctive effects on the optimized economic or multifunctionality values. Net present value was only moderately impacted by shifting from intensive to extensive management, while multifunctionality benefited from less intensive and more diverse management regimes. This is the first study to apply Triad in a European boreal forest landscape, highlighting the usefulness of this approach. Our results show the potential of the Triad approach in promoting forest multifunctionality, as well as a strong trade-off between net present value and multifunctionality. We conclude that simply applying the Triad approach does not implicitly contribute to an overall increase in forest multifunctionality, as careful forest management planning still requires clear landscape objectives.

1. Introduction

A traditional and central objective of forest management is the extraction of timber in a profitable and efficient manner (Dieter, 2001; Faustmann, 1849). This objective is nowadays even more important to satisfy timber demands for bioeconomy (Hetemäki et al., 2017; Winkel, 2017). Advances in mechanized forest harvesting and forest treatments have allowed for innovative practices to enhance forest growth, while forecasting tools have improved extraction planning to maintain an even-flow of timber for the forest industry. Approximately one third of the worldwide forest area is nowadays managed primarily for timber production (FAO, 2020), with some regions being more intensively managed than others, like Fennoscandia (Mönkkönen et al., 2022). The long timber oriented forestry history in Fennoscandia altered the

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structure of forest ecosystems in a way that has often led to simplification and homogenisation of forested landscapes, with frequent trade-offs for biodiversity and ecosystem functioning (Kuuluvainen and Gauthier, 2018; Larsen et al., 2022).

The focus of forest management has evolved over time, as societal priorities are shifting, with ecological and human wellbeing objectives gaining importance (Marchi et al., 2018). Recent development in national and international (e.g., EU) forest policy has emphasized halting biodiversity loss, as well as guaranteeing diverse societal demands (Blattert et al., 2022; Primmer et al., 2021; Wolfslehner et al., 2020). In addition to timber provision and hosting biodiversity, forests provide a wide range of benefits to human societies (hereafter ecosystem services), such as non-wood forest goods (e.g., berries, mushrooms, game), carbon storage, regulation of nutrients and water cycles, as well as cultural services like recreation (e.g, Brockerhoff et al., 2017; Morgan et al., 2022). To enhance the utilization of renewable forest resources together with other benefits, forest planning has been used to manage the trade-offs while exploring the synergies between timber-derived economic value, non-wood ecosystem services, and biodiversity (Bradford and D'Amato, 2012; Lafond et al., 2017; Mönkkönen et al., 2014).

Alternative management regimes have been developed and suggested for European boreal forest to mitigate the negative impacts of intensive forestry on forest biodiversity and ecosystem services, e.g., through the principles of closer-to-nature forestry (Larsen et al., 2022) or natural disturbance emulation (Kuuluvainen et al., 2021). The main idea of these management regimes is to restore structural elements that are important for biodiversity, such as large old trees and deadwood (Bouget et al., 2014; Juutilainen et al., 2014; Larrieu et al., 2017). Using a diversity of management regimes has been proposed to create habitat heterogeneity to benefit various species groups with differing habitat requirements (Duflot et al., 2022a) and to provide multiple ecosystem services (Eyvindson et al., 2021), based on ecological functions such as carbon storage and water filtration (e.g., Zanchi et al., 2021).

Zoning of forest landscapes has been suggested to enhance multifunctionality in forest use by organizing management in space using a combination of intensive, extensive, and unmanaged forest reserves (Box 1 and Fig. 1). Often referred to as Triad zoning (Himes et al., 2022; Messier et al., 2009; Seymour and Hunter Jr, 1999) or the 'third of a third' rule (Hanski, 2011), the core idea is to assign specific objectives and management regimes to different areas of the landscapes. Such threefold division of forested landscapes is a combination of land sparing and land sharing approaches (Fig. 1, Betts et al., 2021; Larsen et al., 2022). The land sparing approach (or functional segregation) relies on intensively managed forests for timber production and forest reserves for biodiversity conservation and non-wood ecosystem services. The opposing side of the spectrum is land sharing (or functional integration) where the forest is managed as a whole to meet multiple purposes, using extensive management regimes to provide timber but also to mitigate forestry impact on biodiversity and ecosystem functioning (Borrass et al., 2017; Krumm and Kraus, 2013). An open question in the Triad approach, limiting its application, is the identification of the most appropriate proportions of forest reserves, extensive, and intensive management zones within landscapes (Betts et al., 2021 but see Côté et al., 2010; Harris and Betts, 2023).

In their recent paper, Himes et al. (2022) encouraged researchers to pursue creative experiments on the potential benefits of the Triad approach. With this motivation in mind, our intention was to explore the effects of Triad on multiple forest objectives in European boreal forest landscapes. We applied a recent simulation and optimization framework, which is particularly suitable to explore the long-term impacts of forest management strategies, to find an optimal solution that balance among conflicting objectives, and to highlight potential trade-offs among them (Blattert et al., 2022; Eyvindson et al., 2018a,b; Vergarechea et al., 2023). In three Finnish forest landscapes, we tested all possible proportions of intensive, extensive, and forest reserve zones (each ranging from 0 to 100% of total forest area). For each zoning combination we maximized either timber-derived economic value (net present value, NPV) or multifunctionality (MF), which we assessed as an aggregated index of various indicators of non-wood ecosystem services, climate change mitigation as well as habitat availability for vertebrate and deadwood species (Eyvindson et al., 2021). Our specific research questions were:

i) What is the optimal Triad landscape zoning – proportion of intensive, extensive, and forest reserve zones – that maximizes either MF or the NPV of a boreal forest landscape?
ii) How are the individual components of MF affected while aiming for maximum MF, or vice versa for maximum NPV?
iii) What are the specific management regimes required within intensive and extensive zones that lead to the optimal provision of each management priority?

Our assumption was that the optimal zoning will differ depending on the landscape-level priority, with high prioritizations for NPV leading to high proportions of intensive management, and with multifunctional prioritizations leading to a balance of management zones and higher proportion of forest reserves.

2. Methods

2.1. Forest data and management simulations

To explore the impacts of landscape zoning, we have conducted our analyses in three distinct production forest landscapes in Central Finland

Box 1
Description of the three management zones in the Triad approach.

Forest reserves (conservation; RES): As forest conservation priorities are often best served using reserves, a proportion of the forested landscapes should be set-aside, where no human interventions are allowed (Duflot et al., 2022b). Safeguarding unaltered habitats is required to promote overall biodiversity (Himes et al., 2022; Nagel et al., 2017).

Extensive management (multi-use; EXT): Extensive management zones can act as a compromise between the competing interests of conservation and economic prioritization. Protected forests are often scarce in regions with long history of timber production (FAO, 2020). Therefore, maintaining forest biodiversity and ecosystem services largely depends on how production forests are managed and how extensive management supports set-aside conservation (Gustafsson et al., 2010; Kuuluvainen, 2009).

Intensive management (production; INT): Industrial and economic priorities rely on existence of areas with intensive timber production. However, timber production normally conflicts with biodiversity and non-wood ecosystem services (Betts et al., 2021; Eyvindson et al., 2018a, b). Zones of intensive management are included in Triad to satisfy increasing demands for forest round wood and to allow dedicating larger areas to conservation, (Betts et al., 2021).

