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20 21	Keywords : Biodiversity; climate change mitigation; continuous cover forestry; ecosystem services; forest planning; optimization.
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23 Abstract:

24 Intensive extraction of forest resources lowers biodiversity and endanger functioning of forest 25 ecosystems. As such, alternative management regimes have emerged, aspiring to promote forest 26 biodiversity and nature protection in managed forests. Among them, continuous cover forestry, (i.e. 27 selective logging), has received considerable attention and is being promoted by some researchers 28 and NGO's. Yet, the full consequences of banning clear-cuts (i.e. rotation forestry) and replacing it 29 entirely with continuous cover forest remains uncertain. We explore how restricting forest 30 management alternatives (either rotation forestry or continuous cover forestry) will affect 31 landscape-scale forest multifunctionality at a range of harvesting levels. We evaluate 32 multifunctionality as a combination of recreational ecosystem services, climate change mitigation, habitat availability for vertebrates, and red-listed deadwood dependent species. Our results show 33 34 that restricting forest management alternatives have a negative impact on forest multifunctionality 35 at all harvest levels when compared to the case with no restrictions. Using only continuous cover 36 forestry management alternatives resulted in higher multifunctionality than the case when only 37 rotation forestry management alternatives were used. We also show that maximizing 38 multifunctionality using all management alternatives led to high proportion of continuous cover 39 forestry over the landscape. We conclude that banning clear-cuts does not promote forest 40 biodiversity and multifunctionality at the landscape scale, especially if there is a requirement for 41 high economic benefits required from the forest. However, we recommend that continuous cover 42 forestry should be considered as a primary management alternative, with selective application of 43 rotation forestry wisely planned at the landscape scale.

44 Introduction

45 Biodiversity at a global scale continues to drastically decline even as we improve our understanding 46 of conservation processes (Pimm et al., 2014; Tilman et al., 2014). Increasing human pressure on 47 land-use, the primary driver for terrestrial biodiversity degradation, further hinders conservation 48 efforts (Díaz et al., 2019; Newbold et al., 2015). To reconcile human activities and biodiversity, land-49 use should be adapted to create multifunctional landscapes that would provide human societies 50 with ecosystem services while maintaining ecosystem integrity. All ecosystems are vulnerable to 51 intensive management; however, some ecosystems seem more resilient than others. Those 52 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. 53 54 Therefore, forests should be resilient to resource extraction if managed and viewed at the landscape 55 scale, applying the most efficient silvicultural practices available at the right extent, scale, and 56 intensity (Messier et al., 2019). Forests are of major global interest as a large part of the world's 57 biodiversity relies on forest ecosystems, and they provide a wide range of ecosystem services to 58 human societies, such as timber, water purification, carbon sequestration for climate mitigation or 59 recreational areas (Harrison et al., 2010).

60 Boreal forests, representing approximately one-third of remaining global forests, provide many 61 important ecosystem services (Hansen et al., 2010). Until now, most of boreal forests have been 62 largely preserved from human activities and shelter a large proportion of the remaining wilderness 63 areas at global scale (Watson et al., 2016). However, European boreal forests have been intensively 64 managed over multiple centuries, with accelerated extraction over past decades to provide energy 65 and raw material for saw and pulp mills (Mönkkönen et al., 2018). Yet, managing boreal forests for 66 timber resources conflicts both with provisioning of non-timber ecosystem services (ESS) and 67 biodiversity (BD) conservation (Eyvindson et al., 2018; Pohjanmies et al., 2017; Schwenk et al., 2012; 68 Triviño et al., 2017). Balancing the protection of boreal forests and growing extraction of forest 69 resources for bioenergy and bio-products (following new bio-economy policy goals) requires 70 development of alternative ways to manage boreal forests (Hetemäki et al., 2017). Yet, the shift in 71 the order of priorities driving forest resources management is essential to obtain multifunctional 72 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
 3

76 that balance economic and ecological objectives have been recently developed. As such, they mimic 77 natural disturbances to emulate forest structures important for biodiversity (Kuuluvainen and 78 Grenfell, 2012) or reduce intensity of forest extraction spatially or temporally (Hanski, 2011). This 79 can be implemented by delaying clear-felling, limiting thinning, conducting selective harvest or 80 simply by leaving areas unmanaged (Äijälä et al., 2014). Forest planning could be applied through 81 spatial allocation of intensive and less intensive resource extraction, such as land-sharing and land 82 sparing approaches (Edwards et al., 2014; Messier et al., 2009). Considering the potential conflict 83 between resource extraction and habitat availability for threatened species, and the diversity of life 84 forms in forests, it is unlikely that a single forest management alternative systematically applied at 85 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 86 87 multifunctionality (Mönkkönen et al., 2014; Triviño et al., 2017). Yet, ecosystem services are 88 provided at various spatial scales, and the planning scale should match or be larger than the scale 89 services are provided (Pohjanmies et al., 2019; Raudsepp-Hearne and Peterson, 2016).

