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High boreal forest multifunctionality requires continuous cover forestry as a dominant management

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Abstract:

Intensive extraction of forest resources lowers biodiversity and endanger functioning of forest ecosystems. As such, alternative management regimes have emerged, aspiring to promote forest biodiversity and nature protection in managed forests. Among them, continuous cover forestry, (i.e. selective logging), has received considerable attention and is being promoted by some researchers and NGO's. Yet, the full consequences of banning clear-cuts (i.e. rotation forestry) and replacing it entirely with continuous cover forest remains uncertain. We explore how restricting forest management alternatives (either rotation forestry or continuous cover forestry) will affect landscape-scale forest multifunctionality at a range of harvesting levels. We evaluate multifunctionality as a combination of recreational ecosystem services, climate change mitigation, habitat availability for vertebrates, and red-listed deadwood dependent species. Our results show that restricting forest management alternatives have a negative impact on forest multifunctionality at all harvest levels when compared to the case with no restrictions. Using only continuous cover forestry management alternatives resulted in higher multifunctionality than the case when only rotation forestry management alternatives were used. We also show that maximizing multifunctionality using all management alternatives led to high proportion of continuous cover forestry over the landscape. We conclude that banning clear-cuts does not promote forest biodiversity and multifunctionality at the landscape scale, especially if there is a requirement for high economic benefits required from the forest. However, we recommend that continuous cover forestry should be considered as a primary management alternative, with selective application of rotation forestry wisely planned at the landscape scale.

Introduction

Biodiversity at a global scale continues to drastically decline even as we improve our understanding of conservation processes (Pimm et al., 2014; Tilman et al., 2014). Increasing human pressure on land-use, the primary driver for terrestrial biodiversity degradation, further hinders conservation efforts (Díaz et al., 2019; Newbold et al., 2015). To reconcile human activities and biodiversity, land-use should be adapted to create multifunctional landscapes that would provide human societies with ecosystem services while maintaining ecosystem integrity. All ecosystems are vulnerable to intensive management; however, some ecosystems seem more resilient than others. Those ecosystems have the largest potential for sustainable resource extraction (Rist et al., 2014). Forests ecosystems have been long time shaped by natural disturbances at different spatio-temporal scales. Therefore, forests should be resilient to resource extraction if managed and viewed at the landscape scale, applying the most efficient silvicultural practices available at the right extent, scale, and intensity (Messier et al., 2019). Forests are of major global interest as a large part of the world's biodiversity relies on forest ecosystems, and they provide a wide range of ecosystem services to human societies, such as timber, water purification, carbon sequestration for climate mitigation or recreational areas (Harrison et al., 2010).

Boreal forests, representing approximately one-third of remaining global forests, provide many important ecosystem services (Hansen et al., 2010). Until now, most of boreal forests have been largely preserved from human activities and shelter a large proportion of the remaining wilderness areas at global scale (Watson et al., 2016). However, European boreal forests have been intensively managed over multiple centuries, with accelerated extraction over past decades to provide energy and raw material for saw and pulp mills (Mönkkönen et al., 2018). Yet, managing boreal forests for timber resources conflicts both with provisioning of non-timber ecosystem services (ESS) and biodiversity (BD) conservation (Eyvindson et al., 2018; Pohjanmies et al., 2017; Schwenk et al., 2012; Triviño et al., 2017). Balancing the protection of boreal forests and growing extraction of forest resources for bioenergy and bio-products (following new bio-economy policy goals) requires development of alternative ways to manage boreal forests (Hetemäki et al., 2017). Yet, the shift in the order of priorities driving forest resources management is essential to obtain multifunctional forest landscapes.

Mitigating the conflict between biodiversity conservation, the provision of non-timber ecosystem services, and timber extraction requires application of less intensive forest management and/or careful landscape planning (e.g., Eyvindson et al., 2018). Several alternative management techniques that balance economic and ecological objectives have been recently developed. As such, they mimic natural disturbances to emulate forest structures important for biodiversity (Kuuluvainen and Grenfell, 2012) or reduce intensity of forest extraction spatially or temporally (Hanski, 2011). This can be implemented by delaying clear-felling, limiting thinning, conducting selective harvest or simply by leaving areas unmanaged (Äijälä et al., 2014). Forest planning could be applied through spatial allocation of intensive and less intensive resource extraction, such as land-sharing and land sparing approaches (Edwards et al., 2014; Messier et al., 2009). Considering the potential conflict between resource extraction and habitat availability for threatened species, and the diversity of life forms in forests, it is unlikely that a single forest management alternative systematically applied at large scale would support multifunctional landscape (Haight and Monserud, 1990). Contrary, a diverse range of management approaches may lead to a diverse forest structure and support forest multifunctionality (Mönkkönen et al., 2014; Triviño et al., 2017). Yet, ecosystem services are provided at various spatial scales, and the planning scale should match or be larger than the scale services are provided (Pohjanmies et al., 2019; Raudsepp-Hearne and Peterson, 2016).

