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Research article

Cost-efficiency analysis of multiple ecosystem services across forest management regimes

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ABSTRACT

Forest management is at the crossroads of economic, environmental, and social goals, often requiring strategic trade-offs. As global demands surge, it's vital to employ management strategies fostering multifunctional landscapes, enabling ecosystem integrity while procuring resources. Historically, the boreal forest in Fennoscandia has been intensively managed for timber, causing environmental shifts and conflicts with biodiversity conservation and climate mitigation policies. Application of current management practices while increasing harvests are a threat to both biodiversity and carbon stocks. To explore this issue, we quantify the cost-efficiency of two forest management regimes: rotation forestry (RF) and continuous cover forestry (CCF), considering specific forest attributes like soil type (mineral and peat soils), site type (fertility classes) and tree stand age, which have been underexplored in previous research. We simulated 45,559 forest stands for 100 years in Northern boreal forests of Finland. We proposed two straightforward cost-efficiency indices (CEI) to evaluate the performance of these management regimes, specifically focusing on their impact on economic output, biodiversity conservation (measured as a biodiversity index for six forest vertebrates, including five bird species and one mammal) and carbon stock. Our findings suggest that continuous cover forestry holds the potential to deliver more cost-efficient ecosystem services and maintain greater biodiversity compared to rotation forestry approaches. Continuous cover forestry, however, is not optimal for all at management units, which calls for alternative management options depending on the stand characteristics. The cost-efficiency indices performance of rotation forestry and continuous cover forestry depend on the characteristics of the initial stand which is largely determined by the previous management of the stand. Our results contribute to guiding forest management towards enhanced sustainability and ecological balance. The great variation in stand characteristics suggest a need for diverse management strategies to create multifunctional landscapes. Our proposed cost-efficiency indices could serve as practical tools for decision-making.

1. Introduction

Forests provide a multitude of ecosystem services, including timber production, biodiversity conservation, carbon sequestration, climate mitigation, and recreational benefits. However, providing these services inevitably involve trade-offs (Andreassen and Øyen, 2002; Akujärvi et al., 2021; Mason et al., 2022; Nakajima et al., 2017; Pohjanmies et al., 2019; Pukkala, 2022; Redon et al., 2014; Sharma et al., 2016). Due to the ever-increasing global demand for forest ecosystem services, it is critical to adapt management strategies that create multifunctional forest landscapes, thereby ensuring the provision of varied ecosystem services without compromising ecosystem integrity (Díaz-Yáñez et al., 2019; Eyvindson et al., 2021). Implementing the appropriate silvicultural practices—precisely calibrated in degree, scale, and extent can foster forests that are both resilient to resource extraction and functionally diverse (Messier et al., 2019).

The boreal forest, accounting one third of the world's remaining forests, has been extensively managed for timber production in recent decades, especially for pulp and sawmill operations (Hansen et al., 2010). Rotation forest (RF) management has been the predominant option for the past decades, driven by the timber demands from industrial needs (Blattert et al., 2023; Gauthier et al., 2015). Clear-cutting,

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promoting homogenous species compositions, and enforcing even-aged structures have instigated enduring environmental shifts, which reflects a dissonance between bioeconomy policies and those aimed at preserving biodiversity and ecosystem services at the national and EU levels (Eyvindson et al., 2018; Vergarechea et al., 2023). With rising harvest levels coupled with current management practices, biodiversity is increasingly under threat (Räty et al., 2023), and carbon sinks are decreasing, which pose challenges for the forests to mitigate and adapt to climate change (Mäkelä et al., 2023; Mönkkönen et al., 2022).

Efforts can be made to support biodiversity and carbon stocks through forest management, and to guide the effort, new knowledge is needed about economic viability and how different management regimes affect these variables on different soil and site (habitat) types. Forests in Fennoscandia are key biodiversity habitats, with 32% and 42% of the red-listed species are forest-dwelling, respectively for Finland and Sweden (Andersson et al., 2020; Hyvärinen et al., 2019). This highlights the pressure and threats to forest biodiversity in the region, given the dependency of many red-listed species on forest ecosystems. Forest species composition and carbon stock vary based on forest management regime, site type, and age class of tree stands (Akujärvi et al., 2021; Repo et al., 2021). Forest age structure has shifted towards younger age classes due to earlier clear-cutting. The species most negatively influenced by forests management are typically those specialized in old-growth habitats (Hjältén et al., 2023). Concerning carbon stocks, clear-cutting results in periods of low carbon stocks and leads to fluctuating carbon stocks over time, depending on the age class of the stand. While younger forests possess lesser carbon storage capacities than their older counterparts, their rapid growth rates enable them to sequester carbon at a more pronounced rate (Díaz-Yáñez et al., 2019).

Continuous cover forestry (CCF) (Pukkala and Gadow, 2012) represents a management alternative that maintains a permanent forest canopy through avoidance of clear-felling, potentially enhancing biodiversity and offering stable, larger carbon stocks compared to RF (Peura et al., 2018; Pukkala, 2016). Previous research indicates that the effectiveness of CCF compared to RF in promoting biodiversity is context-dependent and varies with factors such as species type and management intensity. While CCF can provide more habitats for mature forest species and affect understory vegetation and soil fauna, its superiority in conserving biodiversity over RF is not absolute and depends on specific ecological conditions and management practices (Atlegrim and Sjijberg, 1996; Atlegrim and Sjöberg, 2004; Calladine et al., 2015; Jalonen and Vanha-Majamaa, 2001; Kuuluvainen et al., 2012; Matveinen-Huju and Koivula, 2008; Pukkala, 2016; Pukkala et al., 2010, 2013, 2016; Siira-Pietikäinen and Haimi, 2009). Additionally, CCF may economically benefit forest owners more than RF (Pukkala, 2016; Tahvonen, 2016; Tahvonen et al., 2010; Tahvonen and Rämö, 2016), though results vary regarding economic profitability (Andreassen and Øyen, 2002; Juutinen et al., 2018). The debate about CCF's overall benefits persists due to a lack of long-term large-scale empirical research. Though prior studies highlight CCF's potential in delivering multiple services (Pukkala, 2016), there is limited focus on the cost-efficiency of forest management regimes in relation to the forest stand attributes particularly regarding soil and site types and age classes.

There are a number of studies on economic and ecological impacts of forest management in boreal forests. However, in prior research studies (e.g., Díaz-Yáñez et al., 2019; Eyvindson et al., 2018, 2021; Juutinen et al., 2018, 2021; Peura et al., 2018; Pukkala, 2016, 2021; Triviño et al., 2017), forest attributes such as soil (mineral soil versus peat soil), site types (fertility classes) and tree stand age class were not explicitly analyzed. We specifically focus on differentiating between peat and mineral soils, classifying distinct site types, and identifying various age classes of tree stands. Unlike previous studies, we did not attempt to optimize ecosystem services. Instead, our aim was to conduct a comparative analysis across these variables, offering an in-depth insight into their influence on ecosystem services under alternative management regimes. By doing so, we focus to enhance the discussion and guide the development of cost-efficient forest management methods.

The objective of this study was to assess the cost-efficient provision of biodiversity and carbon stocks by comparing how RF and CCF influences on these variables. Specifically, cost-efficiency is assessed in terms of the ratio of ecological benefits (biodiversity and carbon stocks) to the economic performance (net present value, NPV) involved in each management regime. We employed a simulation approach to answer four research questions:

(Question 1) How do different management regimes (RF and CCF at two levels of harvest intensity) impact the economic performance of timber production?

(Question 2) What could be the potential effects of the management regimes on biodiversity indicators (measured as a biodiversity index for six forest vertebrates, including five bird species and one mammal)?

(Question 3) How do different forest management regimes influence the change in carbon stock?

(Question 4) How does the management regime affect cost-efficiency of enhancing biodiversity and carbon benefits?

2. Materials and methods

2.1. Study areas

Our study area was the municipality of Ii in northern Finland. Ii is part of the boreal biogeographical zone, characterized by extensive boreal forests, mires, and lakes (Ahti et al., 1968). The climate in North Ostrobothnia features an annual rainfall of between 353 and 756 mm and an average annual temperature range of −0.3 to 5.2 °C.

We employed publicly available forest inventory data maintained by the Finnish Forest Centre (www.metsaan.fi) (Fig. 1). The forests in the study area consist of 45,559 forest stands. The predominant tree species include Scots pine (*Pinus sylvestris*), which is the primary species in 60% of the stands, followed by Norway spruce (*Picea abies*) at 19%, silver birch (*Betula pendula*) comprising 20%, and downy birch (*B. pubescens*) representing 0.5%. Approximately 60% of the stands and their area coverage locate on mineral soils and 40% on peat soils. The age group of 50–75 years is dominant amongst the stands, stands over 100 years being notably rare. The majority of the stands (57%) in the study area are small, spanning less than 1 ha. Stands represents both nutrient-rich site types (Mineral soil (OMT, MT), Peat soil (Mtkg I, Mtkg II)) and nutrient-poor site types (Mineral soil (VT, CT), Peat soil (Ptkg I, Ptkg II)).

2.2. Forest management regimes

We conducted a simulation of 45,559 forest stands over a 100-year period. We applied two management regimes with two variants of each to all forest stands, regardless of their initial conditions and subsequent development:

1. Rotation forest management (RF)
2. Extended rotation by 15 years (RF+15)
3. Continuous cover forestry (CCF high post-harvest BA)
4. Continuous cover forestry (CCF low post-harvest BA)

The proposed management regimes were informed by the 'best practices guide' for forest management in Finland (Äijälä et al., 2014). Two regimes were variations of the traditional RF with final felling, while two others followed CCF practices. The silvicultural systems under CCF involve continuous maintenance of forest cover, with only selected trees being harvested (Eyvindson et al., 2021; Peura et al., 2018; Repo et al., 2020). This assortment of management regimes facilitated diverse decision-making for each specific stand.