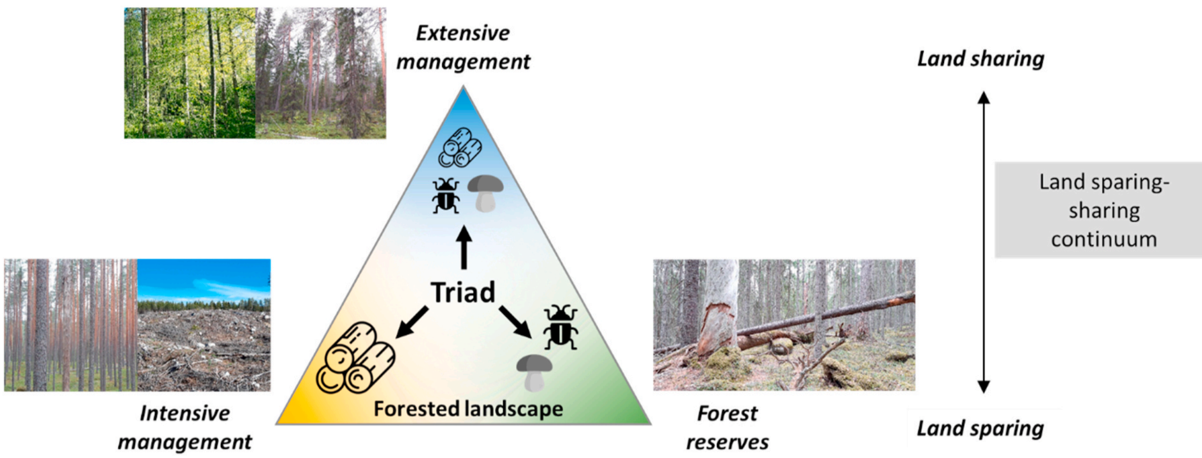

Fig. 1. Illustration of the Triad landscape functional zoning and its relationship with land sparing and land sharing approaches, expressed as a continuum (vertical arrow). In the Triad approach, a landscape is divided into three forest zones: 1) intensively managed for timber production, 2) extensively managed for multiple uses, and 3) forest reserves for conservation (unmanaged). In the visualization, each corner of the triangle corresponds to the maximal share of a particular management zone within the landscape. Combinations of management zones are then located within the triangle.

(Supplementary Material S1, S6 and S7), however, to ease interpretability we focus on a single landscape. This landscape of 2242 ha has been defined by the watershed boundary and consists of 1475 forest stands, i.e., small and homogenous forest area that correspond to a management unit. The mean stand size was 1.5 ± 1.6 ha (mean ± sd). This landscape is composed of approximately 50.7% Scots pine (*Pinus*

Table 1
Description of the simulated forest management regimes: reference management (BAUwt), forest reserves (RES), the 16 alternatives of BAUwt, and four alternatives of continuous cover forestry (CCF), and how the regimes are allocated into extensive (EXT) and intensive (INT). Management regimes used as threshold between extensive and intensive Triad zones are highlighted in bold and italic. The range of regimes were characterized by its thinnings, rotation length, harvest threshold and retention trees and were applied to forest stands depending on site productivity classes: basal area (BA) requirements typically increase, and rotation length decrease with higher productivity; for rather mature stands a first thinning is applied after final harvest in the new rotation cycle. Number of stands represents to how many stands of the simulated landscape the regime was applied (out of 1475 stands in total), some regimes may not be applied due to the specific initial conditions of the stand.

Management description	Acronym	Thinning from below	Retention (/ha)	Minimum rotation length or harvest threshold	Avg. Cumulative harvest	Number of stands	Triad zoning
Forest reserves (unmanaged)	RES	no	–	–	0	1475	RES
BAU with thinning and extended rotation (+30y)	BAUwT_30	yes	10 trees	90–110 y	352.25	975	EXT
BAU without thinning and extended rotation (+10y)	BAUwoT_10	no	10 trees	70–90 y	385.52	1392	EXT
BAU without thinning	BAUwoT	no	10 trees	60–80 y	408.59	1420	EXT
BAU and extended rotation (+30y)	BAU_30	after 1st harvest	10 trees	90–110 y	423.82	1126	EXT
BAU without thinning and shorter rotation (−20y)	BAUwoT_m20	no	10 trees	40–60 y	424.98	1422	EXT
BAU with thinning and extended rotation (+15y)	BAUwT_15	yes	10 trees	75–95 y	451.2	975	EXT
BAU and extended rotation (+15y)	BAU_15	after 1st harvest	10 trees	75–95 y	463.19	1349	EXT
BAU with thinning and higher tree retention	BAUwT_GTR	yes	30 trees	60–80 y	464.83	975	EXT
BAU with thinning and extended rotation (+10y)	BAUwT_10	yes	10 trees	70–90 y	467.52	975	EXT
BAU with thinning and extended rotation (+5y)	BAUwT_5	yes	10 trees	65–85 y	471.27	975	EXT
BAU and extended rotation (+10y)	BAU_10	after 1st harvest	10 trees	70–90 y	472.94	1392	EXT
BAU management, with thinning, clear-felling	***BAUwT***	***yes***	***10 trees***	***60–80 y***	***475.1***	***975***	***INT***
BAU and extended rotation (+5y)	BAU_5	after 1st harvest	10 trees	65–85 y	480.64	1408	INT
BAU with higher tree retention	BAUwGTR	after 1st harvest	30 trees	60–80 y	484.06	1420	INT
BAU with thinning and shorter rotation (-5y)	BAUwT_m5	yes	10 trees	55–75 y	488.28	975	INT
BAU	BAU	after 1st harvest	10 trees	60–80 y	493.23	1420	INT
BAU and shorter rotation (-5y)	BAU_m5	after 1st harvest	10 trees	55–75 y	506.75	1421	INT
CCF with increased harvest threshold	CCF_4	no	min BA = 9–10m^2	BA = 22–28 m^2/ha	488.52	1367	EXT
CCF with increased harvest threshold	CCF_3	no	min BA = 9–10m^2	BA = 19–25 m^2/ha	507.72	1405	EXT
CCF with basic BA threshold	***CCF_2***	***no***	***min BA = 9–10m^2***	***BA = 16–22 m^2/ha***	***536.42***	***1420***	***INT***
CCF with reduced harvest threshold	CCF_1	no	min BA = 9–10m^2	BA = 13–19 m^2/ha	542.72	1422	INT

sylvestris), 33.9% Norway spruce (*Picea abies*), and other tree species including birch (*Betula pendula* and *Betula pubescens*) and other broad-leaved trees. The dominant soil type was mineral (74.2%) and organic (25.7%), with 61.5% of stands being located on fertile and 38.5% on poor sites. All forest stand-level data used in this study are publicly available through the national portal of the Finnish Forest Centre (http://www.metsn.fi/).

We projected the future development of the forest using the open source forest simulator SIMO (Rasinmäki et al., 2009). We simulated the development of the forest for 100 years (2016–2116), consisting of 20 five-year periods. For each forest plot, we simulated up to 22 management regimes. First, we modelled a reference management (hereafter business-as-usual, BAU) following the official Finnish recommendation. BAU regime typically includes 1–3 thinnings, has a rotation length of 80 years, and a final clear cut with green tree retention (remaining living trees), followed by artificial regeneration of planting trees (Äijälä et al., 2014). Then, we simulated 16 regimes that represent modifications of BAU, four regimes representing continuous cover forestry, and a set aside with no management actions to represent forest reserves (Table 1). Variations in BAU forest management involve shifting the specific timing and intensity of forest management actions, including final felling, thinning, selection harvest, and tree retention. Continuous cover forestry (CCF) management followed the recommendations from Äijälä et al. (2014), with the timing of harvesting activities determined by the site-specific basal area (BA) requirement (Table 1), and targeted diameter of trees to be harvested (target diameter cut). Under CCF no final clear cut is taking place and the occurrence and intensity of harvest activities are instead distributed over time (i.e., selective harvesting). Together with natural ingrowth of trees (no planting), this leads to a permanently covered and uneven-aged forest structure. The management regimes were based on earlier work (Eyvindson et al., 2018a,b).