Specific forest management alternatives have been recommended for their ability to provide specific ESS. In the last few decades, rotation forestry has been clearly the dominant method for timber extraction throughout the boreal forest, as well as in large areas of planted forests in temperate regions (Appelroth et al., 1948)(Appelroth et al., 1948). Since 1950s, intensive practices using clear-cut harvesting resulted in impoverished stand structural diversity, fragmented forest structures, and lowered structural variability at the landscape scale in most forests in Fennoscandia (Kuuluvainen et al., 2012). Alternatively, continuous cover forestry, which maintains a forest canopy at all times, and does not use clear-felling, has received considerable attention for application in boreal and temperate forests (Pukkala and Gadow, 2012). In Fennoscandia, selective logging of individual large trees that reached a certain size (target diameter harvesting) is among others the most applied silvicultural system for continuous cover forestry. Recent research compared selective logging (further referred as continuous cover forestry – CCF) with clear-felling approaches (result of traditional rotation forestry – RF) in a wide range of forest conditions (Peura et al., 2018; Pukkala et al., 2011). These studies highlighted the potential for CCF to perform better in terms of providing ecosystem services, biodiversity, and general multifunctionality than RF.

To reconcile the negative effects of long-term clear-cutting and the potential benefits of CCF, many researchers and NGOs are advocating in favour of the latter to replace the former. For instance, a citizen initiative (VN/1699/2018[1]) in Finland aims to promote biodiversity and nature protection, through fully banning clear-cut activities in State-owned forests. However, this could lead to a consistent application of CCF management approaches throughout a forested landscape, and may thereby homogenize the landscape, i.e. lower diversity of forest structures. In addition, the land-use intensity and negative environmental impacts could be higher with consistent application of CCF than with consistent application of RF. For a given amount of timber extraction, CCF as compared to RF may be less intensive in space but more intensive in time; hence increasing frequency of human-induced disturbances. This may potentially have negative impacts to biodiversity and ecosystem services other than timber.

Efficient resource use and conservation efforts require careful planning, where a combinations of management alternatives and their share over the landscape can fulfill specific management objectives. Here we explore the trade-offs between management alternatives through an optimization approach, focusing on efficient uses of forest resources. Restricting the range of the management alternatives could reduce the efficiency of the overall management objectives. We hypothesise that exclusive and consistent use of a single type of forest management will likely reduce the full potential efficiency of the forest landscape to simultaneously deliver ESS and maintain BD. Nevertheless, restricting some management options could facilitate the implementation of optimal planning in the real world by reducing possibilities to choose from for forest owner. Our study aims to evaluate the independent performance of consistent use of CCF or RF management alternatives, compared to combinations of all available management alternatives in providing landscape-level BD and ESS. We examine the entire range of land-use intensity by varying the desired net present income (NPI) of the landscape from no income, landscape level set-aside (SA) management to the maximal NPI revenues. Further, we evaluate the performance of the scenarios in terms of their multifunctionality at the landscape level. Our multifunctionality metrics include both BD and non-timber ESS indicators.

[1] https://www.kansalaisaloite.fi/fi/aloite/3184

Materials and Methods

Forest data and simulations under alternative management alternatives

Our study area represents a typical Finnish production forest landscape (see Fig. 1), consisting of forest stands located within a single watershed in Central Finland. We used the forest stand information from the Finnish Forest Centre that is publicly available (www.metsään.fi). The watershed was used as a natural boundary consisting of 1,475 relatively structurally homogenous forest stands over 2,242 ha. The growth and management of the forest was simulated using the open-source forest simulator SIMO (Rasinmäki et al., 2009) for 100 years, separated into 20 five-year periods. For each stand, we simulated a maximum of 58 management alternatives. The exact number of management alternatives applied depends on the specific initial conditions of each individual forest stand. In total, 17 possible variations were available for RF management, 40 variations for CCF management, and one alternative where no management actions (set-aside) were taken in the forest. Variations in RF management included changes to the timing of final felling, optional thinning, and increased green tree retention (see further details in Eyvindson et al., 2018). A basic form of CCF management follows the set of rules identified in Äijälä et al. (2014). To create a maximum of CCF alternatives, we varied two rules defining timing of harvesting. First, we varied the pre-defined site-specific basal area (m^2/ha) requirement (16 m^2/ha for less fertile sites to 22 m^2/ha for fertile sites) prior to harvesting by -3, ±0, +3, +6. Additionally, we varied the timing of the first harvest in 5 year increments up to a delay of 45 years. The cutting cycle were afterwards determined within the simulation based on basal area requirements. A summary of the management alternatives is presented in Appendix A.

Ecosystem services and biodiversity indicators

We calculated indicators for four BD and ESS components at the stand level, based on available models and the simulated structural characteristics of each stand. The four components reflect important aspects for Finnish nature and people: i) recreational ecosystem services and non-timber production; ii) climate change mitigation, iii) suitable habitat for terrestrial vertebrate biodiversity, and iv) suitable habitat for red-listed species dependent on deadwood.

Recreational ESS and non-timber production included bilberry, mushrooms and scenic beauty. Bilberry (*Vaccinium myrtillys*) is one of the most common wild berries in Finland and has high recreational and commercial value (Vaara et al., 2013). Bilberry yield (kg) was estimated using the models of Miina et al. (2016) which predicts yield based on stand characteristics such as age, basal area and dominant tree species. Mushrooms have also both recreational and commercial value in Finland (Peura et al., 2016). Marketed mushrooms yield (kg) was estimated using the models of Tahvanainen et al. (2016). While the mushroom models were developed for Eastern Finland in Spruce dominating stands, the model cannot provide highly accurate estimations for mushroom yield (the models have a predictive capacity of 23%). Yet, they provide an indication on the suitability of the sites for mycorrhizal mushrooms. Scenic beauty (no unit) was calculated using the index developed by Pukkala et al. (1988), which estimates people's average opinion about the recreational value and beauty of forests based on slides and computer drawings of managed stands. The age and size of trees increased the recreational and beauty value as well as a big share of pines and birches.