90 Specific forest management alternatives have been recommended for their ability to provide specific 91 ESS. In the last few decades, rotation forestry has been clearly the dominant method for timber 92 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-93 94 cut harvesting resulted in impoverished stand structural diversity, fragmented forest structures, and 95 lowered structural variability at the landscape scale in most forests in Fennoscandia (Kuuluvainen et 96 al., 2012). Alternatively, continuous cover forestry, which maintains a forest canopy at all times, and 97 does not use clear-felling, has received considerable attention for application in boreal and 98 temperate forests (Pukkala and Gadow, 2012). In Fennoscandia, selective logging of individual large 99 trees that reached a certain size (target diameter harvesting) is among others the most applied 100 silvicultural system for continuous cover forestry. Recent research compared selective logging 101 (further referred as continuous cover forestry – CCF) with clear-felling approaches (result of 102 traditional rotation forestry – RF) in a wide range of forest conditions (Peura et al., 2018; Pukkala et 103 al., 2011). These studies highlighted the potential for CCF to perform better in terms of providing 104 ecosystem services, biodiversity, and general multifunctionality than RF.

105 To reconcile the negative effects of long-term clear-cutting and the potential benefits of CCF, many 106 researchers and NGOs are advocating in favour of the latter to replace the former. For instance, a 107 citizen initiative (VN/1699/2018¹) in Finland aims to promote biodiversity and nature protection, 108 through fully banning clear-cut activities in State-owned forests. However, this could lead to a 109 consistent application of CCF management approaches throughout a forested landscape, and may 110 thereby homogenize the landscape, i.e. lower diversity of forest structures. In addition, the land-use 111 intensity and negative environmental impacts could be higher with consistent application of CCF 112 than with consistent application of RF. For a given amount of timber extraction, CCF as compared to 113 RF may be less intensive in space but more intensive in time; hence increasing frequency of human-114 induced disturbances. This may potentially have negative impacts to biodiversity and ecosystem 115 services other than timber.

116 Efficient resource use and conservation efforts require careful planning, where a combinations of 117 management alternatives and their share over the landscape can fulfill specific management 118 objectives. Here we explore the trade-offs between management alternatives through an 119 optimization approach, focusing on efficient uses of forest resources. Restricting the range of the 120 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 121 122 reduce the full potential efficiency of the forest landscape to simultaneously deliver ESS and 123 maintain BD. Nevertheless, restricting some management options could facilitate the 124 implementation of optimal planning in the real world by reducing possibilities to choose from for 125 forest owner. Our study aims to evaluate the independent performance of consistent use of CCF or 126 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 127 the desired net present income (NPI) of the landscape from no income, landscape level set-aside 128 129 (SA) management to the maximal NPI revenues. Further, we evaluate the performance of the 130 scenarios in terms of their multifunctionality at the landscape level. Our multifunctionality metrics

131 include both BD and non-timber ESS indicators.

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

132 Materials and Methods

133 Forest data and simulations under alternative management alternatives

134 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 135 136 information from the Finnish Forest Centre that is publicly available (www.metsään.fi). The 137 watershed was used as a natural boundary consisting of 1,475 relatively structurally homogenous 138 forest stands over 2,242 ha. The growth and management of the forest was simulated using the 139 open-source forest simulator SIMO (Rasinmäki et al., 2009) for 100 years, separated into 20 five-year 140 periods. For each stand, we simulated a maximum of 58 management alternatives. The exact 141 number of management alternatives applied depends on the specific initial conditions of each 142 individual forest stand. In total, 17 possible variations were available for RF management, 40 143 variations for CCF management, and one alternative where no management actions (set-aside) were 144 taken in the forest. Variations in RF management included changes to the timing of final felling, 145 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 146 147 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 148 149 for fertile sites) prior to harvesting by -3, ± 0 , +3, +6. Additionally, we varied the timing of the first 150 harvest in 5 year increments up to a delay of 45 years. The cutting cycle were afterwards determined 151 within the simulation based on basal area requirements. A summary of the management 152 alternatives is presented in Appendix A.