The first regime, a traditional RF method representing business as usual management regime, was guided by decision-making rules which

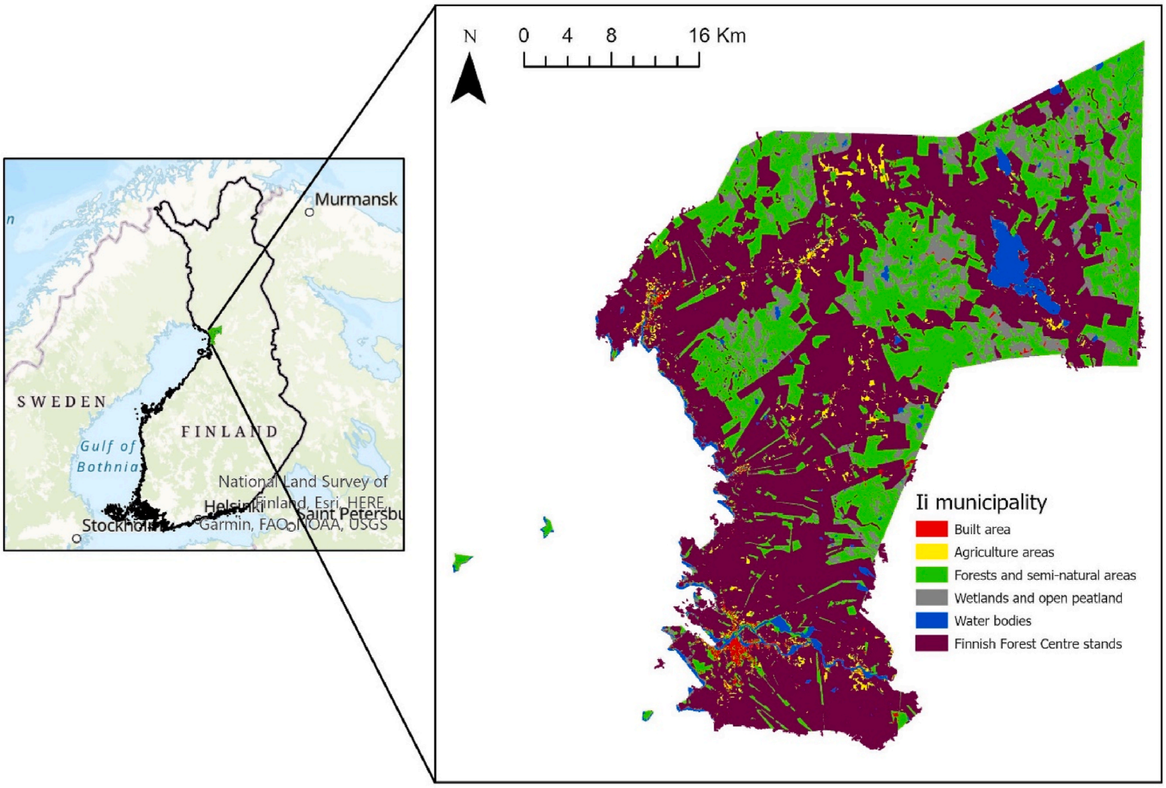

Fig. 1. Land use in the municipality of Ii in 2018. Stands data were provided by the Finnish Forest Centre (dark brown). CORINE land cover data were provided by the Finnish Environment Institute.

took into account several factors, including height of the dominant tree species, age and site type of the stands (Eyvindson et al., 2021; Repo et al., 2020). Depending on the site type, final felling was conducted when the dominant height exceeded either 16 or 14 m, and the stand age was over 70 or 90 years. After final felling, the stand was prepared for regeneration, which was achieved artificially through planting or seeding. We retained five retention trees per hectare. We conducted pre-commercial thinning to promote growth by reducing competition for resources. We employed two thinning rules: one without thinning at the beginning of the simulation and another incorporating thinning where possible. The option that provided the larger NPV was selected for our analysis. The second regime, RF+15, was a modified version of RF approach, extending the rotation time by 15 years representing therefore a more environmentally friendly management option compared to the RF regime (Eyvindson et al., 2021; Repo et al., 2020).

The CCF management alternatives were designed through a structured decision tree (Eyvindson et al., 2021; Repo et al., 2020). Harvesting actions under CCF regimes involved thinning from above, promoting natural regeneration of the stand. To promote economic efficiency, we did not require the maintenance of retention trees in CCF stands, with the assumption being increased economic value at an ecological cost. The decision to conduct thinning was based on stand basal area, with specific thresholds dependent on the site fertility. To create two variations of CCF, we adjusted the basal area threshold, resulting in a high basal area regime (CCF high post-harvest BA, 14–16 $m^2\ ha^{-1}$) and a low basal area regime (CCF low post-harvest BA, 8–10 $m^2\ ha^{-1}$), with the specific limit depending on site fertility (Eyvindson et al., 2021; Repo et al., 2020). Hence, these two regimes represent extensive and intensive CCF options, respectively.

2.3. SIMO forest stand simulations

We utilized the freely available SIMO (SIMulation and Optimization) forest simulator to simulate tree growth and yield, as outlined by Rasinmäki et al. (2009). The SIMO framework uses a range of models that represent natural processes like growth and mortality, along with forestry operations (Kangas and Rasinmäki, 2008). Growth and yield predictions for RF used the models devised by Hynynen et al. (2002). These models were grounded in extensive field measurement data sourced from the National Forest Inventory. This means that the models are designed to accommodate all primary tree species and site types found in Finland (Hynynen et al., 2002). In contrast, we used model for growth, and yield as defined by Pukkala et al. (2013) for CCF management. We opted to use these sets of models, as they are the best available models for the different management styles. We chose a time horizon of 100 years, split into 20 periods of 5 years each. This time horizon is long enough for the economic and ecological effects of different harvest regimes to manifest.

2.4. Net present value, biodiversity, carbon stock, and cost-efficiency index

We computed the net present value (NPV), biodiversity, and carbon stock at the stand level. These components encapsulate key aspects crucial to Finland's natural environment, specifically timber production, the creation of appropriate habitats for terrestrial vertebrate biodiversity, and measures for mitigating climate change, respectively.

NPV: We computed the NPV for each stand and each management regime. The NPV was calculated as the sum of discounted net income at each time step using a 3% discount rate:

$$NPV_{i,j} = \sum_{k=1}^{20} \frac{Net\ income_{i,j,k}}{1.03^{year,k}},$$

where $NPV_{i;j}$ represents the NPV of timber production for stand i under management regime j. $Net\ income_{i;j;k}$ signifies the income remaining after deducting costs from harvest revenues at time step *k*, while 1.03 accounts for a 3% discount rate. *Year, k* denotes the mid-year of time-step *k*. For our NPV calculations, we determined stumpage prices for eight timber assortments. These encompassed pulp wood and saw logs from different tree species: Norway spruce, Scots pine, birch, and other deciduous trees. In addition, we factored in the unit costs for silvicultural and operational work components: harvesting, mounding, fertilization, tending, planting, and tending of seedling stands (Table S1). The stumpage prices applied were different for RF and CCF, to reflect the change in costs associated to timber extraction (Table S2).

Biodiversity (BD): Following Triviño et al. (2017), we analyzed the habitat suitability index (HSI) of six focal species: hazel grouse (*Bonasia bonasa*), siberian flying squirrel (*Pteromys volans*), western capercaillie (*Tetrao urogallus*), lesser-spotted woodpecker (*Dendrocopos minor*), long-tailed tit (*Aegithalos caudatus*), and three-toed woodpecker (*Picoides tridactylus*) as indicator for biodiversity. The specific models for the HSI were originally presented in Mönkkönen et al. (2014). The selection of these focal species was guided by their embodiment of a wide spectrum of habitat types, along with their cultural and economic importance. Hazel grouse inhabits mixed forests, preferring areas with dense coniferous (especially *Norway spruce*) or deciduous undergrowth (Angelstam et al., 2004). Hazel grouse also holds economic value in hunting. Also, the siberian flying squirrel, a strictly protected species under the Habitats Directive (92/43 EC) of the European Union, prefers mature mixed boreal forests (Hanski, 1998). The presence of Norway spruce (*Picea abies*) and deciduous trees provides a suitable habitat for the species. However, the habitat of Siberian flying squirrel has been adversely affected by intensive rotation forestry regime (Hanski et al., 2000). The Capercaillie, a game bird of significant social and economic importance, serves as an umbrella species (Pakkala et al., 2003). Meanwhile, the Lesser-spotted woodpecker is a resident bird species that thrives in woodlands characterized by aged deciduous trees and an abundance of such trees showing signs of decay (Angelstam et al., 2004). The Long-tailed tit is known to favor habitats primarily consisting of middle-aged to old deciduous stands (Jansson and Angelstam, 1999). The three-toed woodpecker favors mature, predominantly coniferous forests with dead or dying trees, which are essential for its feeding and breeding. The habitat suitability models of these focal species were based on the expert insights concerning the specific habitat prerequisites (Mönkkönen et al., 2014; Triviño et al., 2017). Following the methodology of Tikkanen et al. (2007), and Mönkkönen et al. (2014), we also analyzed the HSI of four species groups associated with dead wood. We modeled dead wood decay using the decomposition models suitable to Finnish conditions (Mäkinen et al., 2006). These groups included endangered Ditylus and vulnerable Ceruchus, (insects), as well as the endangered, vulnerable, near threatened Piloporia and Amyloporia (fungi). The groups comprised 1, 1, 6, 5 species, respectively. We selected species associated with dead wood as our focal taxa, recognizing the significant proportion of species in boreal forests that depend on dead and decaying wood. The HSI, which ranges from 0 (unsuitable) to 1 (most suitable), indicates the probability of a species being present in a stand. Due to the varied habitat preferences of the 10 focal species and the varying characteristics of the studied forests stands, the habitat suitability for each species can vary widely, thereby contributing differently to the combined HSI. This type of measurement of biodiversity is an appropriate approach for a dynamic landscape level analysis including many stands that can provide habitat for different species and whose characteristic change over time. Notice also that this measure assigns a larger HSI for stands that can provide suitable habitat for several species at the same time. The combined HSI over a 100-year period was calculated for each stand and management regime. In addition, we assessed several forest characteristics under the management regimes, including deadwood diversity index, deadwood volume, deciduous tree volume, basal area of fresh deadwood, basal area of fresh deciduous deadwood, tree age and stem density. Deadwood diversity index is the volume of deadwood weighted by the types of deadwoods (e.g., snags and logs) and diversity of decay stages such as recently died, weakly decayed, medium decayed, very decayed, and totally decayed (Triviño et al., 2017).

Carbon stock (C): We computed carbon stock for each forest stand considering the carbon content in standing timber, dead wood, and soil, all quantified in tons of carbon (tons per ha C) (Eyvindson et al., 2021). We calculated carbon content of the standing timber based on the total volume from different tree species. We determined the volume of dead wood as the sum of various types of deadwood, which included different tree species at various decay stages, as per the decomposition models from Mäkinen et al. (2006). We assessed the carbon content of standing timber and deadwood to be 50% of the dry biomass.

For mineral soils, we computed initial stock of soil carbon based on Liski and Westman (1997) and the Yasso07 modeling framework to predict soil carbon stock development (Tuomi et al., 2011). The Yasso07 model accounts for soil carbon inputs from various sources such as thinning, natural mortality, understory vegetation and living tree litter (leaves, roots, branches, and stems) and incorporates decay functions to model the decomposition and subsequent carbon release (Mäkinen et al., 2006). For peatland soils, we applied the carbon stock models suggested by Ojanen et al. (2014). Here, the carbon stock is the sum of the understory vegetation and the living tree litter (leaves, roots, branches, and stems) with an additional contribution of 300 tons as an initial stocks of carbon in peat soils (Sarkkola, 2008).

Cost-efficiency index (CEI): We proposed two straightforward CEI indices as a means to assess the efficiency of different management regimes. These indices were implemented to evaluate the performance of these regimes, specifically focusing on their impact on biodiversity conservation, carbon storage, and NPV output. The indices were calculated using following two formulas:

$$CEI_{HSI} = \frac{HSI_i / HSI_{max}}{(1.1 - NPV_i / NPV_{max})}$$

$$CEI_C = \frac{C_i / C_{max}}{(1.1 - NPV_i / NPV_{max})}$$

here, CEI_{HSI} represents biodiversity-based CEI index, while CEI_C represents carbon-based CEI index. HSI_i denotes the biodiversity value at a given stand i, while HSI_{max} indicates the maximum biodiversity value observed across all stands and all management regimes. Similarly, C_i stands for the carbon storage value at a specific stand i, with C_{max} denoting the maximum carbon storage value among all stands and all management regimes. The NPV at the stand is designated as NPV_i, and the maximum NPV across all stands and all regimes is NPV_{max}. By dividing the relative biodiversity or carbon storage value by the adjusted relative NPV, we obtain a measure of the CEI of each stand in providing these ecosystem services. The maximum index value a stand can achieve is 10, representing the case where biodiversity or carbon storage are in perfect synergy (both are at the maximal level simultaneously). Thus, the objective is to strive to have the highest CEI as possible, indicating low economic costs while generating either positive biodiversity or carbon storage impacts.