Climate change mitigation considered the mass of carbon contained within timber (kg C), dead wood (kg C), and soil (kg C) as a proxy for carbon stock. Timber was calculated as the total volume of standing timber from the different tree species. Dead wood volume (m^3) was measured as the total amount of dead wood from the different dead wood types comprising different tree species and decay stages. Deadwood decomposition was modeled through five decay stages using decomposition models from Mäkinen et al. (2006). To estimate soil carbon, for mineral soils we used the models from Liski and Westman (1997) to provide initial soil carbon values, and to model the development of soil carbon we used the Yasso07 modelling framework (Liski et al., 2005; Tuomi et al., 2011, 2009). Drained peatland soils were modeled using the carbon flux models proposed by Ojanen et al. (2014). In this study we do not include the potential carbon storage through long-lasting wood products, as the forest landscape is our system boundary.

Suitable habitat for vertebrate biodiversity included the habitat availability for six species: western capercaillie (*Tetrao urogallus*), siberian flying squirrel (*Pteromys volans*), hazel grouse (*Bonasia bonasa*), long-tailed tit (*Aegithalos caudatus*), lesser-spotted woodpecker (*Dendrocopos minor*), and three-toed woodpecker (*Picoides tridactylus*). We selected these species to represents a wide range of habitat types, and diverse social and economic values including game birds, umbrella, and threatened species. The habitat suitability models were taken from Mönkkönen et al. (2014).

Finally, we explored the suitable habitat availability for 27 red-listed species dependent on dead wood (fungi and arthropods). Dead wood is a critical resource in boreal forests (Stokland et al., 2012); a good indicator of forest biodiversity (Gao et al., 2015; Lassauce et al., 2011), and the lack of dead wood is the most important threat for species in Finnish forests (Tikkanen et al., 2006). The habitat suitability models were taken from Tikkanen et al. (2007). A total of six ESS and 33 BD criteria were integrated into a multifunctionality assessment.

Forest multifunctionality

We explored forest multifunctionality as a landscape metric rather than a stand-level characteristic. Therefore, all indicators were first evaluated at stand level and then aggregated over the study area to produce the total value over the landscape. We measured the ability of the forest landscape to maintain high levels of all ESS and BD components (van der Plas et al., 2016). We defined multifunctionality as the sum of the four normalized components (eq. 1, standardized by theoretical maximum and minimal values derived from the pay-off table, Table 1), with equal priorities between the components of multifunctionality. We aggregated indicators within components through two measures: as the average value between all indicators (eq. 2a) and as the minimum value across all indicators (eq 2b). For climate change mitigation and non-timber ESS, components were estimated as the average (of equal importance) of their indicators (eq. 2a) while BD components were estimated as the minimum value across the biodiversity indicators (eq. 2b). We rationale that : i) in climate mitigation, carbon sequestration in deadwood can substitute carbon in standing timber; ii) in non-timber ecosystem services, we maximize the summed production of these social benefits and iii) for biodiversity, we want to preserve all species, hence maximize the habitat availability for the species with lowest score. All species have an existence value, and we cannot thus assume that the suffering of a single species can be offset by the success of other species.

To account for the increased costs of selective harvesting by the CCF alternatives, timber prices obtained from CCF management are set to be 75% of estimated price of RF. This adjustment reflects a doubling in harvesting costs per m^3, while CCF management extract approximately 50% of harvested timber than RF operations. As discount rate for the NPI, we considered a factor of 2%, which is often applied to cover long-term economic problems in forestry, and to reflect on increasing discount rate we examined a 4% rate in Appendix B. The NPI was chosen as economic indicator as it does not account for the remaining standing timber values under set aside, where forest values are rather important for conservation reasons.

Through the computational material, readers can explore the use of average or minimum value used in combination for all components (gitlab.jyu.fi/kyjoeyvi/multifunctionality_costs). The mathematical translation of these choices is shown in more detail in the following section.

Formulation of the optimization problem

Through an optimization framework we explore the trade-offs between the net present income (NPI) obtained through harvesting operations and forest multifunctionality. We have opted to use NPI as the economic value of the forest, as this is how Metsähallitus (the Finnish governmental organization managing state owned forests) selects stands to harvest. The higher NPI values represent higher intensity of timber extraction. The optimization process was performed three times: i) including all management alternatives, ii) including only RF management alternatives, and iii) including only CCF management alternatives.

The general frame for the optimization problem is one where we maximize multifunctionality (eq. 1), subject to a constraint where NPI meets or exceeds a particular targeted value (eq. 5). This optimization can be seen as a goal programming formulation (such as in Eyvindson, 2012), where different components can be treated with different distance measures. The proposed objective function is:

$$\max \sum_{b \in B} \frac{(D_b - D_{b*})}{(D_b^* - D_{b*})} \tag{1}$$

subject to:

$$D_b = \frac{1}{\#T_b} \sum_{t \in T_b} \frac{(f_t - f_{t*})}{(f_t^* - f_{t*})} \tag{2a}$$

$$D_b = argmin_{t \in T_b} \frac{(f_t - f_{t*})}{(f_t^* - f_{t*})}, \forall b \in B \tag{2b}$$

$$f_t = \sum_{p \in P} \left(\frac{\sum_{j \in J} \sum_{k=1}^{K_j} x_{jk} \, z_{jkp}^t}{\#P} \right) \tag{3}$$

$$f_{NPV} = \sum_{p \in P} \left(\frac{\sum_{j \in J} \sum_{k=1}^{K_j} x_{jk} \, z_{jkp}^I}{(1+r)^{(2.5+(p-1)*5)}} \right) \tag{4}$$