153

154 Ecosystem services and biodiversity indicators

155 We calculated indicators for four BD and ESS components at the stand level, based on available

156 models and the simulated structural characteristics of each stand. The four components reflect

157 important aspects for Finnish nature and people: i) recreational ecosystem services and non-timber

158 production; ii) climate change mitigation, iii) suitable habitat for terrestrial vertebrate biodiversity,

and iv) suitable habitat for red-listed species dependent on deadwood.

- 160 Recreational ESS and non-timber production included bilberry, mushrooms and scenic beauty.
- 161 Bilberry (Vaccinium myrtillys) is one of the most common wild berries in Finland and has high

162 recreational and commercial value (Vaara et al., 2013). Bilberry yield (kg) was estimated using the 163 models of Miina et al. (2016) which predicts yield based on stand characteristics such as age, basal 164 area and dominant tree species. Mushrooms have also both recreational and commercial value in 165 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 166 167 Spruce dominating stands, the model cannot provide highly accurate estimations for mushroom 168 yield (the models have a predictive capacity of 23%). Yet, they provide an indication on the 169 suitability of the sites for mycorrhizal mushrooms. Scenic beauty (no unit) was calculated using the 170 index developed by Pukkala et al. (1988), which estimates people's average opinion about the 171 recreational value and beauty of forests based on slides and computer drawings of managed stands. 172 The age and size of trees increased the recreational and beauty value as well as a big share of pines 173 and birches.

174 Climate change mitigation considered the mass of carbon contained within timber (kg C), dead wood 175 (kg C), and soil (kg C) as a proxy for carbon stock. Timber was calculated as the total volume of 176 standing timber from the different tree species. Dead wood volume (m³) was measured as the total 177 amount of dead wood from the different dead wood types comprising different tree species and 178 decay stages. Deadwood decomposition was modeled through five decay stages using 179 decomposition models from Mäkinen et al. (2006). To estimate soil carbon, for mineral soils we used 180 the models from Liski and Westman (1997) to provide initial soil carbon values, and to model the 181 development of soil carbon we used the Yasso07 modelling framework (Liski et al., 2005; Tuomi et 182 al., 2011, 2009). Drained peatland soils were modeled using the carbon flux models proposed by 183 Ojanen et al. (2014). In this study we do not include the potential carbon storage through long-184 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

188 three-toed woodpecker (*Picoides tridactylus*). We selected these species to represents a wide range

189 of habitat types, and diverse social and economic values including game birds, umbrella, and

190 threatened species. The habitat suitability models were taken from Mönkkönen et al. (2014).

191 Finally, we explored the suitable habitat availability for 27 red-listed species dependent on dead

192 wood (fungi and arthropods). Dead wood is a critical resource in boreal forests (Stokland et al.,

193 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.

197 Forest multifunctionality

198 We explored forest multifunctionality as a landscape metric rather than a stand-level characteristic. 199 Therefore, all indicators were first evaluated at stand level and then aggregated over the study area 200 to produce the total value over the landscape. We measured the ability of the forest landscape to 201 maintain high levels of all ESS and BD components (van der Plas et al., 2016). We defined 202 multifunctionality as the sum of the four normalized components (eq. 1, standardized by theoretical 203 maximum and minimal values derived from the pay-off table, Table 1), with equal priorities between 204 the components of multifunctionality. We aggregated indicators within components through two 205 measures: as the average value between all indicators (eq. 2a) and as the minimum value across all 206 indicators (eq 2b). For climate change mitigation and non-timber ESS, components were estimated 207 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 208 209 climate mitigation, carbon sequestration in deadwood can substitute carbon in standing timber; ii) in 210 non-timber ecosystem services, we maximize the summed production of these social benefits and iii) 211 for biodiversity, we want to preserve all species, hence maximize the habitat availability for the 212 species with lowest score. All species have an existence value, and we cannot thus assume that the 213 suffering of a single species can be offset by the success of other species. 214 To account for the increased costs of selective harvesting by the CCF alternatives, timber prices 215 obtained from CCF management are set to be 75% of estimated price of RF. This adjustment reflects

a doubling in harvesting costs per m³, while CCF management extract approximately 50% of

217 harvested timber than RF operations. As discount rate for the NPI, we considered a factor of 2%,

218 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

221 rather important for conservation reasons.