Each simulated management regime was classified into one of three classes: intensive management, extensive management, and forest reserves (i.e., unmanaged, Table 1). For management regimes applying rotation forestry (i.e., with clear cut), the classification was based on average cumulative harvest (m^3/ha) over the simulation horizon. We set the threshold between intensive and extensive management at the harvest intensity of the BAU management with thinning (BAUwT). Management regimes with higher or equal cumulative harvests were assigned to the intensive zone, while those regimes with lower cumulative harvests were assigned to the extensive zone. CCF management regimes followed a different approach, which was motivated by the multifunctional benefits that usually arise from uneven-aged and diverse forest structures (e.g., see Juutinen et al., 2021; Koivula et al., 2020; Peura et al., 2018; Pukkala, 2016). Also, comparison between rotation forestry and CCF in terms of harvesting volume is not straightforward since CCF conducts harvesting at a much higher frequency and at a reduced intensity than BAU. Thus, we classified CCF variants based on the harvest intensity of the basic alternative, which describes the BA value required to conduct harvests (Table 1). CCF variants with equal to or using a lower basic BA threshold were assigned to the intensive zone (CCF 1 & 2), while those with higher threshold were assigned to the extensive zone (CCF 3 & 4, Table 1).

2.2. Ecosystem services and biodiversity indicators

To evaluate the landscape-level MF, we calculated indices for a selection of biodiversity and non-wood ecosystem service indicators and aggregated them into a single index consisting of four components. The framework to assess MF correspond to that of Eyvindson et al. (2021) (for details see Table 2 and Supplementary Material S2). Biodiversity was represented by two components, using habitat suitability for six vertebrate species and 27 red-listed deadwood-dependent species. These indicator species require varying stand-level forest characteristics and can be seen as umbrella indicators for biodiversity conservation. The ecosystem service components were non-wood ecosystem services, including recreational value and collectable goods (bilberry, cowberry and marketable mushrooms), as well as climate change mitigation potential (carbon storage). These indicators were estimated at the stand level based on the attributes resulting from the simulations outputs. Stand-level values were then aggregated at the landscape level as the sum of area weighted values across stands.

Table 2
Non-wood ecosystem services and biodiversity indicators included in the index representing multifunctionality. See Supplementary Material S2 for detailed information on the used indicators.

Component	Indicator	Description	Units	References
Vertebrate species habitat	Habitat availability	An index combining the habitat suitability models of six indicator vertebrate species	–	Mönkkönen et al. (2014)
Deadwood species habitat	Habitat availability	An index combining the habitat suitability models of 27 deadwood indicator invertebrate species	–	Tikkanen et al. (2007)
Non-wood ecosystem services	Scenic beauty	An index based on forest age, density, and tree species composition	–	Pukkala et al. (1988, 1995)
Non-wood ecosystem services	Bilberry	Yield of bilberry (*Vaccinium myrtillus*)	kg ha^{-1}	Miina et al. (2009, 2016)
Non-wood ecosystem services	Mushroom	Yield of marketed mushrooms	kg ha^{-1}	Tahvanainen et al. (2016)
Climate mitigation	Carbon storage	Carbon in biomass Carbon in mineral soils (Yasso07 model) Carbon in peatlands	m^3 ha^{-1}	Lehtonen et al. (2004), Liski et al. (2005), Ojanen et al. (2014), Tuomi et al. (2009, 2011)

2.3. Multi objective optimization

We explored the bi-objective function where we aimed to maximize both timber-derived economic value (NPV – using a 3% discount rate) and MF. For this case, we evaluated MF as the summation of the average normalized values of non-wood ecosystem services and climate mitigation (reflecting the potential for substitution) and the minimum normalized values of vertebrate species habitat and deadwood species habitat (reflecting the lack of substitution within species groups) across the landscape.

Using the mathematical formulation below, we explore how the specific zoning of management will impact the optimal output of the specific objective (either MF, NPV or a weighted combination see Supplementary Material S3 and S4). For each zoning alternative using a specific preference for MF and NPV, we ran the optimization model, obtaining a unique solution. We explored the entire range of all possible zoning alternatives of intensive, extensive and forest reserve zones ranging from 0% to 100% of the total forest area with permutations of zonings with 10% increments. This means that we conducted a total of 66 optimization for each objective. For each zoning combination and objective, forest stands were assigned to one of the 22 predefined management regime used to represent the intensive and extensive zones, next to the dedicated proportion of reserves.

We used the following objective function:

$$lex\ max - \sum_{m \in M}(p_m + n_m), (\lambda + \epsilon)MF + (1 - \lambda + \epsilon)NPV \quad (1)$$

subject to:

$$NPV = \sum_{p\in P}\sum_{j\in J}\sum_{k\in K_j}\frac{\left(x_{jk}z^i_{jkp}\right)}{(1+r)^{(2.5+5(p-1))}} + \sum_{j\in J}\sum_{k\in K_j}\frac{\left(x_{jk}z^e_{jk}\right)}{(1+r)^{(5(\#P))}} \tag{2}$$

$$MF = \sum_{b\in B} D_b \tag{3}$$

$$D_b = \frac{1}{\#T_b}\sum_{t\in T_b}\left(\frac{f_t - f_{t*}}{f^*_t - f_{t*}}\right), \forall b \in B_1 \tag{4}$$

$$D_b = argmin_{t\in T_b}\left(\frac{f_t - f_{t*}}{f^*_t - f_{t*}}\right), \forall b \in B_2 \tag{5}$$

$$f_t = \sum_{p\in P}\sum_{j\in J}\sum_{k\in K_j}\left(x_{jk}z^t_{jkp}\right), \forall t \in T_b, \forall b \in B_1 + B_2 \tag{6}$$

$$w_m * \sum_{j\in J} a_j - \sum_{j\in J_m}\sum_{k\in K_j} x_{jk}a_j - p_m + n_m = 0, m \in M \tag{7}$$

$$\sum_{k\in K_j} x_{jk} = 1, \forall j \in J \tag{8}$$

$$w_m \in [0,1], \forall m \in M \; x_{jk} \in [0,1] \forall j \in J, k \in K_j \tag{9}$$

$$\begin{aligned} p_m &\geq 0 \forall m \in M, \\ n_m &\geq 0 \forall m \in M, \\ M &\in \{SA, INT, EXT\}, \end{aligned} \tag{10}$$

where M is the set listing the management regimes assigned to different management categories; p_m and n_m respectively represent the positive and negative deviations from the targeted management category; λ is a parameter that assigns a weight to the objectives; ϵ is a small positive value acting as an augmentation term to ensure efficiency of the objective function; MF is the multifunctionality value of the landscape; NPV is the net present value of the landscape; P is the set of periods used in the analysis; J is the set of stands in the landscape; K_j is the set of management options simulated for stand j; x_{jk} is the decision variable to manage stand j according to management option k; z^i_{jkp} is the net income produced from stand j according to management option k at time period p; z^e_{jk} is the value of stand j according to management option k outside of the planning horizon; r is the discount rate applied; B_1 and B_2 are the sets of MF components which respectfully assigned to being evaluated as the average attainment value and the minimum attainment value; D_b is the attainment value of the MF component b; T_b is the set of indicators used to evaluate MF component b; f_t, f_{t*}, f^*_t respectively represents the attained, minimum and maximal value for criterion t; w_m is the proportion of the landscape assigned to management regime m; a_j is the area of stand j. Table 3 presents the description of notation in a more readable fashion.