$$f_{NPI} \geq q * f_{NPI}^* \tag{5}$$

$$\sum_{k=1}^{K_j} x_{jk} = 1, \forall j = 1, \dots, J \tag{6}$$

$$[7] \qquad q \in (0,1), x_{jk} \in [0,1], \forall j \in J, k \in K$$

where D_b, D_b^* and D_{b*} represents the measured, *ideal and anti-ideal* deviation for component *b*; *B* is the set of components, f_t^*, f_{t*} and f_t respectively represent the ideal, anti-ideal and obtained value for indicator *t;* f_{NPI} is the value for NPI; T_b is the set of indicators in component b, x_{jk} is the decision to harvest stand j according to management alternative k; K_j is the set of management types for stand *j*; z_{jkp}^t is the value of indicator *t* associated with conducting management alternative k on stand j during period p; P is the set of periods under consideration; r is a parameter for the discount rate, and q is a parameter that determines the required proportion of the maximum net present income. To calculate the ideal and anti-ideal values, a series of separate optimization problem was run both maximizing and minimizing the single indicator using all feasible management alternatives.

Multifunctionality is measured at the landscape level indicating the sum of specific normalized distances for each component. To normalize each component, we calculated a payoff table by independently optimizing the components, with and without the NPI constraint. This identifies the trade-offs between component groups and the range each multifunctionality measure can take. The ideal and anti-ideal values (D_b^* and D_{b*}) were extracted from that payoff table (Table 1). We assessed multifunctionality as aggregate of the distance values from each of the four components. Distance was measured in two ways, using the L^1 distance (also known as the Manhattan distance) and the as the L^∞ distance (also known as Chebyshev distance). These measures have a preferential translation, where L^1 distance measures the efficiency amongst criteria while L^∞ measures equity between criteria (Diaz-Balteiro et al., 2013).

For this problem formulation, the objective (Eq. [1]) maximizes the summed normalized distance from each component of multifunctionality. Eq. [2] measures the distance of each component of the multifunctionality, where 2a measures the distance for non-timber ESS and carbon storage using the L^1 distance metric while 2b measures the L^∞ distance for BD. Each component of multifunctionality is measured by either of these equations, depending on how the components of multifunctionality are measured. Eq. [3] evaluates the obtained landscape level value for the specific criterion t. Eq. [4] evaluates the obtained NPI for the landscape. Eq. [5] establishes a required minimum obtained NPI. Eq. [6] is the constraint requiring that each stand has some form of management alternative used. Eq. [7] sets the range of values for the parameters and decision variables. All variables used in this problem formulation are described in Table 2. The optimisation problem was solved using Pyomo (Hart et al., 2011) in conjunction with both CPLEX and CBC (Forrest et al., 2018). To allow for replication we uploaded the code on an online repository together with a sample dataset (gitlab.jyu.fi/kyjoeyvi/multifunctionality_costs).

Results

For each scenario, the proportion of unmanaged forested areas decrease following a negative linear trend as the monetary value extraction increases (Fig. 2). Irrespective of the land-use intensity (represented as increasing timber extraction, and measured as NPI), CCF scenario always outperforms RF scenario in terms of overall landscape multifunctionality (Fig. 3a). CCF scenarios provide corresponding multifunctionality values to the scenario where all management options are allowed, at low and intermediate land-use intensities (NPI < 5 k€ / ha). Only at high timber extraction levels, excluding the RF from forest management alternatives caused multifunctionality losses (CCF relative to all management types). At maximal NPI, a consistent use of CCF results in about half of the multifunctionality reduction than relying consistently on the RF alternatives. In other words, if all management options are allowed, CCF is a prevailing forest management method except at high levels of land-use intensity, where it is optimal to combine CCF and RF when targeting multifunctionality (Fig. 2).

If solely RF management alternatives are applied, multifunctionality monotonically decline with increasing land-use intensity (Fig. 3a). This trend in overall multifunctionality stems from the continuous decrease of non-timber ESS, carbon storage, and vertebrate BD components. (Fig. 3b-d.). Deadwood BD exhibited a dampened humped shape curve, peaking at about 6k €/ha (Fig. 3e.).

Under CCF and all management alternative scenarios, the pattern for overall multifunctionality is unimodal, and maximum multifunctionality values are achieved with an intermediate attainment of NPI (approximately 4 k €/ha, Fig. 3a). The pattern is likely because of the BD components of multifunctionality, while the provision of non-timber ESSs remains relatively stable and the carbon storage declines steadily with increasing NPI (Fig. 3b-e.).

Individual non-timber ESS and vertebrate habitat suitability indicators show contrasting patterns along the timber extraction intensity gradient irrespective of whether RF or CCF management is applied. This suggests conflict among the indicators, and shows that there is much variation in terms whether CCF is better than RF, or vice versa. This trend is also seen in the payoff table (Table 1), as the range and variation between the components is similar to the trade-off seen in the scenario analysis. The development of the dead wood dependent species is interesting, as the set of 27 indicator species seem to follow one of two trends (Fig. 3e). These species seemingly either prefer forests that receive no forest management or they prefer moderate management actions. This trend is very similar between only using CCF or RF. However, maximum value is reached with CCF and the optimum for RF is at higher NPI than for CCF.