222 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

224 mathematical translation of these choices is shown in more detail in the following section.

225 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.

233 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

- 236 different components can be treated with different distance measures. The proposed objective
- 237 function is:

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

238 subject to:

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

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

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

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

$$[5] f_{NPI} \ge q * f_{NPI}^*$$

[6]
$$\sum_{k=1}^{K_j} x_{jk} = 1, \forall j = 1, ..., j$$

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

239 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 240 241 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 242 to harvest stand j according to management alternative k; K_i is the set of management types for 243 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 244 245 rate, and q is a parameter that determines the required proportion of the maximum net present 246 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. 247 248 Multifunctionality is measured at the landscape level indicating the sum of specific normalized 249 distances for each component. To normalize each component, we calculated a payoff table by 250 independently optimizing the components, with and without the NPI constraint. This identifies the 251 trade-offs between component groups and the range each multifunctionality measure can take. The 252 ideal and anti-ideal values $(D_b^*$ and D_{b*}) were extracted from that payoff table (Table 1). We 253 assessed multifunctionality as aggregate of the distance values from each of the four components. 254 Distance was measured in two ways, using the L¹ distance (also known as the Manhattan distance) and the as the L^{∞} distance (also known as Chebyshev distance). These measures have a preferential 255 256 translation, where L^1 distance measures the efficiency amongst criteria while L^{∞} measures equity 257 between criteria (Diaz-Balteiro et al., 2013).

258 For this problem formulation, the objective (Eq. [1]) maximizes the summed normalized distance 259 from each component of multifunctionality. Eq. [2] measures the distance of each component of the 260 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 261 262 measured by either of these equations, depending on how the components of multifunctionality are 263 measured. Eq. [3] evaluates the obtained landscape level value for the specific criterion t. Eq. [4] 264 evaluates the obtained NPI for the landscape. Eq. [5] establishes a required minimum obtained NPI. 265 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 266 267 problem formulation are described in Table 2. The optimisation problem was solved using Pyomo 268 (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).

271 Results

272 For each scenario, the proportion of unmanaged forested areas decrease following a negative linear 273 trend as the monetary value extraction increases (Fig. 2). Irrespective of the land-use intensity 274 (represented as increasing timber extraction, and measured as NPI), CCF scenario always 275 outperforms RF scenario in terms of overall landscape multifunctionality (Fig. 3a). CCF scenarios 276 provide corresponding multifunctionality values to the scenario where all management options are 277 allowed, at low and intermediate land-use intensities (NPI < 5 k€ / ha). Only at high timber extraction 278 levels, excluding the RF from forest management alternatives caused multifunctionality losses (CCF 279 relative to all management types). At maximal NPI, a consistent use of CCF results in about half of 280 the multifunctionality reduction than relying consistently on the RF alternatives. In other words, if all 281 management options are allowed, CCF is a prevailing forest management method except at high 282 levels of land-use intensity, where it is optimal to combine CCF and RF when targeting 283 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

300 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 301 302 optimum for RF is at higher NPI than for CCF.

Discussion 303

304 The results of this study highlight the significant potential for conflicts between timber extraction 305 and forest multifunctionality. Within selected indicators, we found negative effects of timber 306 extraction on deadwood habitat indicators, scenic beauty, and carbon storage. On the other hand, 307 harvesting can positively affect a small subset of the indicators such as mushrooms yield, and both 308 continuous cover forestry (CCF) and rotation forestry (RF) showed initial positive trend for some 309 dead wood habitat indicators. The complexity of how individual species groups respond to 310 extraction levels and forest management alternatives increases with an increasing number of species 311 considered. Some vertebrate species benefits from CCF, other vertebrate species can be maintained 312 using RF until the requirement for NPI exceeds a specific level. Yet, the siberian flying squirrel's 313 habitat decreased with increasing timber extraction level regardless of the applied harvesting system 314 as this endangered species inhabits old spruce-dominated mixed forests (Wistbacka et al., 2018). 315 As a political tool for improving conservation practices, restricting forest management alternatives 316 may not be a fully justifiable position. In this case, if we restrict the range of usable forest 317 management alternatives to either CCF or RF, both economic and ecological outcomes may either 318 remain similar or perform more poorly than if managers have all options available. However, this 319 analysis is based on the use of optimization, and implies that managers are making well-informed

320 decisions regarding both the economic and ecological performance of the forest, and that all forest

321 owners have a consistent preference for non-timber ecosystem services and biodiversity protection.