The problem formulation starts with an equation, which presents a lexicographic objective function with the first priority of the optimization is to ensure the targeted management proportions area followed as closely as possible, with the second priority being the trade-off between the attainment of the NPV and MF. Equation (2) evaluates the NPV at a specific discount rate (r). Equation (3) evaluates the MF as the summation of the four component values. Equation (4) calculates the attainment for those MF components, which can be aggregated as the average value. Equation (5) calculates the attainment for those components which are assessed to be the minimum value produced from the set of criteria in T_b. Equation (6) calculates the aggregated production of the indicator. Equation (7) evaluates the deviations away from the specified proportions of extensive (*EXT*) intensive (*INT*) and conservation (*SA*) orientated forest management. Equation (8) is an area constraint, ensuring that each forest stand is managed according to a management regime. Equations (9) and (10) define the scope and range of values the specific variables can hold.

Table 3
Notation used in the optimization formulation (equations 1-10).

Symbol	Description
Sets	
B_1, B_2	The sets of multifunctionality components respectfully assigned to the average attainment value and minimum attainment value
J	The set of stands representing the forest holding
K_j	The set of management options for stand *j*
M	The set listing the management regimes assigned to different management categories
T_b	The set of indicators used to evaluate multifunctionality component *b*
P	The set of time periods under consideration
Variables	
a_j	The area of stand *j*
D_b	The attainment value of multifunctionality component *b*
f_t, f_{t*}, f^*_t	Are respectively the attained, minimum and maximal value for criterion *t*
p_m, n_m	The negative and positive deviations from management category *m*
MF	The multifunctionality value for the landscape
NPV	The net present value for the landscape
x_{jk}	The decision variable for stand *j* and management schedule k
z^e_{jk}	The end economic value of stand *j* for management schedule *k*
z^i_{jkp}	The net income produced from stand *j* for management schedule *k* at period *p*
Parameters	
w_m	The proportion of the landscape to be managed according to management category *m*
λ	The weight assigned to evaluate the trade-offs between objectives
ϵ	A small positive value to act as an augmentation term
r	A parameter describing the discount rate applied

2.4. Analysing optimization outcomes

Optimization outcomes were first analysed regarding the economic (NPV) and MF performance, under the whole range of possible combination of the intensive, extensive, and reserve zones. We first explored how MF and NPV performed when maximizing for one or the other. Secondly, we explored how the individual MF components contribute to the overall MF, allowing us to identify potential trade-offs among them and assess their relative performance at the MF optimum. Thirdly, we assessed the performance of individual biodiversity and ecosystem service indicators and the allocation of the specific management regimes within the intensive and extensive zones, at the optimized Triad zoning combination for MF and NPV. Finally, we examined these variations along the prioritizing gradient for MF relative to NPV.

3. Results

3.1. Optimal landscape zoning for NPV and multifunctionality

When prioritizing the NPV of the forested landscape the management regimes contributing to the economic objective was a combination of both intensive and extensive management. Hence, the combination leading to the maximum NPV was 70% intensive, 27% extensive, and 3% reserves (green dot in Fig. 2a). The 3% of reserves corresponds to stands with very low soil productivity, i.e., with little production value. The maximum achievable NPV was 17.5 M€ for the landscape (i.e., ~7800 €/ha over the whole planning period). Prioritizing the economic value of the forest has a dramatic negative impact on the performance of MF, as MF was at its lowest (0% of its maximum, green dot Fig. 2b). When maximizing for NPV, the lowest MF levels occurred when intensive and extensive zones were the dominating management, while the highest level occurred when 60% or 70% of the landscape was assigned for reserves (Fig. 2b).

When management targeted maximizing MF the optimal solution was achieved under a zoning that consisted of 20% intensive, 50% extensive, and 30% reserves (red dot in Fig. 2c). With a landscape level prioritization of MF, the resulting NPV decreased to 10.7 M€ (i.e.,