Discussion

The results of this study highlight the significant potential for conflicts between timber extraction and forest multifunctionality. Within selected indicators, we found negative effects of timber extraction on deadwood habitat indicators, scenic beauty, and carbon storage. On the other hand, harvesting can positively affect a small subset of the indicators such as mushrooms yield, and both continuous cover forestry (CCF) and rotation forestry (RF) showed initial positive trend for some dead wood habitat indicators. The complexity of how individual species groups respond to extraction levels and forest management alternatives increases with an increasing number of species considered. Some vertebrate species benefits from CCF, other vertebrate species can be maintained using RF until the requirement for NPI exceeds a specific level. Yet, the siberian flying squirrel's habitat decreased with increasing timber extraction level regardless of the applied harvesting system as this endangered species inhabits old spruce-dominated mixed forests (Wistbacka et al., 2018).

As a political tool for improving conservation practices, restricting forest management alternatives may not be a fully justifiable position. In this case, if we restrict the range of usable forest management alternatives to either CCF or RF, both economic and ecological outcomes may either remain similar or perform more poorly than if managers have all options available. However, this analysis is based on the use of optimization, and implies that managers are making well-informed decisions regarding both the economic and ecological performance of the forest, and that all forest owners have a consistent preference for non-timber ecosystem services and biodiversity protection. Forest managers may utilize heuristic optimization (Gigerenzer and Gaissmaier, 2011), or follow simple rules to strategize forest management planning (Äijälä et al., 2014). Unless the forest management planning relies on up to date scientific evidence, the overall timber and overall forest functioning will likely be suboptimal.

The Finnish case study highlights the positive impact from the recent legislative change lifting the ban of practicing CCF. Until a recent legislative change in the Finnish forest act (2014)[2], forest owners had been restricted to intensively manage their forests and extract their timber using a form of clear-felling (Appelroth et al., 1948). However, psychological barriers may prevent forest owners from applying CCF due to a lack of familiarity, preventing the most appropriate management option to be selected for a specific forested area (Isoaho et al., 2019). Yet, CCF methods are still not widely applied. The recent citizen initiative strives to restrict the use of RF in Finnish State-owned forests (~9.1 M ha of which ~85% are located in Northern Finland), while respects private forest owner's decision-making capabilities. The RF restriction initiative aimed to support conservation efforts. If high revenue targets are required from Metsähallitus (the Finnish governmental organization managing state owned forests), exclusive reliance on CCF will have a slight positive impact on ecosystem services and biodiversity considerations, as spatially intensive harvesting would be replaced by temporally intensive harvesting.

The analysis we present highlights the potential benefits of utilizing a diverse range of management alternatives compared to single applied management (Haight and Monserud, 1990). The use of CCF plays an important role in enhancing BD and ESS features while contributing significant economic value (Díaz-Yáñez et al., 2020; Pukkala, 2016). However, our modelling approach contains substantial uncertainties which may have a dramatic impact on the provisions of BD and ESS, and the possible economic output from the forests. As CCF has been used on very limited areas in Fennoscandia, and for a limited amount of time, scientific knowledge on landscape-scale CCF management is lacking. As compared to RF, the modelling of growth, natural regeneration, and mortality under CCF might have larger errors, as large scale, systematic sampling of this management approach has not yet been performed. The economical profitability of CCF or RF depends on the initial conditions of the forest stands and the respective costs of wood procurement. CCF is usually more profitable for less productive stands and can be more profitable even with a sizeable increase in wood procurement costs (Rämö and Tahvonen, 2017) (in our study ~13€ per m^3 for log wood and ~7 € per m^3 for pulpwood).

[2] https://www.finlex.fi/fi/laki/kaannokset/1996/en19961093.pdf

There are several reasons why CCF can be more profitable than RF: i) Log/pulp ratio: CCF provides more log and less pulp wood than RF, as the thinning is done from above, extracting the biggest trees, instead than from below, extracting the smallest trees like in RF; ii) Regeneration method: CCF assumes that there is a natural regeneration whereas in RF the regeneration is artificial by planting new trees which is has a high economic cost. It is uncertain, however, if the natural regeneration is always successful in CCF; iii) Discount rate: this has an influence on the timing of timber harvests and expected rotation lengths of forests (Brukas et al., 2001). Changes in discount rates may change the share of the landscape managed under RF and CCF management alternatives (see Appendix B), where high discount rates reduce the supply of non-timber ESS compared to low discount rates (Pukkala, 2016).

The use of forest planning methods and optimization can provide an optimistic view on how harvesting actions can balance between timber extraction and landscape-level multifunctionality. However, our approach relies on a single climate alternative and neglects potential disturbances throughout the 100-year time horizon. In boreal forests, continuing water availability and increasing temperatures under climate change will likely increase forest growth rates (Kellomäki, 2017). In addition, climate change might increase the risk of wind damage through the shortening of the periods of frozen soil and releasing tree root anchorage during the windiest time of the year (Peltola et al., 2010). Warmer winters may also increase risks of insect outbreaks (Neuvonen and Viiri, 2017), or potential development of newcomer forest pest species, such as *Ips amitius* (Økland et al., 2019). Therefore, omitting disturbances from the forest management planning might overestimate expected revenues (Díaz-Yáñez et al., 2019). We acknowledge that the impacts of climate change and disturbance will affect our results. However, we believe that the consequences of climate change on tree growth and disturbance risk will be equally distributed between CCF and RF management alternatives. Additionally, we anticipate the increased disturbances may have a stronger impact on RF than on CCF management alternatives. This will likely be due to several factors. CCF is likely to have less canopy height variation between stands, i.e., avoiding open edge stands protecting against wind (Zubizarreta-Gerendiain et al., 2019, 2016), and the stands will likely have a higher mixing of species, mitigating potential pest outbreaks (Hlásny et al., 2019). Wider range of applied management regimes increases landscape multifunctionality and compositional diversity. This might provide a buffer against uncertainties and possible disturbances, compared to single objective, or highly correlated ESS management types (Knoke et al., 2016).