322 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 324 management planning relies on up to date scientific evidence, the overall timber and overall forest

325 functioning will likely be suboptimal.

323

326 The Finnish case study highlights the positive impact from the recent legislative change lifting the 327 ban of practicing CCF. Until a recent legislative change in the Finnish forest act (2014)², forest 328 owners had been restricted to intensively manage their forests and extract their timber using a form 329 of clear-felling (Appelroth et al., 1948). However, psychological barriers may prevent forest owners 330 from applying CCF due to a lack of familiarity, preventing the most appropriate management option 331 to be selected for a specific forested area (Isoaho et al., 2019). Yet, CCF methods are still not widely 332 applied. The recent citizen initiative strives to restrict the use of RF in Finnish State-owned forests 333 (~9.1 M ha of which ~85% are located in Northern Finland), while respects private forest owner's 334 decision-making capabilities. The RF restriction initiative aimed to support conservation efforts. If 335 high revenue targets are required from Metsähallitus (the Finnish governmental organization 336 managing state owned forests), exclusive reliance on CCF will have a slight positive impact on 337 ecosystem services and biodiversity considerations, as spatially intensive harvesting would be 338 replaced by temporally intensive harvesting.

339 The analysis we present highlights the potential benefits of utilizing a diverse range of management 340 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 341 342 value (Díaz-Yáñez et al., 2020; Pukkala, 2016). However, our modelling approach contains substantial 343 uncertainties which may have a dramatic impact on the provisions of BD and ESS, and the possible 344 economic output from the forests. As CCF has been used on very limited areas in Fennoscandia, and 345 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 346 347 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 348 stands and the respective costs of wood procurement. CCF is usually more profitable for less 349 350 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 m³ for log wood and ~7 € per m³ for 351

352 pulpwood).

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

353 There are several reasons why CCF can be more profitable than RF: i) Log/pulp ratio: CCF provides 354 more log and less pulp wood than RF, as the thinning is done from above, extracting the biggest 355 trees, instead than from below, extracting the smallest trees like in RF; ii) Regeneration method: 356 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 357 358 regeneration is always successful in CCF; iii) Discount rate: this has an influence on the timing of 359 timber harvests and expected rotation lengths of forests (Brukas et al., 2001). Changes in discount 360 rates may change the share of the landscape managed under RF and CCF management alternatives 361 (see Appendix B), where high discount rates reduce the supply of non-timber ESS compared to low 362 discount rates (Pukkala, 2016).

363 The use of forest planning methods and optimization can provide an optimistic view on how 364 harvesting actions can balance between timber extraction and landscape-level multifunctionality. 365 However, our approach relies on a single climate alternative and neglects potential disturbances 366 throughout the 100-year time horizon. In boreal forests, continuing water availability and increasing 367 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 368 369 periods of frozen soil and releasing tree root anchorage during the windiest time of the year (Peltola 370 et al., 2010). Warmer winters may also increase risks of insect outbreaks (Neuvonen and Viiri, 2017), 371 or potential development of newcomer forest pest species, such as *Ips amitius* (Økland et al., 2019). 372 Therefore, omitting disturbances from the forest management planning might overestimate 373 expected revenues (Díaz-Yáñez et al., 2019). We acknowledge that the impacts of climate change 374 and disturbance will affect our results. However, we believe that the consequences of climate 375 change on tree growth and disturbance risk will be equally distributed between CCF and RF 376 management alternatives. Additionally, we anticipate the increased disturbances may have a 377 stronger impact on RF than on CCF management alternatives. This will likely be due to several 378 factors. CCF is likely to have less canopy height variation between stands, i.e., avoiding open edge 379 stands protecting against wind (Zubizarreta-Gerendiain et al., 2019, 2016), and the stands will likely 380 have a higher mixing of species, mitigating potential pest outbreaks (Hlásny et al., 2019). Wider 381 range of applied management regimes increases landscape multifunctionality and compositional 382 diversity. This might provide a buffer against uncertainties and possible disturbances, compared to 383 single objective, or highly correlated ESS management types (Knoke et al., 2016).