We conducted statistical analyses to assess the significance of the differences in NPV, biodiversity, carbon stock and CEI results between the forest management regimes. We employed ANOVA (Analysis of Variance) followed by post-hoc Tukey-HSD (Honestly Significant Difference) tests to determine whether the average values of NPVs, biodiversity, carbon stock and CEIs for RF, RF+15, and the two CCF regimes were statistically ($p < 0.05$) distinct from one another. All statistical analysis were performed using the R programming language (R Core Team, 2024).

3. Results

3.1. Net present value (NPV)

The RF+15 yielded the smallest NPV per hectare on average, whereas the CCF low post-harvest BA resulted the largest NPV per hectare, followed by the CCF high post-harvest BA and RF (Table 1). This pattern held valid for both mineral and peat soils. When comparing all stands, the RF+15 resulted in 20% smaller NPV than the RF. Conversely, the CCF with high and low post-harvest BA resulted in 73% and 91% larger NPV than the RF, respectively. Notably, NPV values were, on average, 26% smaller in peat soils than in mineral soils, with the range varying between 20% and 38%.

Significant variation in NPV was observed across different stands within each regime (Table 1). As such, the profitability of the management regimes largely hinged on the stand-specific characteristics. Specifically, the CCF regime with low post-harvest BA resulted in the largest NPV for majority (81.65%) of the stands. The proportions decreased to 15.83%, 2.49%, and 0.01% for the CCF high post-harvest BA, RF, and RF+15, respectively.

NPV values were consistently larger in nutrient-rich site types (OMT, MT, Mtkg I, Mtkg II) compared to nutrient-poor site types (VT, CT, Ptkg I, Ptkg II) across both soil types (Fig. 2). For instance, the CT site type recorded 63–75% smaller NPV relative to the MT. Moreover, older forest stands, particularly those aged between 75 and 100 years and those over 100 years old, had larger NPV values compared to the younger age classes (50–75 and under 50 years old). This age-related trend was observable in both peat and mineral soils. For instance, the under 50 years age class yielded an NPV that was 50–85% smaller than the older age classes, relatively speaking. These patterns were similar for all regimes. For the youngest age class (<50), both CCF regimes provided a similar NPV than both RFs. Considering the VT and Ptkg I site types, the NPVs of both CCF were relatively close each other across all age class. In fact, the CCF low post-harvest BA produced the largest NPV for many of stands (varying from 7.4% to 51.1% among the age classes) within these specific site types. Notice also that the NPV of RF was relatively close to the largest NPV in the oldest age class (>100), particularly in the nutrient-rich sites (OMT, MT, Mtkg I, Mtkg II). Importantly, the results for peatland stands are subject to some uncertainty, because the oldest age glass included 55 stands in Mtkg I site type and only 6 stands in Ptkg II site type. In the other categories the number of stands varied from 121 to 4964 among the mineral and peat soil site types and the age classes.

3.2. Biodiversity measured as habitat suitability index (HSI)

On average RF yielded the smaller HSI, while CCF high post-harvest BA resulted the largest HSI, followed by the CCF low post-harvest BA and RF+15 (Table 2). Both mineral and peat soils exhibited this same trend. When all stands were considered, the RF resulted in 17%Ialler HSI values than the RF+15. Conversely, the CCF high post-harvest BA and the CCF low post-harvest BA resulted in 154% and 138% larger HSI than the BAU, respectively. On average, the HSI values were 13% smaller in mineral soils compared to in peat soils, with a range of 11–17%.

Large variation was noted in the HSI between stands within each regime indicating the HSI largely relied on stand-specific characteristic. Specifically, CCF high post-harvest BA achieved the largest HSI for a majority (66%) of the stands. Following this were the CCF high post-harvest BA (25%), RF+15 (7%), and RF (2%), respectively. These differences can be attributed to the increased volume of deciduous trees, and deciduous tree deadwood in the CCF regimes (Fig. S1 and Table S3).

Nutrient-rich site types (OMT, MT, Mtkg I, Mtkg II) generally displayed larger HSI values than nutrient-poor site types (VT, CT, Ptkg I, Ptkg II) across both peat and mineral soil types (Fig. 3). For instance, RF showed that the CT site type yielded an HSI that was 23–41% smaller than the MT, in relative terms. In the nutrient-rich site types, the CCF high post-harvest BA resulted clearly the largest HSI values, whereas in the nutrient poor site types, the differences were less pronounced.

Subtle variation in HSI values were observed across different age classes. For example, in the Ir-100-years age class, RF showed an HSI that varied by 5–26% (either smaller or larger) compared to the 75–100 years age class. Interestingly, a trend of decreasing HSI values was noted when forest stands aged in both RF regimes while no such trend was visible for either CCFs. The relative difference between CCF and RF appeared to be influenced by the site type: the disparity was larger in nutrient rich sites compared to nutrient poor sites. For instance, the difference between RF and CCF high post-harvest BA in 50-years age class was 61% in the MT site type, but only 22% at the CT. Notably, RF+15 performed better in the nutrient poor site types.

3.3. Carbon stock

Variability in carbon stocks across all regimes was relatively modest (Table 3). On average, RF yielded the smallest carbon stocks, whereas CCF high post-harvest BA had the largest. These were closely followed by the RF+15 and CCF low post-harvest BA. This consistency was observed in both mineral and peat soil types. Interestingly, peat soils generally had larger carbon stocks than mineral soils due to their significant carbon stock. It is also worth noting that, compared to NPV and HSI, carbon stock showed less fluctuation across different regimes in both soil types.

The relative differences between the regimes were also quite minimal. In fact, when taking into account all stands, RF reported carbon stock that were only 4% smaller than RF+15. The CCF high post-harvest BA and the CCF low post-harvest BA demonstrated 11% and 3% larger carbon stocks than RF, respectively. Carbon stocks values were, on average, 71% smaller in mineral soils than in peat soils with a range of 70–73%. In terms of stand distribution, the CCF high post-harvest BA resulted in the largest carbon stocks for majority (73.1%) of stands. This compares with 20.4%, 5.6%, and 0.8% for the RF+15, RF and CCF high post-harvest BA, respectively.

In mineral soil, carbon stocks were somewhat larger in nutrient-rich site types (OMT, MT, Mtkg I, Mtkg II) than in nutrient-poor site types

Table 1

Net present value (NPV) at all stands, and separately for soil types under rotation forestry (RF and RF+15), continuous cover forestry (CCF high post-harvest BA and CCF low post-harvest BA). SD – Standard deviation. The ANOVA test confirmed significant ($p < 0.05$) differences in NPV among the management regimes, and Tukey-HSD tests confirmed the pairwise differences were statistically significant.

Regimes	NPV, all stands, per hectare, Mean ± SD	NPV, mineral soil, per hectare, Mean ± SD	NPV, peat soil, per hectare, Mean ± SD	Volume increment m^3, all stands, per hectare, Mean ± SD
RF[a]	4379 ± 7507	4844 ± 8147	3006 ± 4924	2.41 ± 0.79
RF+15[b]	3519 ± 6035	3890 ± 6539	2423 ± 4010	2.29 ± 0.80
CCF high post-harvest BA[c]	7593 ± 10051	8002 ± 10617	6387 ± 8035	3.99 ± 1.04
CCF low post-harvest BA[d]	8381 ± 10935	8850 ± 11589	6999 ± 8573	4.13 ± 1.56

a,b,c,d: Regimes with different letters differ significantly from each other at the 0.05 significance level (Tukey-HSD).

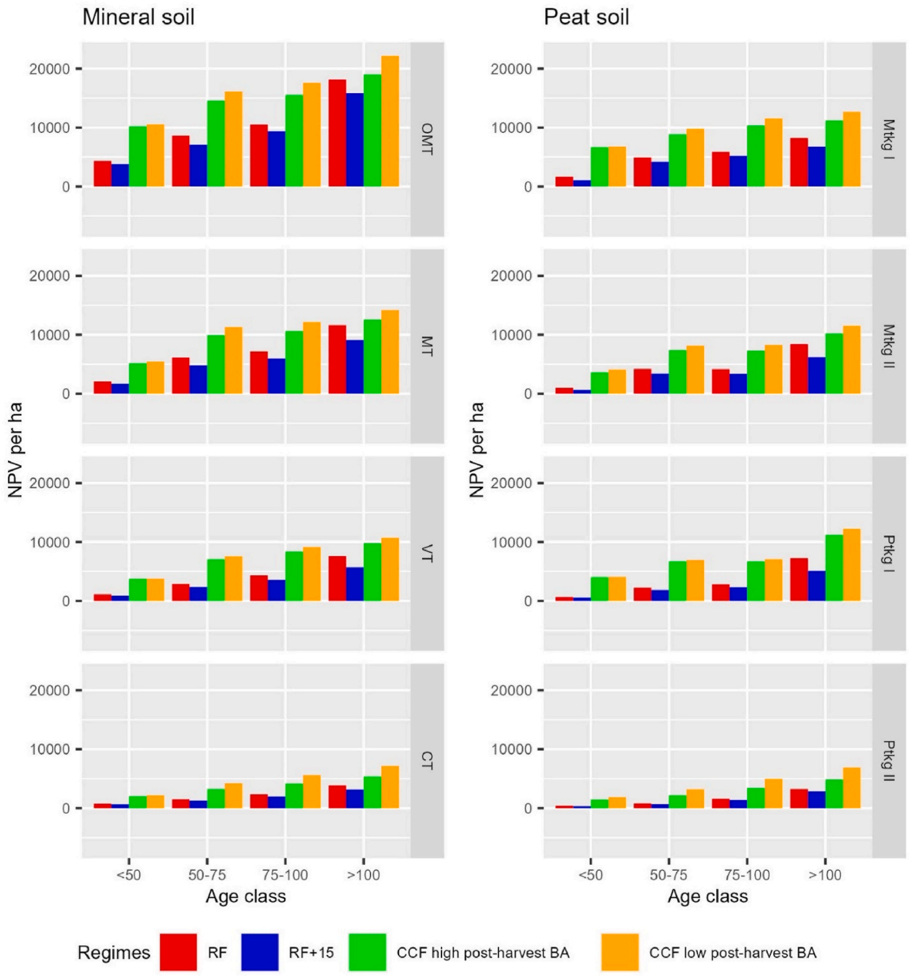

Fig. 2. Net present value (NPV) separately for soil types, site types and age classes for rotation forestry (RF and RF+15), and continuous cover forestry (CCF high post-harvest BA and CCF low post-harvest BA).

(VT, CT, Ptkg I, Ptkg II) (Fig. 4). For instance, relative to the MT site types, the CT site type exhibited 24–27% smaller carbon stock. In peat soil, however, carbon stocks were similar between nutrient-rich and nutrient-poor site types. The variation in carbon stocks among different age classes of stands was also minimal. For example, stands in the RF regime that were older than 100 years showed only a 1–11% variation (either smaller or larger) in carbon stock compared to stands aged 75–100 years. Overall, the trend of carbon stock values remained neutral or stable as stands aged.

CCF high post-harvest BA regime provided typically the largest carbon stocks across various site type and age class categories, ranging from 18.8 to 100% of stands. In contrast, RF+15 provided the largest values specially in the youngest age class (under 50 years) covering 10–67% of stands across different site types. It also performed well in other age classes but mainly in nutrient poor sites (VT, CT, Ptkg I and II). Interestingly, CCF low post-harvest BA rarely led in carbon stock values, except in the nutrient poorest sites (CT, Ptkg II).