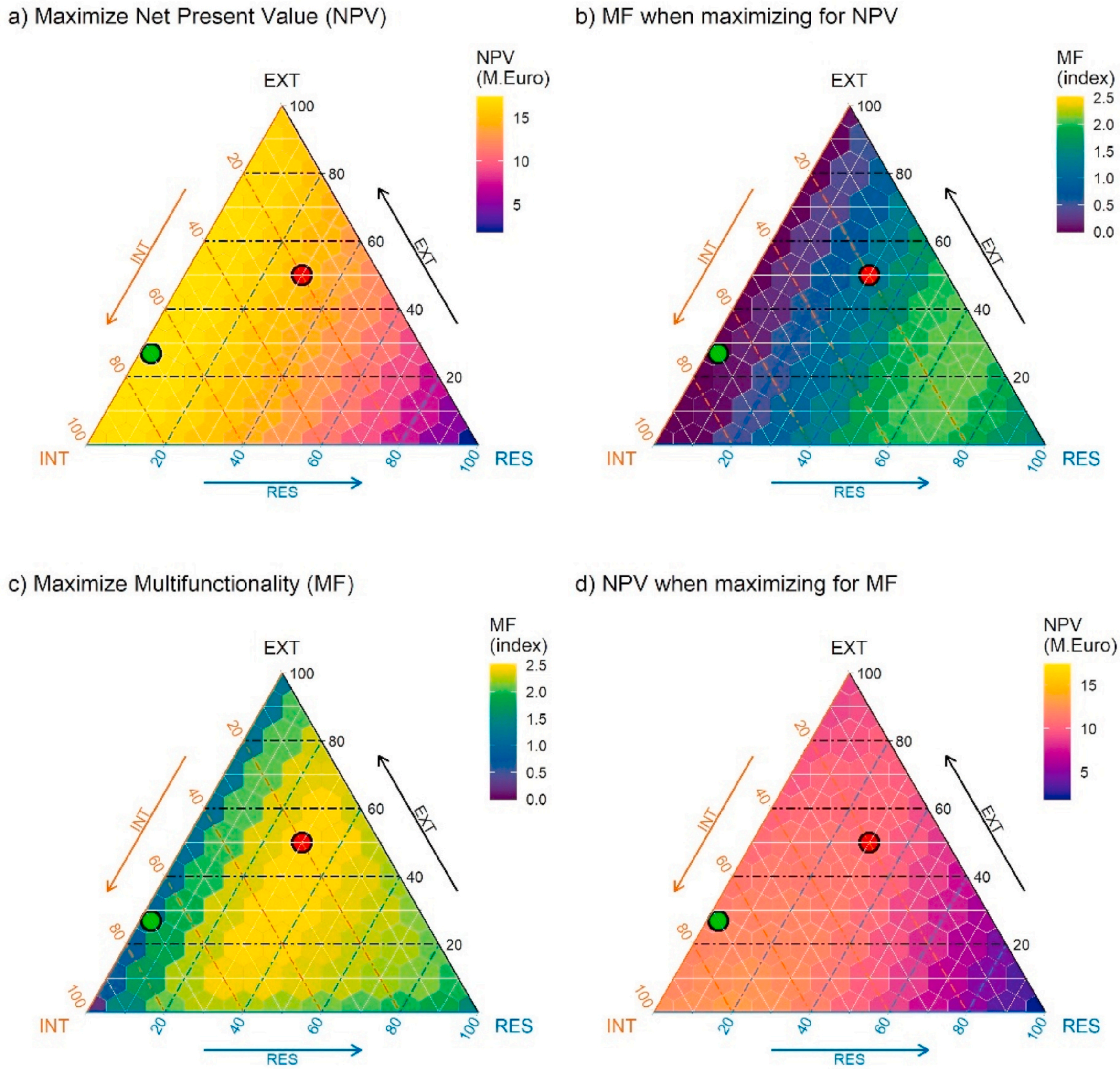

Fig. 2. Effect of landscape zoning on net present value (NPV) and multifunctionality (MF) when maximizing landscape management for either objective. The sides of the triangles show the proportion of each management zone within the analysed landscape (INT: intensive management, EXT: extensive management, and RES: forest reserves). Upper panels show (a) NPV and (b) the corresponding effects on the index of MF (b), while NPV is optimized. Lower panels show (c) MF and (d) the corresponding effect on NPV, while MF is optimized. The dots indicate the zoning combination where values for NPV (green) and MF (red) are highest, when both objectives have been optimized individually (i.e., green dots refer to values shown in panel a), while red dots refer to values shown in panel c), for guidance dots were repeated in each sub-figure). (For interpretation of the references to colour in this figure legend, the reader is referred to the online version of this article.)

~4800 €/ha and planning period), which was 61% of its maximum (green dot in Fig. 2d). However, the combinations of forest zoning strategies with high MF values were quite broad (Fig. 2c), indicating that we can obtain high level of MF in a wide range of forest zoning strategies; yet always incurring high loss of NPV. This reflects how the various components of MF required differing stand characteristics (see section 3.2).

The results for intermediate weightings of NPV relative to MF during the optimizations led to similar proportions of intensive, extensive, and reserve zones that provide the maximum NPV or MF, but achieved lower values (Supplementary Material S3).

3.2. *Effect of zoning options on multifunctionality components*

The impact of landscape zoning on each component of the MF metric, and the trade-offs among them can be explored in Fig. 3. Non-wood ecosystem services were highest, on average, when the landscape management was 70% extensive and 30% reserves. The component of climate change mitigation (carbon storage) had a clear increasing trend from high proportions of intensive and extensive management to high proportion of reserves, with the highest value under a purely unmanaged forest landscape (100% reserves). Vertebrate species habitat was maximized with combining 50% intensive, 20% extensive, 30% reserves, while deadwood species habitat attained highest values with 60% intensive, 10% extensive, and 30% reserves.

Under the management combination that maximized MF (red dot in Fig. 3a–d), non-wood ecosystem services and vertebrate species habitat were the closest to their individual maximum (98.9 and 99.4% respectively). The deadwood dependent species remained high as well (94.5% of its maximum). The largest discrepancy between the optimum for MF and any individual component was for climate mitigation (79.7% of its maximum). This highlights that different management benefited various components of MFand the wide zoning possibility to reach high MF values (Fig. 2b). The same trade-offs among the individual MF

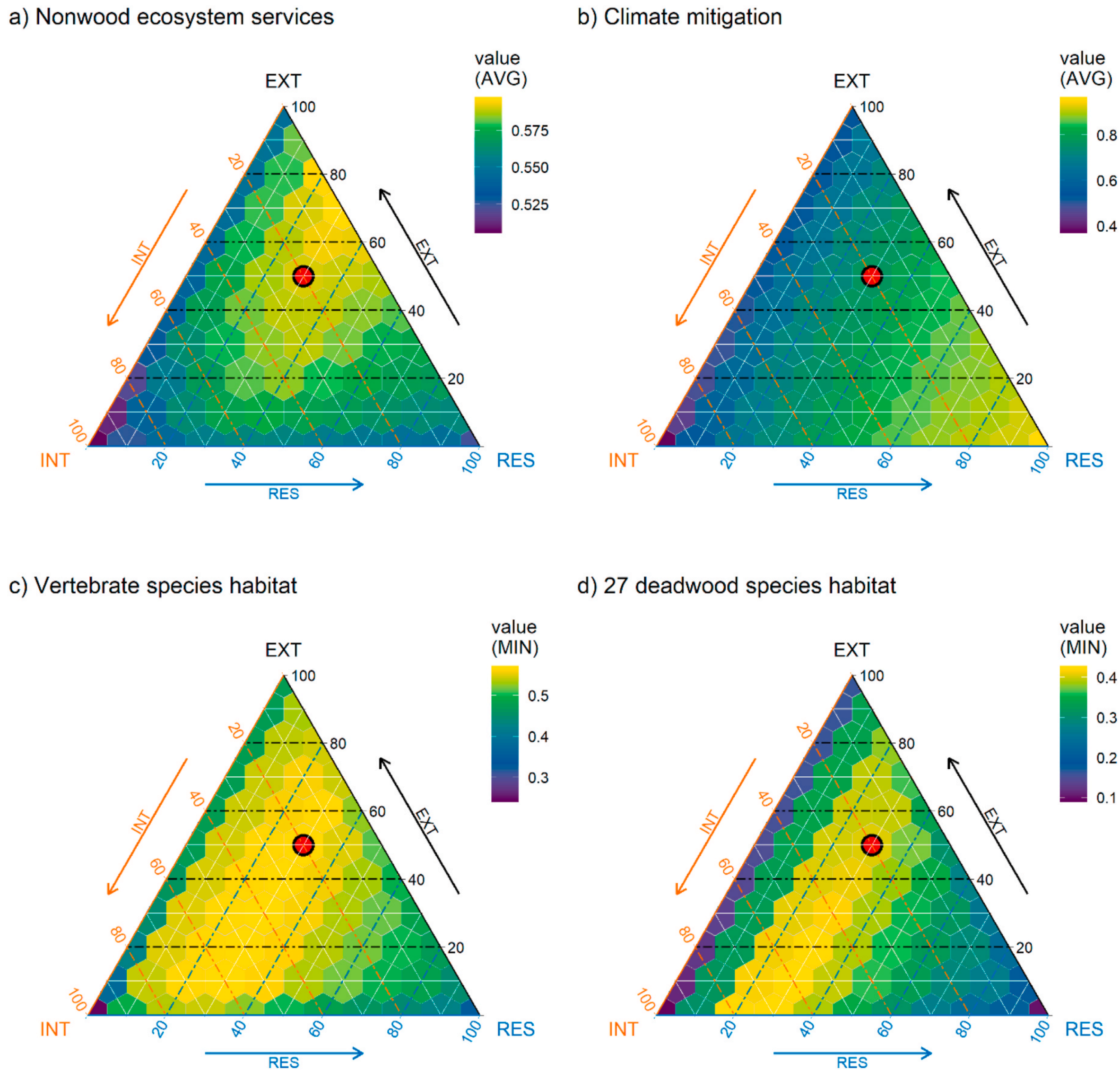

Fig. 3. Effect of landscape zoning on the individual components of multifunctionality (MF), when maximizing for MF: (a) average (AVG) of non-wood ecosystem service indicators, (b) average of climate mitigation indicators (carbon storage), (c) minimum (MIN) of the vertebrate species habitat availability, and (d) minimum of the 27 deadwood species habitat availability. INT: intensive management, EXT: extensive management, and RES: forest reserves. The red dot indicates the zoning combination that maximizes MF (see Fig. 2). Note the different colour scales of each sub-figure. A corresponding figure showing the performance of the MF components while maximizing for NPV is included in the Supplementary Material S5. (For interpretation of the references to colour in this figure legend, the reader is referred to the online version of this article.)

components were observed when maximizing for NPV (see Supplementary Material S5).