384 Conclusion

From a forest planning perspective, limiting the diversity of management options will limit the ability 385 386 of the forest to attain a full potential of multifunctional benefits, especially at high extraction level. 387 Restricting management (either restricting RF or CCF) will likely lower the economic value, and 388 landscape multifunctionality. Thus, achieving an efficient solution between multifunctionality and 389 economic benefit will require a diverse set of management alternatives, utilizing primarily CCF with 390 small share of RF management. Interestingly, in Fennoscandian forest landscapes under natural 391 disturbance regimes, the proportion of stand replacing disturbances has been between 20 - 30%, 392 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 393 394 disturbance dynamics, rotation forestry, which emulates structures typical for stands after stand-395 replacing disturbances, should be secondary to continuous cover forestry, which in turn better 396 emulate fine-scale disturbances. According to our results, to maximize multifunctionality while 397 obtaining high timber extraction rates, the utilization of RF should be between 10 – 25% of the total 398 forest area. In the boreal forests, the primarily forest management alternative applied is RF, 399 reductions in clear cuts would likely improve landscape-scale forest multifunctionality, including 400 non-timber ecosystem services and biodiversity. However, as large proportion of productive forests 401 in Fennoscandia are privately owned, encouraging CCF in these would also be required to improve 402 landscape multifunctionality. On the other hand, complete restriction of RF in State-owned forests, 403 as suggested in Finland, will likely impede the development of the full potential of multifunctional 404 landscape, particularly in the era of bioeconomy and its expected high timber demands.

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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
ent	MAX ESS MF	0.497	<u>0.150</u>	0.027	0.075	0.694	0.395	0.160	0.265
lagem gimes	MAX CM MF	0.354	0.272	<u>0.011</u>	0.063	0.528	0.995	0.234	<u>0.055</u>
mar reg	MAX VH MF	<u>0.345</u>	0.179	0.379	0.077	0.508	0.441	0.686	0.386
All	MAX DW MF	0.372	0.182	0.122	0.171	0.416	0.586	0.238	0.618
lent	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
nagem gimes	MAX CM MF	0.481	0.212	0.037	0.117	0.529	0.994	0.238	0.054
ma reg	MAX VH MF	0.466	0.170	0.376	0.108	0.513	0.444	0.684	0.382
CCF	MAX DW MF	0.482	0.179	0.124	0.168	<u>0.453</u>	0.575	0.347	0.591
ent	MAX ESS MF	0.389	0.171	0.060	0.075	0.563	0.689	0.225	0.136
lagem	MAX CM MF	0.328	0.268	<u>0.042</u>	<u>0.046</u>	0.528	0.994	0.234	0.052
mar reg	MAX VH MF	<u>0.312</u>	0.149	0.182	0.095	0.528	0.935	0.270	0.086
RF	MAX DW MF	0.319	<u>0.136</u>	0.085	0.168	0.430	0.516	0.098	0.420

636

637 Table 1. Payoff table between component groups, for each of the component groups (ESS MF –

638 Ecosystem service multifunctionality, CM MF – Climate mitigation multifunctionality, VH MF -

639 Vertebrate habitat multifunctionality and DW MF – Deadwood habitat multifunctionality). Maximal

640 values are bolded, while the minimal values are underlined.

<u>Symbol</u>	Definition						
Sets:							
В	Set of components						
T _b	Set of criteria use in analysis, for each component b						
Р	Set of time periods under consideration						
J	Set of all forest stands						
Kj	Set of all management alternatives for forest stand <i>j</i>						
Data:							
z_{jkp}^t	The value of criterion t when conducting management alternative k on stand						
	<i>j</i> for period <i>p</i>						
f_t^*	The ideal value obtainable for the criterion <i>t</i>						
f_{t*}	The anti-ideal value obtainable for criterion <i>t</i>						
D_b^*	The ideal value obtainable for the multifunctionality component <i>b</i>						
D_{b*}	The anti-ideal value obtainable for the multifunctionality component <i>b</i>						
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 <i>j</i> according to management alternative <i>k</i>						
Parameters:							
r	The discount rate						
q	Required proportion of maximum net present value						

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



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



- Fig. 2. Land-use intensity in terms of net present income of the different scenarios, measured as
- 652 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
- 654 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
- 657 management alternatives, readers are guided to Appendix A.





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.