3.4. *Cost-efficiency index (CEI)*

When examining biodiversity-based CEI, both CCFs outperformed both RFs (Table 4). Specifically, the CCF low post-harvest BA exhibited the largest CEI value, followed by the CCF high post-harvest BA and RF. The RF+15 yielded the smallest CBI, indicating it was the least cost-efficient in terms of biodiversity. This trend was consistent across both soil types.

Table 2
Average habitat suitability index (HSI) at all stands, and separately for soil types under rotation forestry (RF and RF+15), continuous cover forestry (CCF high post-harvest BA and CC– low post-harvest BA). SD – Standard deviation. The ANOVA test confirmed significant ($p < 0.05$) differences in NPV among the management regimes, and Tukey-HSD tests confirmed the pairwise differences were statistically significant.

Regimes	All stands, Mean ± SD	Mineral soil, Mean ± SD	Peat soil, Mean ± SD
RF[a]	0.24 ± 0.14	0.23 ± 0.13	0.28 ± 0.16
RF+15[b]	0.29 ± 0.17	0.28 ± 0.16	0.32 ± 0.17
CCF high post-harvest BA[c]	0.61 ± 0.22	0.60 ± 0.22	0.67 ± 0.23
CCF low post-harvest BA[d]	0.57 ± 0.20	0.55 ± 0.20	0.63 ± 0.20

a,b,c,d: Regimes with different letters differ significantly from each other at the 0.05 significance level (Tukey-HSD).

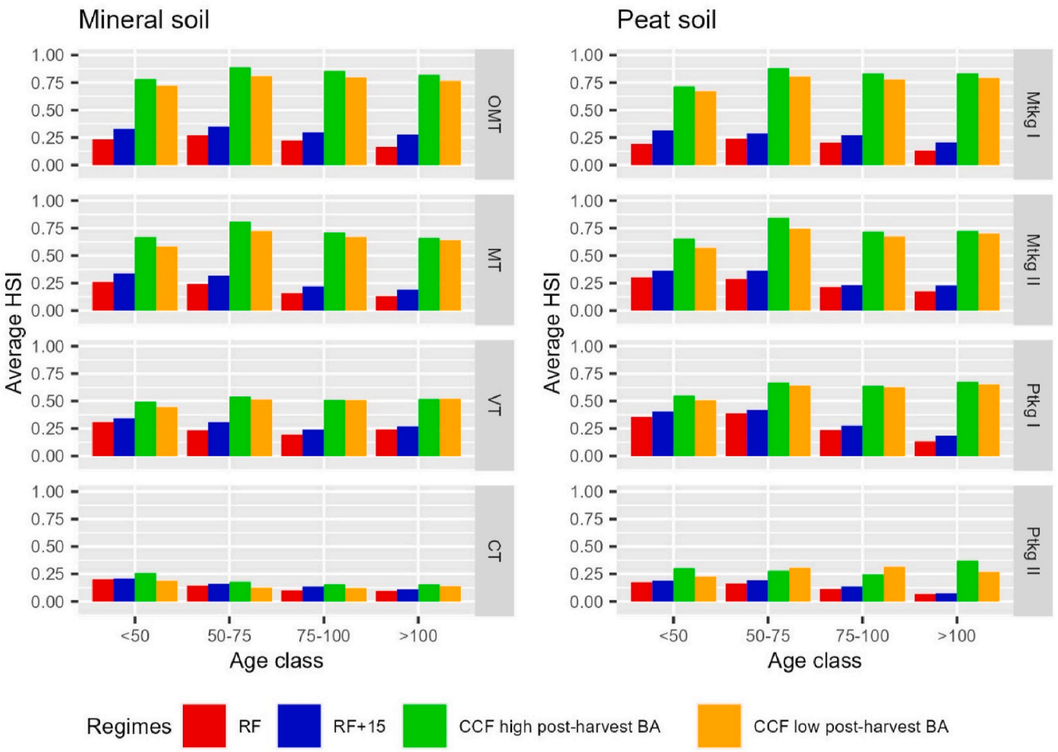

Fig. 3. Average habitat suitability index (HSI) values separately for soil types, site types and age classes for rotation forestry (RF and RF+15), and continuous cover forestry (CCF high post-harvest BA and CCF low post-harvest BA).

Table 3
Carbon stock at all stands, and separately for soil types under rotation forestry (RF and RF+15), continuous cover forestry (CCF high post-harvest BA and CCF low post-harvest BA). SD – Standard deviation. The ANOVA test confirmed significant ($p < 0.05$) differences in NPV among the management regimes, and Tukey-HSD tests confirmed the pairwise differences were statistically significant except between all stands of RF+15 and CCF low post-harvest BA.

Regimes	All stands, tons/ha, Mean ± SD	Mineral soil, tons/ha, Mean ± SD	Peat soil, tons/ha, Mean ± SD
RF^{a}	149 ± 102	90 ± 11	324 ± 8
RF+15^{b,e}	155 ± 101	96 ± 14	328 ± 9
CCF high post-harvest BA^{c}	165 ± 105	104 ± 18	344 ± 10
CCF low post-harvest BA^{d,e}	154 ± 154	93 ± 16	334 ± 9

a,b,c,d: Regimes with different letters differ significantly from each other at the 0.05 significance level (Tukey-HSD).
e: All stands of RF+15 and CCF low post-harvest BA differ insignificantly from each other at the 0.05 significance level (Tukey-HSD).

Interestingly, the variation in CEI between mineral and peat soils was marginal, showing only a slight 0.05% increase for peat soil. The disparities in CEI between RF and CCF were considerable. Specifically, when compared to RF, the CCF low post-harvest BA had a CEI value 6.6 times larger, while CCT high post-harvest BA was 10.5 times larger. Notably, CCF low post-harvest BA displayed a markedly larger CEI than the CCF high post-harvest BA. This suggests that the relative increase in HSI values associated with the CCF high post-harvest BA was insufficient to offset the relative decrease in NPV. The difference between RF and RF+15 was relatively modest at 7%.

In each site type-age class category studied, CCF low post-harvest BA ranked the highest in CEI, followed by CCF high post-harvest BA (Fig. 5). However, the performance of both CCFs was smaller in the nutrient poorest site types (CT, Ptkg II) compared to other site types. In contrast, RF performance improved on nutrient poor sites. The pattern was not that clear for the RF+15. Regarding the age classes, CCF low post-harvest BA maintained quite stable performance across age classes. In contrast, CCF high post-harvest BA displayed a decreasing CEI trend as the forests stand aged. The performance of RF and RF+15 was largest in the oldest age class in mineral soils, but their performance decreased with the stand age in peat soils excluding the site type Mtkg II where the pattern was the opposite.

On the one hand, there was less variation of CEI values across site types for RF and RF+15 (Fig. 5). For example, when expressed in relative terms, MT site type in the RF displayed a 33% smaller CEI than the CT site types with a range of 6–46%. On the other hand, there is more variation of CEI across site types for CCF low and high post-harvest BA. For instance, the MT site type showed a 71% larger CEI in CCF high post-harvest BA than the CT in CCF low post-harvest BA with a range of 36–111%.

Furthermore, minor variation of CEI values were observed within different age classes. For example, in relative terms, the RF had a 17% larger CEI in the under 50 years age class compared to the 50–75 years class.

Carbon-based CEI also favored CCFs over RFs (Table 5). The CCF low post-harvest BA produced the largest CBI, while the RF+15 had the smallest. This was followed by the CCF high post-harvest BA and RF, respectively. This pattern was similar for both mineral and peat soils.

The difference in CEI values between peat and mineral soil was more pronounced for carbon-based CEI, with a 6% increase for peat soils. The

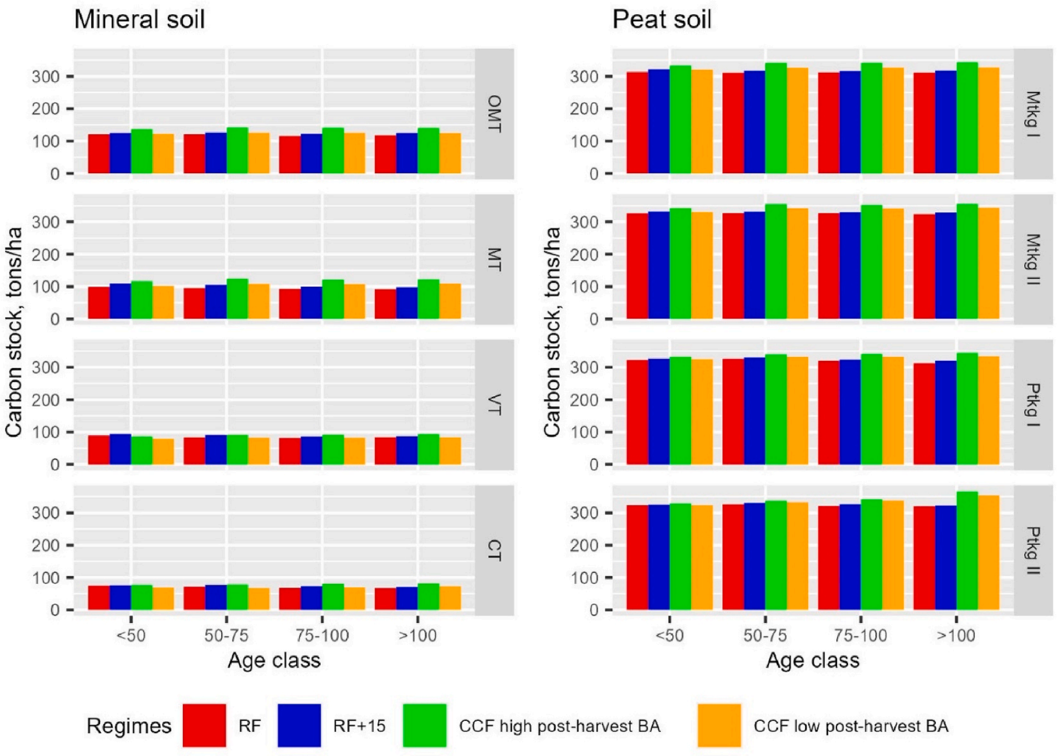

Fig. 4. Carbon stock separately for soil types, site types and age classes for rotation forestry (RF and RF+15), and continuous cover forestry (CCF high post-harvest BA and CCF low post-harvest BA).

Table 4
Biodiversity-based cost-efficiency index (CEI) at all stands, and separately for soil types under rotation forestry (RF and RF+15), continuous cover forestry (CCF high post-harvest BA and CCF low post-harvest BA). SD − Standard deviation. The ANOVA test confirmed significant ($p < 0.05$) differences in NPV among the management regimes, and Tukey-HSD tests confirmed the pairwise differences were statistically significant.

Regimes	All stands, Mean ± SD	Mineral soil, Mean ± SD	Peat soil, Mean ± SD
RF[a]	0.72 ± 0.72	0.71 ± 0.69	0.72 ± 0.77
RF+15[b]	0.67 ± 0.42	0.67 ± 0.42	0.64 ± 0.40
CCF high post-harvest BA[c]	5.48 ± 2.42	5.51 ± 2.38	5.39 ± 2.53
CCF low post-harvest BA[d]	8.23 ± 2.00	8.20 ± 2.02	8.34 ± 1.94

a,b,c,d: Regimes with different letters differ significantly from each other at the 0.05 significance level (Tukey-HSD).

gap in CEI between RF and CCF regimes were substantial. Relative to the RF, the CCF low and high post-harvest BA resulted in 4 times and 2.4 times larger CEI, respectively.