Conclusion

From a forest planning perspective, limiting the diversity of management options will limit the ability of the forest to attain a full potential of multifunctional benefits, especially at high extraction level. Restricting management (either restricting RF or CCF) will likely lower the economic value, and landscape multifunctionality. Thus, achieving an efficient solution between multifunctionality and economic benefit will require a diverse set of management alternatives, utilizing primarily CCF with small share of RF management. Interestingly, in Fennoscandian forest landscapes under natural disturbance regimes, the proportion of stand replacing disturbances has been between 20 – 30%, and cohort dynamics (in pine dominated forests) or gap dynamics (in spruce dominated forests) have been dominating (Kuuluvainen and Aakala, 2011). Thus, from the point of view of mimicking natural disturbance dynamics, rotation forestry, which emulates structures typical for stands after stand-replacing disturbances, should be secondary to continuous cover forestry, which in turn better emulate fine-scale disturbances. According to our results, to maximize multifunctionality while obtaining high timber extraction rates, the utilization of RF should be between 10 – 25% of the total forest area. In the boreal forests, the primarily forest management alternative applied is RF, reductions in clear cuts would likely improve landscape-scale forest multifunctionality, including non-timber ecosystem services and biodiversity. However, as large proportion of productive forests in Fennoscandia are privately owned, encouraging CCF in these would also be required to improve landscape multifunctionality. On the other hand, complete restriction of RF in State-owned forests, as suggested in Finland, will likely impede the development of the full potential of multifunctional landscape, particularly in the era of bioeconomy and its expected high timber demands.

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Review & Editing, Visualization, **Clemens Blattert:** Writing – Review & Editing, Formal Analysis, **Mária Potterf**: Writing – Review & Editing, Investigation, **Mikko Mönkkönen:** Conceptualization, Writing – Review & Editing, Funding acquisition

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		NPI constraint				No NPI constraint			
		ESS MF	CM MF	VH MF	DW MF	ESS MF	CM MF	VH MF	DW MF
All management regimes	MAX ESS MF	0.497	<u>0.150</u>	0.027	0.075	**0.694**	0.395	0.160	0.265
	MAX CM MF	0.354	0.272	<u>0.011</u>	0.063	0.528	**0.995**	0.234	<u>0.055</u>
	MAX VH MF	<u>0.345</u>	0.179	0.379	0.077	0.508	0.441	**0.686**	0.386
	MAX DW MF	0.372	0.182	0.122	0.171	0.416	0.586	0.238	**0.618**
CCF management regimes	MAX ESS MF	0.580	<u>0.164</u>	<u>0.034</u>	<u>0.100</u>	**0.688**	0.414	0.173	0.283
	MAX CM MF	0.481	0.212	0.037	0.117	0.529	**0.994**	0.238	0.054
	MAX VH MF	0.466	0.170	0.376	0.108	0.513	0.444	**0.684**	0.382
	MAX DW MF	0.482	0.179	0.124	0.168	<u>0.453</u>	0.575	0.347	**0.591**
RF management regimes	MAX ESS MF	0.389	0.171	0.060	0.075	**0.563**	0.689	0.225	0.136
	MAX CM MF	0.328	0.268	<u>0.042</u>	<u>0.046</u>	0.528	**0.994**	0.234	0.052
	MAX VH MF	<u>0.312</u>	0.149	0.182	0.095	0.528	0.935	**0.270**	0.086
	MAX DW MF	0.319	<u>0.136</u>	0.085	0.168	0.430	0.516	0.098	**0.420**

Table 1. Payoff table between component groups, for each of the component groups (ESS MF – Ecosystem service multifunctionality, CM MF – Climate mitigation multifunctionality, VH MF - Vertebrate habitat multifunctionality and DW MF – Deadwood habitat multifunctionality). Maximal values are bolded, while the minimal values are underlined.

Symbol	Definition
Sets:	
B	Set of components
T_b	Set of criteria use in analysis, for each component *b*
P	Set of time periods under consideration
J	Set of all forest stands
K_j	Set of all management alternatives for forest stand *j*
Data:	
z_{jkp}^{t}	The value of criterion *t* when conducting management alternative *k* on stand *j* for period *p*
f_t^*	The ideal value obtainable for the criterion *t*
f_{t*}	The anti-ideal value obtainable for criterion *t*
D_b^*	The ideal value obtainable for the multifunctionality component *b*
D_{b*}	The anti-ideal value obtainable for the multifunctionality component *b*
Variables:	
D_b	The deviations away from the each component of multifunctionality
f_t	The value obtained for criterion *t*
Decision Variables:	
x_{jk}	The decision to manage stand *j* according to management alternative *k*
Parameters:	
r	The discount rate
q	Required proportion of maximum net present value

Table 2. A list of notations used throughout the paper.