3.3. Management regime combinations

The impact of landscape zoning on the combinations of management regimes showed large variation in how forest management can be applied across stands, with greater variation under high weights for MF. When looking at the landscape zoning that maximized either NPV or MF there was an increase in the diversity of forest management as the priority shifted from maximum NPV to maximum MF (left to right, Fig. 4). With increasing importance of MF (as the weight shifts from 0 to 1), the intensive and extensive zones included increasing proportions of regimes that have the lowest average harvests among the regimes allocated to EXT and INT (Fig. 4 and Table 1). The Triad zoning maximizing MF (red dot Fig. 2) had a high proportion of forest reserves and extensive CCF dominates managed forest, across the entire priority gradient (Fig. 4, upper panel). When maximizing for NPV (green dot Fig. 2), the Triad zoning was dominated by intensive CCF, with increasing share of both extensive and intensive rotation forestry with increasing emphasis on MF (Fig. 4, lower panel).

3.4. Zoning effect on indicators of multifunctionality components

The effects of Triad zoning on the individual indicators of MF are presented in Fig. 5, separately for two optimal zoning approaches: optimized Triad zoning for MF and for NPV (red and green dots on Fig. 2). The largest differences in the level of biodiversity and non-wood ecosystem service indicators were found for the climate change mitigation and the deadwood-dependent species components across the entire priority gradient. Optimizing forest management zoning for NPV strongly restricted the habitat availability for deadwood-dependent species within the landscape (left & right panel, Fig. 5c) and reduced the average potential of storing carbon in the forest (left & right panel, Fig. 5b). This negative pattern was, to a lower extent, also observed for the vertebrate species (left & right panel, Fig. 5d). Meanwhile, the

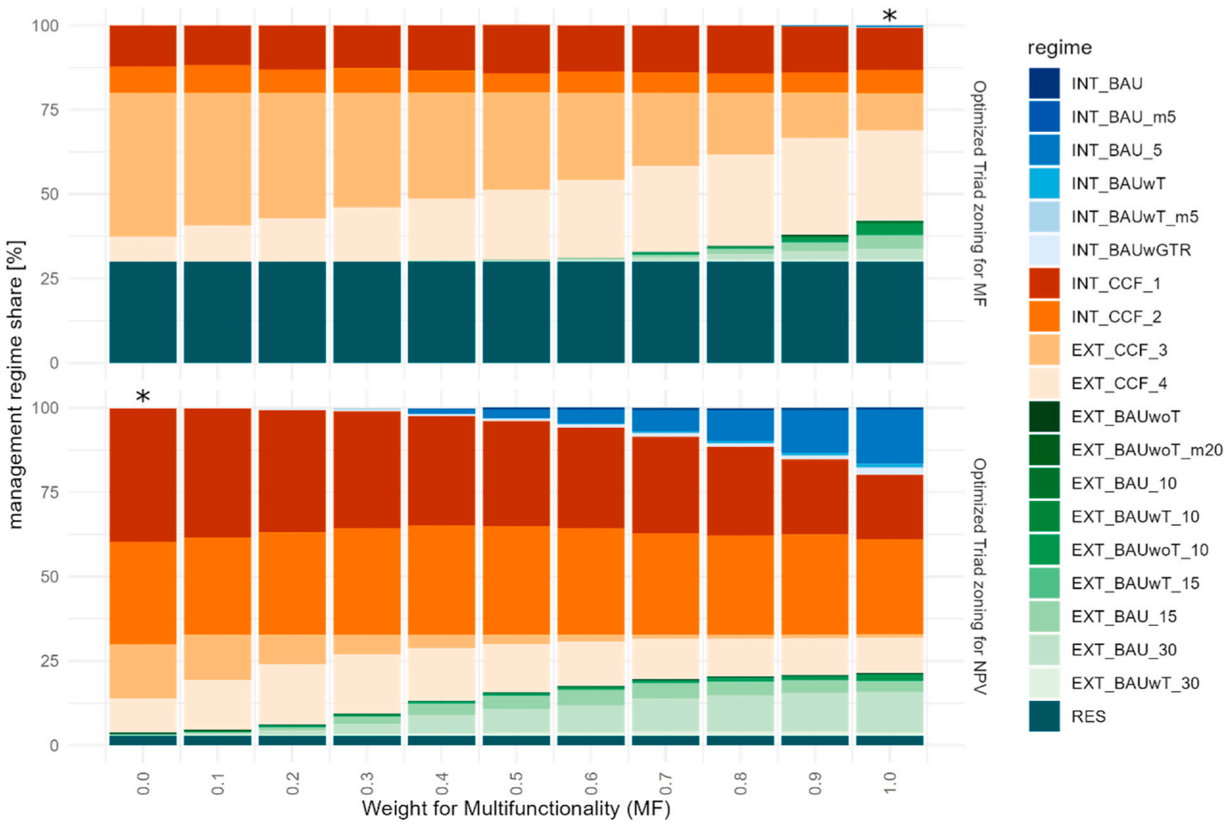

Fig. 4. Proportions of individual management regimes at the optimized landscape zonings where multifunctionality (max MF) and net present value (max NPV) are highest (green and red dots in Fig. 2), and across the weighting gradient of MF relative to NPV. The proportion of management regimes are presented at the optimal landscape zoning for each weighing steps, which is shifting from NPV to MF. A weight of 0 means that the management priority is NPV, at a weight of 0.5 the objectives of MF and NPV are equally important, and weight 1 means that the management priority is MF. * indicates the optimized scenarios with opposite management objectives. (For interpretation of the references to colour in this figure legend, the reader is referred to the online version of this article.)

indicators of non-wood ecosystem services showed a smaller difference, as the average indicator values were almost the same between the optimal landscape zoning for NPV and MF (left & right panel, Fig. 5a). However, zoning for MF resulted in larger differences across indicators, with higher level of aesthetic value (left panel Fig. 5a), while bilberry and mushroom were only marginally affected by the two different optimal zoning combinations (left & right panel).

Overall, the two zoning optimums showed a pattern where climate change mitigation, vertebrate and deadwood-dependent species components increased as the weighting priority for MF increased (from 0 to 1, left to right, Fig. 5). This pattern highlights the importance given to the objective of management, in addition to the proportions allocated to intensive, extensive, and reserve zones.

4. Discussion

Through a simulation and optimization framework we explored the usefulness of applying the Triad approach to sustainably manage forests. Simply applying the Triad approach and allocating specific areas to intensive, extensive, and reserve zones does not implicitly contribute to an overall increase in forest landscape MF. Regardless of how the landscape was allocated into management, a carefully defined and considered management objective is required to guide the development of the forest. The optimal zoning combination deferred greatly depending on the landscape level objective. In addition, we observed that prioritizing either economic value or MFincurred large reduction of the counterpart (highlighting a high trade-off), irrespective of the landscape zoning. As we grouped different management regimes into the “extensive” and “intensive” categories (based on harvest volumes), there remains great variation in how the forest management can be applied within each zone. This leads to gradual replacement of management regimes for a specific landscape zoning depending on whether the primary objective is economic value, in terms of timber production, or MF, based on biodiversity and non-wood ecosystem services.