Generally, older forests showed an upwards trend across all regimes except for CCF high post-harvest BA which showed a decline (Fig. 6). For instance, the under 50 years age class for all site types of the RF demonstrated a CEI value that was 52% (ranging from 22 to 65%) smaller than the over 100 years age class. However, for all site types of the CCF high post-harvest BA, the over 100 years age class resulted in a 36% (range 24–45%) larger CEI than the under 50 years age class. Notice however that the trend was not linear with respect to the age classes in all site types. In particular, the differences in the CEI of the CCF low post-harvest BA between the age classes were small.

Moreover, the relative difference between the CCF and RF regimes does not appear to be dependent on the age class of the stands. Changes in CEI value also do not seem to be influenced by the site type, except that the performance of RF deteriorated when moving from nutrient rich to the nutrient poor sites, especially in the older age classes. In general, the RF seem to perform better in mineral than peat soil while the opposite is true for the CCF low post-harvest BA, but the differences were quite small. Regarding the CCF high post-harvest BA, there was not any systematic differences in CEI between the soil types across the studies site type-age class categories.

4. Discussion

Forests management faces challenges regarding contrasting environmental, economic, and social targets. Compromises may therefore be needed to find the most cost-efficient strategy to reach the targets. In many cases, landowners must consider which trade-offs between biodiversity/carbon stock and the economic performance are acceptable according to their management objectives. Our study demonstrates the benefits of adopting diverse management approaches. Utilizing forest growth simulations, we examined long-term effects of four management regimes including rotation forest management (RF), and continuous cover forestry (CCF) on net present value (NPV), biodiversity and carbon stock by categorizing the effects by soil and site types and age classes. Our findings suggest that CCF holds the potential to deliver more cost-efficient ecosystem services and maintain greater biodiversity in Northern boreal forests of Finland compared to RF approaches.

Reflecting on the outcomes of our case study, we again consider our research questions. *First, how do different management regimes (RF and CCF at two levels of harvest intensity) impact the economic performance of timber production?* In our study, the CCF low post-harvest BA, in which the stand was thinned to the lower BA limit defined by the forest law performed well across both nutrient rich and poor sites. Interestingly, CCF high post-harvest BA performed also relatively well in nutrient poor sites. This suggests that CCF is more effective than RF in promoting forest growth and potentially leading to higher timber yields. This aligns with previous research demonstrating the benefits of intensive thinning

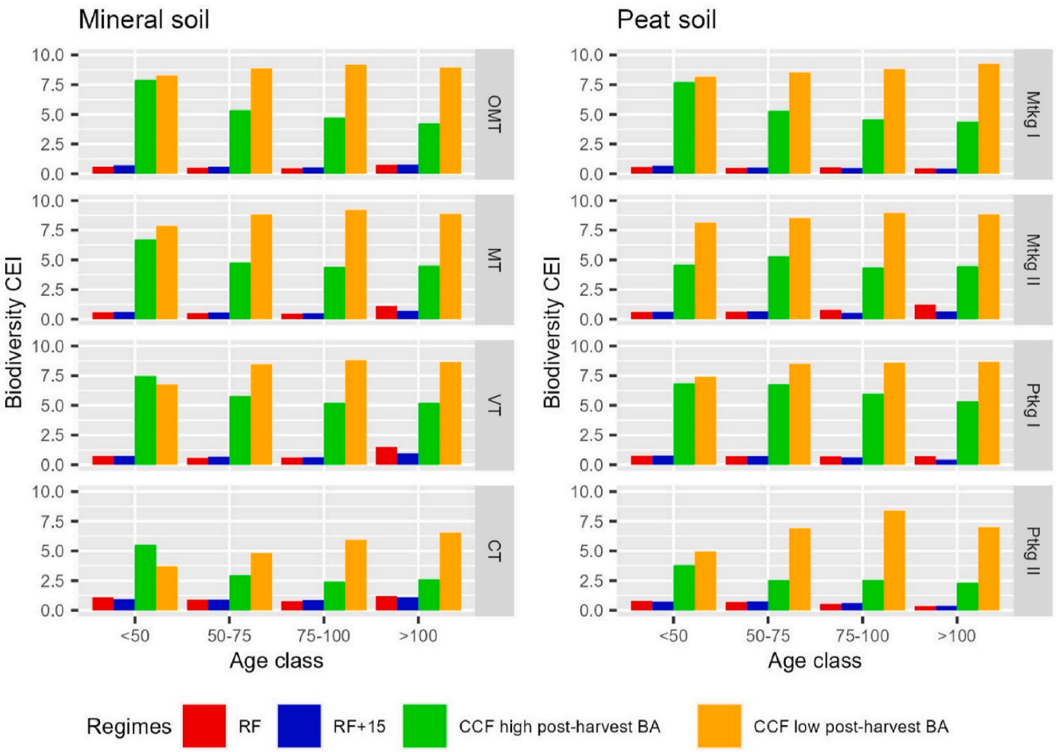

Fig. 5. Biodiversity-based cost-efficiency index (CEI) values separately for soil types, site types and age classes for rotation forestry (RF and RF+15), and continuous cover forestry (CCF high post-harvest BA and CCF low post-harvest BA).

Table 5
Carbon-based cost-efficiency index (CEI) at all stands, and separately for soil types under rotation forestry (RF and RF+15), continuous cover forestry (CCF high post-harvest BA and CCF low post-harvest BA). SD – Standard deviation. The ANOVA test confirmed significant ($p < 0.05$) differences in NPV among the management regimes, and Tukey-HSD tests confirmed the pairwise differences were statistically significant.

Regimes	All stands, Mean ± SD	Mineral soil, Mean ± SD	Peat soil, Mean ± SD
RF[a]	1.65 ± 1.27	1.62 ± 1.14	1.73 ± 1.59
RF+15[b]	1.35 ± 0.66	1.35 ± 0.58	1.37 ± 0.85
CCF high post-harvest BA[c]	5.63 ± 2.40	5.64 ± 2.33	5.60 ± 2.59
CCF low post-harvest BA[d]	8.37 ± 1.58	8.14 ± 1.48	9.05 ± 1.66

a,b,c,d: Regimes with different letters differ significantly from each other at the 0.05 significance level (Tukey-HSD).

in CCF regimes (Pukkala et al., 2010; Rämö and Tahvonen, 2017). It is important to emphasize that the increase in timber yield under CCF compared to RF largely accounts for the higher NPV observed for CCF in our study. However, a higher long-term timber yield in RF regimes compared to CCF regimes was also reported in several studies (e.g., Ekholm et al., 2023).

If the timber yield in CCF were similar to that of RF, the economic advantage of CCF would diminish, making its NPV closer to that of RF, depending on factors like management costs and market prices. In such a situation, non-economic services, such as biodiversity and carbon stock, might become more decisive factors in management decisions. Moreover, existing literature highlights that the relative economic performance of RF and CCF depend on the characteristics of the initial stand which is largely determined by the previous management of the stand (Juutinen et al., 2018; Nakajima et al., 2017; Tahvonen and Rämö, 2016). For instance, old even-aged stands managed according to the RF may not be that suitable for CCF in terms of financial performance (Juutinen et al., 2018).

Second, what could be the potential effects of the management regimes on biodiversity indicators? The relative effectiveness of RF and CCF in terms of biodiversity depends on specific initial stand characteristics particularly the site type, which includes both mineral and peat soils across various fertility classes and age classes. This highlights the significant influence of fertility class on biodiversity. This is consistent with previous studies (e.g., Calladine et al., 2015; Díaz-Yáñez et al., 2019; Peura et al., 2018; Pukkala, 2016, 2022), that the CCF method can achieve higher biodiversity values (HSI). The six focal species and four deadwood associated species examined in our study depend on various forest characteristics for their survival including basal area, age, stem density, deadwood volume and the volume of deciduous trees (Fig. S1 and Table S3). However, there are differences in biodiversity value between the species groups (Peura et al., 2018). The proportion of deciduous tree volume is positively influenced with all vertebrate species except the Hazel grouse which prefers 20–40% deciduous tree volume. With respect to the proportion of pine volume, the Siberian flying squirrel shows a negative influence while the Capercaillie shows a positive influence (Miettinen et al., 2024; Mönkkönen et al., 2014). It is important to note that, the habitat of the flying squirrel diminishes with increasing levels of timber extraction, regardless of the management scenarios (Eyvindson et al., 2021). The deadwood volume is positively influenced with all vertebrate species.

The use of RF could potentially decrease species diversity, particularly if young forests are managed according to recommendations that involve removing most deciduous trees during tending and weeding treatments. In contrast, CCF promotes biodiversity by minimizing clearfelling, increased broadleaf trees due to ingrowth and avoiding the establishment of pine or spruce monocultures (Díaz-Yáñez et al., 2019; Peura et al., 2018). The presence of mature trees in CCF regimes contribute to higher suitability for these species compared to RF regimes. Additionally, CCF promotes higher vertical and horizontal

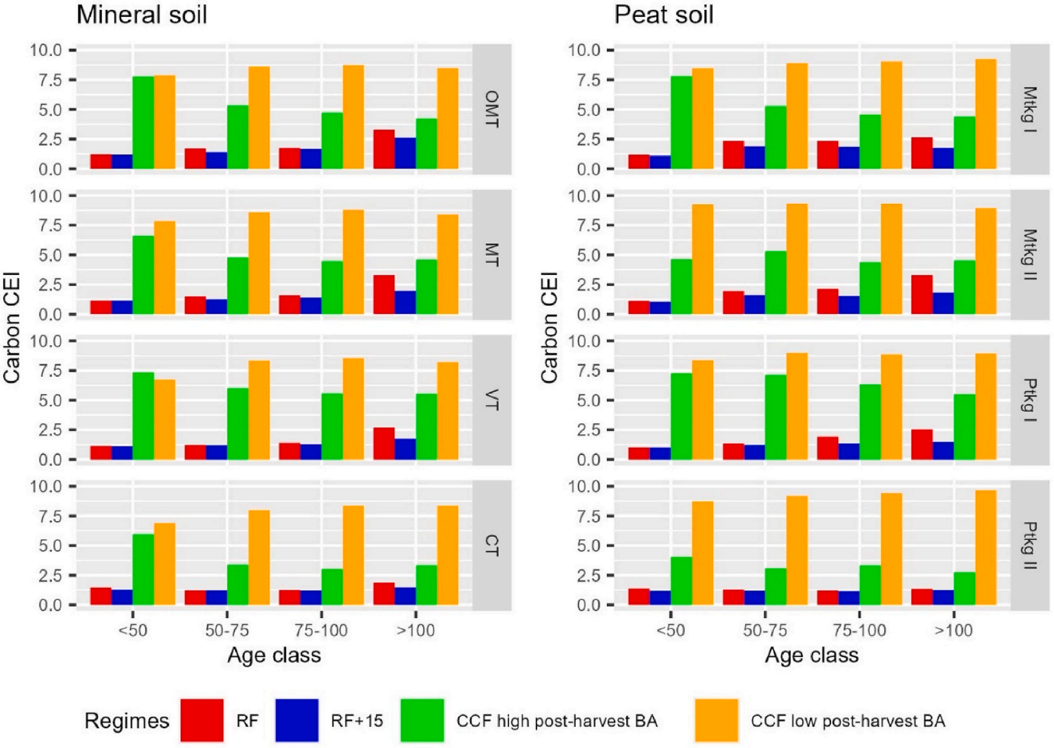

Fig. 6. Carbon-based cost-efficiency index (CEI) values separately for soil types, site types and age classes for rotation forestry (RF and RF+15), and continuous cover forestry (CCF high post-harvest BA and CCF low post-harvest BA).

structural diversity, including a mix of tree ages, species, spatial distribution of trees and openings within the forest, resulting in a complex habitat that beneficial for the focal species (Schütz et al., 2012; Mason et al., 2022). These features provide diverse nesting, foraging, and shelter opportunities for birds and the flying squirrel (Klein et al., 2020). CCF management regimes provides higher levels of deadwood, deciduous trees, and stem density, contributing to greater structural complexity and potentially increased biodiversity. Conversely, RF, particularly in old even-aged stands (>80 years), may not offer such habitat complexity, leading to lower biodiversity suitability values (Savilaakso et al., 2021).