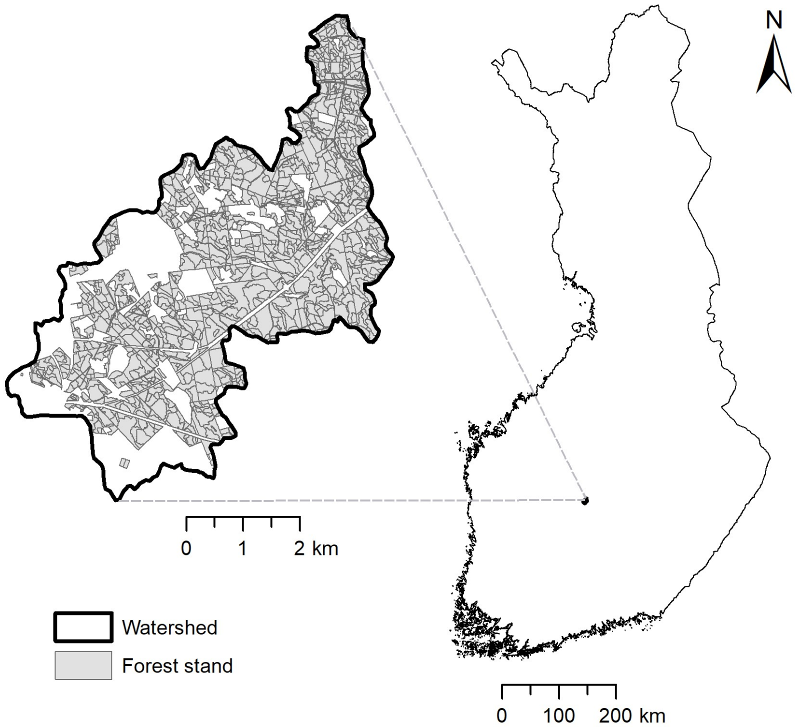
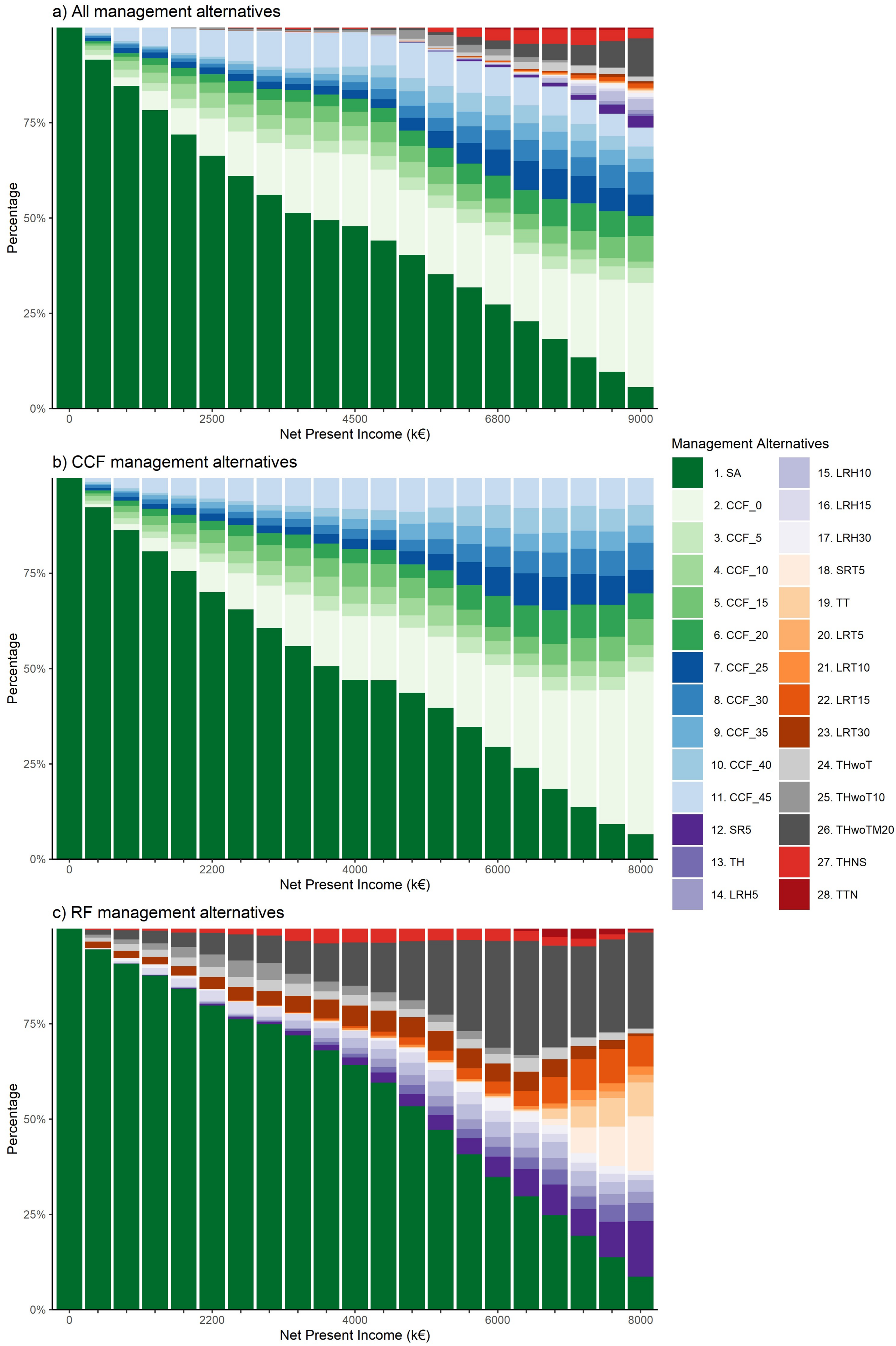
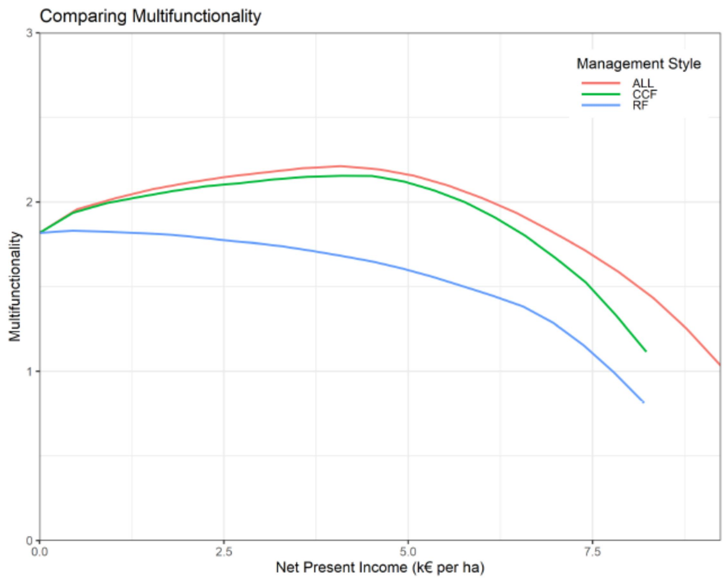