4.1. *Triad management for multifunctionality and NPV*

Maximizing MFled to a joint land sharing-sparing management plan, which contained a combination of 20% forest area managed intensively, 50% extensively, and 30% allocated to forest reserves. Such landscape zoning represented a good compromise between the four studied MF components (as they performed >80% of their maximum level) and maintained 61% of the maximum achievable economic value (NPV). These results can be compared to earlier studies, with a similar zoning distribution to best achieve the multifunctional targets of both the Finnish forest and bioeconomy strategies (Blattert et al., 2022) and the Norwegian forest strategies (Vergarechea et al., 2023). In contrast, for a Canadian (hemi-) boreal landscape, Côté et al. (2010), found that the scenario that most resembled the absence of management (i.e., landscape with natural disturbances) had a much lower allocation to reserves (12%) but higher extensive management (60–74%).

When maximizing for NPV, the Triad zoning consisted of 70% of the forest area under intensive management, 27% under extensive management, and only 3% of forests set-aside in reserves. This case prioritizes timber production through intensive management, despite the relatively large share of extensive management. This scenario resulted in a minimum share of protected areas on land that are not economically profitable, i.e., low-productive sites are primarily allocated to reserves. However, low productive forest habitats are usually not threatened and thus not a conservation priority in Fennoscandia (Angelstam and

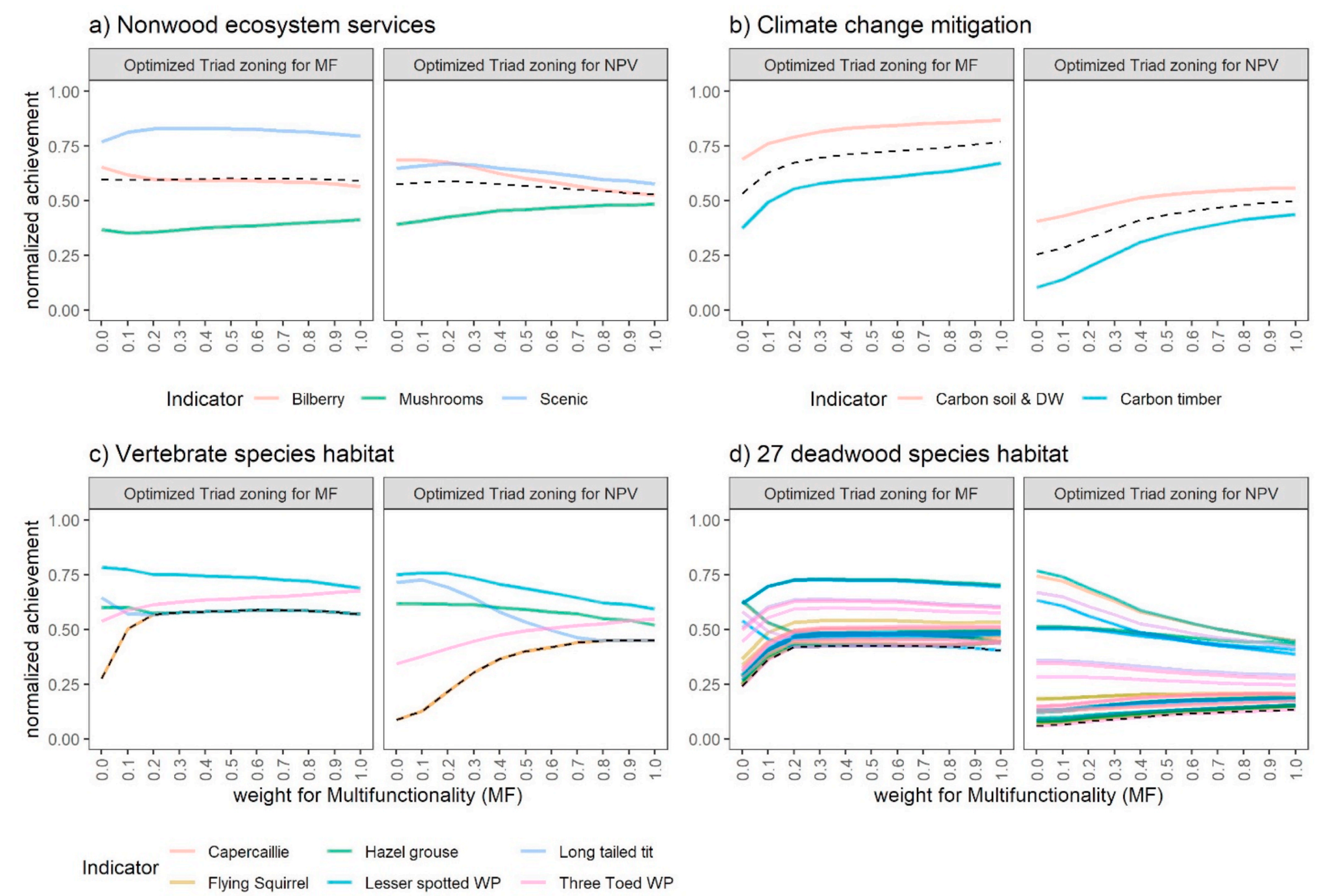

Fig. 5. Effect of optimized zoning for MF and NPV on individual indicators of multifunctionality (MF) components at the Triad landscape zoning where MF and net present value (NPV) are optimal (see green and red dot in Fig. 2). The level of biodiversity and non-wood ecosystem service indicators are presented at the optimal landscape zoning along the entire weighting gradient for MF, which is shifting from 0 (maximum NPV) to 1 (maximum MF). The black dashed lines represent the aggregated MF components: average value (a, b), or minimum value (c, d) across indicators. (For interpretation of the references to colour in this figure legend, the reader is referred to the online version of this article.)

Andersson, 2001; Hanski, 2005). However, this is in clear contradiction with the current recommendations for biodiversity conservation that requires a distribution of reserves across all forest site types and productivity classes with the emphasis on the most rare and threatened habitats.

4.2. Triad in the land sharing-sparing continuum

The Triad approach allows for the navigation between land sparing and sharing strategies. Our results highlight that there is a severe trade-off between timber production and forest MF when managing forest. We found that the conflict is mitigated through the combined use of land sparing and sharing management within the same landscape. Blattert et al. (2018) also found that a combination of three zones with intensive, extensive and reserves provided best the multifunctional benefits in a central European case study. Our results, however, contradict earlier suggestions that in forest management, land sparing would better achieve biodiversity conservation than land sharing (Edwards et al., 2014; Naumov et al., 2018). These studies often lack consideration of non-wood ecosystem services and focused on timber production vs. biodiversity conservation. Notably, the sparing – sharing debate often implies a strong dichotomy between production and conservation, although land sparing and sharing are not mutually exclusive, as previously criticized, for instance in the agricultural landscape context (Ekroos et al., 2016; Grass et al., 2019). In addition, strategies that utilize predominantly land sparing options to allow for efficient monofunctional production can lead to the erosion of landscape level MF, giving rise to negative ecological and social consequences (Fischer et al., 2017).

By using mixtures of intensive, extensive and forest reserves, the Triad approach is a much more flexible and nuanced approach to landscape zoning when compared to the sharing–sparing framework. However, the specific zoning requirements are landscape specific, and the optimal zoning strategy largely depend on stand properties and the overall planning objectives. Additionally, the outcome is likely influenced by landscape characteristics such as the historical use of the forests (Angelstam et al., 2013), the dominant natural disturbance regime (Côté et al., 2010), as well as the public acceptability of intensive management, especially the use of clear-cuts (Tahvanainen et al., 2001). In our boreal forest landscape, the maximal MF required 30% of forest reserves and 50% of extensive management. This highlights the limitation of the EU biodiversity strategy (EC, 2020), simply aiming to conserve 30% of the EU's land area (of which 10% should be strictly protected) seems not to be enough in our investigated case study. Results might, however, differ if other European forest ecosystems are considered. Thus, we advocate for similar studies to be conducted in other European areas.