It is also important to note that CCF is not necessarily the universally best approach. Duflot et al. (2022) highlight that while CCF generally benefits some species, CCF might not be optimal for all stands at the landscape level, especially when considering specific management alternatives. Klein et al. (2020) also note that the requirements of suitable habitat of a species differ across species groups, and the presence or diversity of a specific species group doesn't necessarily imply the presence of suitable habitat in other groups. Further research is needed to explore the nuanced effects of these management regimes on a wider range of species.

Third, how do different forest management regimes influence the change in carbon stock? Across all regimes, fluctuations in carbon stocks were relatively minor, irrespective of soil type, forest stand age classes, and site types. However, the CCF high post-harvest BA typically yielded the largest carbon stock values. It should be noted that while CCF can potentially hold larger carbon stocks in the forest ecosystem itself, it might produce less timber (and hence less carbon stored in long-lived wood products) than RF, which should also be taken into account in a comprehensive carbon accounting framework (Peura et al., 2018). Previous studies such as those by Ahtikoski et al. (2022), Lehtonen et al. (2023), Nieminen et al. (2018), Peura et al. (2018), highlighted that CCF outperformed RF in terms of carbon sequestration efficiency, particularly in mineral soils and peatlands. These studies emphasized the ecological benefits of avoiding clearcutting in RF and maintaining continuous natural regeneration in CCF.

Last, how does the management regime affect cost-efficiency of enhancing biodiversity and carbon benefits? Our findings align with earlier studies (Peura et al., 2018; Pukkala, 2022) showing that CCF can enhance biodiversity indicators and carbon storage while maximizing the NPV. This is not surprising, as CCF eschews clear-felling, a practice detrimental to the habitat of the six focal species we studied. Nonetheless, CCF may sometimes decrease biodiversity, as highlighted in studies by Felton et al. (2016), Nolet et al. (2018), and Schall et al. (2018). Previous research suggests the positive impact of CCF on CEIs may fluctuate when applying more specific indicators, such as the habitat suitability for certain species (Pukkala, 2016). In our case, NPV largely drives the cost-efficiency index (CEI) results. CCF implements thinning from above, focusing primarily on larger trees, which yields more sawlogs and less pulpwood compared to RF's strategy of thinning from the below, and targeting smaller trees. Additionally, CCF relies on natural regeneration, which reduces costs associated with the artificial planting practices employed in RF. These features improve the financial performance of CCF relative to RF (Eyvindson et al., 2021). Norway spruce, being more shade-tolerant than other common Finnish tree species like Scots pine and downy birch, which require direct sunlight and typically establish after disturbances like fire or clear-cutting, may become more dominant under CCF. This suggests that CCF implementation could result in forests becoming more spruce-dominated, as other native species may not naturally regenerate as effectively (Laudon and Hasselquist, 2023). CCF may boost certain species, its success in natural regeneration is not guaranteed, potentially affecting its profitability and if natural regeneration fails, the forest must be regenerated by the artificial regeneration which increase the costs. However, the cost-efficiency depends on the choice of variables included in the analysis. Readers should exercise caution when attempting to generalize our results to other regions, as the ecosystem services can vary significantly by forest characteristics and forest management with spatial trade-offs

(Mazziotta et al., 2023; Vergarechea et al., 2023).

Over the past century, boreal forests management has largely been dominated by RF due to its ability to provide quick yields and relatively predictable economic returns (Puettmann et al., 2015). In contrast, CCF emerges as an alternative that poses fewer ecological risks and allows for a more heterogenous forest structure, which not only supports diverse habitats but can also enhance the resilience of forests against pests and diseases (Mason et al., 2022). Despite these advantages, the dissemination of knowledge and skill development for CCF lags behind RF, hindering its widespread adoption. In fact, the practice of CCF was not legal in Finland until 2014, when the Finnish forest legislation was changed. Yet, the paradigm in forests management is shifting. Heightened awareness about climate change, habitat destruction, and biodiversity decline has intensified interest in CCF. Consequently, CCF, with its multifaceted ecological benefits, is drawing attention from both researchers and practitioners. However, CCF necessitates active management, including the removal of damaged and insect-infested trees. CCF also requires the implementation of harvesting techniques that minimize damage to the remaining trees and the careful management of natural regeneration. Thus, CCF management practices can be intensive (Mason et al., 2022; Seedre et al., 2018). However, transformation to CCF need not be more costly than RF if natural regeneration is successful (Davies and Kerr, 2015). Research on CCF practices in Scots pine-dominated forests are still under development, and its effectiveness as a preferred management regime requires further research (Häggström et al., 2024). A recent study by Miettinen et al. (2024) highlights a potential challenge: the large gap size needed for Scots pine regeneration could potentially affect CCF's ability to maintain water levels. This is an important consideration for future research.

Although our modeling approach offers valuable insights, it has certain uncertainties, particularly in economic returns, biodiversity, and carbon stock. First, our study may have overestimated the economic performance of CCF for several reasons. Hynynen et al. (2019) suggested that timber yield from CCF might decrease over time, but this was not taken into account in our simulations. Additionally, Ahtikoski and Hökkä (2019) showed that an optimized RF management regime could yield a higher NPV than what is officially recommended. In our study, the NPV of CCF was probably closer to an optimal level than the NPV of RF because the low post-harvest BA regime has been found to be close to optimum in previous studies. Also, it's likely that tree growth rates for RF could surpass those predicted in our simulations, given the use of genetically improved seedling (Ahtikoski et al., 2020). The growth models for RF used in our study bases on empirical data which probably does not fully capture this effect. A lower growth increment from CCF compared to RF was reported in Hannerz et al. (2017), Lundqvist (2017), and Hynynen et al. (2019). Second, we focused on select umbrella species to represent biodiversity, but other indicators exist. For instance, species that depend on decaying wood or old growth could benefit more from the RF+15 scenario. Still, as Jonsson et al. (2010) demonstrated, extending rotation length is not always cost-effective, even though it increases substrate availability for wood-dwelling species, as shown in three Swedish regions. Third, the road network was sufficient in our study area where small patches of forest are frequently harvested across the landscape. This requirement to continually harvest small patches has already had a dramatic impact on road networks, and can be compared to other countries that do not have as extensive road networks (Angelstam et al., 2018). Fourth, thinning from below or clear-felling in RF, which beneficial in certain contexts, requires careful planning and execution to avoid negative impacts on the forest ecosystem, such as reduced biodiversity, and potentially increased vulnerability to pests and diseases. Fifth, CCF characterized by continuous forest cover and understory, may inadvertently increase the risk of surface fires escalating to the canopy, thereby heightening forest fire severity. However, the link between CCF and elevated fire risks is complex and not directly established by studies. The inherent nature of CCF could theoretically aid in the spread of fires from the surface to the canopy. Nevertheless, this risk depends on a range of factors, including forest composition, climatic conditions, and specific management practices tailored to CCF (Hyytiäinen and Haight, 2012). Last, we used carbon stock as an indicator variable from viewpoint of climate change. However, the carbon stock is not fully representative of the impact of forest management on climate change, particularly concerning peatlands. This is because it doesn't differentiate between various types of greenhouse gases like CO_2, N_2O and CH_4, which have distinct global warming potentials and radiative forcing effects. Accurately measuring soil emissions from peatland under different management regimes remains a challenging task (Alm et al., 2022). Notice also that the carbon storage and sequestration calculations are sensitive to the time frame considered. In our case, we considered a 100-year period (i.e., approximately one rotation in RF regime), and therefore, the average carbon stock calculated over the period did not vary much between the management regimes.

In conclusion, our results indicate that CCF is an underutilized forest management practice in Finland, with substantial potential for more widespread application. Its multifaceted benefits lend support to this proposition. However, previous forest law may have contributed to its current underutilization. Forest owners are also showing a growing intention to utilize CCF more frequently in the future, suggesting a need for additional information and guidance in this area (Juutinen et al., 2020; Pukkala, 2021). This is further corroborated by public support, as indicated by Mäntymaa et al. (2023). Finally, it is important to notice that there was great variation in the stand characteristic among the studied stands, so it is likely that the forests should be managed in multiple ways to create multifunctional forest landscapes. Further research is needed on forest increment and Scots pine regeneration under CCF practices. For this purpose, our proposed cost-efficiency indices may provide a more practical decision-making tool than stand-level optimization knowledge, which is often impractical due to its time-consuming and data-intensive nature (Kurttila et al., 2013).

CRediT authorship contribution statement

Parvez Rana: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Artti Juutinen:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Kyle Eyvindson:** Writing – review & editing, Validation, Software, Resources, Methodology, Formal analysis. **Anne Tolvanen:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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References

Ahti, T., Hamet-Ahti, L., Jalas, J., 1968. Vegetation zones and their sections in northwestern Europe. Ann. Bot. Fenn. 5, 169–211.

Ahtikoski, A., Hökkä, H., 2019. Intensive Forest Management — Does it Pay off Financially on Drained Peatlands ?, vol. 1113, pp. 1101–1113.

Ahtikoski, A., Ahtikoski, R., Haapanen, M., Hynynen, J., 2020. Economic performance of genetically improved reforestation material in joint production of timber and carbon sequestration : a case study from Finland. Forests 11, 1–12.

Ahtikoski, A., Rämö, J., Juutinen, A., Shanin, V., Mäkipää, R., 2022. Continuous cover forestry and cost of carbon abatement on mineral soils and peatlands. Front. Environ. Sci. 10, 1–11.

Äijälä, O., Koistinen, A., Sved, J., Vanhatalo, K., Väisänen, P. (Eds.), 2014. Hyvän Metsänhoidon Suositukset— Metsänhoito. Metsätalouden Ke- Hittämiskeskus Tapio.

Akujärvi, A., Repo, A., Akujärvi, A.M., Liski, J., 2021. Bridging mapping and simulation modelling in the ecosystem service assessments of boreal forests: effects of bioection on carbon dynamics. For. Ecosyst. 8 https://doi.org/10.1186/s40663-021-00283-2.

Alm, J., Wall, A., Myllykangas, J., Ojanen, P., Heikkinen, J., Henttonen, H.M., Laiho, R., 2022. A new method for estimating carbon dioxide emissions from drained peatland forest soils for the greenhouse gas inventory of Finland. Biogeosciences 20, 3827–3855.

Andersson, Å., Berg, C., Eriksson, M.O.G., Grahn, J., Green, M., Nilsson, J., Nilsson, S.G., Tjernberg, M., 2020. Red List 2020. SLU Artdatabanken, Uppsala.

Andreassen, K., Øyen, B.H., 2002. Economic consequences of three silvicultural methods in unevenaged mature coastal sps of central Norway. Forestry 75, 483–488. https://doi.org/10.1093/forestry/75.4.483.