Fig. 1. Location of the forested watershed in Central Finland and location of individual forest stands.

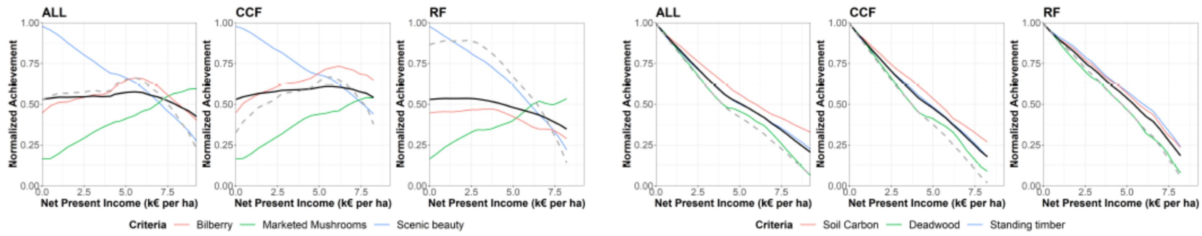

a) All management alternatives
Percentage
0%
25%
50%
75%
0
2500
4500
6800
9000
Net Present Income (k€)
b) CCF management alternatives
Percentage
0%
25%
50%
75%
0
2200
4000
6000
8000
Net Present Income (k€)
c) RF management alternatives
Percentage
0%
25%
50%
75%
0
2200
4000
6000
8000
Net Present Income (k€)
Management Alternatives
1. SA
2. CCF_0
3. CCF_5
4. CCF_10
5. CCF_15
6. CCF_20
7. CCF_25
8. CCF_30
9. CCF_35
10. CCF_40
11. CCF_45
12. SR5
13. TH
14. LRH5
15. LRH10
16. LRH15
17. LRH30
18. SRT5
19. TT
20. LRT5
21. LRT10
22. LRT15
23. LRT30
24. THwoT
25. THwoT10
26. THwoTM20
27. THNS
28. TTN

650

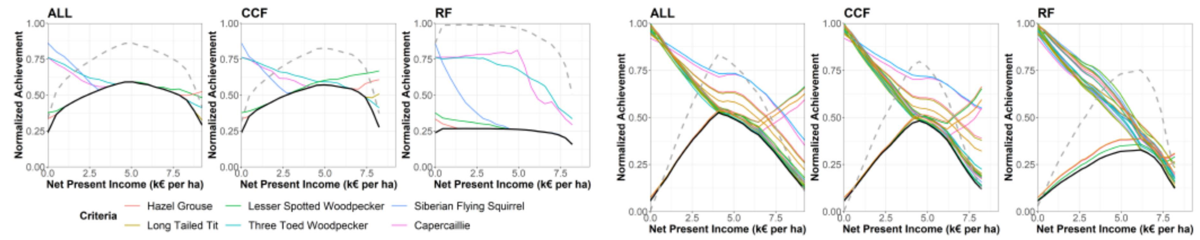
Fig. 2. Land-use intensity in terms of net present income of the different scenarios, measured as proportion of unmanaged forests. Between the figures the x-axes have slightly different range, as each scenario has differing maximal values. All – all management options allowed, CCF – only continuous cover forest (alternatives 1 – 11), RF – only rotation forestry management (alternatives 1 and 12-28). Note: to aid in figure clarity, the modifications to the BA requirement for CCF harvesting are aggregated and represents a total of 40 alternatives. For a detailed explanation of the management alternatives, readers are guided to Appendix A.



(a) landscape level multi-functionality



(b) Ecosystem service multi-functionality (c) Climate mitigation multi-functionality



(d) vertebrate habitat multi-functionality (e) Deadwood habitat multi-functionality

Fig. 3. Comparison of the multifunctionality measures for a) landscape-scale multifunctionality, and b)-e) individual multifunctionality components and their indicators. The black line represents the distance value for the set of indicators of a specific component: average value (b, c), or minimum value across indicators (d, e). The grey dashed line represents the normalized distance value from the range within each component groups (scaled with the minimal and maximum values from the payoff table (Table 1)). The list of names for the 32 deadwood habitats can be found in Tikkanen et

al. 2007. ALL - All management alternatives are allowed, CCF - only continuous cover forestry alternatives are allowed, RF - only rotation forestry alternatives are allowed.