4.3. Implementing Triad landscape planning in European boreal forest

Adoption of the Triad approach over the European boreal forests is a huge challenge, because this region has a long history of intensive forestry. Hence, implementing Triad functional zoning may require shifting large areas of intensively managed forests into extensive management, and increasing the area of forest reserves (Himes et al., 2022). Our case study shows that shifting forest management planning towards MF will provide economic benefit, however on a lower level when compared to scenarios emphasizing timber revenues. Despite these losses in timber-derived economic value, emphasis should be put on the multiple gains associated to increased MF. Landscape MF is not only about which ecosystem services are being generated, but also about who benefits from these diverse services and if they are accessible to a broader range of beneficiaries (Fischer et al., 2017). Although our analysis focused on a restricted set of biodiversity features and non-wood ecosystem services, using an ecological lens, our results suggest that zoning targeting MF has many benefits beyond the forestry sector and forest owners. Thus, future studies should consider stakeholders' preferences of forest management approaches and ecosystem services (e.g., Hallberg-Sramek et al., 2023). More specifically, stakeholders could get involved in the selection process of indicators used to measure MF or when classifying management approaches into the intensive and extensive class. Local and Indigenous communities often have culturally embedded multifunctional use of forests. Including their traditional knowledge and alternative values of forests can provide valuable insights for sustainable use of forest resources, while increasing environmental justice (Angelstam et al., 2011; Teitelbaum et al., 2023).

Another challenge of the Triad approach is related to the ownership structure of forest lands. Across Europe over 60% of forests are owned by small private owners (Weiss et al., 2019). This is the case in Finland, where fragmented private ownership represents 52% of the forest land (Vaahtera et al., 2023). Small forest properties and multiple forest owners can increase potential conflicts among management objectives between adjacent forests. Implementation of large-scale management planning in such small-scaled and privately-owned land requires a tremendous amount of cooperation and coordination; otherwise ecological strategies may be confined to state-owned land (Himes et al., 2022). Alternatively, governmental incentives can be used to motivate private forest owners to manage their forest accordingly. Corresponding programs already exist in Finland, like the METSO-program that provide financial compensations to forest owners willing to setting-aside their forests as reserves. Regulations may also be adopted to encourage constraining management to a range of intensive or extensive options within a particular zone.

4.4. Methodological limitations and future perspectives

A limitation of our optimization framework is the lack of spatial configuration of the management zones. High connectivity among forest habitats across the landscape is important for biodiversity conservation and climate change adaptation (Duflot et al., 2022b; Messier et al., 2019) and also affect important ecosystem services such as water quality (Zanchi et al., 2021). In its "third of a third" zoning proposal, Hanski (2011) suggests that forest reserves should be aggregated in the landscapes and surrounded by the extensive management zone. In the Triad approach, it is recommended to firstly allocate forest reserves and secondly distribute intensive areas away from reserves to guarantee their connectivity (Himes et al., 2022; Tittler et al., 2015). In an optimization framework, spatial aspects could be considered after the "optimal zoning" proportions are elaborated based on agreed objectives. Several spatial optimization tools could be used to aggregate reserves or extensively managed stands, or create corridors (Augustynczik, 2021; Heinonen, 2019; Heinonen et al., 2018; Mazziotta et al., 2023). Future optimization studies should aim to spatially constrain the allocation of zones, e.g., using additional objectives that take into account the migration distances of certain species, or the principles of spatial conservation prioritization, including representativeness and complementarity to achieve a more even distribution of reserve areas (Knight et al., 2011). The spatial scale at which Triad management is applied will affect the spatial configuration of the management zones. Large scale applications (e.g., continental, or national) carry the risks of aggregating management zones towards specific areas, which can be detrimental to the representativeness of environmental gradients, or to excessive fragmentation of the zones into functionally isolated and scattered fragments. However, applying Triad zoning to landscapes may mitigate these risks.

A further limitation of our approach is that we did not consider climate change and natural disturbances (storm, insect pests, fires) in the simulation, which will greatly influence boreal forest in the future (Venäläinen et al., 2020). Including disturbances, either within the simulations (Perera et al., 2015; Seidl et al., 2011), or by additional disturbance risk indicators within the optimization (Díaz-Yáñez et al., 2019; Potterf et al., 2022; Temperli et al., 2020) would most likely affect the outcome of the optimal zoning and should be included in future studies exploring the optimal zones of Triad. However, Triad not only aims at minimizing conflicts among management objectives, but indirectly also leads to a more diversified forest landscape, when optimizing for MF. Enhanced forest structural variability is also seen as an important forest management feature to increase ecosystem resilience against climate change and mitigate future risks (Himes et al., 2022; Messier et al., 2022).

Forest landscape MF was assessed by four components including different forest ecosystems service indicators. While individual indicators were assessed within each stand, the aggregated MF index respond to alternative management at the landscape scale (sparing vs sharing theory). High MF can be obtained at the landscape scale if trade-offs between stand indicators are optimally balanced. All components of MF and their indicators were assumed to be equally important, which might not represent societal demands. Using different indicators or assuming different importance between the indicators (e.g., by considering preferences of forest stakeholders; c.f. (Blattert et al., 2020; Himes et al., 2022; Thrippleton et al., 2021) might considerably change the optimal zoning proportions. However, our approach provides flexibility and alternative indicators can easily be considered, as well as giving certain services a stronger importance. Thus, case-specific optimal zoning proportions could be elaborated considering different stakeholder preferences (Eyvindson et al., 2018a,b; Eyvindson and Kangas, 2015).

5. Conclusion

Our study illustrates two novel aspects in relation to the Triad landscape zoning approach. First, we presented a novel objective method combining forest ecosystem simulation and multi-objective optimization that allows exploring the long-term impacts of different Triad zoning scenarios on ecological and economic forest services. Secondly, we applied for the first time Triad in a European boreal forest case study landscape, highlighting its potential usefulness for this biogeographic region.

In response to our research questions, our results highlight that there is not "one perfect solution" to determine the appropriate zoning. The optimal zoning option strongly depends on the management objectives, implying trade-offs among individual objectives, and the individual indicators. Within the intensive and extensive zones, the management applied will reflect the specific management objectives. Thus, compromises are needed, which can be balanced by varying management and zoning proportions. Nevertheless, we found that multifunctional forest management of European boreal forests requires management diversity with larger shares of extensive management (including continuous cover forestry) and protected areas, which are even beyond current European policy targets. We demonstrate that our framework can inform and help decision makers in developing management plans that target multi-functional forest management and improve the societal and ecological resilience of boreal forest landscapes.

Author contributions

CB – Conceptualization, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing, KE – Conceptualization, Data curation, Methodology, Software, Writing – original draft, Writing – review & editing, MM, KR & MT - Investigation, Writing – review & editing, RD - Conceptualization, Investigation, Writing – original draft, Writing – review & editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in the paper "Enhancing multifunctionality in European boreal forests: the potential role of Triad landscape functional zoning".

Data availability

The code for the forest simulations, optimizations and data analysis can be found on git repository together with data supporting the findings of this study (www.github.com/eyvindson/MF_TRIAD).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119250.

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