Angelstam, P., Boutin, S., Schmiegelow, F., Villard, Marc-andré, Drapeau, P., Host, G., Innes, J., Isachenko, G., Kuuluvainen, T., Mönkkönen, M., Niemi, G., Roberge, J., Spence, J., Stone, D., Angelstam, P., Boutin, S., Schmiegelow, F., Villard, Marc-andr, Drapeau, P., Isachenko, G., Kuuluvainen, T., Mikko, M., Roberge, J., Spence, J., Host, G., Niemi, G., 2004. Targets for boreal forest biodiversity conservation: a rationale for macroecological research and adaptive management. Ecol. Bull. 51, 487–509.

Angelstam, P., Naumov, V., Elbakidze, M., Manton, M., Priednieks, J., Rendenieks, Z., 2018. Wood production and biodiversity conservation are rival forestry objectives in Europe's Baltic Sea Region. Ecosphere 9 (3), e02119.

Atlegrim, O., Sjijberg, K., 1996. Effects of clear-cutting and single-tree selection harvests on herbivorous insect larvae feeding on bilberry (Vaccinium myrtillus) in uneven-aged boreal Picea dies forests. For. Ecol. Manage. 87, 139–148.

Atlegrim, O., Sjöberg, K., 2004. Selective felling as a potential tool for maintaining biodiversity forests. Biodivers. Conserv. 13, 1123–1133. https://doi.org/10.1023/B:BIOC.0000018148.84640.fd.

Blattert, C., Mönkkönen, M., Burgas, D., Di Fulvio, F., Toraño Caicoya, A., Vergarechea, M., Klein, J., Hartikainen, M., Antón-Fernández, C., Astrup, R., Emmerich, M., Forsell, N., Lukkarinen, J., Lundström, J., Pitzén, S., Poschenrieder, W., Primmer, E., Snäll, T., Eyvindson, K., 2023. Climate targets in European timber-producing countries conflict with goals on forest ecosystem services and biodiversity. Commun. Earth Environ. 4, 1–12. https://doi.org/10.1038/s43247-023-00771-z.

Calladine, J., Bray, J., Broome, A., Fuller, R.J., 2015. Comparison of breeding bird assemblages in conifer plantations managed by continuous cover forestry and clearfelling. For. Ecol. Manage. 344, 20–29. https://doi.org/10.1016/j.foreco.2015.02.017.

Davies, O., Kerr, G., 2015. Comparing the costs and revenues of transformation to continuous cover forestry for Sitka spruce in great Britain. Forests 6, 2424–2449. https://doi.org/10.3390/f6072424.

Díaz-Yáñez, O., Pukkala, T., Packalen, P., Peltola, H., 2019. Multifunctional comparison of different management strategies in boreal forests. Forestry 93, 84–95. https://doi.org/10.1093/forestry/cpz053.

Ekholm, A., Lundqvist, L., Axelsson, E.P., Egnell, G., Hjältén, J., Lundmark, T., Sjögren, J., 2023. Long-term yield and biodiversity in stands managed with the selection system and the rotation forestry system: a qualitative review. For. Ecol. Manag. 537, 120920 https://doi.org/10.1016/j.foreco.2023.120920.

Eyvindson, K., Repo, A., Mönkkönen, M., 2018. Mitigating forest biodiversity and ecosystem service losses in the era of bio-based economy. For. Policy Econ. 92, 119–127. https://doi.org/10.1016/j.forpol.2018.04.009.

Eyvindson, K., Duflot, R., Triviño, M., Blattert, C., Potterf, M., Mönkkönen, M., 2021. High boreal forest multifunctionality requires continuous cover forestry as a dominant management. Land Use Pol. 100 https://doi.org/10.1016/j.landusepol.2020.104918.

Felton, A., Gustafsson, L., Roberge, J.M., Ranius, T., Hjältén, J., Rudolphi, J., Lindbladh, M., Weslien, J., Rist, L., Brunet, J., Felton, A.M., 2016. How climate change adaptation and mitigation strategies can threaten or enhance the biodiversity of production forests: insights from Sweden. Biol. Conserv. 194, 11–20. https://doi.org/10.1016/j.biocon.2015.11.030.

Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A.Z., Schepaschenko, D.G., 2015. Boreal forest health and global change. Science 349, 819–822. https://doi.org/10.1126/science.aaa9092.

Häggström, B., Gundale, M.J., Nordin, A., 2024. Environmental controls on seedling establishment in a boreal forest: implications for Scots pine regeneration in continuous cover forestry. Eur. J. For. Res. 143, 95–106. https://doi.org/10.1007/s10342-023-01609-1.

Hyggesfritt skogsbruk: en kunskapssammanställning från Sverige och Finland. In: Hannerz, M., Nordin, A., Saksa, T. (Eds.), 2017. Future Forests Rapportserie 2017:1. Swedish University of Agricultural Sciences (SLU), Umeå.

Hansen, M.C., Stehman, S.V., Potapov, P.V., 2010. Quantification of global gross forest cover loss. Proc. Natl. Acad. Sci. U. S. A 107, 8650–8655. https://doi.org/10.1073/pnas.0912668107.

Hanski, I.K., 1998. Home ranges and habitat use in the declining flying squirrel Pteromys volans in managed forests. Wildl. Biol. 4 (1), 33–46. https://doi.org/10.2981/wlb.1998.013.

Hanski, I.K., Mönkkönen, M., Reunanen, P., Stevens, P., 2000. Ecology of the Eurasian flying squirrel (*Pteromys volans*) in Finland. In: Goldingay, R., Scheibe, J. (Eds.), Biology of Gliding Mammals. Filander Verlag GmbH, Fürth, Germany, pp. 67–86.

Hjältén, J., Kouki, J., Tolvanen, A., Sjögren, J., Versluijs, M., 2023. Ecological restoration of the boreal forest in fennoscandia. In: Boreal Forests in the Face of Climate Change: Sustainable Management. Springer International Publishing, Cham, pp. 467–489.

Hynynen, J., Ojansuu, R., Hökkä, H., Siipilehto, J., Salminen, H., Haapala, P., 2002. Models for Predicting Stand Development in MELA System. Finnish Forest Research Institute. Research Papers no. 835. 116.

Hynynen, J., Eerikäinen, K., Mäkinen, H., Valkonen, S., 2019. Growth response to cuttings in Norway spruce stands under even-aged and uneven-aged management. For. Ecol. Manage. 437, 314–323. https://doi.org/10.1016/j.foreco.2018.12.032.

Hyvärinen, E., Juslén, A., Kemppainen, E., Uddström, A., Liukko, U.-M. (Eds.), 2019. The 2019 red list of Finnish species. Ympäristöministeriö & Suomen ympäristökeskus, Helsinki, p. 704.

Hyytiäinen, K., Haight, R.G., 2012. Optimizing Continuous Cover Forest Management. Continuous Cover Forestry, pp. 195–227.

Jalonen, J., Vanha-Majamaa, I., 2001. Immediate effects of four different felling methods on mature boreal spruce forest understorey vegetation in southern Finland. For. Ecol. Manage. 146, 25–34. https://doi.org/10.1016/S0378-1127(00)00446-1.

Jansson, G., Angelstam, P., 1999. Threshold levels of habitat composition for the presence of the long- tailed tit (*Aegithalos caudatus*) in a boreal landscape. Landsc. Ecol. 14, 283–290.

Jonsson, M., Ranius, T., Ekvall, H., Bostedt, G., 2010. Cost-effectiveness of silvicultural measures to increase substrate availability for wood-dwelling species: a comparison among boreal tree species. Scand. J. For. Res. 25, 46–60. https://doi.org/10.1080/02827581003620347.

Juutinen, A., Ahtikoski, A., Mäkipaä, R., Shanin, V., 2018. Effect of harvest interval and intensity on the profitability of uneven-aged management of Norway spruce stands. Forestry 91, 1–14. https://doi.org/10.1093/forestry/cpy018.

Juutinen, A., Tolvanen, A., Koskela, T., 2020. Forest owners' future intentions for forest management. For. Policy Econ 118, 102220. https://doi.org/10.1016/j.forpol.2020.102220.

Juutinen, A., Shanin, V., Ahtikoski, A., Rämö, J., Mäkipää, R., Laiho, R., Sarkkola, S., Laurén, A., Penttilä, T., Hökkä, H., Saarinen, M., 2021. Profitability of continuous-cover forestry in Norway spruce dominated peatland forest and the role of water table. Can. J. For. Res. 51, 859–870. https://doi.org/10.1139/cjfr-2020-0305.

Kangas, A., Rasinmäki, J., 2008. SIMO — Adaptable Simulation and Optimization for Forest Management Planning, vol. 41. University of Helsinki, Department of Forest Resource Management Publications.

Klein, J., Thor, G., Low, M., Sjögren, J., Lindberg, E., Eggers, S., 2020. What is good for birds is not always good for lichens: interactions between forest structure and species richness in managed boreal forests. For. Ecol. Manage. 473, 118327.

Kurttila, M., Pykäläinen, J., Hujala, T., 2013. Optimoinnin käyttö yksityismetsien tilatason metsäsuunnittelussa [Use of optimization in holding-specific forest management planning]. Metsätieteen aikakauskirja 1, 61–70 (in Finnish).

Kuuluvainen, T., Tahvonen, O., Aakala, T., 2012. Even-aged and uneven-aged forest management in boreal fennoscandia: a review. Ambio 41, 720–737. https://doi.org/10.1007/s13280-012-0289-y.

Lehtonen, A., Eyvindson, K., Härkönen, K., Leppä, K., Salmivaara, A., Peltoniemi, M., Salminen, O., Sarkkola, S., Launiainen, S., Ojanen, P., Räty, M., Mäkipää, R., 2023. Potential of continuous cover forestry on drained peatlands to increase the carbon sink in Finland. Sci. Rep. 13, 1–13. https://doi.org/10.1038/s41598-023-42315-7.

Liski, J., Westman, C.J., 1997. Carbon storage in forest soil of Finland. Biogeochemistry 36, 239–260.

Lundqvist, L., 2017. Tamm review: selection system reduces long-term volume growth in Fennoscandic uneven-aged Norway spruce forests. For. Ecol. Manage. 391 (Suppl. C), 362–375.

Mäkelä, A., Minunno, F., Kujala, H., Kosenius, A.K., Heikkinen, R.K., Junttila, V., Peltoniemi, M., Forsius, M., 2023. Effect of forest management choices on carbon sequestration and biodiversity at national scale. Ambio. https://doi.org/10.1007/s13280-023-01899-0.

Mäkinen, H., Hynynen, J., Siitonen, J., Sievänen, R., 2006. Predicting the decomposition of Scots pine , Norway spruce , and Birch stems in Finland. Ecol. Appl. 16, 1865–1879.

Mäntymaa, E., Artell, J., Forsman, J., Juutinen, A., 2023. Is it more important to increase carbon sequestration, biodiversity, or jobs? A case study of citizens' preferences for forest policy in Finland. For. Policy Econ 154. https://doi.org/10.1016/j.forpol.2023.103023.

Mason, W.L., Diaci, J., Carvalho, J., Valkonen, S., 2022. Continuous cover forestry in Europe: usage and the knowledge gaps and challenges to wider adoption. Forestry 95, 1–12. https://doi.org/10.1093/forestry/cpab038.

Matveinen-Huju, K., Koivula, M., 2008. Effects of alternative harvesting methods on boreal forest spider assemblages. Can. J. For. Res. 38, 782–794. https://doi.org/10.1139/X07-169.

Mazziotta, A., Borges, P., Kangas, A., Halme, P., Eyvindson, K., 2023. Spatial trade-offs between ecological and economical sustainability in the boreal production forest. J. Environ. Manag. 330, 117144 https://doi.org/10.1016/j.jenvman.2022.117144.

Messier, C., Bauhus, J., Doyon, F., Maure, F., Sousa-Silva, R., Nolet, P., Mina, M., Aquilué, N., Fortin, M.J., Puettmann, K., 2019. The functional complex network approach to foster forest resilience to global changes. For. Ecosyst. 6 https://doi.org/10.1186/s40663-019-0166-2.

Miettinen, J., Hallikainen, V., Valkonen, S., Hökkä, H., Hyppönen, M., Rautio, P., 2024. Natural regeneration and early development of Scots pine seedlings after gap cutting in northern Finland. Scand. J. For. Res. 39 (2), 89–100. https://doi.org/10.1080/02827581.2024.2303022.

Mönkkönen, M., Juutinen, A., Mazziotta, A., Miettinen, K., Podkopaev, D., Reunanen, P., Salminen, H., Tikkanen, O.P., 2014. Spatially dynamic forest management to sustain biodiversity and economic returns. J. Environ. Manag. 134, 80–89. https://doi.org/10.1016/j.jenvman.2013.12.021.

Mönkkönen, M., Aakala, T., Blattert, C., Burgas, D., Duflot, R., Eyvindson, K., Kouki, J., Laaksonen, T., Punttila, P., 2022. More wood but less biodiversity in forests in Finland: a historical evaluation. Memo. Soc. Fauna Flora Fenn. 98, 1–11.

Nakajima, T., Shiraishi, N., Kanomata, H., Matsumoto, M., 2017. A method to maximise forest profitability through optimal rotation period selection under various economic, site and silvicultural conditions. New Zeal. J. For. Sci. 47, 1–13. https://doi.org/10.1186/s40490-016-0079-6.

Nieminen, M., Hökkä, H., Laiho, R., Juutinen, A., Ahtikoski, A., Pearson, M., Kojola, S., Sarkkola, S., Launiainen, S., Valkonen, S., Penttilä, T., Lohila, A., Saarinen, M., Haahti, K., 2018. Could continuous cover forestry be an economically and environmentally feasible management option on drained boreal peatlands? For. Ecol. Manage. 424, 78–84. https://doi.org/10.1016/j.foreco.2018.04.046.

Nolet, P., Kneeshaw, D., Messier, C., Béland, M., 2018. Comparing the effects of even- and uneven-aged silviculture on ecological diversity and processes: a review. Ecol. Evol. 8, 1217–1226. https://doi.org/10.1002/ece3.3737.

Ojanen, P., Lehtonen, A., Heikkinen, J., Penttilä, T., Minkkinen, K., 2014. Soil CO2 balance and its uncertainty in forestry-drained peatlands in Finland. For. Ecol. Manage. 325, 60–73. https://doi.org/10.1016/j.foreco.2014.03.049.

Pakkala, T., Pellikka, J., Linden, H., 2003. Capercaillie Tetrao urogallus, a good candidate for an umbrella species in taiga forests. Wildl. Biol. 9, 309–316.

Peura, M., Burgas, D., Eyvindson, K., Repo, A., Mönkkönen, M., 2018. Continuous cover forestry is a cost-efficient tool to increase multifunctionality of boreal production forests in Fennoscandia. Biol. Conserv. 217, 104–112. https://doi.org/10.1016/j.biocon.2017.10.018.

Pohjanmies, T., Eyvindson, K., Mönkkönen, M., 2019. Forest management optimization across spatial scales to reconcile economic and conservation objectives. PLoS One 14, 1–16. https://doi.org/10.1371/journal.pone.0218213.

Puettmann, K.J., Wilson, S.M.G., Baker, S.C., Donoso, P.J., Drössler, L., Amente, G., Harvey, B.D., Knoke, T., Lu, Y., Nocentini, S., Putz, F.E., Yoshida, T., Bauhus, J., 2015. Silvicultural alternatives to conventional even-aged forest management - what limits global adoption? For. Ecosyst. 2 https://doi.org/10.1186/s40663-015-0031-x.

Pukkala, T., 2016. Which type of forest management provides most ecosystem services? For. Ecosyst. 3 https://doi.org/10.1186/s40663-016-0068-5.

Pukkala, T., 2021. Measuring the social performance of forest management. J. For. Res. 32, 1803–1818. https://doi.org/10.1007/s11676-021-01321-z.

Pukkala, T., 2022. Assessing the externalities of timber production. For. Policy Econ 135. https://doi.org/10.1016/j.forpol.2021.102646.

Pukkala, T., Gadow, K., 2012. Continuous Cover Forestry, second. Springer Berlin Heidelberg, London. https://doi.org/10.1002/jbm.b.30154.

Pukkala, T., Lähde, E., Laiho, O., 2010. Optimizing the structure and management of uneven-sized stands of Finland. Forestry 83, 129–142. https://doi.org/10.1093/forestry/cpp037.

Pukkala, T., Lähde, E., Laiho, O., 2013. Species interactions in the dynamics of even- and uneven-aged boreal forests. J. Sustain. For. 32, 371–403. https://doi.org/10.1080/10549811.2013.770766.

Pukkala, T., Laiho, O., Lähde, E., 2016. Continuous cover management reduces wind damage. For. Ecol. Manage. 372, 120–127. https://doi.org/10.1016/j.foreco.2016.04.014.

R Core Team, 2024. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.

Rämö, J., Tahvonen, O., 2017. Optimizing the harvest timing in continuous cover forestry. Environ. Resour. Econ. 67, 853–868. https://doi.org/10.1007/s10640-016-0008-4.

Rasinmäki, J., Mäkinen, A., Kalliovirta, J., 2009. SIMO: an adaptable simulation framework for multiscale forest resource data. Comput. Electron. Agric. 66, 76–84. https://doi.org/10.1016/j.compag.2008.12.007.

Räty, M., Juutinen, A., Korhonen, K.T., Syrjänen, K., Kärkkäinen, L., 2023. EU wood production vs. biodiversity goals–possible reconciliation in Finland? Scand. J. For. Res. 38, 287–299. https://doi.org/10.1080/02827581.2023.2229732.

Redon, M., Luque, S., Gosselin, F., Cordonnier, T., 2014. Is generalisation of uneven-aged management in mountain forests the key to improve biodiversity conservation within forest landscape mosaics? Ann. For. Sci. 71, 751–760. https://doi.org/10.1007/s13595-014-0371-7.

Repo, A., Eyvindson, K., Halme, P., Mönkkönen, M., 2020. Forest bioenergy harvesting changes carbon balance and risks biodiversity in boreal forest landscapes. Can. J. For. Res. 50, 1184–1193. https://doi.org/10.1139/cjfr-2019-0284.

Repo, A., Rajala, T., Henttonen, H.M., Lehtonen, A., Peltoniemi, M., Heikkinen, J., 2021. Age-dependence of stand biomass in managed boreal forests based on the Finnish National Forest Inventory data. For. Ecol. Manage. 498, 119507 https://doi.org/10.1016/j.foreco.2021.119507.

Sarkkola, S., 2008. Greenhouse Impacts of the Use of Peat and Peatlands in Finland, Research Programme Final Report. Ministry of Agriculture and Forestry, Helsinki.

Savilaakso, S., Johansson, A., Häkkilä, M., Uusitalo, A., Sandgren, T., Mönkkönen, M., Puttonen, P., 2021. What are the effects of even-aged and uneven-aged forest management on boreal forest biodiversity in Fennoscandia and European Russia? A systematic review. Environ. Evid. 10, 1–38. https://doi.org/10.1186/s13750-020-00215-7.

Schall, P., Gossner, M.M., Heinrichs, S., Fischer, M., Boch, S., Prati, D., Jung, K., Baumgartner, V., Blaser, S., Böhm, S., Buscot, F., Daniel, R., Goldmann, K., Kaiser, K., Kahl, T., Lange, M., Müller, J., Overmann, J., Renner, S.C., Schulze, E.D., Sikorski, J., Tschapka, M., Türke, M., Weisser, W.W., Wemheuer, B., Wubet, T., Ammer, C., 2018. The impact of even-aged and uneven-aged forest management on regional biodiversity of multiple taxa in European beech forests. J. Appl. Ecol. 55, 267–278. https://doi.org/10.1111/1365-2664.12950.

Schütz, J.-P., Pukkala, T., Donoso, P.J., von Gadow, K., 2012. Historical emergence and current application of CCF. In: Pukkala, K., Gadow, von (Eds.), Continuous Cover Forestry, Springer Science, pp. 1–28.

Seedre, M., Felton, A., Lindbladh, M., 2018. What is the impact of continuous cover forestry compared to clearcut forestry on stand - level biodiversity in boreal and temperate forests ? A systematic review protocol. Environ. Evid. 7, 1–8. https://doi.org/10.1186/s13750-018-0138-y.

Sharma, A., Bohn, K.K., Jose, S., Dwivedi, P., 2016. Even-aged vs. Uneven-aged silviculture: implications for multifunctional management of southern pine ecosystems. Forests 7, 1–17. https://doi.org/10.3390/f7040086.

Siira-Pietikäinen, A., Haimi, J., 2009. Changes in soil fauna 10 years after forest harvestings: comparison between clear felling and green-tree retention methods. For. Ecol. Manage. 258, 332–338. https://doi.org/10.1016/j.foreco.2009.04.024.

Tahvonen, O., 2016. Economics of rotation and thinning revisited: the optimality of clearcuts versus continuous cover forestry. For. Policy Econ 62, 88–94. https://doi.org/10.1016/j.forpol.2015.08.013.

Tahvonen, O., Rämö, J., 2016. Optimality of continuous cover vs. clear-cut regimes in managing forest resources. Can. J. For. Res. 46, 891–901. https://doi.org/10.1139/cjfr-2015-0474.

Tahvonen, O., Pukkala, T., Laiho, O., Lähde, E., Niinimäki, S., 2010. Optimal management of uneven-aged Norway spruce stands. For. Ecol. Manage. 260, 106–115. https://doi.org/10.1016/j.foreco.2010.04.006.

Tikkanen, O.P., Heinonen, T., Kouki, J., Matero, J., 2007. Habitat suitability models of saproxylic red-listed boreal forest species in long-term matrix management: cost-effective measures for multi-species conservation. Biol. Conserv. 140 (3–4), 359–372.

Triviño, M., Pohjanmies, T., Mazziotta, A., Juutinen, A., Podkopaev, D., Le Tortorec, E., Mönkkönen, M., 2017. Optimizing management to enhance multifunctionality in a boreal forest landscape. J. Appl. Ecol. 54, 61–70. https://doi.org/10.1111/1365-2664.12790.

Tuomi, M., Rasinmäki, J., Repo, A., Vanhala, P., Liski, J., 2011. Soil carbon model Yasso07 graphical user interface. Environ. Model. Software 26, 1358–1362. https://doi.org/10.1016/j.envsoft.2011.05.009.

Vergarechea, M., Astrup, R., Fischer, C., Øistad, K., Blattert, C., Hartikainen, M., Eyvindson, K., Di Fulvio, F., Forsell, N., Burgas, D., Toraño-Caicoya, A., Mönkkönen, M., Antón-Fernández, C., 2023. Future wood demands and ecosystem services trade-offs: a policy analysis in Norway. For. Policy Econ 147. https://doi.org/10.1016/j.forpol.2022.102899.